Article

Flood Mitigation Performance of Permeable Pavements in an Urbanised Catchment in Melbourne, Australia (Elizabeth Street Catchment): Case Study

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Abstract: Permeable pavement (PP) systems have been shown to provide onsite stormwater management as well as contaminant removal benefits. Therefore, significant research has taken place in recent years to analyse the performance of these structures in terms of the volume of stormwater harvested and the water quality improvements at small scales. However, there is limited understanding of their performance for reducing stormwater runoff volume to prevent natural disasters, such as catchment-scale flooding. With larger flooding events projected to occur more frequently as a result of urbanisation and climate change, PP systems have the potential to mitigate loss by reducing peak flows and runoff volumes. Therefore, this research investigates the performance of PP at the catchment scale under a range of design rainfall and land-use scenarios. Results indicate that the integration of permeable pavements in urban settings is effective in mitigating surface flooding in an urbanised catchment in Melbourne, Australia by reducing the peak flows by 7–16%. However, in practice, flood reduction ability can markedly decrease with time due to the clogging of pavements. Our results provide preliminary data to show that the integration of permeable pavements into the existing urban landscape can reduce the risk of flooding by providing areas for water to infiltrate if maintained properly. These results are envisioned to assist councils and stormwater managers with the option evaluation of the water-sensitive urban design systems and selecting the appropriate stormwater management measures.

Keywords: permeable pavements; flood mitigation; rainfall intensity; MUSIC; catchment scale

1. Introduction

Urbanisation has a significant impact on the natural hydrologic cycle in urban cities due to impervious surfaces [1]. These effects include reduced evapotranspiration, infiltration, groundwater recharge, and increased surface runoff [1,2]. When runoff volume exceeds the carrying capacity of the drainage system, urban areas experience flooding of varied severity depending on the intensity of rainfall. Further, stormwater runoff delivered to the receiving waters via drainage pipes has negative consequences for in-stream biota and water quality. With increased threats to public safety and damage to infrastructure and the environment, there is a greater need to manage stormwater at the source of generation to prevent shifting the problem downstream.

Many stormwater management practices have been developed to address these issues, including permeable pavements, swales, rain gardens, green roofs, and rainwater tanks—collectively called water sensitive urban design (WSUD) in Australia. These practices integrate sustainable water management and urban planning to protect water quality, restore water balance, and reduce hydromodification (peak flows and runoff volumes) [3].

Among these systems, permeable pavements are designed to enhance stormwater infiltration without consuming any land area [1] and are appropriate for a range of industrial, commercial, and residential applications based on the material and different design configurations [4]. The multiple benefits provided by PP include enhanced stormwater infiltration, baseflow recharge, and flood reduction while maintaining regular use of the land area. There are three major types of permeable pavements, called porous concrete, porous asphalt, and permeable interlocking concrete paving [5].

Approximately 25% of impervious surfaces in urban catchments comprise of impervious pavement, making them a major producer of runoff [6,7]. Retrofitting these areas by permeable pavements is one potential solution to reduce the risk of flooding by increasing the time of concentration (the time at which peak flow is reached) and decreasing the hydraulic efficiency of the catchment (disconnecting impervious surfaces) [7]. Permeable pavements have been shown to reduce peak flows for frequent storms of lower intensity by allowing on-site storage of water for reuse or to provide baseflows [8–11]. These pavements can be laid in locations usually occupied by roads, parking lots, and walkways [12]. Permeable pavements generally consist of pavers, which have small, structured voids in the surface to allow for the infiltration of runoff. There are four main components or layers of permeable pavement systems: pavers, bedding layer, base material layer, and subgrade or underlying soil [4]. It is common to include a geotextile membrane layer between the bedding and base material to discourage the mixing and migrating of sand from the bedding layer into the base filter media [13]. The systems can be constructed with an underdrain, whereby water is collected via a drainage pipe or without an underdrain, in which case all water infiltrates into the underlying soil [13]. Common applications of permeable pavement systems include residential driveways, car parks, pedestrian walkways, bicycle trails, slope stabilisation and erosion control and land irrigation [14].

While PP systems have been widely investigated from a water quality perspective, there is limited understanding of their performance to reduce critical storm events at the watershed scale. With larger flooding events projected to occur more frequently as a result of urbanisation and climate change, PP systems have the potential to mitigate floss by reducing peak flows and runoff volumes. This research aims to address this knowledge gap by investigating the performance of permeable pavements under a range of storm events and land-use scenarios. The scenarios considered in this research comprise rainfall events ranging in duration from 10 min to 24 h and average recurrence interval (ARI) (5, 20, and 100 year ARI). Land-use changes that can vary the impervious area within the catchment have also been modelled. Further, we also simulated the effects of significant clogging to the permeable pavement system over time. The performance of permeable pavements under these predictive hydrological scenarios is envisioned to assist councils and stormwater managers in selecting the appropriate stormwater management measures. The research employs eWater's model for stormwater improvement conceptualisation (MUSIC) to investigate the capability of permeable pavements to reduce peak flows and runoff volumes for mitigating floods downstream.
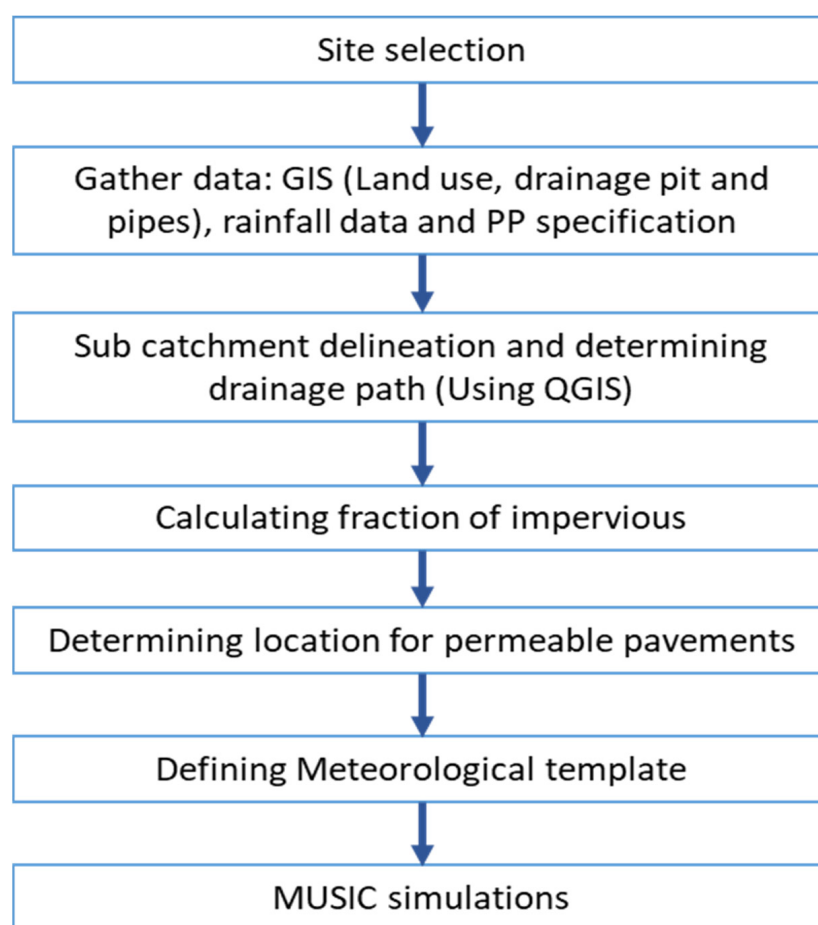
2. Methodology

Figure 1 presents the stepwise methodology adopted for this study.

2.1. Study Site

This study was carried out within one of the most urbanised catchments in Melbourne, Australia: the Elizabeth Street Catchment. Elizabeth Street was built upon a historically natural creek and is the lowest point in the Melbourne CBD. The Elizabeth Street Catchment shown in Figure 2 is managed by the City of Melbourne and begins at College Crescent in Carlton where the University of Melbourne is located and ends where Elizabeth Street drains out to the Yarra River. The catchment has been classified as an Extreme Flood Risk by Melbourne Water [15]. Since 1884, the Elizabeth Street underground drain has been responsible for collecting stormwater from the Carlton and CBD surroundings and

transferring it into the Yarra River, and has experienced frequent flash flooding events (services). Recently, the City of Melbourne has developed the Elizabeth Street Catchment Integrated Water Cycle Management Plan 2015. Targets included in the plan include upgrading the existing drainage infrastructure to be able to handle a 1:20 ARI event, i.e., a stormwater event that is predicted to occur once in 20 years [15]. As the University of Melbourne's Parkville campus is located at the upstream location of this catchment (Figure 2), reducing surface runoff from the campus through the installation of permeable pavements presents an excellent opportunity to reduce the potential flooding downstream, and therefore has been chosen as the study location. The scale of the campus can be classified as a watershed as it is approximately 21.2 hectares. Further, the site presents many suitable locations with mild slopes for the implementation of permeable pavements, as well as multiple carparks, pedestrian pathways, and low traffic areas.

Figure 1. Flow chart of the methodology.

2.2. Model Input Data: Site Characteristics (GIS and Soil Characteristics) and Rainfall Data

Inputs required to develop the MUSIC model were obtained from various sources. GIS data was obtained from Kunapo et al. 2018, [16]. The GIS data assisted with delineating the land use into impervious (roads, footpaths, and residential land) and pervious surfaces (open space). We developed a synthetic rainfall series with known ARIs. Permeable pavements were modelled as per guidelines specified by Melbourne Water Corporation. Hydrocon was identified as a leading manufacturer in Australia that supplies porous concrete products for a range of uses in driveways, carparks, walkways, courtyards, and tree-surrounds in residential and commercial environments [17]. Hence, specifications of their permeable pavements were directly used in our model simulations.
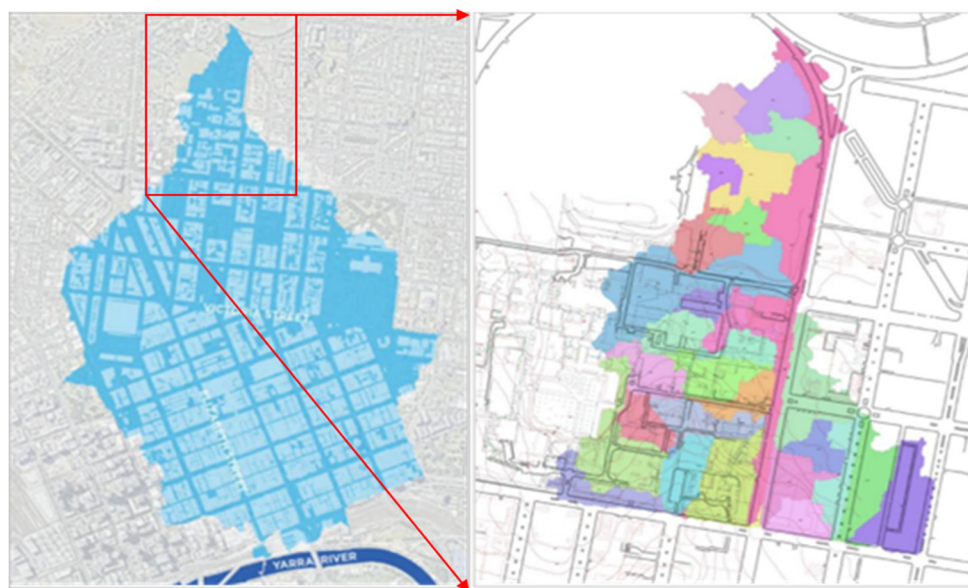
Figure 2. Elizabeth St. Catchment in blue (**left**) and The University of Melbourne Parkville Sub catchments shown in different colours (**right**), also shown by red boundary on the left.

2.3. Determining the Drainage Path

The GIS data yielded 39 sub catchments at the Parkville site. These sub catchments drain to the major pipe network located at Grattan St., which is represented as the receiving node in the MUSIC model. QGIS was employed to highlight individual sub catchments and to overlay elevation levels, as well as the pipe network. Starting at the top of the catchment, storms drains, pits, and pipes were located to identify the entry and exit points for stormwater. Contour lines were then followed from the highest point at 46.9 m Australian height datum (AHD) down to 34 m AHD to determine the natural course of surface runoff flowing into entry points of the drainage system within their respective sub catchments. Concentric circles of contour lines indicated a hill while closely spaced and widely spaced lines indicated steep and gentle slopes, respectively. The pipe overlay provided the direction of flow once surface water entered the drainage system. This allowed the drainage path to be visualised and conceptually modelled within MUSIC.

2.4. Calculating Fraction of Imperviousness

QGIS was used to calculate sub catchment areas, pervious (tree canopy and nature strips) and impervious (roof, roads, and footpath) areas, in addition to aerial photographs. The fraction of the impervious area of each sub catchment was determined by dividing total impervious areas by the area of the sub catchment.

2.5. Determining Locations for Permeable Pavements

In total, 14 sites were identified as practical and feasible locations for the implementation of permeable pavement based on slopes, traffic in the area, and distance from buildings (Figure 3). These sites exhibit mild slopes (less than 4%) and low traffic areas which is important for sustaining the performance of the system over long periods to keep maintenance costs low. An appropriate buffer distance of 10 feet down-gradient and 100 feet up-gradient from significant buildings is recommended, as the extensive infiltration of water into underlying soils can lead to subsidence for surrounding structures. In this study, this risk was mitigated by having underdrains beneath the system to allow flow into the stormwater network. QGIS was used to determine the extent of pavement surfaces and determine their respective areas. These areas were then used as inputs for the filter area within the model.
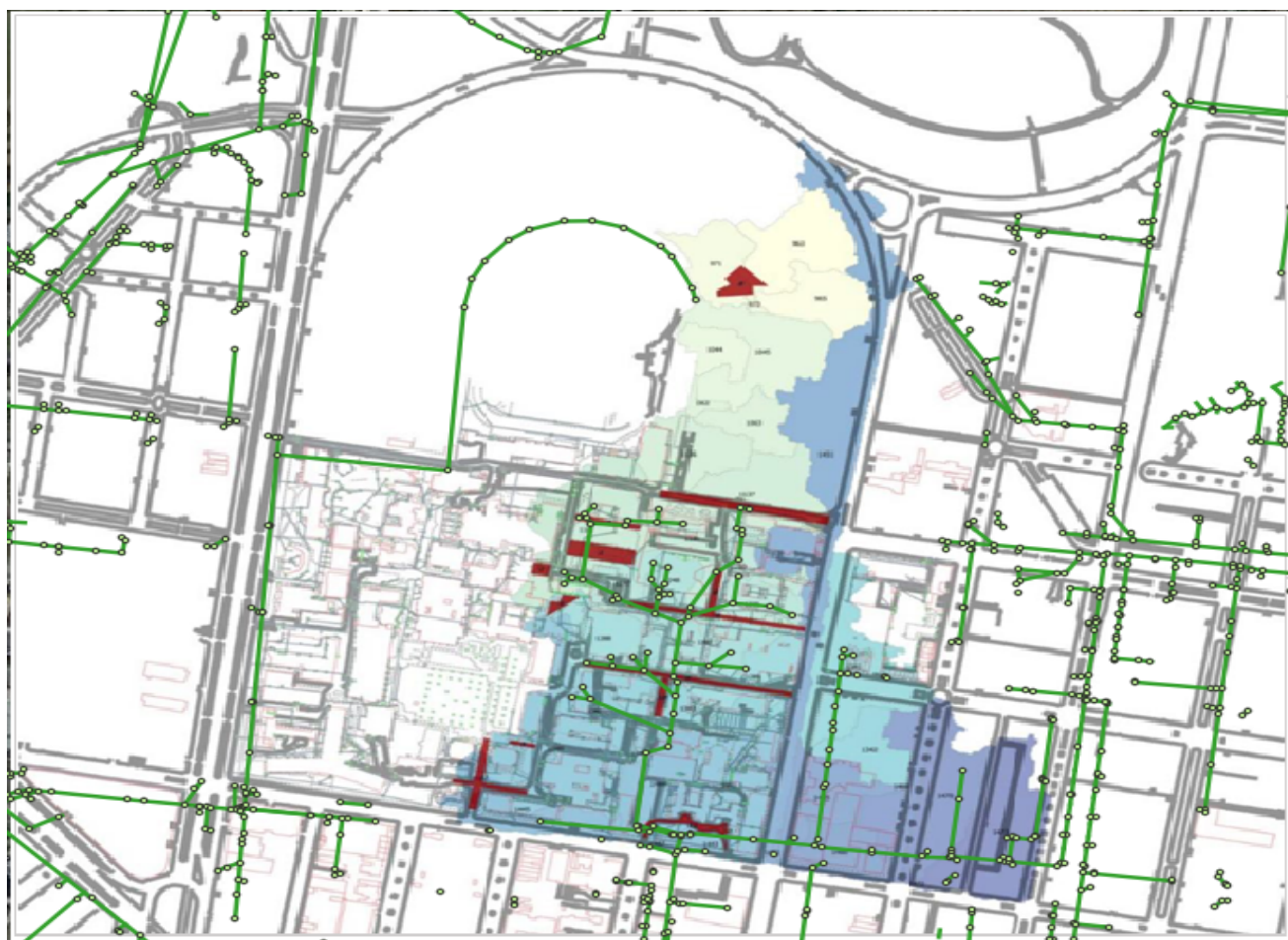
Figure 3. Locations identified for implementation of permeable pavements (areas marked in red). The green lines indicate drainage network.

2.6. Meteorological Template

We constructed a time-series of rainfall using rain events with known ARIs (design rainfalls derived from the Bureau of Meteorology; http://www.bom.gov.au/water/designRainfalls/revised-ifd/, accessed on 15 March 2016) along with ~1 year of rainfall recorded at a pluviograph. This synthetic rainfall time-series featured repeating sequences of the observed rainfall and the different design rainfalls considered. The observed rainfall was included to ensure that model storages were at similar levels before each design rain event was simulated. The resulting rainfall input file was ~100 years of 6-min data. This presented operational challenges for our computational system and the entire rainfall series could not be run as a single simulation. Instead, we extracted 10 years of rainfall data for each of the 5, 20, and 100 ARI storm events ranging from 10 min to 24-h. This does not affect the validity of our results, as the rainfall events that we are interested in are the 5 year ARI (against which current stormwater infrastructure is designed), 20 year ARI (against which infrastructure is to be upgraded), and 100 year ARI events (to model the 1 in 100-year flood disaster).

We note that due to data and time constraints, the synthetic rainfall time-series used is representative of another location named Mt. Evelyn (some ~43 km away from our study site at 37.7830° S and 145.3850° E). This had minimal influence on our study outcomes, as differences in design rainfalls between these locations are small. For example, the design rainfall intensity for a 10-min 5-year ARI storm at our study site is 69.2 mm/h and for

Mt. Evelyn it is 67.3 mm/h. This point is further illustrated in Table 1, which illustrates relatively small percentage differences in design rainfall intensities between the sites.

Table 1. Percentage differences in rainfall intensities between the University of Melbourne and Mt. Evelyn.

Storm Event Intensity	Percentage Difference (%) *
10 min 5 ARI	3
30 min 5 ARI	3
2 h 5 ARI	2
10 min 20 ARI	9
30 min 20 ARI	11
2 h 20 ARI	11
10 min 100 ARI	17
30 min 100 ARI	20
2 h 100 ARI	23

* Rainfall intensities at the University of Melbourne are higher than at Mt. Evelyn.

2.7. MUSIC Software and Simulations

The research uses eWater's model for stormwater improvement conceptualisation (MUSIC) to investigate the capability of permeable pavements to reduce peak flows and runoff volumes for mitigating floods downstream. MUSIC is capable of operating at a range of temporal and spatial scales with results viewed using a range of graphical and tabular formats.

For each of the 5, 20, and 100-year ARI storm events, a base case (no implementation of permeable pavements) and an alternative case (with permeable pavements implemented) was modelled to compare the effects of the permeable pavements in reducing peak flows and volumes. The performance of permeable pavements was also modelled under significantly clogged conditions and with the increased imperviousness of the catchment by 10%. Figure 4 shows the hydrological models for the base and alternative case respectively.

Figure 4. MUSIC model for base case (**left**) and with implementation of permeable pavements (**right**).

Inputs to the MUSIC model comprised urban nodes to represent the areas of roads, footpaths, and other impervious surfaces draining into pavements indicated as "area draining" within the model. The media infiltration node represents the permeable pavements and junction nodes indicate the locations of pits, pipes and areas of confluence. These nodes were connected by primary linkages to indicate the path of drainage as either surface flow and/or pipe flow. Sub catchments were lumped if they were found to drain into common

permeable pavements or common pipe entry points. Rainfall on roofs was modelled to enter directly into the stormwater network, as it was considered to otherwise overload the permeable pavements. There are, however, technologies available to capture the rainfall that falls on roofs (rainwater tanks, rooftop gardens). These systems were not considered in the model, and permeable pavements served as the standalone system for controlling runoff. The validity of this assumption will be discussed in proceeding sections.

We used manufacturer specifications to model permeable pavements (i.e., filter depth, filter median particle size, and depth below underdrain). The actual paver layer was assumed to be free draining (no water detention or ponding on pavement surfaces) meaning that the amount of water that can infiltrate is controlled by underlying layers. It was assumed that underdrains would be built beneath the pavements to prevent the subsidence of significant structures; the substrate layer formed the "determining" layer. This layer comprises coarse aggregates of sand and gravel. The corresponding exfiltration rate for this layer (the rate at which water can expel) was assumed to be 3600 mm/h, as suggested by MUSIC for this type of soil (coarse aggregates of sand and gravel).

Routing was applied to primary linkages (arrowed lines) to represent the time it takes for the furthest point of each sub catchment (urban node) to be contributing runoff to its outlet (either storm pipe or permeable pavements). This is termed as the "time of concentration" and is an important aspect of hydrological modelling, as it yields the minimum duration (time) for peak flows to occur (discharge in m^3/s). A simplified method was used to estimate the time of concentration by assuming that each sub catchment is square in shape with the longest flow path being the hypotenuse of an equilateral triangle. This method is suitable for providing estimates for the planning phase, where later detailed design may be investigated to verify and/or modify the initial estimates.

3. Results

Before characterizing the impact of permeable pavements on flood discharge and peak flow reductions, we estimated critical flooding flow rates in the Elizabeth Street Catchment. The majority of Melbourne's drainage infrastructure is over 60 years old with most areas only able to accommodate 5 year ARI events (Australia 2015). Therefore, for our analysis, we have taken the critical flooding flow rate as the peak flow of the 5 year ARI for the base case scenario (without permeable pavements) which is 2.1 m^3/s. If the flow rate is below 2.1 m^3/s, the catchment will be safe from flooding and if it exceeds this volume, the catchment will experience flooding.

3.1. Impact of Rainfall Duration on Flood Discharge and Peak Flows

The flooding of the drainage system for both scenarios (base case and with permeable pavements, PP installed) was investigated under different storm events (5-, 20-, and 100-year ARI) and different rainfall durations (Figure 5) at the outfall of the Elizabeth St. Catchment. Table 2 represents peak flows and the corresponding rainfall duration for each ARI event. The simulation results show that for low intensity storm events, flood discharges are high when rainfall duration is large. However, for high rainfall intensity events, high flood discharges are observed even for low rainfall durations.

Overall, permeable pavements reduced flood discharges for all rainfall scenarios (Figure 5: continuous lines, base case flood discharges; and dashed lines, after implementing permeable pavements). Flow peaks of the 5 year ARI were consistent for each duration of storm events averaging around 2 m^3/s. The highest peak flow recorded for the base case was 2.07 m^3/s for a 3-h duration storm event. With the implementation of permeable pavements, the amount of stormwater that enters the major pipe network from the University of Melbourne was attenuated to 1.7 m^3/s (16% flow reduction). Flow peaks in 20 year ARI are more varied, ranging from 2.1 m^3/s for the 10-min event to 2.7 m^3/s for the 24-min event. Permeable pavements have reduced the discharge by 12% and attenuate the highest peak flow from the base case to 2.4 m^3/s. The 100 year ARI flood event produces much more varied flow peaks than previous cases, with the highest flow observed (3.68 m^3/s) for

the 18-min duration. Permeable pavements attenuate the highest peak flow to 3.3 m³/s
with a reduction of 10%.
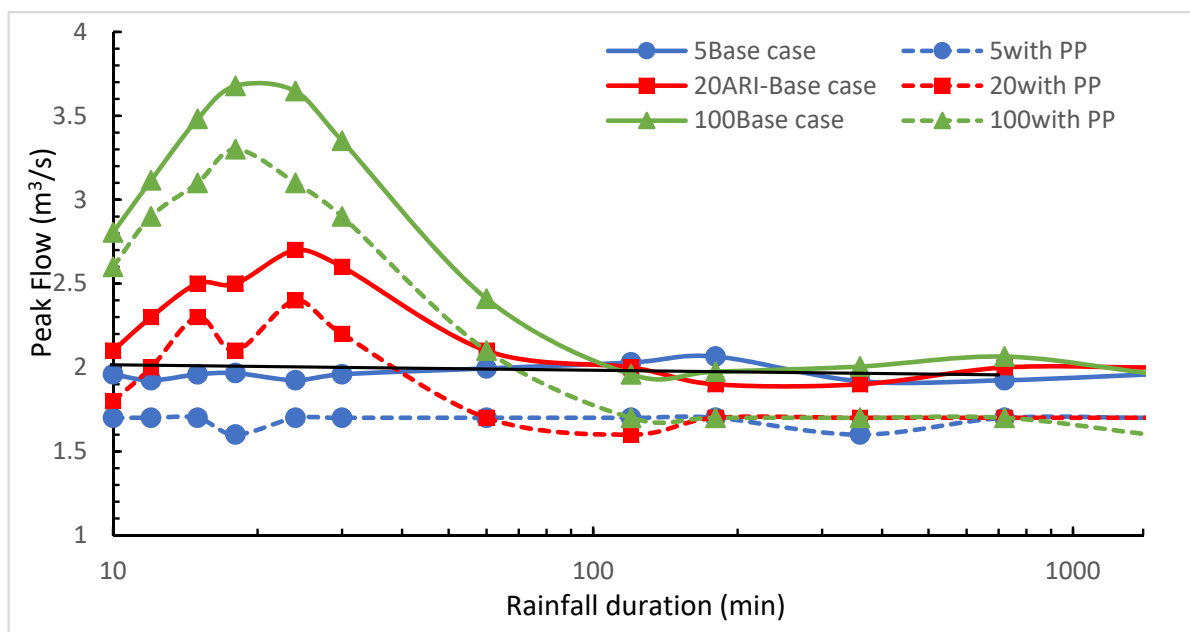
Figure 5. Discharges for different ARI storm events with and without permeable pavements. Critical
flooding rate is shown by the black continuous line in the figure.

Table 2. Peak flow and corresponding rainfall duration for each storm event considered.

Storm Event	Duration (min)	Date	Peak Flow (m³/s)	Peak Flow with PP (m³/s)
5-year ARI Base case	180	15 February 2046 21:48	2.1	1.7
20-year ARI Base case	24	27 August 2066 4:06	2.7	2.4
100-year ARI Base case	18	25 August 2089 5:30	3.7	3.3

We evaluated the impact of rainfall duration on flood discharge reduction. According
to our simulation results, permeable pavements are effective at reducing peak discharges
and runoff volumes for shorter but more frequent storm events of up to 18-min. After
18 min, its performance reduces to 9% (Table 3), suggesting that the pavers have become
saturated as a result of the intense burst of rainfall (around 30 mm/h). The performance
of permeable pavements for the 5 year ARI storm improves once the rainfall intensity
subsides and the system has had time to drain. This is evidenced by the increase in flow
reduction at 180- and 360-min durations. It is observed that this tread continues as the
duration Increases. For the 20-year ARI storm, permeable pavements are most effective for
storms of a 120-min duration with moderate rainfall intensities (around 15 mm/h). For the
1 in 100-year flood, pavements become overloaded for short and highly intense rainfall but
can reduce flows by up to 17% at the 24-h mark where intensities are much lower (around
3 mm/h).

For the same rainfall intensity, as the rainfall duration increased, the percentage of
flood discharge reduction increased for the 100 year ARI, but no clear trend in flood
discharge reduction is observed for the 5 year ARI and 20 year ARI scenarios (Table 3).
However, previous studies report increases in the reduction rates of flood discharges when
the rainfall duration is longer for any ARI event [10,18].

Table 3. Percentage reduction of flood discharge with the application of permeable pavements for the range of storm durations and average recurrence intervals.

Duration (min)	Volume Reduction (ML/y)			Flood Discharge Reduction %		
	5 ARI	20 ARI	100 ARI	5 ARI	20 ARI	100 ARI
10	6737	10,723	6587	11	16	7
12	5570	10,872	7290	9	15	7
15	6737	6680	12,348	11	8	11
18	10,367	13,017	12,106	17	16	10
24	5570	10,560	15,932	9	12	14
30	6737	11,288	13,043	11	14	12
60	7903	10,237	10,059	13	16	13
120	9070	10,367	6737	14	17	11
180	10,237	5570	7896	16	9	13
360	10,341	6732	9061	17	11	14
720	5570	7903	10,237	9	13	16
1440	6737	9070	10,367	11	14	17

3.2. Impact of Permeable Pavements on Delaying the Timing of Flooding

The effect of permeable pavements on delaying the timing of peak flows for different storm events are shown in Figure 6. The storm duration that produces the greatest peak flows was selected as the critical duration for each ARI. For the 5 year ARI storm event, permeable pavements delay the timing of peak flow runoff after the peak rainfall has occurred by 3 min relative to the base case (Figure 6a). For the 20 year ARI storm event, permeable pavements have delayed the build-up to peak flow runoff by 6 min relative to the base case (Figure 6b). For the 100 ARI storm event, permeable pavements delay the time to the 3.3 m^3/s peak by 6 min relative to the base case (Figure 6c).

These results show that the permeable pavement can infiltrate surface runoff and delay peak flow and amount. However, clogging and the duration of the rainfall events will determine the infiltration capacity of permeable pavements [18].

Overall, our results show that the implementation of permeable pavements reduces flood discharge for all storm events, regardless of the duration and intensity. However, flooding cannot be completely eliminated by implementing permeable pavements in a small fraction of the catchment. However, permeable pavement can reduce flood duration. Permeable pavements are less effective in flood mitigation during shorter and heavier storms. As a case study, this research identified the efficiency level of permeable pavement for the study area, which may not be applicable in other watersheds with different characteristics. Therefore, more work is required for region specific implementation of permeable pavements for flood control.

3.3. Land Use Change Scenario

3.3.1. Increasing the Percentage Impervious by 10% for 20 ARI Storm Event

The effect of increased imperviousness on the performance of permeable pavements was investigated by comparing peak flows for 20 year ARI storm events. The percentage imperviousness for each sub catchment was increased by 10% to model increasing urbanisation at the University of Melbourne. Increasing the impervious cover increases the peak flow by 0.3–0.5 m^3/s for all durations of storm events (Figure 7) when compared to the base case (no PP). However, with the permeable pavements case, stormwater runoff (flood discharge) reduces compared to the base case, demonstrating the role of PPs in flood mitigation. The percentage reductions in flow are similar despite the increase in imperviousness. This shows that permeable pavements remain effective under the modelled land-use change. Additionally, it is noted that the percentage reduction in flood discharge is greater for small duration rainfall events than for larger rainfall durations (100 min and above).
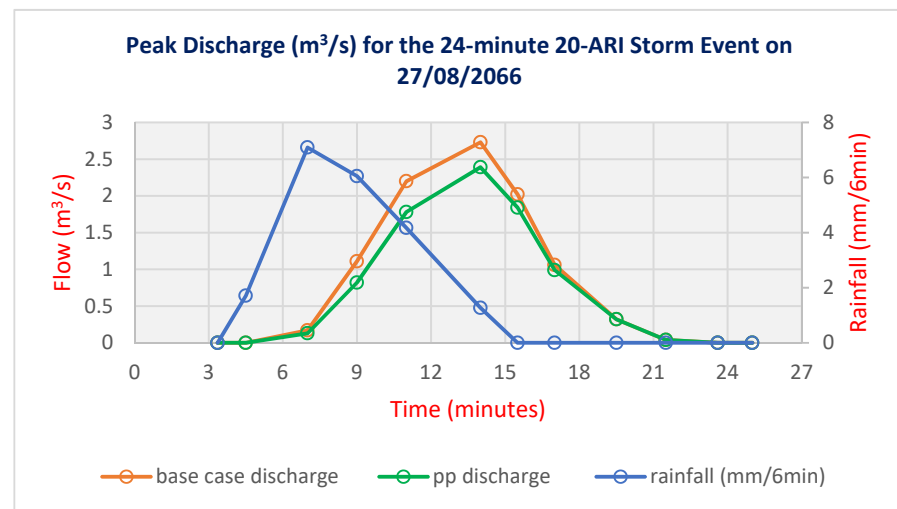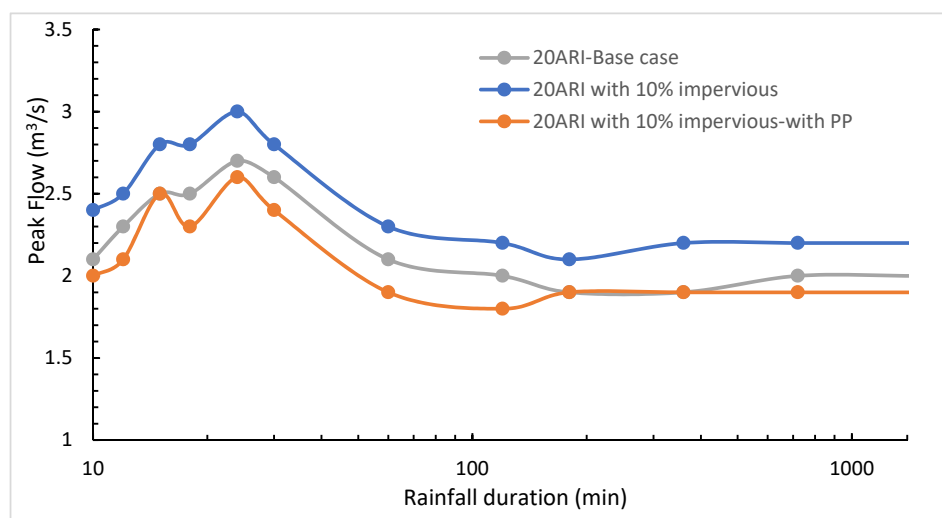
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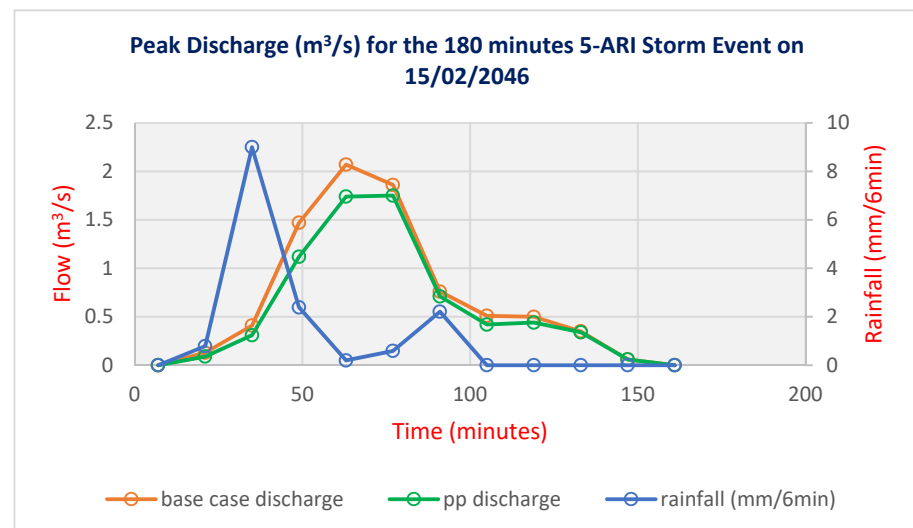
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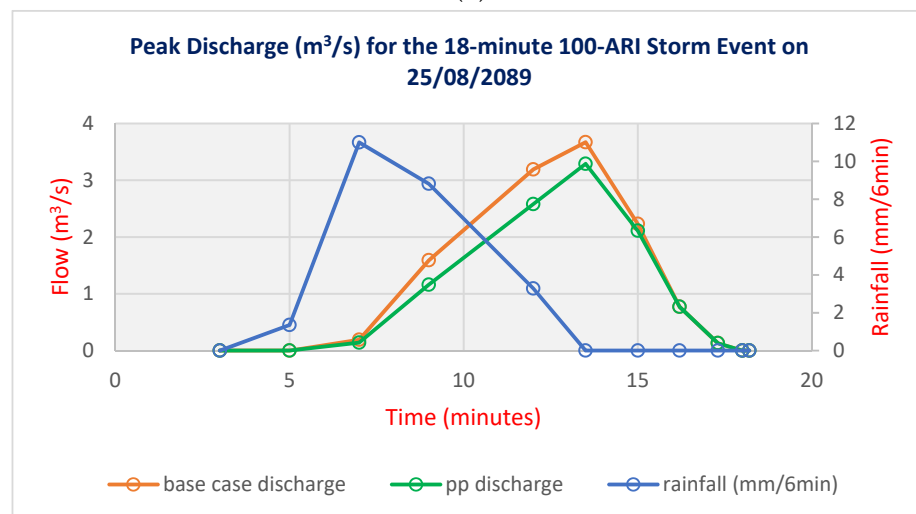
(**c**)

Figure 6. Peak flow delay for different storm events: (**a**) 5 year ARI, (**b**) 20 year ARI, and (**c**) 100 year ARI. The rainfall in mm/6 min has also been plotted to illustrate the lag between peak rainfall and peak runoff. The dates of the storm events are when they occur in the synthetic time-series.
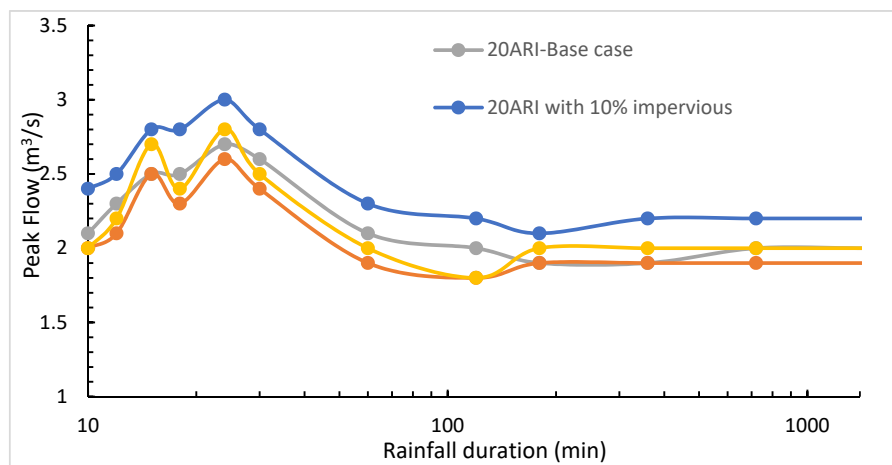
Figure 7. Discharges for 20-Year ARI events with 10% increase in imperviousness.

Land use changes that were modelled by increasing the percentage imperviousness of the catchment by 10% show that permeable pavements retain their capability to reduce runoff for the 20 year ARI storm. This suggests that permeable pavements can still provide benefits for stormwater management despite the changes in land use by reducing the volume of stormwater that is produced and by reducing the size or need for other water retention facilities.

3.3.2. Clogging

Clogging is one of the main issues with permeable pavements in an urban setting. Therefore, we analysed peak flows when permeable pavements are partially clogged. This analysis was built on from the previous scenario (20 year ARI, 10% increase in imperviousness). The exfiltration rate of permeable pavements was reduced from 3600 mm/h full operation to 360 mm/h semi-clogged. Within this scenario, the performance of permeable pavements was reduced very marginally, and results were similar to the fully operational state (Figure 8). Noticeable reductions in performance occurred only when the exfiltration rate was reduced to 36 mm/h, which is significantly clogged. Figure 7 shows that permeable pavement performance can be affected by up to 6%. This equates to a surplus of 4475 megalitres of stormwater that is discharged to the major pipe network per year based on the surface runoff calculated if no PPs were installed.

Figure 8. Discharges for 20 year ARI events with 10% increase in imperviousness and significant clogging of permeable pavements.

Marginal performance reductions were noted when the system was modelled to be significantly clogged. Allowances should therefore be made in the design for a 90% reduction in infiltration capacity over the 20-year design life, after which the aggregate layer may require replacement.

Previous literature reports the continuous decline of infiltration rates through permeable pavements due to clogging a few years after installation [19]. This is due to the deposition of particulate matter on pavement surfaces. Our study proved that clogging could reduce the performance of permeable pavements by 3–6% when pavements are semi-clogged. The trapping of sediments within permeable pavements during infiltration is an important process that contributes to its water quality treatment performance [20]. However, this process also creates clogging within permeable pavements, that reduces the infiltration rates. This issue could be tackled to some extent through maintenance and regular cleaning. Many previous studies have shown that the infiltration rates of permeable pavements can be improved with proper maintenance [18,21,22].

From a commercial point of view, the lifetime cost of floods to the Australian economy are estimated to be upwards of $20 billion [23,24]. This creates a strong case for implementing measures to mitigate the risk of floods to protect both public safety and infrastructure. As mentioned earlier, the majority of Melbourne's drainage infrastructure is over 60 years old with most areas only able to accommodate 5-year ARI events [22]. The City of Melbourne's target of upgrading stormwater infrastructure to be able to handle 20-year ARI storm events will require roughly a 10% increase in the drainage system costs. As such, retrofits of permeable pavements offer an economically viable solution for decision makers to implement, along with other suitable WSUD.

4. Discussion

The performance of PP was investigated under storm durations ranging from 10 min to 24 h and average recurrence intervals of 5, 20, and 100 years. The storm duration that produces the greatest peak flows was selected as the critical duration for each ARI. Results show that PP can achieve reductions to the highest peaks found in the 180-min 5 year ARI, 24-min 20 year ARI, and 18-min 100 year ARI storm by 16%, 12% and 10%, respectively.

The results indicate that PP is effective at reducing peak discharges and runoff volumes for shorter but more frequent storm events of up to 18-min. The performance of PP for the 5 year ARI storm is improved once the rainfall intensity has subsided and the system has had time to drain. For the 20 year ARI storm, PP is most effective for storms of a 120-min duration with moderate rainfall intensities (around 15 mm/h). For the 1 in 100-year flood, pavements become overloaded for short and highly intense rainfall but are capable of reducing flows by up to 17% at the 24-h mark where intensities are much lower (around 3 mm/h).

Land use changes that were modelled by increasing the percentage pervious of the catchment by 10% shows PP retaining its capability to reduce runoff for the 20 year ARI storm. This suggests that PP can still provide benefits to stormwater management despite the changes in land use by reducing the volume of stormwater produced and by reducing the size or need for other water retention facilities.

Marginal performance reductions were noted when the system was modelled to be significantly clogged. Allowances should therefore be made in the design for a sequential reduction in the infiltration capacity over the 20-year design life, after which the aggregate layer may require replacement.

Limitations and Future Work

It should be noted that our models have not been calibrated to the observed rainfall and discharge data in the Elizabeth Street Catchment. The synthetic rainfall series used in our model was for another study at Mt. Evelyn where the rainfall intensities are lower compared to our study site. This means that our model has underestimated the amount of discharge that is produced at the University of Melbourne. For the 5 year ARI, the margin

of inaccuracy is negligible; however, for storm events of 20 and 100-years, this margin increases to 10 and 20% respectively.

Further, water treatment systems should not be modelled in isolation from each other. Our study has solely focused on the impact of permeable pavements on reducing peak flows to the exclusion of other water retention devices such as rainwater tanks and rain gardens. The omission of these other technologies from our model has the implication of over-estimating the flow produced. For the purposes of our highly conceptual study, the runoff routing procedure to determine the time of concentrations was based on a simplified method that should be subject to detailed design. As such, the model results provide useful insights but should be used with caution.

5. Conclusions

This study investigates how permeable pavement implementation impacts urban flooding in a highly urbanised catchment in Melbourne, Australia. The effectiveness of permeable pavement implementation was analysed with various rainfall scenarios (with average recurrence intervals and storm durations) and various land use scenarios (increased imperviousness and clogging). Main findings of our study are summarized below.

The performance of the permeable pavement was substantially affected by the intensity and duration of the rainfall event. Our research has shown that permeable pavements are effective at reducing flows for:

(1) smaller, shorter, and highly intense rainfall events;
(2) larger, longer, but lower intensity storm events

Land use changes were incorporated into our model to simulate a 10% increase in impervious area. For the 20 year ARI storm that was investigated for this scenario, PP has been shown to sustain its performance and reduce flow discharge by up to 17%. Results from the clogging scenario pointed to a reduction in PP capabilities by up to 6% when the exfiltration rate was decreased from 3600 mm/h fully operational to 360 mm/h semi clogged. With appropriate maintenance measures in place, the life of PP can extend to 20 years, which positions the technology as a viable solution for urban stormwater management.

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