Technological Review of Permeable Pavement Systems for Applications in Small Island Developing States (SIDS)

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ABSTRACT

This paper presents a technological review of permeable pavement systems (PPS) for applications in urban areas of small island developing states (SIDS). This review includes a literature survey of PPS, challenges and opportunities of climate change and urban development in SIDS and key aspects worth considering for widespread acceptance and use of PPS in SIDS. SIDS comprise of several nations located across the Atlantic, Pacific and Indian Oceans and the Caribbean, Mediterranean and South China seas. They are particularly susceptible to the effects of climate change and increasing urbanisation. Urban stormwater management and flooding are often serious challenges faced by authorities in most SIDS. PPS are resilient infrastructure which can assist in mitigating flooding by reducing runoff and peak flows and improving the landscape perviousness. PPS can further improve stormwater runoff quality to receiving natural waters by reducing pollutant loadings of suspended solids, heavy metals and hydrocarbons. Unlike most territorial states, the geographical and geologically confined nature of most SIDS present unique parameters for consideration when designing permeable pavements for SIDS. This literature survey found that some of the most important parameters include traffic loads, cost, construction aggregate choice and availability, permeability of existing soil at the intended location, depth of water table, potential for groundwater contamination, slope of the pavement, stormwater reuse option, clogging, maintenance and support from policy makers. Continued practical research into the use of permeable pavements for urban runoff management in SIDS is on-going with the expectation of PPS being utilised in many SIDS.

Abbreviations: AASHTO, American Association of State Highway and Transportation Officials; **ADB**, Asian Development Bank; **ASTM**, American Standards for Testing and Materials; **BMP**, best management practice; **CB**, crushed brick; **CDW**, construction and demolition waste; **CGP**, concrete grid paver; **ICPI**, Interlocking Concrete Pavement Institute; **LWAA**, lightweight artificial aggregate; **LID**, low impact development; **MSWI**, municipal solid waste incineration; **PA**, porous asphalt; **PC**, porous concrete, **PGP**, plastic grid paver; **PICP**, permeable interlocking concrete paver; **PPS**, permeable pavement systems; **PSD**, particle size distribution; **RA**, recycled aggregate; **RAP**, recycled asphalt pavement; **RCA**, recycled concrete aggregate; **SIDS**, small island developing states; **WG**, waste glass

Keywords: Low impact development (LID), Permeable pavements, Resilient Infrastructure, Small island developing states (SIDS), Sustainable urban drainage systems (SUDS), Urban stormwater management,

1 INTRODUCTION

1.1 Geography, Weather and Climate in SIDS

Small island developing states (SIDS) represent a diverse and multicultural group of 37 United Nations (UN) member states and 20 non-UN members/associate members of regional commissions located across the Atlantic, Pacific and Indian Oceans and the Caribbean, Mediterranean and South China seas as illustrated in Figure 1 (https://sustainabledevelopment.un.org/topics/sids/list). They commonly enjoy a rich variety of highly-endemic flora and fauna but limited natural resources.[1]

The climatic conditions of SIDS are variable, generally characterised by large seasonal variability in rainfall throughout the regions. Seasonal temperature differences vary slightly for low-latitude islands but substantially for high-latitude islands.[2]

The Caribbean SIDS have tropical marine climates, with more diurnal and local variations in temperature (22--33°C) rather than seasonal ones. There is a strong seasonal variation in rainfall distribution. Two distinct seasons exist; a dry season from January to May and a wet season from June to December which comprises of a hurricane season from June to November. 75 to 80% of rainfall is received during the wet season.[3]

The climate of SIDS in the central Pacific is tropical and influenced by numerous contributing factors such the trade wind regimes, seasonally varying convergence zones such as the inter-tropical convergence zone (ITCZ) and the South Pacific convergence zone (SPCZ), sub-tropical high pressure belts and southern zonal westerlies, with El Niño Southern oscillation (ENSO) dominating yearly variations.[2, 4]

SIDS climate in the Indian Ocean is mostly influenced by the Asian monsoon. Those of the Mediterranean are influenced mainly by the bordering lands whereby rainfall is predominantly received during the winter months of the Northern hemisphere with prolonged summer droughts being experienced between four and five months.[2]

Average annual rainfall depths and temperature variations amongst the various SIDS groups are presented in Figure 2. Insignificant variances are observed amongst the three SIDS groups with an approximate mean of 2000 mm. The mean annual rainfall comparisons between SIDS and selected developed nations are presented in Table 1. It is noteworthy that the majority of published studies on the field performance of permeable pavement systems (PPS) originate from nations which receive less than 50% of SIDS' mean annual rainfall. This is significant and should be taken into consideration when designing PPS for SIDS.

1.2 Challenges and Constraints

SIDS, in their drive towards sustainable development are confronted by numerous challenges and constraints of which ecological fragility and economic vulnerability dominates.[1] Naturally, most SIDS are geologically confined by coastal zones with small and isolated (such as archipelagic states) land extents of either volcanic derivation or coral based. These challenges often lead SIDS to be highly reliant on international trade and consequently are exposed to global economic variances.[1] Geographically, most SIDS are extremely vulnerable to natural disasters such as hurricanes, cyclones, floods and droughts, all of which threaten lives, property, natural resources and critical urban infrastructure.[6] The effects of these disasters are often extremely costly. Cyclones have accounted for 76% of the reported disasters in the Pacific island region from 1950 to 2004 with an average estimated cost per cyclone of US$ 75.7 million.[7] Four countries of the Caribbean (Dominican Republic, Grenada, Jamaica and the Bahamas) amassed an estimated US$2.2 billion in damages resulting from the 2004 Caribbean hurricane season which runs from June to November each year.[7] 2004 was the worst year for the Caribbean region over the last two decades in terms of estimated damage costs from cyclones[8] (unpublished paper). In contrast to larger territorial countries, a SIDS natural disaster can cause total collapse of economic networks, widespread environmental destruction and considerable and extensive disruptions in the social fabric of the affected SIDS.[7]

Amongst the numerous challenges faced by SIDS are the very few common opportunities. These include tourism, aquaculture and fisheries, maritime "blue" economy, renewable energies such as wind, solar and geothermal to some extent, biodiversity and ecosystem-based adaptation.[9]

Despite these common challenges and opportunities, it is noteworthy that SIDS vary politically, socially, culturally, in physical size and character or economic development.[10] The SIDS label is inconsistent given that not all descriptors are true for all SIDS. Papua New Guinea with an area close to 463 000 km^2, is almost twice New Zealand's size and could not be considered "small" compared to Tuvalu's 26 km^2. Belize, Guyana and Suriname are not surrounded by water, hence do not conform to the "island" definition. The Cayman Islands could not essentially be termed "developing" given that their economic data is superior to that of numerous European countries. Netherland Antilles and Montserrat are territories, as opposed to states, implying sovereignty. [11]

1.3 Urban Development in SIDS

The Asian Development Bank (ADB), refers to the term *urban* with regards to SIDS as a small town linked to villages bordering a coast, a small town connected by villages on an island, or a succession of islets.[12] There are approximately 38 million (59%) of the 65 million persons living in SIDS, residing in urban settlements.[6] While there is a wide variation amongst SIDS with respect to the urban population, ranging from Singapore and Nauru, standing at 100% (most urbanized) to Papua New Guinea with 13% and Trinidad and Tobago with 8.5% (least urbanized), they share the common trend of increasing urbanization.[13, 14] Listed in Table 2, are the comparative levels of urbanisation in the Caribbean, the pacific islands, the world and more developed regions (MDR) for the period 1950 to 2014 in addition to 2050 projections. The Caribbean has experienced unprecedented urbanisation over the last few decades and is presently the world's most urbanised island region.[15] Since the 1950s, urbanisation was already at 36% in the Caribbean with this figure increasing to 45.4% by 1970. By 2014 the percentage of people living in urban areas in the Caribbean increased significantly to 70% with projections of 81% by 2050.[13]

For some SIDS, lack of land space available for development has forced development of coastal lands. This is the case for urban cities such as Port of Spain in Trinidad and Tobago which has had to reclaim land for further expansion of the city.[6]

1.4 Climate Change and SIDS

Climate change can have alternative meanings. This paper follows that defined by the Intergovernmental Panel on Climate Change (IPCC) as "*any change in climate over time, whether due to natural variability or as a result of human activity.*"[2] By distinction, the United Nations Framework Convention on Climate Change (UNFCCC), defines climate change as "*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*."[17]

SIDS are predominantly vulnerable to the impacts of climate change which include increased global temperatures, precipitation and sea level rise.[10] This was recognized in the Barbados Programme of Action (BPOA) for the Sustainable Development of SIDS adopted in 1994.[18] Global warming and the resulting sea level rise can become disastrous, threatening the existence and sovereignty of some SIDS whilst potentially reducing the land area in others.[6] A recent study by Simon et al. [19] suggested that five tiny vegetated islands of the Solomon Islands in the Pacific have disappeared due to rising sea levels and erosion. Islands such as the Maldives and the Marshal Islands in the Pacific could also become inundated given that their highest elevations are three meters above sea level. According to UN-OHRLLS [7], sea surface temperatures in oceans surrounding SIDS have been increasing by 0.1 °C per decade with projections exceeding 1.5 °C by the end of the 21st century. There have also been increases in extreme temperatures in the South Pacific and Caribbean regions. Rising sea levels have been estimated at 0.77 mm/year in the Pacific region, 1 mm/year in the Caribbean and 1.5 mm/year in the Indian Ocean.[7] Furthermore, according to UN-OHRLLS [7], changes in rainfall patterns in the Caribbean could result in decreasing numbers of consecutive dry days with a subsequent increase in the number of heavy rainfall events in the Caribbean.

The progress of SIDS striving towards achieving sustainable development goals is under constant threat because of climate change.[6] The urban centres, economic zones and agricultural lands of most SIDS are usually located in lowlands along coastal zones thereby exposing them to sea level rise, extreme tides, and wave and surge events.[10, 20] Nurse et al. [10] presented a literature review on the observed impacts of climate change on human systems in SIDS. In this review Nurse et al. [10] restated that in the case of atoll islands for instance, rapid urbanisation in city centres promoted unplanned developments at vulnerable locations.

Majority of SIDS experience problems regarding access to a reliable, safe, sustainable and affordable supply of potable water.[21] Water resources on SIDS are limited and particularly vulnerable to human-induced and natural stressors. At present numerous SIDS share common problems associated with the reliability and availability of clean water. This is a serious problem for several SIDS today and one which is forecasted to increase in the future because of climate change.[22] Presented in Table 3 are water resource-related issues faced by individual SIDS groups.

Climate change affects groundwater in many SIDS. Sea level rise is projected to widen the areas of seawater intrusion and salinization of coastal groundwater, resulting in decreases in freshwater available at coastal zones in some SIDS. This becomes more critical in some SIDS as groundwater recharge decreases with changes in rainfall distribution.[23] Further, groundwater resources on several SIDS, particularly low-lying carbonate islands are vulnerable because of several factors including limited land area, urbanization and increasing demand over supply, decrease in surface water supply and pollution.[23]

Several SIDS have commenced implementation adaptation approaches to manage climate change. In Vanuatu, villagers who experienced frequent flooding and erosion were moved to higher grounds.[7] The Virgin Islands, in its pursuit towards achieving low-carbon, climate resilient development developed in 2012, *The Virgin Islands Climate Change Adaptation Policy* which includes cost effective actions to adapt to the local impacts of climate change as well as mitigate carbon emissions.[24] In order to mitigate the impacts of climate change to critical infrastructure, human settlements and water resources, the Government of the Virgin Islands is seeking to develop and approve numerous policies. One such policy is to minimize impervious surfaces by using PPS for sidewalks and parking lots in an effort to reduce stormwater runoff.[24] Others include utilisation of green roofs and other SUDS. [24] Singapore's Active Beautiful Clean (ABC) low Impact Development (LID) Waters Program implemented in 2006 will likely be impacted by larger, more intense rainfall events which may lead to modified design features to cope with the changing climate.[25]

SIDS are not alone when it comes to climate change effects. More developed nations such as the Netherlands for example has been affected by sea level rise due to climate change resulting in obstructions in rainwater flow because of longer high tides. For the century prior to 2006, the sea level has risen by 200 mm with projections of 600 mm in the next century. Furthermore, climate change has affected rainfall patterns with heavier and more intense storms have been observed. To address these potential problems, the Netherland authorities recommended PPS with storing capacity as a possible solution.[26]

1.5 Rationale for Permeable Pavement Systems in urban areas of SIDS

'Sustainability' has been recognised as a very important concept for the effective management of urban drainage [27-29]. Sustainability with regards to water systems, focuses on restoration of viable and resilient aquatic biota and the coherent usage of urban water resources by present and future generations.[28, 30] The terms "sustainable urban drainage systems (SUDS)," "low impact development (LID)," "water sensitive urban design (WSUD)," and "best management practices (BMP)" refer to similar concepts.[31] SUDS is used in Europe focusing on the maintenance of good public health, protection of water quality and preservation of biodiversity and natural resources for future needs.[29, 32-34] LID is used in the United States and Canada to describe an approach which aims at achieving stormwater management controls by fundamentally changing conventional site design to create an environmentally functional landscape that mimics natural watershed hydrologic functions.[35] BMP in the United States and LIUDD (low impact urban design and development) in New Zealand are examples of similar approaches.[36] WSUD is used in Australia to mainly refer to a planning and engineering approach to achieve harmony between water and the urban environment through the sustainable integration of urban water management into the city landscape.[37-39]

For several decades, collection and conveyance of stormwater away from urban areas across SIDS have been via conventional drainage systems.[40] The conventional drainage system is mainly a single-objective oriented design which focuses primarily on stormwater quantity control.[41] It does not focus on environmental concerns relating to water quality, visual amenity, biodiversity and ecological protection.[42]

In addition to these environmental fears, the limited capacity and flexibility of conventional drainage systems to adapt to future climate variations and urbanisation has continuously been criticised.[43, 44] Numerous studies [45-49] have reported that urbanisation increases stormwater runoff volume, flow rates and peak flows because of increases in impervious surfaces. This often leads to flooding and erosion problems downstream of the discharge area.[41] Inefficient urban stormwater drainage systems in SIDS often contributes to flooding of varying magnitudes on an annual basis.

In addition to increasing urbanisation, urban drainage problems of many SIDS have often been exacerbated by poor land use practices,[50] improper utilisation of drainage infrastructure (littering) and faulty designs. Furthermore, subsequent operation and maintenance of drainage systems present major challenges to urban authorities.[51]

SUDS such as PPS present a feasible solution to reduce the likelihood and impact of urban floods within most SIDS.[51] PPS replace conventional paving surfaces with a source control resilient infrastructure which can prevent or significantly delay stormwater runoff generation.[52] Additionally, PPS can increase groundwater recharge, treat stormwater runoff and reduce pollution of natural watercourses.[53] Lack of land space in urban SIDS often restrict the implementation of other SUDS such as retention/detention ponds and wetlands.

Very few SIDS have permeable pavement systems in use. There are no published peer-reviewed papers to the authors' best knowledge, evaluating the performance of permeable pavements in SIDS. One guide by Horsley Witten Group (HWG) and Center for Watershed Protection (CWP) [54] listed few SIDS where permeable pavement systems were used. These SIDS were St. Croix, St. Thomas and St. John of the US Virgin Islands and American Samoa. The site at St. Croix was located at the University of the Virgin Islands Research and Technology Park as part of a "green" building initiative in combination with other LID practices such as vegetated bio-swales. Permeable interlocking concrete pavers and grass pavers were the preferred pavement surface types for both sites. Some of these applications are illustrated in Figure 3. No information is forthcoming regarding the performance of these PPS.

Before permeable pavements can be used effectively and extensively in urban areas of SIDS, further research is needed to evaluate their usage as a long-term sustainable urban drainage option for flood risk reduction and improvement in urban runoff water quality. This paper collates ideas and research outputs from numerous studies worldwide, highlighting PPS as a form of sustainable urban drainage system. The review includes a literature survey of PPS and discusses key aspects for consideration when designing PPS for SIDS.

2 LITERATURE SURVEY OF PEARMEABLE PAVEMENTS

2.1 Overview

The use of PPS dates back to the early 1970s.[55] The process allows for infiltration of stormwater runoff through structural pavements, promoting pollutant removal and pre-development site conditions.[56] Typical applications include roadway shoulders, residential driveways, parking lots, sidewalks, bicycle lanes and pedestrian access.[57] The vertical profile of a typical PPS is illustrated in Figure 4.

2.2 Permeable Pavement Systems Structure

The primary objectives and design requirements of PPS are in contrast to traditional pavements.[58] Traditional pavements, designed for use by vehicular traffic, is normally constructed in layers consisting of a rigid or flexible surface layer and one or more compacted aggregate subbase/ base courses overlying a compacted subgrade.[58] Stormwater is typically not permitted through the surface layer of conventional pavements. Permeable pavements, on the contrary, allow the infiltration of stormwater through the pavement structure [59] thereby mimicking the natural soil environment. A cross section schematic of a PPS with geotextiles is shown in Figure 5. The structure typically consists of a permeable paving surface and layers of coarse aggregate (subbase and base) materials that function as a storage reservoir during rainfall events, a bedding layer which supports the paving surface and optional geotextile layer(s).

The typical materials used for permeable pavements include natural aggregates with gradations based on ASTM C33, Specification for concrete aggregates.[60] ASTM No. 8 aggregate is typical for the bedding layer, ASTM No. 57 for base and ASTM No. 2 for the subbase. For improved hydraulic and structural performance, these aggregates are typically clean, single-sized or open-graded and angular. The excessive voids between the aggregates permit high permeability usually in excess of 25 m/h.[61] Underdrains and geotextile layers are optional depending on design requirements and in-situ subgrade (natural soil) permeability conditions.

The primary purpose of geotextiles in PPS is separation. They are often used to restrict the movement of fines into the aggregate storage reservoir. Furthermore, geotextiles assist in retaining pollutants and degrading oil.[62-64] Placement of a geotextile layer in PPS has however been inconsistent with some studies proposing reasons either for or against them. Mullaney and Lucke [65] conducted a literature review on the inclusion of a geotextile layer in PPS and reported some concerns. Geotextile layers were thought of as providing restrictions to the hydraulic conductivity of PPS in addition to compromising the structural integrity of the pavement through the creation of a slip plane which reduced the friction between the various aggregate layers of the pavement.[65] Either way additional scientific evidence is required to support both arguments.

The typical design of PPS considers various boundary conditions for either no, partial or full infiltration into the *in-situ* soil.[56] When infiltration into the in-situ soil (sub-grade) is not desired, an impermeable geotextile layer is often used to separate the subgrade and the sub-base layer along An underdrain (perforated pipe) positioned at or near the bottom of the sub-base layer collects and conveys runoff to a desired outfall. This is often the case for permeable pavements installed over clayey subgrade soils with high shrink-swell potential and low permeability. These pavements are typically designed with a thicker aggregate storage layer for increased structural capacity.[66]

2.3 Types of Permeable Pavements

A variety of permeable pavements have been identified based on their surface layer which are either monolithic, modular or grid types. Monolithic permeable pavements facilitate infiltration of water through their surfaces. Examples include porous asphalt (PA) and porous concrete (PC). Modular pavements consist of concrete blocks placed adjacent to each other in various patterns with infiltration taking place through the joints between the blocks. The most prevalent modular units are permeable interlocking concrete pavers (PICP). Grid pavements consist of large gaps which facilitate infiltration. Examples include concrete grid pavers (CGP) and plastic grid pavers (PGP).[67]

PA is traditional hot mix asphalt with a reduced percentage of fines. The reduction in fines creates interconnected void spaces which facilitate drainage of stormwater. Voids of approximately 22% have been reported by van Heystraeten and Moraux [68] for compacted PA. These voids increase skid resistance and reduce aquaplaning, splash, spray, noise level and light reflection [68]. For improved structural integrity and temporary stormwater storage, an underlying base course layer is typically required.[61]

PC is concrete with a high porosity achieved due to the absence of fines thereby creating a highly interconnected void content.[69] Typically, PC has a water to cementitious materials ratio of 0.35 to 0.45 with a void content of 15 to 25% (www.nrmca.org/GreenConcrete/CIP%2038p.pdf). Due to the high void content, PC is lightweight with densities ranging from 1600 to 1900 kg/m^3. PC pavements are typically placed as a 100 to 200 mm thick mat with a gravel base to facilitate storage or infiltration. Compressive strengths of PC pavements are limited, ranging from 2.8 to 28 MPa (www.nrmca.org/GreenConcrete/CIP%2038p.pdf).

PICP consists of manufactured modular concrete units of various shapes and sizes placed adjacent to each other in various patterns.

Drainage is typically through small joints/ openings between the units which range from 3 to 13 mm. These openings usually comprise 5 to 15% of the surface area of the units and are filled with highly permeable small aggregates. In the U.S.A., PICPs conform to ASTM C936 [70] which ensures that paver blocks have a minimum depth and compressive strength of 60 mm and 55 MPa, respectively. Figure 6 illustrates the minimum compressive strengths required of block pavers in developed nations. Compressive strengths range from 40 MPa (New Zealand) to 60 MPa (Germany). PICPs, when designed and constructed adequately, are attractive, durable, easily repaired, require low maintenance and can withstand heavy vehicle loads.[71]

CGP conform to ASTM C 1319,[73] which defines concrete grids as having maximum dimensions of 610 mm long by 610 mm wide and a minimum nominal thickness of 80 mm.[66, 71] Open/void area percentage ranges from 20 to 50% comprising typically of soil and grass, sand, gravel or aggregates in the open spaces.[66] Photoanalysis determined that CGP surface was approximately 30% open.[74] A pavement structure utilizing CGP typically consists of fill media, a bedding sand layer (25 to 38 mm thick),a gravel base course layer, and a compacted soil subgrade.[75]

PGP also referred to as geocells, are made up of heavily voided flexible plastic interlocking units which can be infilled with gravel, soil and grass that permit infiltration of stormwater. It is typical for the installation to include a sand bedding layer and a gravel base course layer to improve infiltration and storage. Grids are usually 90 to 98% open space when empty. As such, void space depends on the fill media.[61]

Where PPS have been utilised, PICPs have been the preferred option primarily because of their superior structural capacity and infiltration performance, lower maintenance and ease of installation.[76]

2.4 Design of permeable pavement systems

In general, the success of a permeable pavement takes into account both its structural and hydrologic integrity. Structural design considers pavement strength to support loads.[77] To date, no standard structural design procedure has been adopted for all permeable pavement types.[78] Hydrologic design considers the capacity required for infiltration, storage and detention of water as a sustainable stormwater management approach.[77] The provision and maintenance of surface infiltration and storage capacity is fundamentally important to allow an adequate volume of stormwater to be captured and treated.[79] The design process of permeable pavements has been well documented by several researchers.[77, 78, 80]

2.5 Hydrologic Performance

PPS hydraulic characteristics generally contribute to four areas of hydrologic control: peak flow, volume, hydrograph timing and duration.[52] Numerous conditions should be considered when comparing results relating to the hydrologic performance of PPS. The major factors include local climatic and in-situ soil conditions, depth of pavement structure, boundary drainage conditions and age of the PPS.[81] Other conditions such as rainfall intensity and duration should be monitored to ensure full characterisation of the hydrologic behaviour of a permeable pavement. Spatial heterogeneity is typical for field-scale installations due to differential inputs, traffic loadings, drainage patterns and installation and maintenance conditions across the pavement surface.[81]

Booth and Leavitt [82] evaluated the long-term performance of four full-scale field PPS and reported a virtual absence of surface runoff from all the PPS. Abbott and Comino-Mateos [83] presented a paper on the hydraulic performance of an in-situ operational PPS in Wheatley, U.K They (Abbott and Comino-Mateos [83]) reported an average 77.5% surface runoff reduction for various storm events. In a 26-month monitoring study of a permeable parking lot consisting of two sections of PICPs, one CGP and one PC in Eastern North Carolina, USA, Bean et al. [74] reported a reduction and at times an elimination of surface runoff. Collins et al. [84] found that for the same area of study, PICPs and CGPs were able to retain up to 6 mm of rainfall with no runoff. Alyaseri and Zhou [85] evaluated the effectiveness of permeable pavement in reducing the volume of stormwater in combined sewers and reported reductions in stormwater runoff of 36, 13 and 46% from PC, PA and PICP pavements, respectively.

Some studies[86, 87] use volumetric runoff coefficient (different from the Rational Method runoff coefficient) to assess the hydrologic performance of permeable pavements. The average volumetric runoff coefficient defined as the total runoff volume to the total depth of rainfall for conventional pavements are typically of the order of 80 to 95 %.[86] Hunt et al. [87] reported average volumetric runoff coefficients ranging from 0.2 to 0.5 for a permeable paving parking lot with a concrete grid paver constructed over sandy soils in North Carolina, USA. Rushton [86] found that for a permeable pavement section of a parking lot in Florida, USA, the average volumetric runoff coefficient was found to be 0.10 as compared to 0.58 for an asphalt surface section.

Other studies use the runoff coefficient as defined in the Rational Method as the ratio of the peak rate of runoff to the rainfall intensity [88] to assess the hydrologic performance of permeable pavements. In essence, this is the supply period of rainfall resulting in runoff after initial losses have occurred. Ball and Rankin [89] found supply period runoff coefficients ranging from 0.04 to 7.33% for permeable section of a suburban street in Manly, Australia. The comparable values for pervious surfaces are from 5 to 35% respectively. Furthermore, the installation of the permeable pavement section reduced the effective imperviousness of the catchment from 45 to 3% thereby restoring permeability to an urban catchment.

The deficiency of using volumetric runoff coefficients is that different storms for the same PPS will have different volumetric runoff coefficients given that the rainfall depths vary per storm event.

Very few studies[52, 90, 91] have reported on the hydrologic performance of PPS over fine grained soils with low permeability. Dreelin et al. [90] evaluated porous pavement as a viable Best Management Practice (BMP) for controlling stormwater runoff on fine-grained clay soils. They compared the performance of an asphalt parking lot and a porous pavement parking lot of grass pavers in Athens, Georgia, USA and reported that the porous lot produced 93% less runoff than the asphalt lot. However, rainfall events were relatively small and of low intensity. Further, the reported percolation rates of the subgrade soils actually had high permeability from 48 to 167 mm/h. Fassman and Blackbourn [52] investigated the hydrologic performance of a 200 m^2 PPS constructed over clayey subgrade soils with an estimated permeability of 0.01 mm/day in New Zealand over a two year period. The impermeable nature of the subsoils had little impact on the hydrologic performance of the pavement. According to the researchers, the findings were 'exceptional' given that peak discharges from the underdrain were lower than modelled predevelopment conditions for most storm events. Tyner, et al. [91] measured exfiltration from pervious concrete through a clay subgrade soil at 8mm/d and suggested that constructing features such as infiltration trenches and boreholes, or ripping the subgrade soil could enhance infiltration.

2.6 Water Quality/ Environmental Performance

It is typical for stormwater runoff from urban areas to be laden with pollutants gathered from impermeable surfaces from a wide variety of anthropogenic activities and environmental processes.[81, 89] These include suspended solids, oils, heavy metals, organic matter, bacteria and nutrients. The origin of the majority of these pollutants is often from varying sources including decomposing litter, building materials, vehicle wear and traffic emissions. Left untreated, the quality of nearby watercourses and the environment in general is at risk.[63]

Permeable pavements have been shown to reduce stormwater pollutants including heavy metals, motor-oil, sediments and some nutrients.[74, 92-95] However, the nutrient removal capabilities of permeable pavements are less understood[66] with some studies[74, 84, 96, 97] reporting varying results. Day et al. [96]; Bean et al. [74] and Gilbert and Clausen [97] reported removal of total phosphorous (TP) attributed to adsorption to sand and gravel subbase materials whilst a similar study[84] has reported little change in TP concentrations. A handful of studies[97, 98] have shown a reduction in concentrations of all measured nitrogen species (NH_4-N, TKN and NO_3-N) whereas other studies[84, 96] have reported certain forms of nitrogen concentrations to rise or remain unchanged. These differences could be attributed to varying local environmental conditions.

PPS can act as powerful in-situ bioreactors that can reduce hydrocarbon contamination by 99%.[99] The large surface area within the existing voids within the pavement structure creates a biological diverse micro-ecosystem capable of degrading pollutants such as oil leaks from automobiles.[61] Pratt et al. [100] evaluated the in-situ microbial bio-degradation of mineral oil within a full-scale laboratory model of a permeable pavement system over a 300-day period at Coventry University, U.K. The authors reported that the pavement performed as an effective in-situ bioreactor, reducing petroleum contamination in the effluent by 97.6%. According to Pratt et al. [100], nutrient supply is essential to maintain biodegradation efficiency. The authors used a slow-release fertilizer to provide a constant, low-level supply of nutrients to the biomass which promoted sustained oil-degradation within the structure. It is noteworthy that efficient use of nutrients must be ensured, otherwise there is danger that high levels in the effluent can lead to eutrophication problems in receiving waters. Newman et al. [99] assessed the nature and biodiversity of microbes (microbial fauna) found within a laboratory-scale PPS after four years of continuous oil and simulated rainfall inputs. The authors reported 99 % efficiency in terms of oil retention.

2.7 Reduction in Urban Heat Island

Urban heat island (UHI) can be defined as the increase of the sub-surface, surface, or air temperatures observed in an urban environment compared to the relatively low temperatures of rural surroundings.[101] High urban heat is mainly the result of anthropogenic heat sources such as vehicles, power plants and air conditioners as well as re-radiated solar radiations stored in large concrete and asphalt infrastructure.[102] Human thermal comfort, air quality and energy usage of nearby vehicles and buildings can potentially be affected by surface and near-surface heat islands.[103]

The United States Environmental Protection Agency (US EPA), identifies 'cool pavements' in addition to cool roofs as an urban heat island mitigating strategy.[104] Permeable pavements have been considered 'cool' because of their ability to potentially reduce the temperatures of both pavements and air at or near the surface [105] through evaporative cooling.[106] Li et al. [103] studied the use of permeable pavements for heat island mitigation in California and found that the permeable pavements, under wet conditions, recorded reduced surface temperatures as compared to impermeable pavements.

3 Discussion

3.1 Considerations and Solutions for use of Permeable Pavements in SIDS

A literature survey has been performed on a broad scale to categorise PPS in terms of types, performance and applications. This survey provides guidance and support to SIDS engineers.

Urban stormwater control in tropical zones where most SIDS are located is different to other regions of the world because of political instability, economic fragility, climate change vulnerability and infrastructural and maintenance challenges. Additionally, flooding remains a huge challenge for SIDS. The ultimate goal of maintaining an efficient and sustainable urban drainage system still applies. It is noteworthy however, that rainfall events in most SIDS are more frequent and of higher intensities than nations of temperate regions where permeable pavements have been used extensively. The literature survey presented previously attests to that. Consequently, the selection of appropriate LID strategies will require special consideration given the numerous variations amongst SIDS. Discussed below are some key factors for consideration if PPS are to be used successfully in SIDS.

3.1.1 Physical

3.1.1.1 Structural Integrity and loading applications

The anticipated traffic supported by the permeable pavement can be characterised according to AASHTO [107] as equivalent 80 KN (18 000 lb) single axle loads (ESALs) and average daily traffic (ADT).[108] Permeable pavements in North America have typically been designed for applications not exceeding approximately 1 million ESALs.[109] Traffic loadings in SIDS are expected be to significantly less than 1 million ESALs due to the lower traffic volumes, smaller parking lots and fewer heavy trucks.

3.1.1.2 Aggregate selection and availability

Given the geological confinement of most SIDS, suitable aggregates for incorporation into PPS may not be available in sufficient quantities and at the particular time of need. Further, there is a growing demand for construction aggregates in SIDS as demand for housing and other public infrastructure increases with urbanization. In Trinidad and Tobago for instance, the demand for construction has seen a drastic increase during the past decade. In most recent times, however, the global economic slowdown has since resulted in a decline in construction activity.[110] Nevertheless, the demand for civil engineering materials, construction aggregates in particular remain high.[110] In 2015, the contractor on one of the major highway extension projects in Trinidad and Tobago, imported virgin aggregates by cargo ship from Canada; a journey of 3785 km. Some SIDS practice unsustainable methods to obtaining construction aggregates for meeting this demand. For instance, beach mining of aggregates is heavily practiced in the coral nation of Kiribati, one of the Pacific islands. This practice coupled with climate change, increases the probability of damages and disasters associated with rising sea levels.[111] Other volcanic SIDS such as most of those of the Caribbean produce high quality construction aggregates through quarrying. This practice too is not sustainable and presents an environmental challenge.

Preserving the environment and conserving the rapidly diminishing natural resources should be the core of sustainable development.[112] SIDS nations should, therefore, consider the use of waste, recycled or recyclable materials in PPS such as construction and demolition waste (CDW), crushed brick (CB), recycled aggregates (RA), recycled concrete aggregates (RCA) and lightweight artificial aggregates (LWAA) made from municipal solid waste incineration (MSWI) ash. MSWI is, however, beyond the reach of most SIDS due to the high costs involved.[113] Kinnaman [114] also argues that incineration may not be appropriate for several SIDS for two main reasons. Firstly, MSW in these SIDS are not very combustible because of the high percentage of organic waste component which contain low levels of energy and high levels of moisture. Interestingly, Trinidad and Tobago, one of the more developed SIDS in terms of gross domestic product (GDP) recorded only 27% organics in their waste characterization study conducted in 2010.[115] Secondly, Kinnaman [114] mentions economies of scales in incineration whereby it becomes uneconomical for plants to operate at less than 1100 tons of waste per day. Indeed Kinnaman [114] suggested that Trinidad and Tobago was able to capture these scale economies due to its large population; but small SIDS nations such as Barbados, St. Lucia, Antigua and those of the Pacific fell short.

Numerous researchers[72, 116-120] have reported using recycled waste materials in civil engineering applications worldwide. CB, RCA and reclaimed asphalt pavement (RAP) have been reported to be suitable for pipe backfilling materials for stormwater and sewer pipes.[116] RCA and CB have been used for unbound subbase materials.[117-119] Blast furnace slag has been found suitable for use in road subbases.[120] LWAA have been used in several construction applications including lightweight concrete, lightweight blocks, lightweight geotechnical fill, insulation products, filters, and drainage. Their typical particle densities range between 0.8 to 2.0 g/cm^3. Particle densities of natural aggregates tend to range between 2.4 and 2.8 g/cm^3.[121] Waste glass (WG) has been used in pavements for several decades. Jamshidi et al. [72] presented a thorough review of the use of WG on the structural performance, durability and sustainability of asphalt, concrete and concrete block pavements.

Very few studies[53, 120, 122, 123] have reported on the performance of recycled waste material in permeable pavements. Blast furnace slags were used in permeable paving blocks with no reported leaching by Nishigaki [120] Rahman et al. [53] during a laboratory study, investigated the hydraulic performance and pollutants removal efficiency of PPS using CDW materials in combination with geotextile. The recycled CDW materials used were CB, RCA and RAP. Rahman et al. [53] reported that the geotechnical and hydraulic properties of CDW materials in the pavement filter layers were consistent or superior to that of typical quarry aggregates. With regards to LWAA in permeable pavements, research is ongoing in the Caribbean and England by Tota-Maharaj et al. [124] on the novel use of LWAA, referred to as Carbon-negative Aggregates in permeable pavement systems. Khankhaje et al. [122] compared the effect of using two different sizes of oil palm kernel shell (OPKS) and cockle shell (CS) as partial replacement of natural coarse aggregate on the properties of pervious concrete pavement. The authors reported a decrease in compressive strength of the pervious concrete with increased shell contents but suggested that the values obtained satisfied the requirements for lightly traffic areas such as parking lots and footpaths. Çetin [123] incorporated recycled household plastics (low density polyethylene (LDPE)) as a supplemental aggregate (1, 3 and 6%) in porous asphalt to produce a permeable plastic pavement. Çetin [123] reported that when compared to traditional flexible pavements, permeable plastic pavements are superior in terms of sustainability.

3.1.1.3 Subgrade conditions

Permeable pavements are designed for full, partial or no infiltration based on the *in-situ* soil hydraulic conditions or Hydrologic Soil Groups (HSG).[125] Permeable pavements constructed over fine-grained soils (silts and clays) generally require thicker pavements than those constructed over coarse-grained soils (sands and gravels).[77] The characterisation of the subgrade should consider in addition to hydraulic design, structural characteristics. California bearing ratio (CBR) has often been used to provide a measure of the structural support provided by the subgrade. The CBR values for varying subgrade soil types are listed in Table 4. The geologic structure and composition of SIDS vary from either volcanic, coral atoll, raised coral atoll, reef island, or emergent limestone. Similarly, soil types vary in SIDS from clays to loam to sandy soils. Infiltration from permeable pavements into expansive clays such as those found in the southern parts of Trinidad and Tobago and several other Caribbean SIDS is not recommended. In such instances, designs may recommend a subgrade replacement layer such as sand or the addition of stabilization additives such as cement or lime to the existing clay subgrade.[77]

3.1.1.4 Water Table

Engineering guidelines recommend that permeable pavements be installed between 600 mm [54, 77] and 1000 mm [30] above the maximum groundwater level. This ensures a depth of unsaturated soils to help ensure the infiltration performance of the PPS in addition to protecting the underlying groundwater from possible contamination.[30] Some urban cities in SIDS are located on coastal lowlands, which by nature have high water table levels. Permeable pavements may be undesirable at these locations.

3.1.1.5 Groundwater contamination

The majority of published research focuses on impacts to surface runoff quality; however since several PPS include partial or full infiltration, potential groundwater contamination becomes a concern.[126] These concerns have been minimised since according to Wilson et al. [127], the incorporation of an adequately designed and constructed impermeable geotextile at the base of the permeable pavement structure, should protect against any possible pollutant migration. Moreover, numerous long-term studies[128-130] and simulations of pollutant distributions in PPS have reported insignificant risks relating to accumulation of pollutants in the subsoil and groundwater contamination. Groundwater is a significant contributor to the water sector for several low-lying coral islands such as the Barbados and the Maldives and raised atolls such as Nauru.[7] Hence protecting groundwater from contamination is crucial to those islands.

3.1.1.6 Pavement slope

Several SIDS have steep urban catchments which can have an impact on locations for installation of permeable pavements. Although numerous laboratory studies[131-134] on the infiltration performance of permeable pavements on slopes up to 5% [131, 132] and 10% [133, 134] exist, limited information is available in the literature regarding field studies. Fassman and Blackbourn [52] in their field study investigated permeable pavements installed on slopes between 6.0 and 7.4%. Lucke and Beecham [135] reported success when the authors investigated the infiltration performance of a field-scale PICP pavement installed on slopes between 0 and 20%. Lucke and Beecham [135] concluded that typical PICP design guidelines that recommend a maximum pavement slope of 5% were overly conservative. It must be noted however, that the test pavement used in their study was newly installed with no prior noticeable clogging. Should sloping ground be inevitable, internal check dams or berms can be incorporated into the subsurface to enable an even distribution of temporary detained subsurface flow as depicted in Figure 7. Underdrains may be placed at each dam location should there be a requirement for them.[71]

3.1.1.7 Stormwater storage/ reuse potential

As compared to most developed territorial states, a majority of SIDS do not have stormwater collection systems. Instead, stormwater is often channelled towards natural water courses such as rivers and oceans using conventional storm drains.

Despite significant yearly rainfall amounts in SIDS, there is an ever-present stress on their water resources [136] primarily because of their small size, geology, topography, inadequate reservoir storage facilities, scarce financial resources, and climatic variations.[3] Further, as many of these SIDS economies are heavily dependent on agriculture or tourism activities, both major consumers of freshwater, economic losses are likely to result when operations have to be discontinued.[21]

The use of PPS present an opportunity for stormwater harvesting in many SIDS whereby partially-treated stormwater collected from parking lots can be used for non-potable purposes such as toilet flushing and external cleaning, thereby reducing the consumption of potable water, minimizing water rationing and decreasing the shortage of water resources.[137] Rainwater harvesting has been practiced in the Caribbean for many years; although on the decline. The mechanisms used for capture, conveyance and storage are building roofs, gutters and polythene tanks respectively.[138] Pratt [139] suggested that permeable pavements could be used as a reservoir for stormwater treatment and storage for subsequent reuse. Nnadi et al. [140] presented a paper which reported that a pervious pavement system has the capability to recycle stormwater to a quality that meets the standards for use for agricultural irrigation irrespective of sub-base type.

3.1.1.8 Clogging

The importance of permeable pavement maintenance and its relevance to the integrated stormwater management agenda of urban SIDS cannot be stressed enough. Sadly, the culture of poor maintenance practices of valuable infrastructure is widespread throughout most SIDS. The unavoidable consequences of significant under-investment and neglect of stormwater management systems over many years are increasingly visible and is always a subject of considerable public concern.

PPS have been commended by numerous studies[67, 74, 93, 141, 142] for the trapping of sediments and other pollutants during infiltration of stormwater runoff. However, this process can result in the clogging of the pavement surface leading to reduced infiltration rates. There is a perception that a conflict of interest therefore exists. Nevertheless, permeable pavements as with all filtration systems, will over time require removal of trapped solids. Some studies[92, 143, 144] have found that for PICPs, fine particles accumulate in the upper layer of the pavement joints. Finer particles trap larger particles resulting in increases in the rate of clogging.[145] In a study conducted on 52 permeable pavement sites, Nichols and Lucke [146] found that particle size distribution (PSD) curves could not be used as a stand-alone tool to infer PICP clogging processes but found that fine particles of sizes 251 to 550 μm contributed to lower infiltration rate measurements. Charlesworth et al. [142] found that after three years of monitoring, the majority of the sediments were located in the surface layer of a porous asphalt laboratory test rig.

Numerous researchers[147-149] have shown an exponential decay of surface infiltration rate as a function of age of the permeable pavement (Figure 8). Emerson et al. [150] reported that infiltration rates of permeable pavers were reduced by one to two orders of magnitude after three years of operation. Borgwardt [151] reported that the infiltration performance of permeable pavments decreases in the order of the power of ten after a few years of operation. Categories of PICP pavement clogging and associated infiltration rates are listed in Table 5.[152] These values could be used by engineers as a guide to assess clogging.

Presently, there are no global standards for maintenance of PPS. Nethertheless, some studies have used surface infiltration tests as a means of assessing clogging within PPS. The ASTM double-ring or single-ring infiltrometer tests [155, 156] have been used in numerous studies.[31, 147, 152, 157-161] These tests utilise rings that are sealed to the pavement's surface and filled with water. An average infiltration rate is recorded based on the time taken for the water to infiltrate through the pervious surface using either a constant or falling head.[162] These methods have however been reported as time consuming [152, 158], costly, and not possible for remote monitoring.[163]

A more recent assessment of clogging in PPS is through the use of time domain reflectometry (TDR),[164] typically for PPS without drain pipes. The travel time (period), of an electromagnetic pulse of energy of known frequency as it travels back and forth through a conductive waveguide is measured by TDR sensors. When these sensors are inserted through a material of interest, the dielectric properties (or charge storing properties) of the surrounding material alter the travel time. As such, the volumetric water content (VWC) of soils could be measured.[165, 166] Water content refectometer (WCR) sensors were first used in the aggregate storage layer under permeable pavements by Stander et al. [167]. The sensors successfully quantified the size and timing of the moisture front as inflow progressed through the various layers of a PPS. Brown and Borst [168] successfully installed TDR to measure spatial infiltration and assess clogging dynamics (demonstrate the progression of surface clogging from the upgradient edge) of PPS in Edison, New Jersey, and Louisville, Kentucky of the United States. The pavements consisted of porous surfaces of either PICP, PC or PA over an open-graded subbase reservoir of AASHTO No. 2 recycled concrete aggregate.

3.1.2 Economical

3.1.2.1 Cost

The financing and cost-recovery of urban drainage systems remains a challenge to many SIDS.[51] Initial costs of PPS usually exceed those of conventional pavements primarily due to PPS having thicker aggregate layers necessary to maximise stormwater storage and to provide sufficient structural support to accommodate vehicle loading. However, a life-cycle cost analysis may realise actual cost savings with PPS as compared to conventional pavements when a holistic approach is considered towards stormwater management systems. Savings and benefits include reduced need for conventional stormwater infrastructure such as retention basins and drainage ditches, less developable land consumed for stormwater ponds, improved aesthetics and reduced urban heat island effect.[169]

Furthermore, there is often difficulty to install permeable pavements on a large scale due to high initial costs and infrastructural factors. As such PPS are often combined with other stormwater management practices for entire catchments.[53]

3.1.2.2 Maintenance

Maintenance of the integrity of permeable pavements for the provision of the necessary support to handle traffic loads, requires monitoring of the pavement for signs of distress which could alter the structural integrity of the pavement. Some of these distresses include clogging, depression, rutting, edge restraint damage, ravelling, cracking, excessive joint width, joint filler loss and horizontal creep.[77]

As discussed previously, clogging is the most common challenge with peremable pavements. Numerous researchers[58, 129, 145, 170-172] have cited periodic maintenance as being fundamental to limiting clogging of PPS. Examples of maintenance techniques include manual removal of the upper 20 mm of fill material, mechanical street sweeping, regenerative-air street sweeping, vacuum street sweeping, hand-held vacuuming, high pressure washing, and milling of porous asphalt.[147, 173] Some studies [129, 174] have reported improvement in surface infiltration rates (SIR) after applying various maintenance techniques to clogged permeable pavements. Dierkes et al. [129] reported 1500% improvement in infiltration rates after the use of cleaning vehicles consisting of high pressure cleaners with direct vacuum suction on a permeable pavement test site in Germany. Radfar and Rockaway [174] reported that average SIR increased after cleaning methods (street sweep trucks, pressurized air jets and hydro-excavator trucks) were used.

Vacuum and street sweeping trucks are not readily available in SIDS and would attract significant importation costs. Vacuuming is therefore not recommended for SIDS facing economic challenges. Consequently, this eliminates the use of porous asphalt and porous concrete pavements given that vacuuming is the most effective maintenance option for these pavement types. The use of paver blocks is the preferred option in this regard, as maintenance options such as removal and replacement of the infill material [175] are cheaper.

3.1.3 Political

3.1.3.1 Institutional and legislative framework

Approximately 50% of SIDS use the common law system as adopted from their former colonial administration; England. In these SIDS, the government comprises of a legislative arm which makes or repeals laws through the parliament, an executive arm which administers the laws and the judicial arm which interprets the laws. The remaining 50% uses the civil law system, which is a codified system of law that takes its origin from Roman law (www.cia.gov/library/publications/resources/the-world-factbook/fields/2100.html).

These systems form part of the institutional and legislative framework in SIDS which are used to achieve various policies and goals. Urban stormwater management as mentioned previously remains a huge challenge for SIDS authorities. Drainage problems are usually not prioritised and are often dealt with in a reactive manner. For instance, expensive water treatment methods are applied to polluted water sources rather than preventing the pollution. Drainage channels are often cleared of solid wastes, rather than the solid waste problem addressed beforehand.[41]

Additionally, in the Caribbean for instance, institutions charged with enforcing policies surrounding existing stormwater management are often relaxed in their approach. This is evident in Trinidad and Tobago by the vast number of properties constructed on drain reserves and flood plains. Unplanned development near urban cities is rampant and often exacerbates flooding problems.[16]

There is an increasing demand for improved drainage in society. Policy makers need to be cognizant of the added benefits of adequately managed SUDS such as PPS in addition to the various issues which may be confronted. This knowledge would seek to reduce the need for reactive spending and promote long-term integrated planning instead.[41]

The implementation of successful PPS in SIDS depends heavily on aggressive enforcement of policies relating specifically to PPS and SUDS as a whole. There are currently no guidelines developed for PPS specifically targeting most SIDS. Singapore is perhaps one of the only exceptions. Developed nations such as the USA, U.K and Australia are far ahead in this regard.

4 RESEARCH GAPS

- The impact of recycled waste materials such as lightweight aggregates from municipal solid waste incineration (MSWI) on the structural, hydraulic and environmental performance of PPS is not known.
- The ability of PPS to remove nutrients is not yet fully understood and requires further research as numerous studies have reported varying results.
- Further research is required regarding the short- and long-term effects of pollutants that remain in the PPS.
- Small island developing states (SIDS) usually lack financial resources for infrastructural projects. As such, additional research into a life cycle cost analysis of PPS in the Caribbean is recommended. Perhaps innovative ways of reducing the initial costs of PPS can also be researched.
- Further research is required regarding PPS installed on impermeable expansive clay. The structural and water quality performance of PPS needs to be investigated thoroughly on this type of boundary condition.
- The effects on urban hydrology and water quality requires quantification for PPS installed at multiple locations within an urban watershed.
- Emphasis must be placed at each phase of implementing a PPS project, to the maximum use of labour-intensive methods to install and maintain the PPS.

5 Conclusion and outlook

Permeable pavement systems (PPS) towards application to urban areas in small island developing states (SIDS) is a sustainable way forward for resilient infrastructure. Numerous studies have reported successful applications of permeable pavements worldwide but mostly in developed countries such as the USA, United Kingdom and Australia. There are no peer-reviewed published studies of PPS being an integral part of stormwater management system across SIDS; there are however, only a handful of reported cases. PPS reduce pollutants from infiltrating stormwater runoff, provide vital reservoir storage for potential reuse of stormwater and improve the hydrologic functions of various locations.

Urban stormwater management is one of the biggest challenges facing SIDS today. Urban cities in SIDS are often flooded from heavy rainfall events. These challenges are further amplified because of climate change and urbanisation in the absence of sustainable and effective adaptation measures. SIDS are extremely susceptible to the effects of climate change which include increased global temperatures, precipitation and sea level rise. For SIDS where cities often flood, such as Port of Spain in Trinidad and Tobago, Castries in St. Lucia and Bridgetown in Barbados to name a few, consideration should be given to assessing the feasibility of an integrated stormwater management strategy which combines conventional stormwater drainage with sustainable urban drainage systems (SUDS) such as PPS.

SIDS are unique countries whereby key aspects should be considered when designing PPS for their use. These include weather, climate, climate change, urbanisation, cost, material selection and availability, permeability of subgrade at intended location, depth of water table, potential for groundwater contamination, slope of the pavement, stormwater reuse option, clogging, maintenance and support from policy makers. Reluctance to implement PPS in SIDS may include technical uncertainty in performance, lack of data, and social perceptions. Therefore, if PPS are to be used effectively as resilient SUDS in urban areas across SIDS, research is needed to evaluate their usage.

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Figure 1. Map of Small Island Developing States (SIDS); Caribbean①, Atlantic Ocean, Indian Ocean, Mediterranean, South China Seas (AIMS)②, Pacific Islands③

Figure 2. Average annual rainfall and temperature across SIDS groups (adapted from: http://data.worldbank.org/indicator/ag.lnd.prcp.mm,[5])

Figure 3. Permeable Interlocking Concrete Pavers (PICP), (a) and (b) with apertures at St. Croix, (c) and (d) Plastic Grid Pavers (PG) in St. John, USVI (source: https://docs.lib.noaa.gov/noaa_documents/CoRIS/Stormwater_manag_Pacific_Caribbean_Guide.pdf)

Figure 4. Vertical profile of typical permeable pavement systems with urban stormwater runoff

Figure 5. Cross section schematic of a permeable pavement system with geotextiles (adapted from [53])

Figure 6. Minimum compressive strengths required of block pavers in various developed countries (adapted from [72])

Figure 7. Flow barriers in PPS on sloping ground (adapted from: [71])

Figure 8. Permeable Pavement Surface infiltration rate with time (adapted from: [153, 154])

Table 1. Average annual rainfall depths for selected nations

Nation	Mean annual rainfall (mm)
SIDS	2000
United Kingdom*	1220
Spain*	635
France*	867
Australia*	534
Germany*	700

Canada*	537
United States*	715

*Source: www.worldbank.org

Table 2. Comparative levels of urbanisation in the Caribbean, 1950–2050 (adapted from [13, 16])

Year	Percentage of total population living in urban areas			
	Caribbean	Pacific islands*	World	MDR
1950	36.1	9.0	29.6	54.6
1970	45.4	19.0	36.6	66.7
2014	70.0	23.0	53.6	78.0
2050	80.7	30.0	66.4	85.4

*Melanesia, Micronesia, Polynesia

Table 3. Water resource challenges faced by specific SIDS groups (adapted from UNEP, et al. [21])

SIDS Group	**Water resource related issues**
Caribbean	– Rainfall highly variable depending on wet or dry season – Deforestation – Conflicting land use activities within catchments – Reduced soil permeability due to erosion – Inefficient water distribution networks – Demands by rapid population growth and competing economic sectors
Pacific	– Reliable groundwater lenses absent – Polluted groundwater on larger atolls – Unregulated watershed developments cause mass sedimentation – Poor sanitisation – Fluctuating rainfall patterns – Salinisation – Inefficient water distribution networks
AIMS	– Fluctuating rainfall patterns – Significant runoff intensified by mountainous landscape – High soil porosity – Competing demands from tourism, industrial sectors and population growth

Table 4. CBR values for varying subgrade soil types (adapted from [108])

Subgrade soil type	**Support**	**CBR**
Fine grained soils such as silts and clays	Low	2.5–3.5
Sands and gravels with low amounts of fines	Medium	4.5 to 7.5
Sands and gravels with no fines	High	8.5 to 12

Table 5. Categories of PICP pavement blockage and associated infiltration rates (adapted from: [152])

Average infiltration rate (mm/h)	Bloackage category
>2000	Unblocked
30-2000	Medium blocked
<30	Fully blocked
97.2*	Minimum European PICP infiltration rate

*Listed for reference purposes