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Towards improving the hydrologic design of permeable pavements

Elhadi Mohsen Hassan Abdalla[a,b,*], Tone Merete Muthanna[b], Knut Alfredsen[b] and Edvard Sivertsen[a]

[a] SINTEF community, S.P. Andersens vei 3, Trondheim, Trondelag 7031, Norway
[b] Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, Andersens vei 5, Trondelag 7031, Norway
*Corresponding author. E-mail: elhadi.m.h.abdalla@ntnu.no

EMHA, 0000-0002-9871-9034; TMM, 0000-0002-4438-2202; KA, 0000-0002-4076-8351; ES, 0000-0003-1968-170X

ABSTRACT

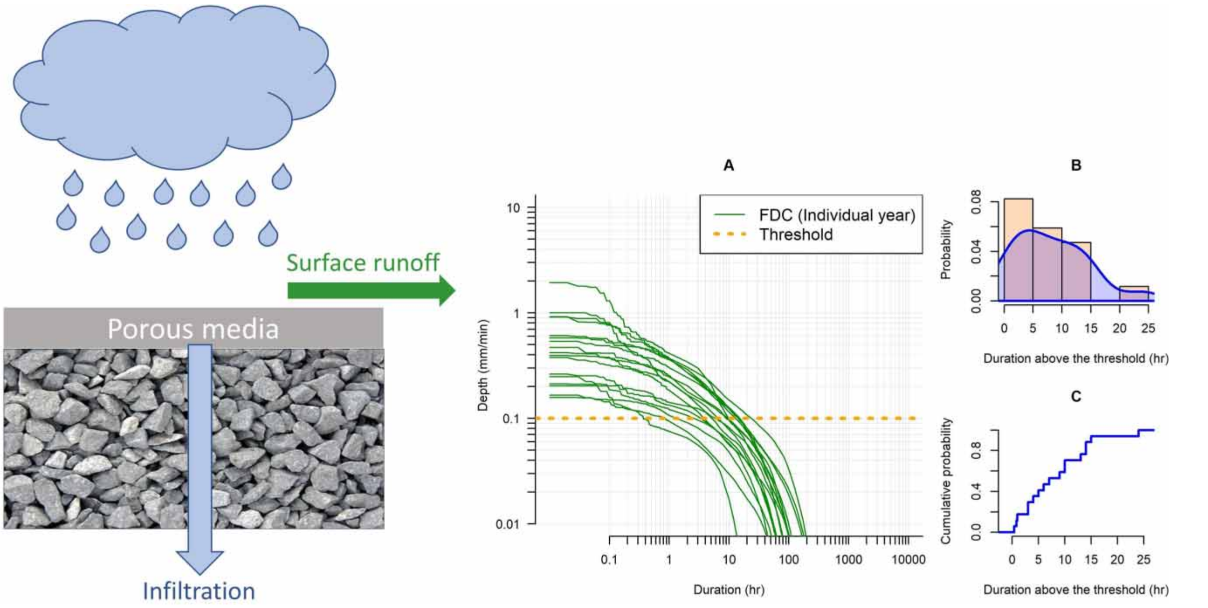
The common approach to the hydrologic design of permeable pavements (PPs) uses synthetic rainfall events. This study assessed the validity of the design approach using synthetic rainfall events for undrained PP. Synthetic rainfall events (25-year return period) were used to design undrained pavements for five Norwegian cities. The effectiveness of these pavements was tested using long-term simulation (12–30 years) with high temporal resolution (1 min). The Storm Water Management Model (SWMM) was used to generate time series of surface runoff for PPs and flow duration curves were applied to analyse the hydrological performances. Designing PP using synthetic rainfall events was found to underestimate the storage layer depth of the permeable pavements leading to the frequent occurrence of surface runoff, which is considered a failure of the hydrologic design of undrained pavements. Long-term simulation of surface runoff was found to provide valuable information for the hydrologic design of PP and can be used as a basis for the PP hydrologic design. In the future, it is recommended to use long-term precipitation data generated from climate change models to incorporate the effect of climate change in the design of PP.

Key words: low-impact development, permeable pavements, stormwater modelling, SWMM

HIGHLIGHTS

- The study assessed the validity of the hydrologic design approach using design rainfall for permeable pavement.
- The hydrologic design approach using design rainfall underestimated the depth of the storage layer leading to frequent surface flooding.
- The study provided methods for the hydrologic design of permeable pavement using long-term precipitation data.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Due to climate change, the amount and intensity of precipitation in Norway are expected to increase in the future (Hanssen-Bauer *et al.* 2017). Additionally, the expected increase in temperature will enhance snow melting. On the other hand, urbanization changes the permeable land use area into impervious surfaces which decreases the natural infiltration and hence increases surface runoff. The combined impact of climate change and rapid urbanization will increase the amount of runoff in the urbanized catchment and hence increase the risk of flooding in the future (Yazdanfar & Sharma 2015).

Permeable pavements (PPs) have emerged as sustainable stormwater measures that could mitigate the impact of climate change and restore the pre-development hydrology of urban catchments (Fassman & Blackbourn 2010). PP increases the permeability of urban catchments which enhances infiltration (Kuruppu *et al.* 2019). Moreover, PP improves the quality of stormwater runoff (Collins *et al.* 2010), reduces urban temperature (Liu *et al.* 2020), and enhances groundwater recharge (Yang *et al.* 2015), among other benefits (Kuruppu *et al.* 2019).

Regarding the hydrological functionality of PPs, they can be categorized into three main types. The first is the undrained-unlined PP that infiltrates the water into the native soil (type A). The second type is the drained-unlined PP which is equipped with a drainage pipe and at the same time allows for water to infiltrate (type B). The third type is the drained-lined PPs with a drainage pipe and a bottom liner that does not allow for water to infiltrate into the native soil (type C). In general, type A is suitable for locations with deep groundwater levels and high infiltration rates. Type C is preferred for sites with shallow groundwater while type B is suited for locations with low permeability.

The hydrological performance of PP can be quantified by determining retention and detention metrics. Retention is the permanent reduction of stormwater either due to infiltration to native soils beneath the pavement or due to the evaporation from the water stored in the pavement layers. The detention is the delay and attenuation of stormwater flows measured at the drainage network connected to the pavement. The detention is typically estimated by several indicators such as peak reduction, peak delay, and centroid delay (Stovin *et al.* 2017).

Several field experiments have been conducted in the literature to quantify the hydrological performance of the three permeable pavement types. For type A, high volume reduction rates (up to 90%) due to infiltration were reported, even under soils with low permeability (Dreelin *et al.* 2006). Ball & Rankin (2010) found surface runoff to only occur over type A pavement for rainfall events with intensity exceeding 20 mm/h. For type B, reported values range between 15 and 70% (Fassman & Blackbourn 2010; Braswell *et al.* 2018; Winston *et al.* 2018) depending on rainfall intensity and antecedent conditions. Furthermore, type B pavement was found to detain drainage flow effectively with an average peak reduction of around 80% (Braswell *et al.* 2018; Winston *et al.* 2018) and average peak delay values range between 20 min and 2 h (Brattebo & Booth 2003; Fassman

& Blackbourn 2010; Braswell *et al.* 2018). For type C pavement, reported peak reduction values reach up to 98% and peak delay values up to 4 h (Pratt *et al.* 1995; Abbott & Comino-Mateos 2003; Støvring *et al.* 2018).

The hydrologic design of PP aims at optimizing parameters of PP which includes the sizes and material properties of PP's layers (i.e. pavement, subbase, and base layers) in order to enhance infiltration, storage, and attenuation of drain outflows, taking into consideration the local conditions (i.e. infiltration capacity of the native soil, connecting sub-catchments, drainage network properties, etc.) and climatic forcing (i.e. precipitation) (Weiss *et al.* 2019; Kia *et al.* 2021). The common approach for the hydrologic design of PP relies on synthetic design rainfall hyetographs, such as the Chicago hyetograph method (Keifer & Chu 1957). In this approach, the total storage capacity of the pavement layers is optimized to store a synthetic design rainfall event with a specific return period. Hydrological models could be applied to establish inflow–outflow relationships that can help to design the pavement (Swan & Smith 2010; Martin & Kaye 2014; Martin & Kaye 2015; Jabonero *et al.* 2018; Kia *et al.* 2021). However, this approach does not take into consideration the initial saturation of the pavement before rainfall events. Therefore, even if the pavement was designed to accommodate a 20-year return period of rainfall, much smaller rainfall events could cause surface flooding if they fall when the pavement storage is full. An alternative approach is to design PP based on long-term continuous simulation data. This approach, arguably, offers a more reliable approach that can incorporate the effect of climatic conditions on pavement performance. While some papers were found to evaluate the hydrological performance of PP using long-term simulation data (Liu & Chui 2017; Randall *et al.* 2020), no study was found to use long-term data for the hydrologic design (i.e. sizing) of PP.

The current study assessed the validity of the design rainfall approach for undrained permeable. Type A pavements were designed for five Norwegian cities, using design rainfall (25 years of return period). The reliability of these PP was tested using long-term simulation data (12–30 years) with high temporal resolution (1 min). Furthermore, the study attempted to provide methods for analysing long-term simulation data which can be used for the hydrologic design of permeable pavements.

2. DATA AND METHODS

2.1. Precipitation data

2.1.1. Long-term data

The study used long time series of precipitation data (12–30 years) with a 1-min resolution from five Norwegian cities. Figure 1 presents the location and the annual precipitation of the five Norwegian cities. Bergen is the wettest city among the five, based on the amount of annual precipitation, followed by Kristiansand while Hamar city is the driest one. The five cities cover three climatic classes, based on the Köppen Geiger classification system (Kottek *et al.* 2006), as presented in Table 1. The precipitation data are collected and quality-checked (Lutz *et al.* 2020) by the Norwegian Meteorological Institute (MET). Hence, no further data processing has been done to the precipitation data.

2.1.2. Design rainfall

In Norway, stormwater infrastructures are typically designed to accommodate rainfall events with 10–30 years of the return period, for the urbanized catchment. The variation depends on the land use and the local drainage system conditions (Trondheim Kommune 2015). In this study, design storms with a 25-year return period were constructed based on the IDF (Intensity–Duration–Frequency) curves of the five cities, as shown in Figure 2. IDF data were obtained from the Norwegian climatic surface website (https://klimaservicesenter.no/). The duration of design storms was selected as 1 h, following the design guidelines for urbanized catchments (Stenius *et al.* 2015) and similar studies (Hernes *et al.* 2020).

2.2. The hydrological modelling

The study applied the low-impact development module of the Storm Water Management Model (SWMM) (Rossman 2015). The model is widely used for modelling the hydrological performance of permeable pavements (Kim *et al.* 2015; Chui *et al.* 2016; Xie *et al.* 2017; Randall *et al.* 2020). The validity of the SWMM-LID module has been investigated in many studies by comparing the simulation with measured data. For instance, Liu & Chui (2017) confirmed the ability of the SWMM-LID model to simulate drainage flow from the permeable pavement with high accuracy (Nash–Sutcliffe efficiency higher than 0.9). Similarly, Palla & Gnecco (2015) reported Nash–Sutcliffe efficiency values higher than 0.75 of the simulated drainage flows of a calibrated SWMM-LID model for a laboratory permeable pavement.

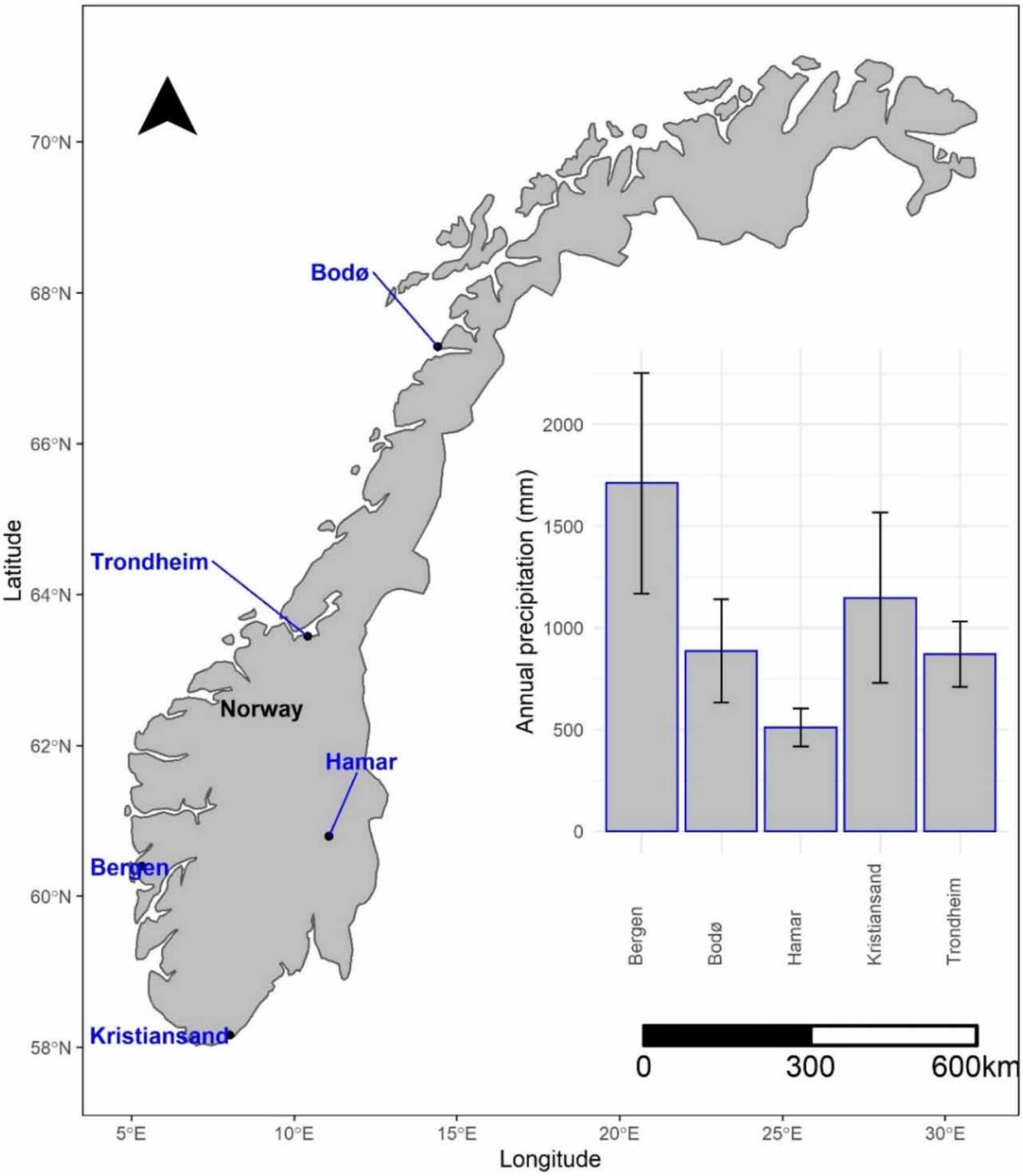


Figure 1 | Locations and annual precipitation of the five Norwegian cities.

Table 1 | Climate classes of the five Norwegian cities and their precipitation data

City	Climate class (Köppen Geiger)	Precipitation data
Bergen	Temperate oceanic climate (Cfb)	[1990–2020]
Trondheim	Subarctic climate (Dfc)	[1990–2020]
Bodø	Subarctic climate (Dfc)	[1997–2020]
Kristiansand	Temperate oceanic climate (Cfb)	[1999–2020]
Hamar	Warm-summer humid continental climate (Dfb)	[2008–2020]

In SWMM-LID, the pavement can be represented by five layers: surface, soil, pavement, storage, and drain (Rossman 2015). Each layer contains parameters that control the water movement and need to be adjusted from field measurements, calibration or from the SWMM manual. Precipitation water infiltrates through the

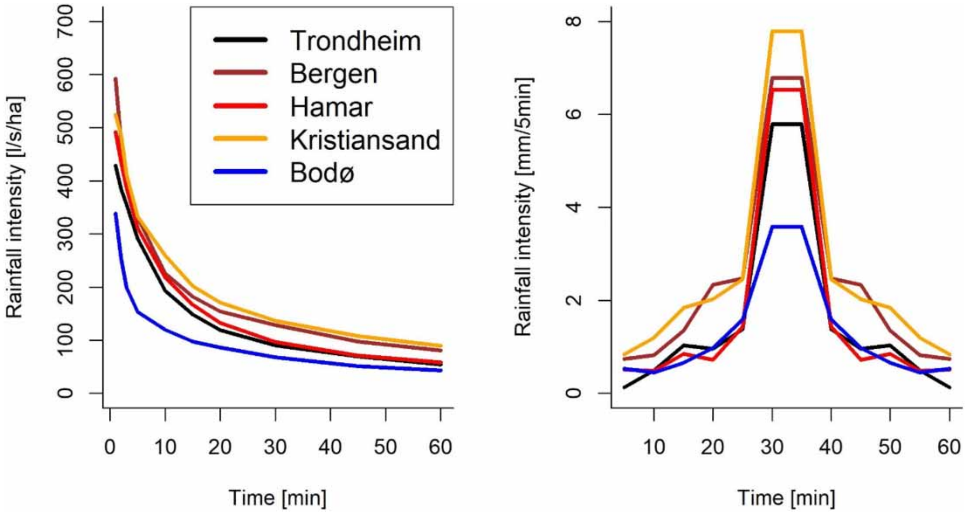


Figure 2 | Left: IDF curves of the five cities (return period = 25 years). Right: design storms of the five cities (return period = 25 years).

pavement layer to the soil layer limited by the permeability of the pavement layer (Rossman 2015). The infiltrated water is stored in the soil layer until the soil moisture reaches the field capacity. After that, the water percolates into the storage layer following Darcy's law (Rossman 2015). The water accumulates in the storage layer and can either infiltrate into the native soil for type A and type B pavements or be discharged to the drainage pipe for type B and type C pavements.

The SWMM-LID assumes a constant value of the infiltration to the native soil (Rossman 2015), which can be set to the minimum infiltration capacity of a given location. Indeed, this assumption is conservative since the infiltration capacity is a function of the soil moisture (when the soil is dry the infiltration capacity is high). However, Martin & Kaye (2014) argued that such an assumption is appropriate since the soil beneath the storage layer takes a longer time to dry in comparison to the soil on the surface.

The soil layer of the LID module is optional and can be used to represent the bedding layer for permeable interlocking concrete pavements (Rossman 2015). The soil layer contains many parameters that are considered sensitive (Randall *et al.* 2020; Abdalla *et al.* 2021) which require careful measurement or calibration. On the other hand, for other types of permeable pavement, such as pervious concrete, the soil layer is not required (Jato-Espino *et al.* 2016; Wang *et al.* 2019). In this study, the pavement systems were modelled as pervious concrete without soil layers.

The parameters of the SWMM are presented in Table 2. The average values of the recommended ranges of the void ratio of the pavement and storage layers are selected from the SWMM manual (Rossman 2015), following

Table 2 | SWMM parameters used in the study

Parameter	Layer	Selected value(s)	Unit
Manning	Surface	0.1	–
Berm height		0	mm
Slope		1	%
The thickness of the pavement layer	Pavement	80	mm
Void ratio		0.17	–
Impervious surface fraction		0.9	–
Permeability		3,600	mm/h
Void ratio	Storage	0.63	–
Depth of the storage layer (D)		10, 20, 50, 100, 300, 400	mm
Infiltration to the native soil		0.1, 0.5, 1, 3, 5, 10, 20	mm/h

the work of Zhang & Guo (2015). The berm height of the surface layer was selected as zero to allow for surface runoff to occur if the pavement is full while the pavement slope was selected as 1% (Zhang & Guo 2015). The impervious surface fraction parameter is selected arbitrarily as 0.9. This parameter, together with the void ratio of the pavement layer, is only used by the SWMM in clogging conditions (Rossman 2015). In this study, however, we assumed no clogging conditions during the pavement lifetime through frequent maintenance. Randall *et al.* (2020) found the void ratio of the pavement layer to be an insensitive parameter for the SWMM with no clogging condition. The permeability of the pavement was set as 3,600 mm/h, which is a typical value for permeable pavement that is designed with permeable materials (Zhang & Guo 2015; Vaillancourt *et al.* 2019).

The depth of the storage layer varied between 10 and 400 mm, which represents the design parameter, controlling the performance of type A pavement. The infiltration capacity of the native soil varied between 0.1 and 20 mm/h, following the study of Muthanna *et al.* (2018) in which they conducted serval field measurements for the infiltration capacity of urban areas in Trondheim city (Figure 1).

It should be noted that, during the winter months (November–March), most of the precipitation in Norway falls as snow. However, in the current study, snow modelling was not considered. Hence winter months were excluded from the analysis. In addition, all simulations were done for a permeable pavement with an area of 100 m^2 (8 $\times$ 12.5) that is not connected to any adjacent catchment

2.3. The hydrologic design of undrained permeable pavement

The hydrologic design of undrained permeable pavement (type A) aims at optimizing the depths of the different layers of the pavements to eliminate or minimize the occurrence of surface runoff (Jabonero *et al.* 2018; Kia *et al.* 2021). Indeed, surface runoff in urban catchments is highly undesirable due to the associated negative impact of floods. Additionally, the standing surface water in urban catchments creates odour and health issues (Kuruppu *et al.* 2019). In this study, the depth of the storage layer was optimized for the reduction of surface runoff.

2.4. Analysis of continuous simulation

Flow duration curves (FDC) of the surface runoff were plotted to analyse the performance of PP. This study applied a modified version of FDC that relates between the flow and the duration of time in which this flow value is exceeded, which is recommended by Abdalla *et al.* (2021). To improve the visualization, FDC were plotted in log-log scales.

In this study, we present two methods for analysing information from FDC, in order to obtain a proper hydrologic design of permeable pavements. In the first method, the probabilities of surface runoff durations above a defined threshold are extracted. In the second method, depth–duration plots are generated which show the relationship between the depth of the storage layer and the duration when the surface flow is higher than zero.

2.5. Analysis of rainfall–runoff events

The rainfall events of the five cities were further analysed to compare the climatic conditions of the five cities. Rainfall events were separated from the long-term data sets with 6 h intra-event periods, similar to previous literature into sustainable stormwater measures (Stovin *et al.* 2012; Johannessen *et al.* 2018). For each rainfall event, four characteristics were determined: amount (mm), duration (min), average intensity (mm/h), and antecedent dry weather periods (ADWP) (h), which refers to the periods between each two consecutive rainfall events. Cumulative distribution functions of the four characteristics were plotted and compared between the five cities.

3. RESULTS

3.1. The hydrologic design of undrained pavements using design storms

Surface runoff hydrographs for type A pavements were plotted for the five cities and the different values of native soil infiltration rates and storage depths (Table 2). Figure 3 presents an example of surface runoff hydrographs at Kristiansand city for a native soil infiltration value of 0.1 mm/h. As shown in Figure 3, surface runoff was eliminated when the storage depth of the PP was greater than or equal to 100 mm.

Figure 4 illustrates the peak values of surface flow for type A PP at the five cities with varying storage depths and infiltration capacities of the native soil. It can be noted from Figure 4 that surface runoff was eliminated when the storage depth of the PP was greater than or equal to 100 mm for all the cities and the different infiltration

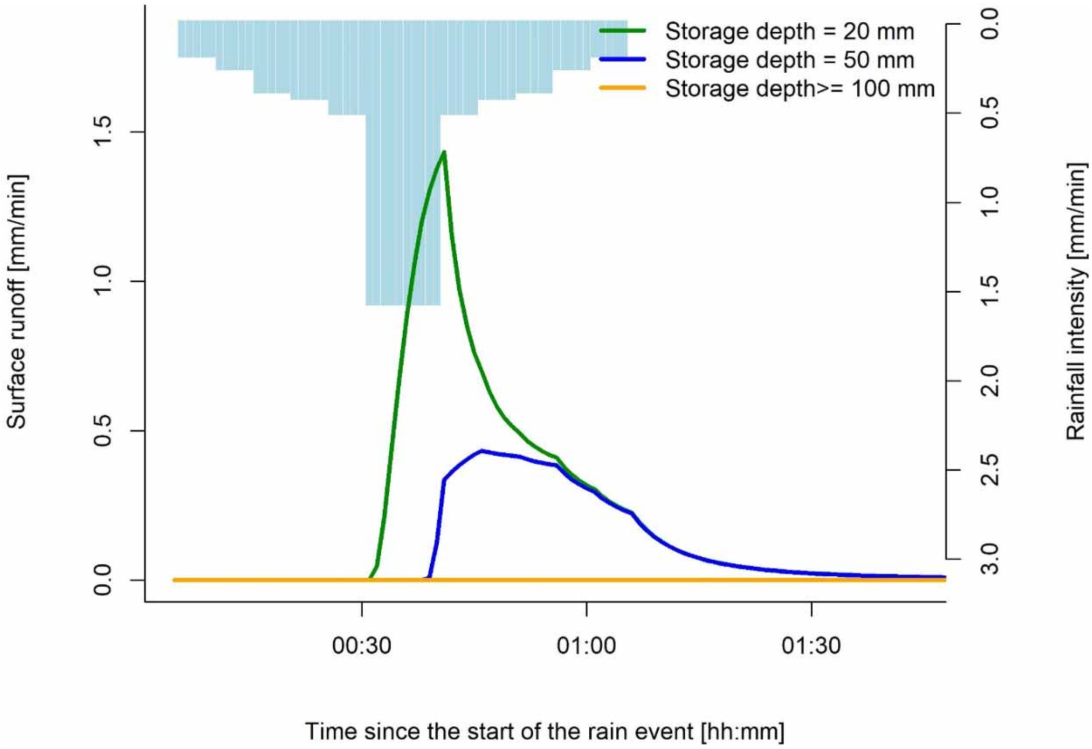


Figure 3 | Surface runoff hydrographs for undrained permeable pavements at Kristiansand for varying storage depths (infiltration of the native soil = 0.1 mm/h).

capacities. For Trondheim and Bodø, a depth of 50 mm was found to be sufficient to eliminate the occurrence of surface runoff.

Based on the results in Figure 4, it can be concluded that a type A pavement with 100 mm is sufficient for all five cities in the study, even for soils with low infiltration capacity (0.1 mm/h). To verify this conclusion, annual FDC were plotted for surface runoff of type A pavements with a depth of storage of 100 mm for the five cities and native soil infiltration of 0.1 mm/h. Figure 5 presents these results which showed that surface runoff occurred annually with durations exceeding 100 h each year in some cities. One can note the variation among cities, even though the pavement design is the same. For instance, in Bergen, the surface runoff duration ranged between 100 and 500 h/year, while in Trondheim, the duration of surface runoff varied from less than 10 to 200 h/year.

The common design approach using design rainfall events resulted in underestimation of storage layer depths leading to the frequent occurrence of surface runoff in the pavements, which is considered a failure of the hydrologic design concerning the functionality of undrained pavements. To analyse the shortcoming of the design rainfall approach, the variation of water levels in the storage layers after the start of rainfall events was plotted for type A pavements in Kristiansand city (Figure 6). After the rainfall event, the pavement takes time to dry by infiltrating the stored water into the native soil. This time is called the drawdown time (Martin & Kaye 2014). As can be noted, the drawdown time is longer for soils with low infiltration capacities. Hence, if the next rainfall event occurred before the pavement is completely dry (i.e. before the end of the drawdown time), the pavement capacity to accommodate the event will be lower than the design value, which could lead to surface runoff. This could occur even if the next rainfall event has a return period lower than the one used for design. For instance, historical rainfall events of Kristiansand were found to have a lower return period than 25 years (Figure 7).

3.2. The hydrologic design of undrained pavements using long-term precipitation data

The depth–duration plots were generated from the FDC. Figure 8 presents depth–duration plots of individual years for Trondheim city (native soil infiltration = 0.1 mm/h). The results showed a wide range which represents the variation of rainfall events between the years. In addition, the results showed that when increasing the depth of the storage layer to 400 mm, surface runoff only occurred in 8 out of the 30 years.

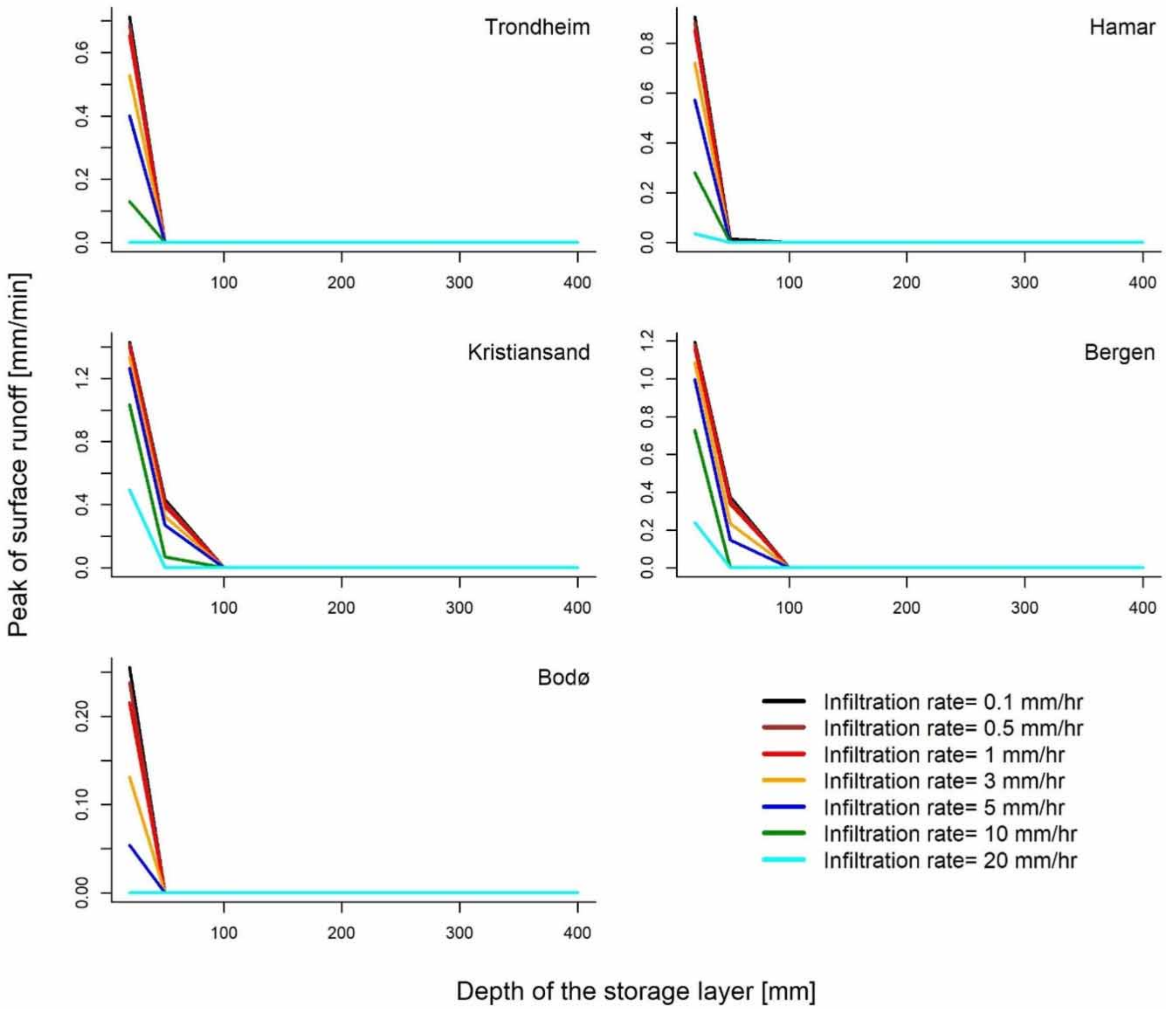


Figure 4 | Peak values of surface flow for undrained permeable pavement (using design storms with 25 years of return period) at the five cities with varying storage depths and varying infiltration rates to the native soil.

Figure 9 presents the maximum values of depth–duration plots for the five cities with varying values of infiltration to the native soil. The result shows that optimizing the depth of the storage layer, to eliminate the surface runoff, is highly dependent on the location and infiltration capacity of the native soil. For Kristiansand and Bergen, deeper storage layers are required in comparison to the other cities for the same infiltration capacities of the native soil.

A comparison of rainfall characteristics between the five cities is presented in Figure 10. Although Bergen has the highest annual rainfall among the five cities (Figure 1), its events have almost the same amount as Kristiansand's rainfall because Kristiansand's events have higher intensities but with shorter durations and longer intra-event periods (ADWP). In contrast, Hamar's events have the lowest amount and duration while Trondheim's and Bodø's events have the lowest average intensity. As a result, a pavement with a storage depth of 100 mm could eliminate the occurrence of surface runoff in Hamar for sites with infiltration capacities higher than or equal to 1 mm/h. However, for the same infiltration capacity, a storage depth of 200 mm is required in Hamar and Bodø, and Trondheim, while a depth of 300 mm would be required for Bergen and Kristiansand to eliminate surface runoff.

Sometimes, it can be acceptable to allow for surface runoff, up to a specific threshold value that triggers unwanted events (e.g. flooding). For instance, if the pavement is not directly connected to critical infrastructures. In such cases, the probabilities of durations above the critical threshold value can be extracted from the FDC of individual years and can be used for flood risk management (Jha *et al.* 2012). Figure 11 illustrates an example of a type A pavement with a depth of 100 mm in Kristiansand city (native soil infiltration of 0.1 mm/h). A value of 0.1 mm/h was selected as a threshold value that triggers flooding. The depth of the storage layer can be varied until the risk of surface flooding is acceptable.

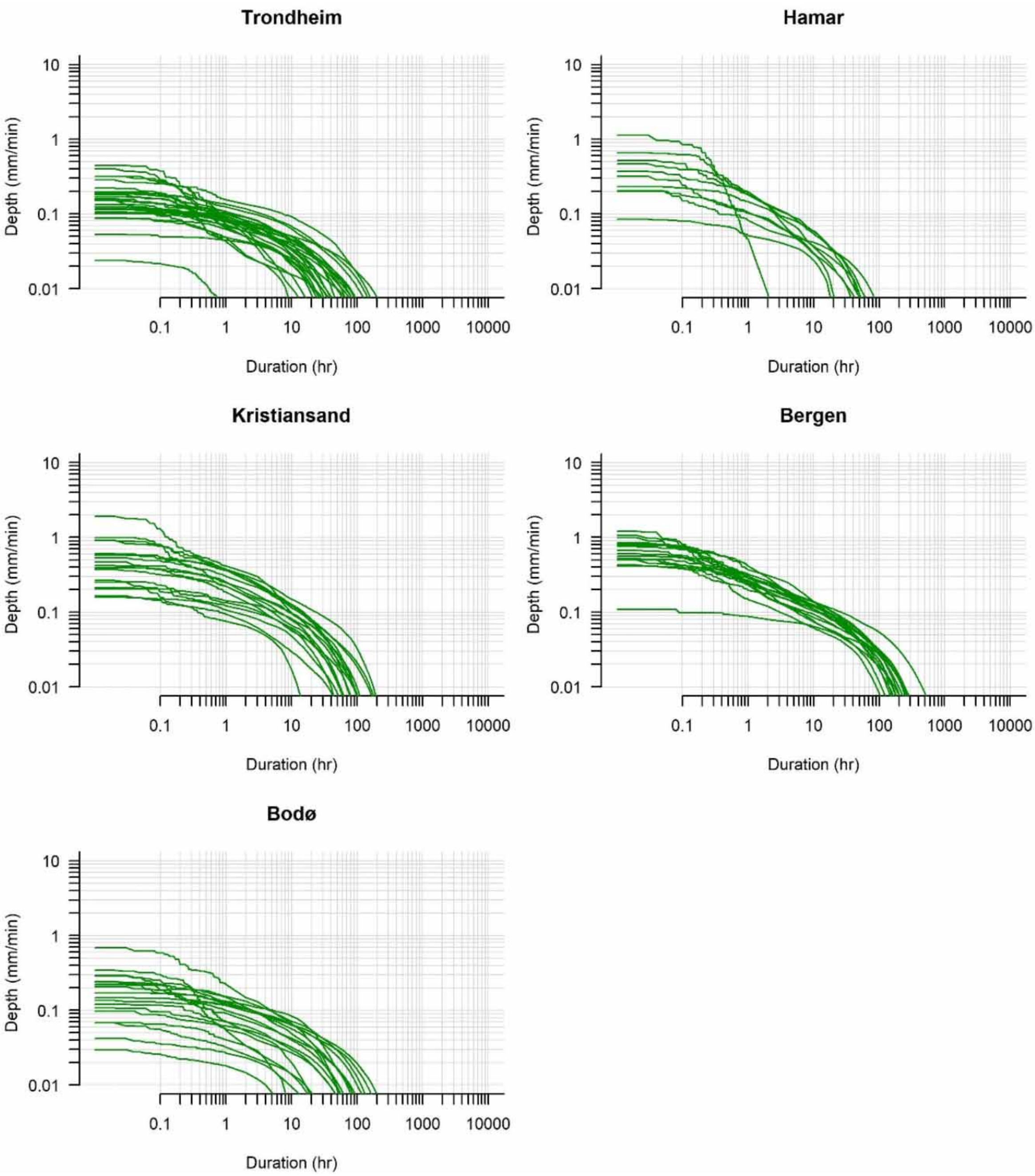


Figure 5 | Annual FDCs of surface runoff for undrained permeable pavements with depth of storage of 100 mm for the five cities and native soil infiltration of 0.1 mm/h.

4. DISCUSSION

The design storm approach underestimated the storage layer depths, as it did not take into consideration the initial saturation of the pavement prior to the rainfall event. One could argue that the design storm approach can be applied if a proper initial saturation is selected. However, it is very difficult, if not impossible, to define a 'proper' initial saturation without continuous simulations. It can also be argued the design storm method can be used if the drawdown time is considered; if the drawdown time of a proposed pavement design is very long, the depth can be increased, and/or an underdrained pipe can be installed (Martin & Kaye 2014). However, what defines a 'long' drawdown time can be subjective without taking into consideration the long-term rainfall characteristics of the locations.

Another issue with the design storm method is that only one rainfall hyetograph is typically used in the design. Nevertheless, the shape of the design storm hyetograph can affect the flooding outputs of pavements. For

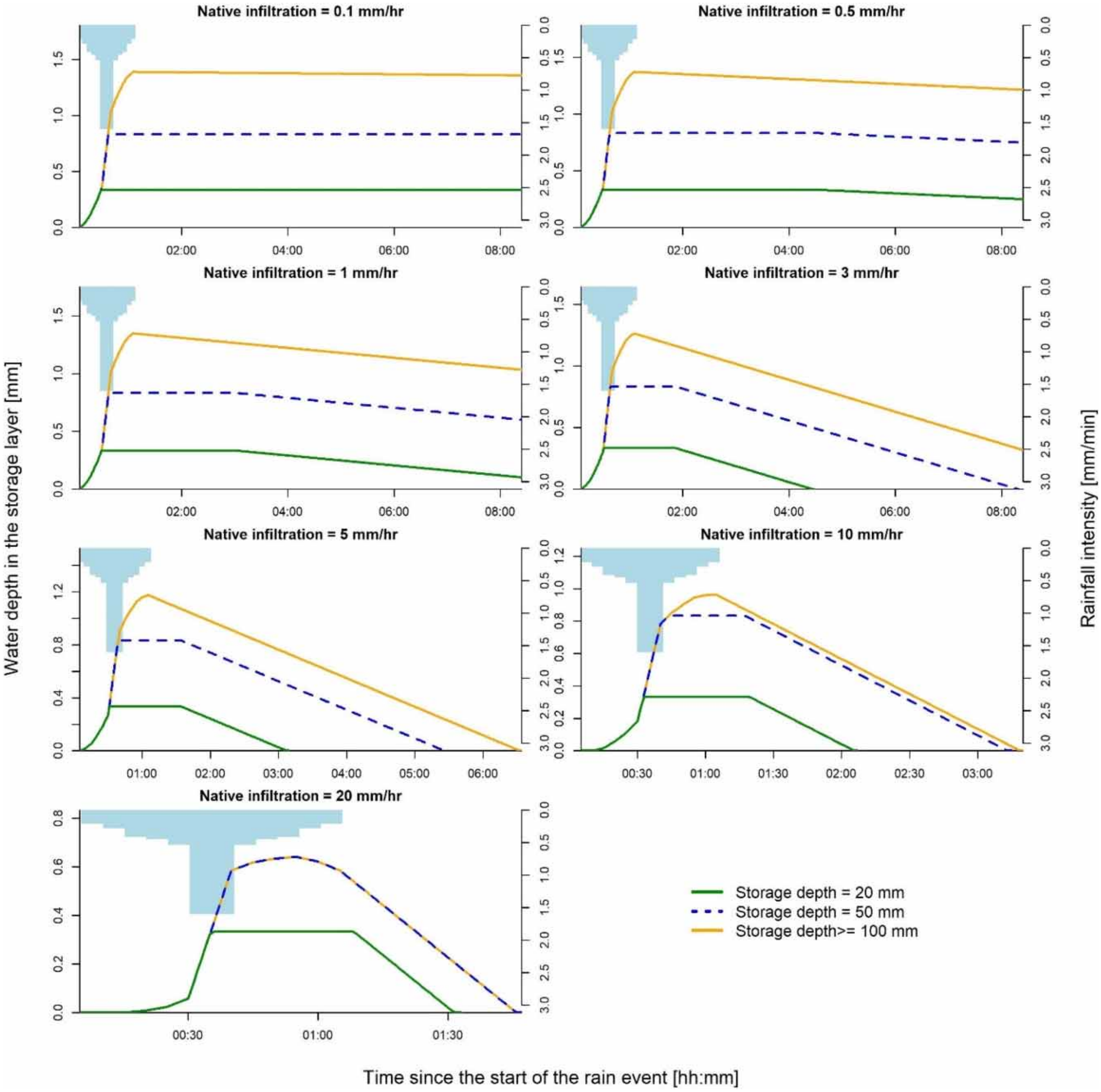


Figure 6 | Variation of water level in the storage layer for undrained pavements in Kristiansand city with different storage layer depths and native soil infiltration. These simulations were done using a design rainfall storm (25 years of return period).

instance, Hamouz *et al.* (2020) analysed the effect of changing rainfall hyetograph on the drainage flow of a green roof. Martin & Kaye (2014) acknowledged the effect of rainfall hyetograph and presented different design charts for each design rainfall hyetograph. However, natural rainfall hyetographs could differ significantly from the design rainfall ones and can be different among cities. Therefore, it can be considered more realistic to use long-term measured precipitation data for validating the effectiveness of a pavement design, which takes into consideration the influence of hyetograph shapes and initial conditions of the specific location.

Long-term simulation of surface runoff can provide valuable information for the PP design. However, it can be challenging to analyse the huge amount of data in order to obtain an appropriate pavement design. Hence, the study suggested two methods to summarize the information from FDC of the surface runoff. If the goal of stormwater management is to eliminate the occurrence of surface runoff, the depth–duration plots using the maximum values, as shown in Figure 9, can be used. If it is acceptable to allow for surface runoff up to a critical value, the probabilities of durations above that critical value can be extracted from the FDC of individual years and can be used for risk management.

In future studies, it is recommended to use long-term precipitation data generated from climate change models, to incorporate the effect of climate change in the design of permeable pavements. Climate change is expected to

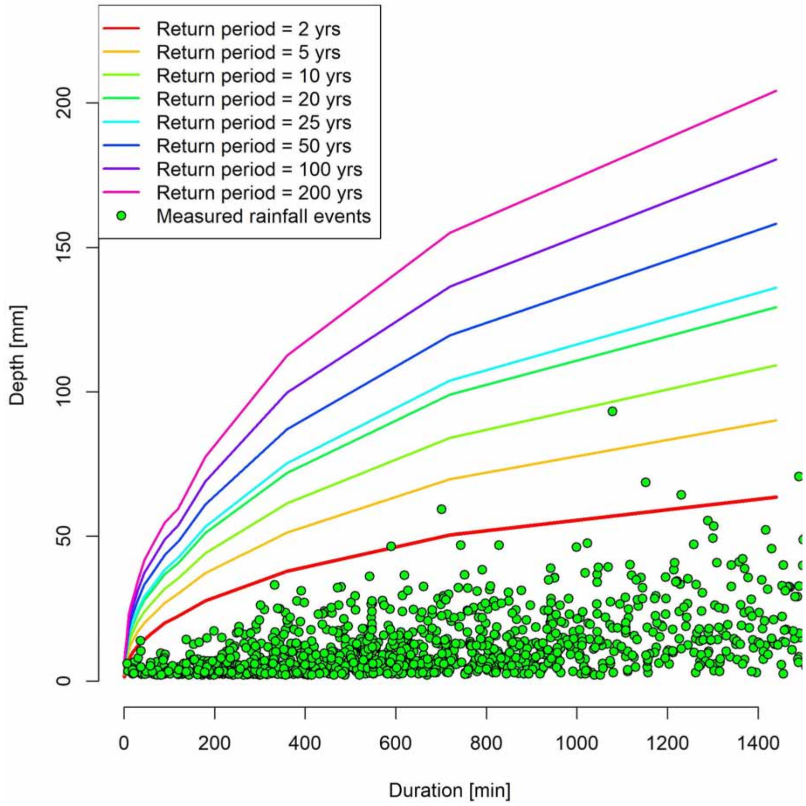


Figure 7 | Depth–duration frequency curves for Kristiansand city and the historical measured rainfall events.

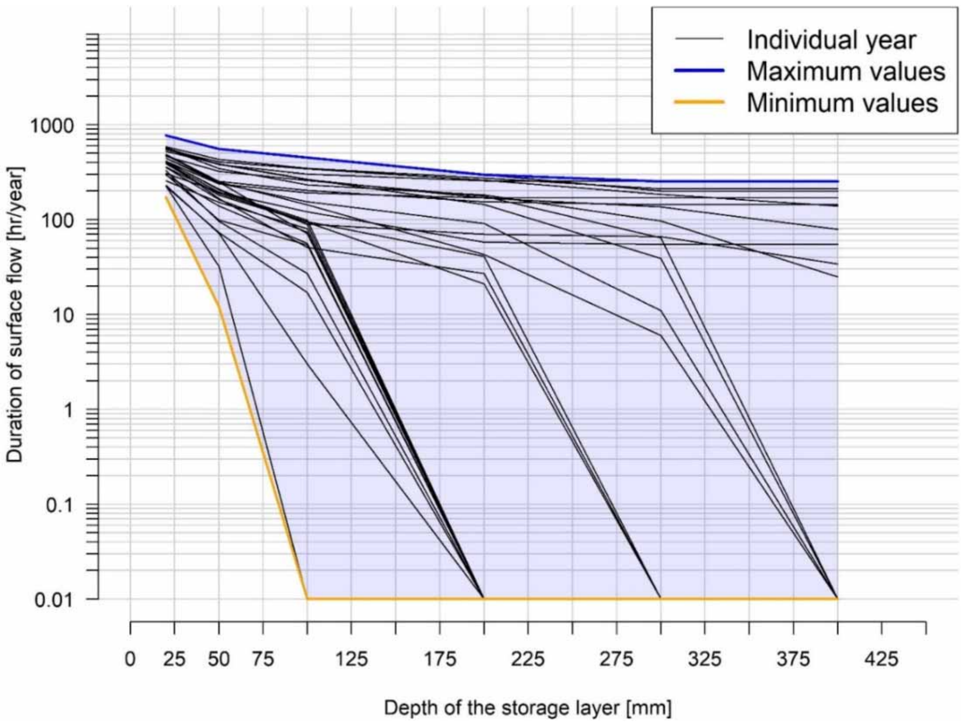


Figure 8 | The relations between the depth of the storage layer and the duration when the surface flow is higher than zero (depth–duration plots) for individual years. These were done for Trondheim city and infiltration to the native soil of 0.1 mm/h. The plot shows the maximum and minimum values and the range.

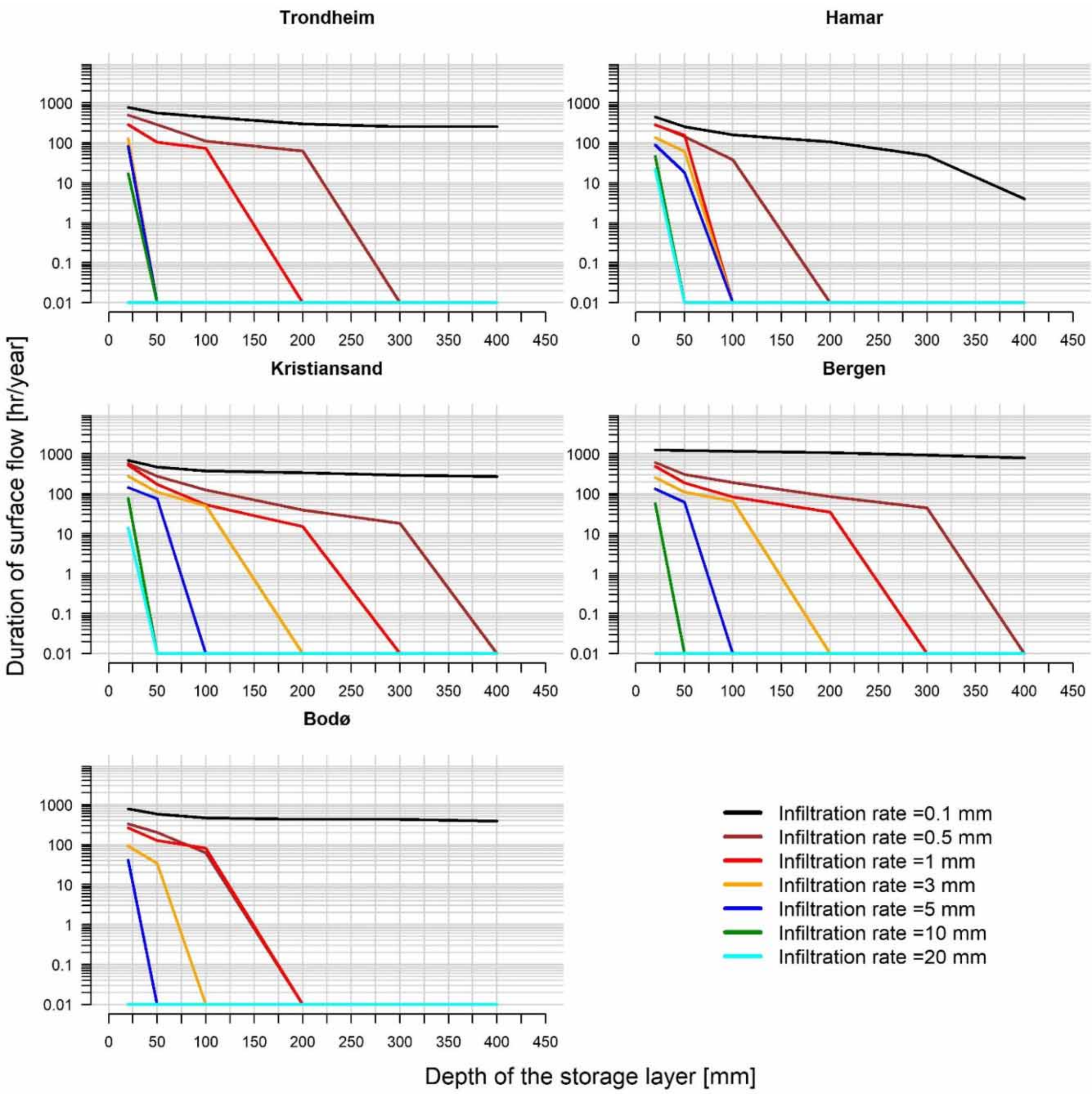


Figure 9 | The relations between the depth of the storage layer and maximum values of duration when the surface flow is higher than zero (depth–duration plots). These were done for the five cities and varying values of infiltration to the native soil.

alter the rainfall characteristics (e.g. intensity, ADWP, durations, etc.). However, the temporal resolutions of the current climatic change models are daily time steps, which is too coarse for such analysis. Recently, Pons *et al.* (2022) evaluated different statistical approaches to downscaling climate change models from daily to 6-min resolution, which is suitable for stormwater analysis. Hence, the methodology applied in Pons *et al.* (2022) can be used to generate long-term precipitation data with high resolution, for designing permeable pavements, for future cities.

5. SUMMARY AND CONCLUSION

Undrained pavements (type A) were designed for five Norwegian cities using a design storm with 25 years of return period. The effectiveness of the designed pavements was tested using long-term simulation data (12–30 years) with high temporal resolution (1 min). The common design approach using design rainfall events resulted in underestimation of storage layer depths leading to the frequent occurrence of surface runoff in the pavements, which is considered a failure of the hydrologic design with respect to the functionality of undrained pavements.

Long-term simulation of surface runoff can provide valuable information for the PP design. Due to the difficulties of analysing long-term simulation data, the study proposed methods for summarizing the information from

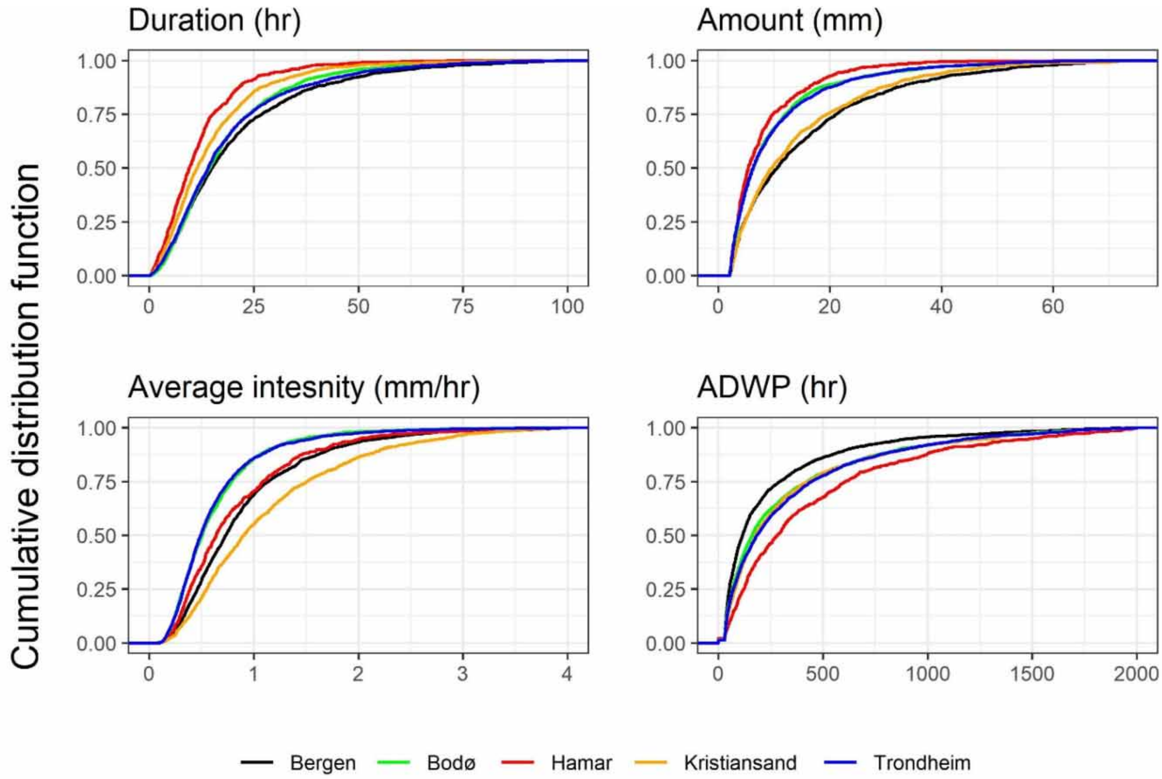


Figure 10 | The cumulative distribution functions of the rainfall events characteristics at the five Norwegian cities.

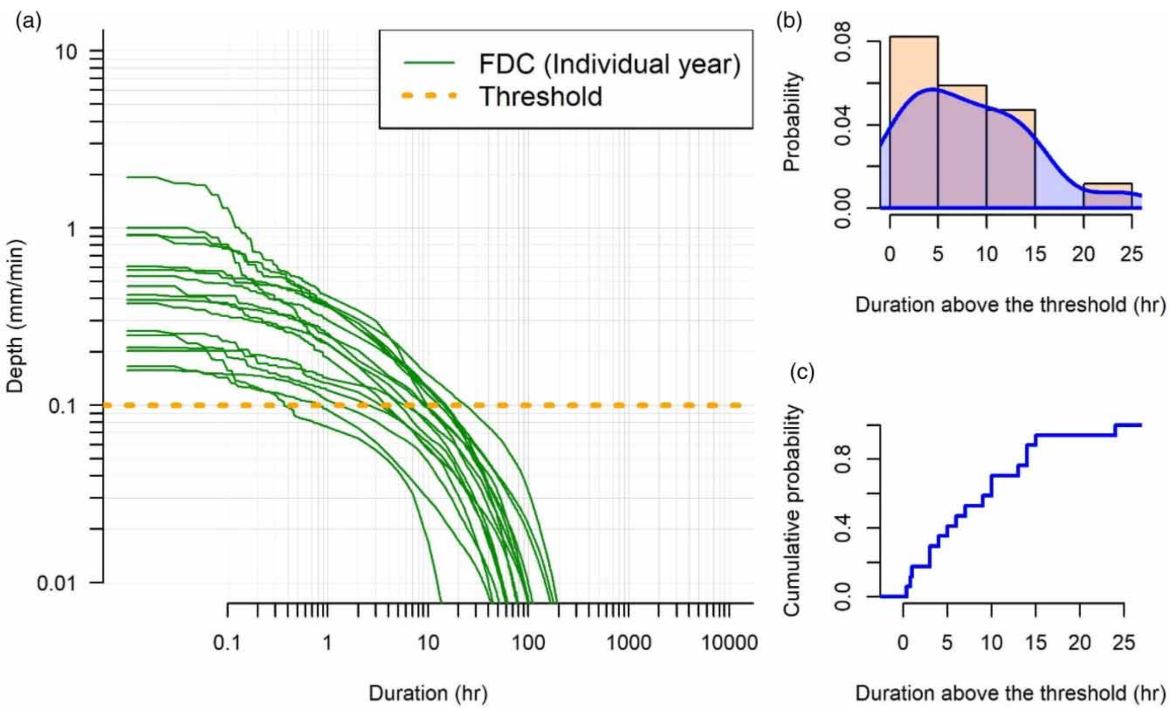


Figure 11 | (a) Annual FDCs of surface runoff for undrained permeable pavements with a depth of storage of 100 mm for Kristiansand city (native soil infiltration of 0.1 mm/h). (b) Probability density function of surface runoff durations above a defined threshold (0.1 mm/min). (c) Cumulative probability of surface runoff durations above a defined threshold (0.1 mm/min).

FDC of the surface runoff, which can assist in the hydrologic design of PP. In future studies, it is recommended to use long-term precipitation data generated from climate change models, to incorporate the effect of climate change in the design of permeable pavements.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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