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# Spatial Analysis of the Water Harvesting Potential of Permeable Pavements in Australia

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**Abstract:** An increase in impermeable surface areas with urban development contributes to the rapid and large amount of surface runoff during rainfall. This often requires higher capacity stormwater collection systems, which can cause stress on the existing drainage system and this subsequently contributes to urban flooding. However, urban runoff can be reduced and managed for flood control and converted into a useful resource by harvesting and reusing the water. This can be achieved by switching from impermeable to permeable pavements. However, the amount of stormwater that can be harvested in a permeable pavement system depends on many factors, including rainfall, the water reuse demand and the materials used. This research aims to assess the requirements for permeable pavement design across Australia to balance demand, runoff reduction and construction requirements. A design approach employing the hydrological effects of the infiltration system was adopted for the analysis, along with a spatial analysis for a probabilistic prediction. A relationship was also established to predict a probable design thickness of pavement for various parameters. The research showed that in most Australian cities, for a 120 mm permeable pavement thickness, 40–80% of rainfall-runoff could be harvested, meeting about 10–15% of domestic water demand. The approach developed in this study can be useful for screening the potential of permeable pavements for water harvesting and for predicting spatially where a circular economic approach can be more efficient.

**Keywords:** permeable pavements; water harvesting and reuse; design thickness; pavement performance; spatial analysis

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## 1. Introduction

Permeable pavements are made of open-pore materials that allow water to pass through them into a deeper layer for storage and detention, which improves water quality, reduces surface runoff [1–4] and enables harvesting for later reuse [5,6]. Research also demonstrated that the quality of the harvested water is better than that of the direct runoff due to the filtering of suspended solids and other associated pollutants, particularly heavy metals [5]. In addition, harvesting and reusing stormwater on site instead of collecting it in the municipal stormwater system and transferring it away from the site promotes a circular economy by turning a waste product into an asset for the community. The application of permeable pavements can generally reduce the total surface runoff by 40% and peak flows from 7 to 43% [7–9]. While flooding due to highly intense rainfall is an issue in Australia, using permeable pavements can be a potential solution for runoff control [10–13] and harvesting water of suitable quality for non-potable reuse [14].

Figure 1 shows the typical component layers of a permeable pavement system. The water-harvesting capacity of such a system depends mainly on the pavement materials and the thickness of the base course layer, which consists of aggregates that are suitable for both storing water and providing structural stability [15–20]. The permeable pavements at the surface layer help to infiltrate the stormwater runoff into the base layer, which holds the water within the interparticle voids of the aggregates. The use of equally graded materials (with a void ratio of approximately 40%) for the permeable pavement base course is typical in the United States and the United Kingdom [21]. The reason for using these materials is that they have high void ratios, which allows them to hold high volumes of water for a given pavement thickness, and they have sufficiently high stiffness to support the load dissipation to the subgrade [22]. Using such coarse homogeneous materials on roads and streets is unlikely to offer satisfactory service under heavy traffic conditions [23]. However, it is still suitable for low-speed traffic areas, such as car parks [24]. While a standard well-graded granular road base is used in permeable interlocking concrete pavements (PICPs) in Canada, the United States and Australia, such pavements have only been in service for a short time, and their long-term performance is uncertain [25]. As the homogeneity and size of the paving materials used for construction increase, the permeability and water storage capacity of the granular materials used for pavements will generally improve [6]. However, studies have shown that a good balance between permeability and elastic modulus might be achieved with relatively modest alterations to typical gradings, for instance, by using materials with void ratios from 15 to 20% [26]. Other research has also shown that it is possible to make a cement-treated base for PICPs [20,27].

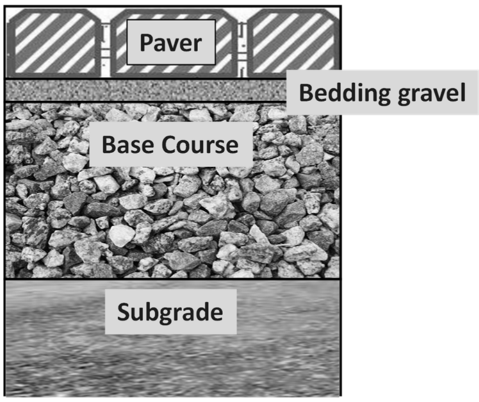

**Figure 1.** Typical permeable pavement configuration: pavement containing only a granular base course.

As well as pavement materials, the intensity and duration of rainfall regulate the amount of water passing through permeable pavement [1,3,28]. Rainfall intensity and duration may vary with the geographical region and wide-ranging rainfall patterns are observed across Australia. Australia's rainfall patterns vary from low yearly averages across most of the continent to a higher range in the northern and eastern parts [29]. Therefore, the design of permeable pavements varies from one place to another depending upon these factors. As permeable pavements are mainly applied in driveways, car parks, public space paving, or residential streets with low traffic loads [30], the hydraulic design instead of the mechanistic design usually determines the base course thickness. However, the mechanistic design approach may be integrated with the hydraulic design process for higher traffic loads, but this is not within the scope of this research.

As the rainfall intensities and patterns vary geographically, the efficiency of water harvesting would also vary geographically across Australia. This study aims to assess how the design thickness of a permeable pavement changes geographically, depending on rainfall patterns, water demand, and pavement materials. The spatial variability is assessed by analysing the data for several Australian cities. In addition, the statistical relationship is evaluated between characteristics such as water-harvesting rate, pavement thickness, and materials. Previous research studies have analysed the factors that impact pavement permeability and the stormwater runoff reduction rate using permeable pavements [16,20,23,31–35]. The performance of permeable block pavements was also assessed for the various conditions [36–39]. However, the integration of all the factors and their influence on the design thickness has not been analysed before. This research seeks to bridge that gap by examining how the pavement's design thickness can change based on various design parameters.

The subsequent analysis provides an understanding of the practicality of permeable pavements as a water-sensitive urban planning tool by giving a preliminary overview of the construction required. An initial overall assessment of the design requirements before the final design would benefit municipalities and planners by identifying alternative options for developing new roads, car parks, footpaths and driveways. The research also aims to evaluate the efficiency of permeable pavements compared to impermeable pavements. The Australian standard design software, DesignPave v2.0 [40], is used in this research for the hydraulic design of pavement structures for water harvesting. The analysis was conducted for permeable interlocking block pavements suitable for car parks only.

## 2. Methods

### 2.1. Selection of Cities

The cities considered for pavement design assessment were selected by applying criteria to residents living in the city. Population filtering was performed so that the analysis not only represented most of the country's geographical area but also selected a viable location for construction. Therefore, a minimum resident headcount of 500 living in a city was considered for the research, resulting in 108 cities selected for the analysis (Figure 2).

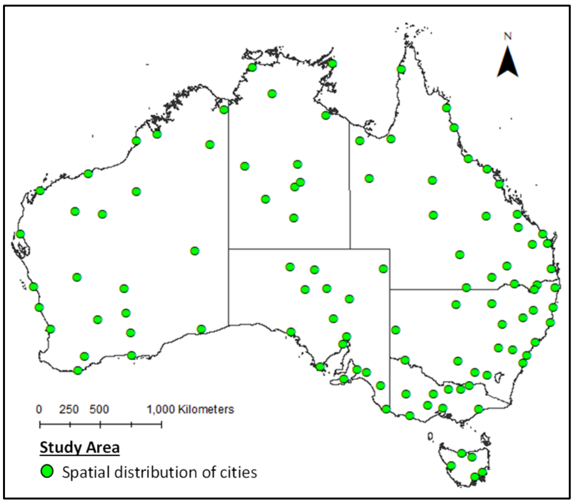

**Figure 2.** Selected cities in Australia for assessing the permeable pavement thickness requirements for water harvesting and reuse.

### 2.2. Design Considerations

The design can be carried out for any combination of factors, including variations in materials, use of the pavement (load on it), catchment area, modelling approach, etc. The following design factors were considered in the analysis:

- Design thickness assessment for water harvesting using the DesignPave v2.0 modelling tool;
- Design for car parks only, applicable for low-traffic loadings;
- Layer configuration:
    - Paver: Market standard pavers with openings along narrow joints; thickness 80 mm; permeability $9 \times 10^{-5}$ m/s [41];
    - No water infiltration to subgrade was allowed, as the water was to be collected for later reuse.
- Uniform granular material (void ratio 40%) was selected for assessing the design thickness of permeable pavements for all selected locations. This allowed for the maximum water-harvesting potential of each pavement system;

- The design thickness was assessed for a 100 $m^2$ permeable paving area, directly exposed to rainfall. No runoff from additional contributing areas was considered for the assessment;
- Spatial analysis was carried out based on 108 cities' data through kriging interpolation in ArcGIS, which estimated the probabilistic value of unknown points across Australia based on the known 108 pieces of data.

### *2.3. Rainfall Data*

Annual average rainfall data were obtained from the Bureau of Meteorology (BOM) website (http://www.bom.gov.au/climate/data/?ref=ftr (accessed on 25 June 2022)). For most locations, rainfall data were available for at least 20 years, while for some stations, data were available for up to 90 years. The annual average rainfall value of 2020 was opted for this research where available, as 2020 data can be considered the latest validated data. In case of the year 2020 data being unavailable, the most recent year's data was considered for that city. The average rainfall for all the years was also found to be within the 10 to 15% range of the most recent year's data. The spatial distribution of collected rainfall data (Figure 3a) and the 30 years' average annual rainfall data (Figure 3b) provided by the Bureau of Meteorology (http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp (accessed on 25 June 2022)) also showed a similar distribution pattern. Therefore, the collected rainfall data were considered to be appropriate for a representative analysis.

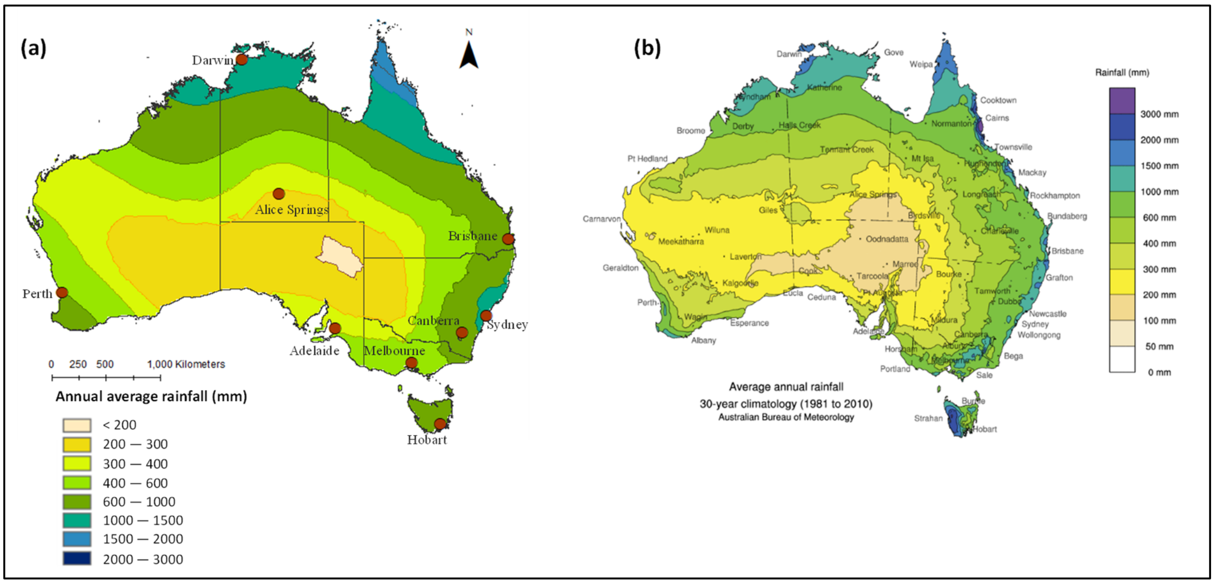

**Figure 3.** Spatial distribution of rainfall across Australia considering (**a**) average annual rainfall for 2022, and (**b**) 30-year average rainfall adapted from the Bureau of Meteorology of Australia, BOM (2022) [29].

### *2.4. Water Demand*

The design thickness of the permeable pavement system depends on the quantity of harvested stormwater that needs to be stored for later reuse. Typical water demand in Australia is found to be 200 litres per person per day [42], although the water demand might vary with location and the season of the year. On average, for a 2-person household, the demand would be 400 litres per day. With the aim of meeting 25% of this water demand from harvested water with a 100 $m^2$ permeable pavement, the design water demand was assumed to be 100 L/day. This gross average water demand was considered for all the cities in this research to assess the spatial variability of the calculated design thickness. For further parametric analysis, the water demand was varied to determine subsequent changes in the design thickness.

### *2.5. Hydrological Effectiveness*

The pavement base course design thickness ($D$) is the ratio of the volume of water harvested from the storage ($SH$) to the pavement area ($A$) and the void ratio ($VR$) of the base course (Equation (1)).

$$D = \frac{SH}{A \times VR} \tag{1}$$

The pavement area and material void ratio depend on the design requirements. The volume of harvested water in the storage (base course) depends on the runoff volume and the pavement system's storage ratio. Each city has a hydrological effectiveness curve (HEC), which determines the efficiency of water discharge capacity (discharge unit rate, $\mathrm{L/s/m^2}$) from an infiltration system with the storage (as a percentage of Mean Annual Runoff Volume or % MARV, denoted as the Storage Ratio). A lower storage ratio corresponds to a higher discharge rate and vice versa, the discharge rate being higher with higher system efficiency. Hydrological effectiveness curves for all of Australia's capital cities are shown in Figure 4.

From these HECs, a storage volume can be obtained depending on the desired efficiency and unit water demand (demand per unit area, which is supplied by the runoff). The supply efficiency of the permeable pavement system can also be obtained, which determines the rate of supply (S) that can be achieved from the runoff. The corresponding storage ratio from the hydrological effectiveness curve was considered to determine the harvested water volume ($SH$) (Equation (2)).

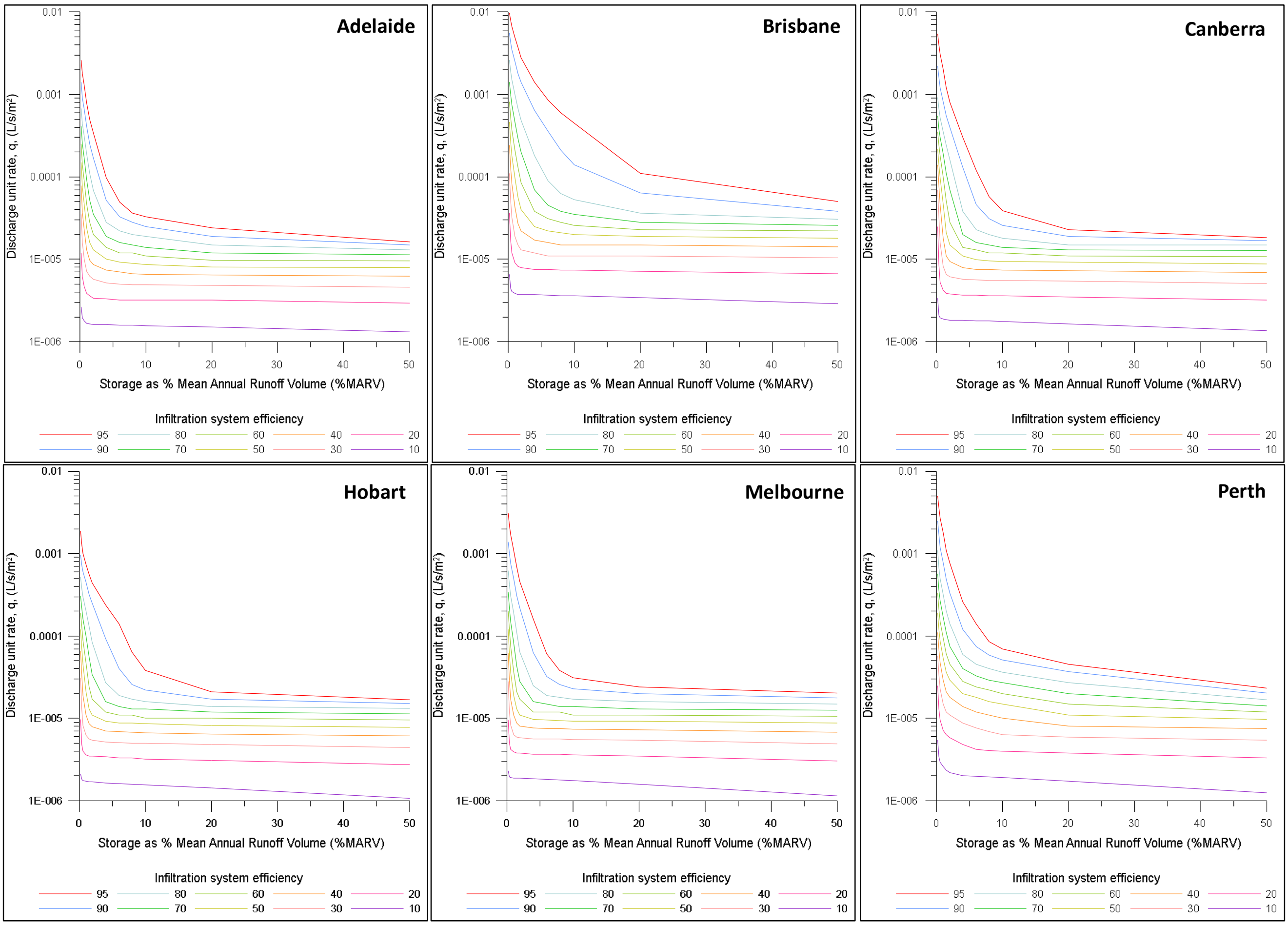

**Figure 4.** *Cont.*

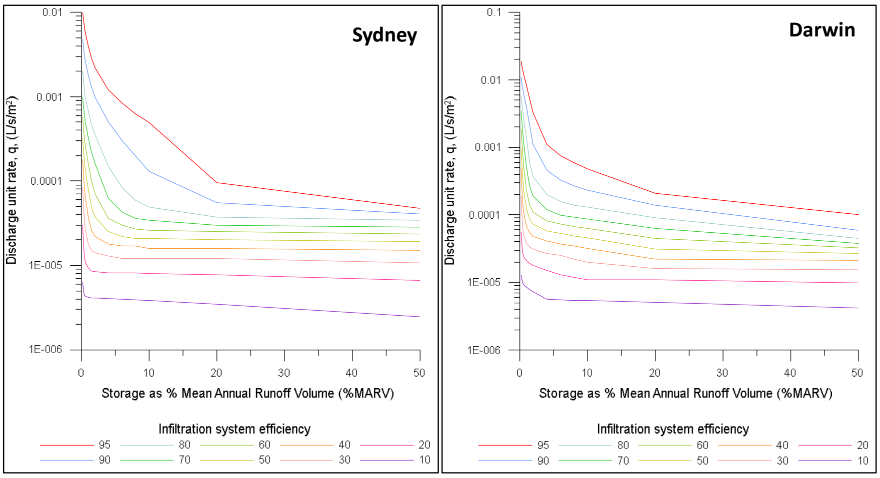

**Figure 4.** Hydrological effectiveness curves for the capital cities of Australia [43].

For an efficient solution, a discharge rate was selected from the distribution, which provides the most supply efficiency. The supply (S) capacity of the pavement vs. harvesting rate (*SH*) relationship maintains a steady relationship without putting high stress on the supply. For example, Figure 5 shows a typical supply vs. harvesting rate relationship for Sydney, Australia, considering a water demand of 100 L/day and average annual rainfall of 1150 mm/year.

$$SH = \%\ MARV \times AAR \tag{2}$$

where

$\%\ MARV$ depends on the efficiency of the system and

$AAR$ = average annual runoff, which is distinct for each area and dependent on rainfall data ($AvgR$) (Equation (3)).

$$AAR = AvgR \times CA \tag{3}$$

where $CA$ is the total catchment area, the sum of the permeable paving area and any non-permeable contributing catchment area (in this case, no contributing catchment area was considered for the design).

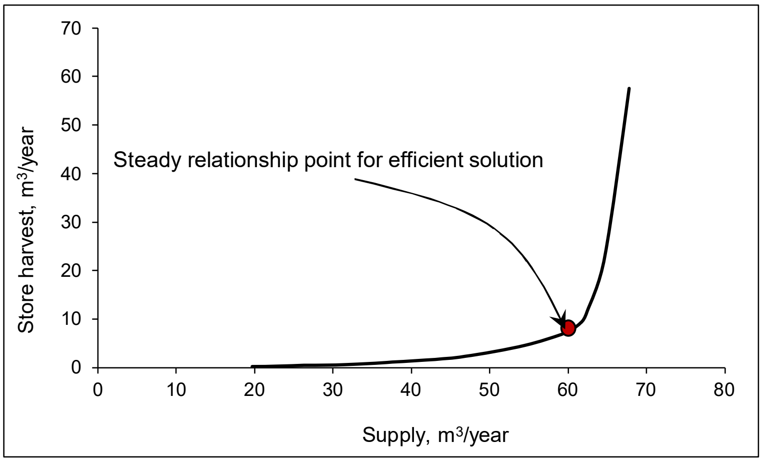

**Figure 5.** A typical supply vs. harvesting rate relationship for Sydney, Australia. Supply vs. harvesting slope is steeper beyond steady relationship point for efficient solution.

All these factors were considered in the pavement hydraulic design software package, DesignPave v2.0, developed by the authors and implemented in the Australian pavement industry. In this research, the software was used to calculate the design thickness of the pavement that would offer 95% system efficiency and provide a solution that balances the water demand and design thickness requirements. It should be noted that the analysis did adopt a 100% supply solution, where all the demands could be supplied with the adopted hydrological effectiveness.

The amount of stormwater harvested from the runoff was also assessed. The amount of water harvested ($HW$) depends on the hydrological effectiveness ($E$) and the average annual runoff volume ($AAR$) (Equation (4)).

$$HW = E \times AAR \tag{4}$$

If the design thickness is larger and the runoff volume is high, the pavement can collect and store more stormwater. However, for a low runoff value zone, a thicker pavement would not be useful, and thus the hydraulic design would suggest a suitable design thickness for the pavement considering its use and location.

### 2.6. Pavement System Performance Analysis

The efficiency of the pavement system would be higher in the case where the construction cost is lower and a higher portion of demand is supplied by harvesting more runoff. The efficiency can be better estimated with the economic evaluation of the benefits and costs of implementing the permeable pavement system. However, in this research, a scaled measurement approach (matrix analysis) was adopted to evaluate the performance efficiency of permeable pavements across Australia. A similar matrix approach, although in a different context, was used earlier [44] to assess the risk or performance of a system.

The magnitude of demand supplied, the design thickness of the pavement and the water-harvesting rate were considered for the performance matrix (Table 1). A general rule was applied because there is no standard method for scaling the magnitudes. For instance, for demand supplied and a portion of runoff harvested in the pavement:

- Index = 3: more than or equal to 75%;
- Index = 2: more than or equal to 50%;
- Index = 1: less than 50%.

**Table 1.** Performance analysis matrix as a factor of % of demand supplied, % of harvested stormwater runoff and the design thickness.

| **Depth Index** | **Demand Supply Index** | | |
|---|---|---|---|
| | **[3] $\geq$ 75%** | **[2] $\geq$ 50%** | **[1] < 50%** |
| [3] ($\leq$150 mm) | Excellent (5) | Competent (3) | Satisfactory (2) |
| [2] ($\leq$175 mm) | Strong (4) | Competent (3) | Satisfactory (2) |
| [3] ($\geq$175 mm) | Competent (3) | Satisfactory (2) | Partial (1) |
| | [3] $\geq$ 75% | [2] $\geq$ 50% | [1] < 50% |
| | Runoff harvesting index | | |

The index was also considered differently for the design thickness as the priority was to be given to the minimum thickness level for maximum benefit. Therefore:

- Index = 3: less than or equal to 150% of the minimum thickness, i.e., 150 mm;
- Index = 2: less than or equal to 175% of the minimum thickness, i.e., 150 mm to 175 mm;
- Index = 1: more than 175 mm.

Thus, the average of all the indices was used to assess the performance index, which was categorised into five indices based on the results:

- Excellent = 5: average index is equal to the average total score for all the criteria, i.e., average index = 3;
- Strong = 4: average index is greater than or equal to 80% of the average total score, i.e., 3 > average index $\geq$ 2.4;

- Competent = 3: average index is greater than or equal to 60% of the average total score, i.e., 2.4 > average index ≥ 1.8;
- Satisfactory = 2: average index is greater than or equal to 40% of the average total score, i.e., 1.8 > average index ≥ 1.2;
- Partial = 1: average index is less than 40% of average total score, i.e., average index < 1.8.

## 3. Results and Discussion

### *3.1. Spatial Distribution of Design Thickness*

Based on the annual rainfall for each city, with a base course material with a 40% void ratio, and constant water demand of 100 L/day, the minimum base course design thickness for stormwater harvesting throughout Australia is presented in Figure 6. The design thickness is for an efficient solution for harvesting the incident rainfall on the pavement and meeting the water demand, that is a balanced supply vs. demand relationship is ensured. A supply of 100% of the demand was not considered in this research, as this was likely to be uneconomical due to the requirement for a very large base course thickness to store and supply all the harvested water.

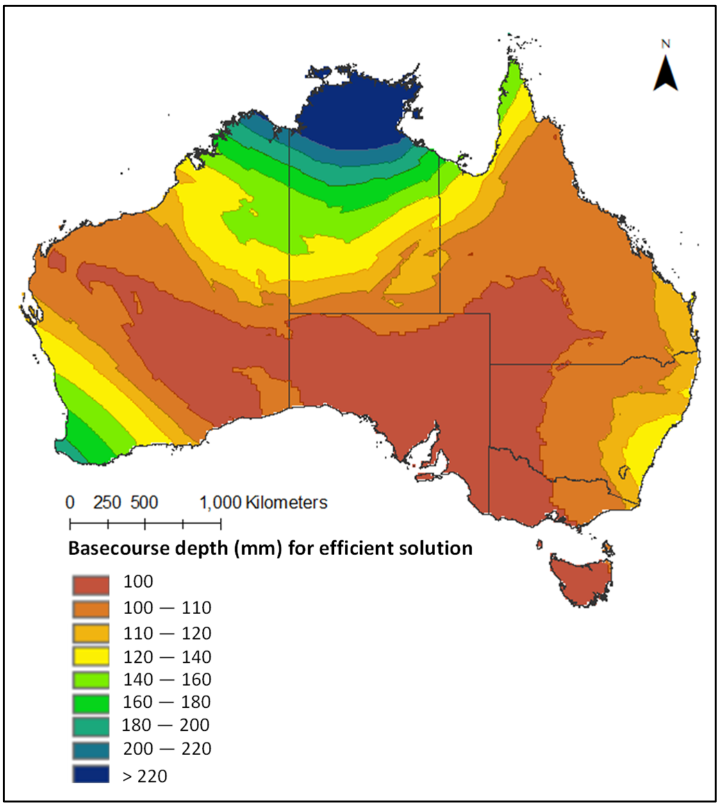

**Figure 6.** Permeable pavement base course design thickness distribution throughout Australia.

Since in this case, the pavement construction parameters are constant, the only determining factors are the runoff received on the pavement at different locations and the hydrological effectiveness for different regions. The spatial distribution demonstrates a clear stratification of base course thickness requirements (Figure 6). In general, similar rainfall zones required a similar level of base course thickness, except for some cases where the hydrological effectiveness influenced the requirement. For example, Hobart requires a similar base course thickness as Adelaide, despite having higher average annual rainfall (Figure 3a). Again, a lower base course thickness is required in the Eastern part of Australia, although it is exposed to very high rainfall. Overall, higher rainfall zones require greater base course thicknesses, particularly in the Northern part of Australia.

Therefore, the pavement performance is not only indicated by the base course thickness requirement but also by the proportion of runoff water harvested (Figure 7) and the demand supplied (Figure 8).

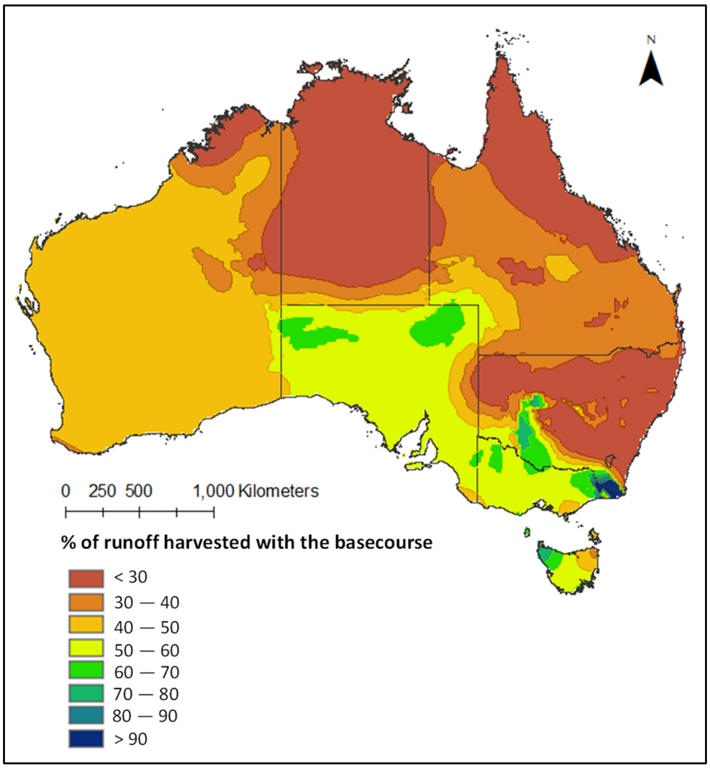

**Figure 7.** Runoff harvesting rate distribution (%) throughout Australia.

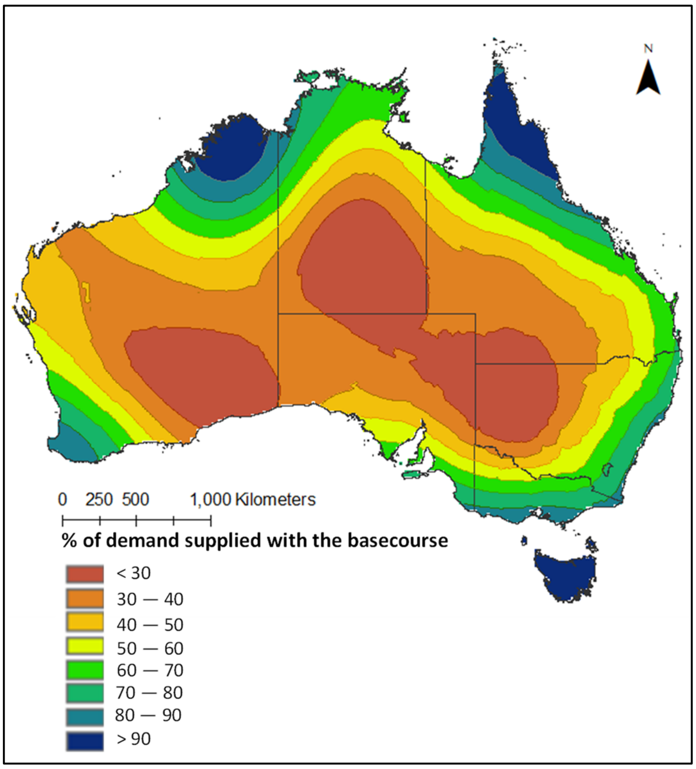

**Figure 8.** Spatial distribution of the rate of demand supplied (%) throughout Australia.

With respect to the percentage of stormwater runoff harvested throughout Australia, as presented in Figure 7, zones with higher rainfalls are found to harvest a lower percentage of stormwater runoff. This is logical because the pavement system was not designed to collect all the water but rather for an efficient solution. Thus, for high rainfall zones, the amount of uncollected water would remain high, resulting in a lower percentage of harvested stormwater runoff. For the same reason, the rate of stormwater runoff harvesting is high in the southern part of Australia, which can reduce peak runoff discharges and therefore act as effective flood control. For other parts of Australia as well, the amount of runoff reduced by the permeable pavement can be significant in flood control, particularly during the peak rainfall period. This can reduce the capacity requirements for the municipal stormwater drainage system as well.

However, apart from a reduction in stormwater runoff, it is also important to assess the amount of demand supplied by the stormwater-harvesting system. Figure 8 shows that in regions where the runoff rate is higher, the demands are generally met in higher percentages. This is also logical, as the demand cannot be satisfied if sufficient water is not present to be harvested. Therefore, the north, northeast, south and southwest portions of Australia are generally found to meet proportionately higher demands.

A constant demand of 100 L/day was assumed in this analysis. Therefore, the reductions in stormwater runoff would vary if the demands were higher, but the spatial distribution would remain the same. In the case of lower demands, the spatial distribution might change, particularly in terms of increasing the spatial coverage of demands being satisfied. This is important as water conservation measures and associated demand management measures are being adopted in water-scarce countries such as Australia.

Combining all the factors, the spatial distribution of the performance of the pavement systems across Australia was analysed and the results are presented in Figure 9. This represents a qualitative assessment of the system based on the average of the ratings. As observed before, some areas performed better in terms of reducing stormwater runoff while others were better at meeting reuse demands. The combined rating was implemented to assess the overall performance. Figure 9 shows that the majority of the areas perform averagely (termed as competent performance), meaning the permeable pavement system is capable of reducing an extent of runoff (>50%), meeting demands (>50%) and being within a reasonable construction requirement (design thickness 150–175 mm). Therefore, most of the areas in Australia can harvest and supply rainwater for reuse, which would enhance the circular economy [45] and reduce the carbon footprint for reduced water supply requirements [46]. In addition to this, strong performances can be seen over significant areas of Australia, particularly in the southern part and some parts of the eastern and northern regions. The southeastern portion of Australia performs excellently, harvesting more than 75% of runoff, supplying more than 75% of demand, and having a base course thickness of less than 150 mm.

### 3.2. Relationship between Design Thickness, Void Ratio and Demand

The analysis conducted for the selected locations indicated a relationship between the required design thickness, the void ratio of the base course materials and water demand. Therefore, a statistical relationship was employed in this study. Not surprisingly, the highest variability between cities was found in the lowest and highest rainfall zones, namely Adelaide and Darwin. Therefore, a parametric analysis was conducted for these two cities to assess the extent of variability in design thickness due to the variability in void ratio and water demand.

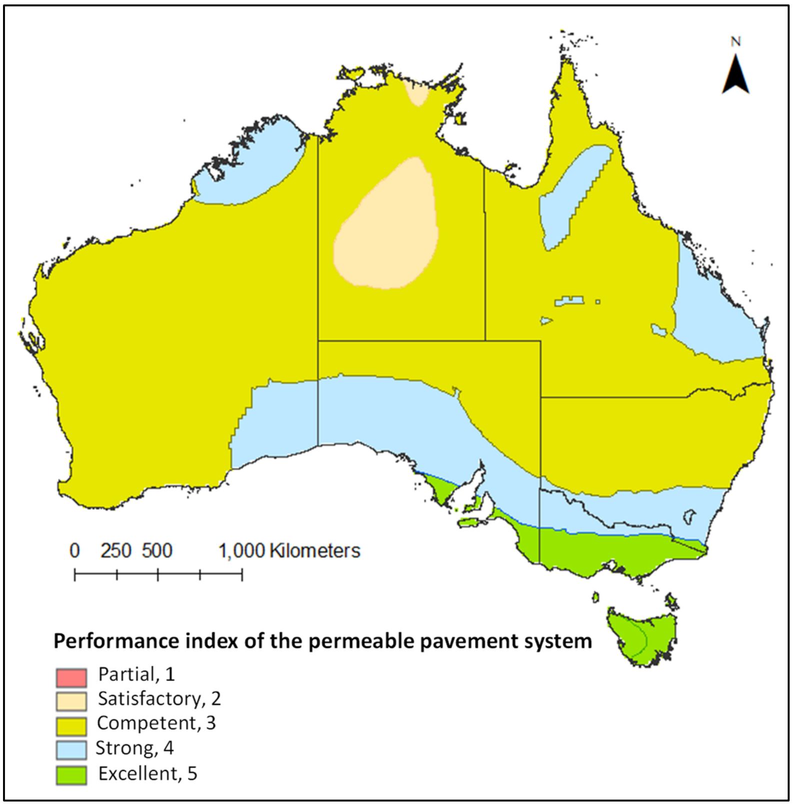

**Figure 9.** Spatial distribution of the overall performance of permeable pavement systems across Australia.

Figure 10a shows a complex relationship between the parameters, which do not follow a specific trend in terms of predicting the design thickness requirements. The relationship between void ratio and design thickness for a given water demand follows a consistent statistical relationship (Figure 10b). However, due to the water demand, the relationships appear to be stepped. For example, in the case of Adelaide, for a base course with a 40% void ratio with up to 150 L/day water demand, the thickness requirement was constant and then increased for 200 L/day water demand. For Darwin, the pattern was similar with different extents of thicknesses. Therefore, Figure 10a shows a combined effect of void ratio and water demand on design thickness to predict probable permeable pavement base course thickness requirements for initial screening of feasibility. As seen from the results, a lower void ratio (15%) and higher water demand (200 L/day) would cause the highest design thickness and vice versa.

As Adelaide and Darwin represent the lowest and highest rainfall zones, respectively, the design thicknesses for any location in Australia would remain within the range shown in Figure 10a. Although not following the same degree of relationship, Sydney and Brisbane would be more similar to the relationship obtained for Darwin, and other areas would lean more towards the relationship assessed for Adelaide. Perth, being in the middle range of rainfall, would be in the mid-range.

Figure 10b also shows a range of design thickness variability for water demand and the material void ratio. For a higher void ratio, the design thickness can vary from 100 mm to 770 mm, depending on the location and water demand. For a lower void ratio of 15%, the extent of thickness can vary between 147 mm and 2053 mm. The higher end of this range would be prohibitive because of excavation costs for the pavement construction. Therefore, the results indicate the importance of selecting the design parameters carefully before opting for a specific permeable pavement design to achieve the maximum efficiency from the system.

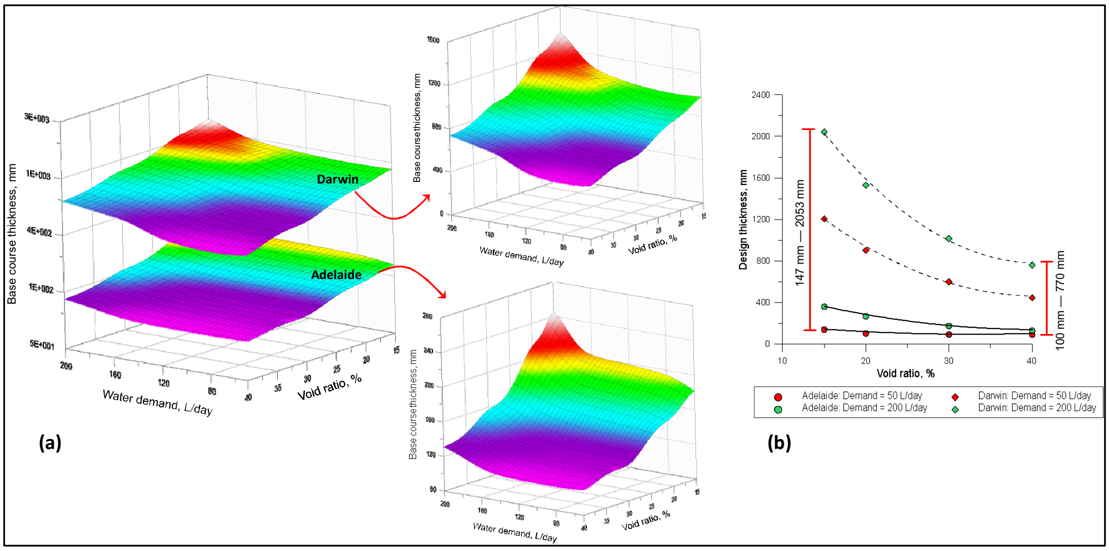

**Figure 10.** (**a**) Relationship between permeable pavement design thickness, void ratio of base course materials and water demand in Adelaide and Darwin; (**b**) probable extent of design thickness variability for void ratio and water demand.

## 4. Conclusions

This research has aimed to assess the design requirements of permeable pavements for water harvesting considering the spatial variability of rainfall and runoff. For the spatial analysis, the pavement system was designed for low traffic conditions, such as car parks, and for constant water demand and pavement materials. Rainfall variability and hydrological effectiveness of infiltration systems for various regions across Australia determined the design thickness requirements. In general, areas with higher rainfall were found to meet more of the reuse demand and the design thickness was often higher in such cases. However, due to the change in other influencing parameters such as base course material void ratio and water demand, the pavement construction requirements changed significantly and were found to vary greatly depending on the requirements and locations.

The analysis was conducted based on certain assumptions. Including average annual rainfall. The research can be further enhanced by considering the temporal distribution of rainfall and designing the thickness accordingly. Furthermore, instead of the hydrological effectiveness approach, future research can be conducted based on the infiltration and storage capacity of the system using a time series approach, which requires a comprehensive assessment of the water extraction rates. However, the parametric study to predict the extent of design thickness and the spatial analysis conducted in this study has provided a comprehensive platform to predict the initial design requirements for planning purposes.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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