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LABORATORY STUDY ON THE STORMWATER RETENTION AND RUNOFF ATTENUATION CAPACITY OF FOUR PERMEABLE PAVEMENTS

Jorge Rodríguez-Hernández[1,*], Valerio C. Andrés-Valeri[2], Agustín Ascorbe-Salcedo[3] and Daniel Castro-Fresno[4]

[1] Ph.D. M.Sc. Civil Engineer, Assistant Professor, Department of Transports and Projects and Process Technology, Civil Engineering School, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain.

[2] Ph.D. Student M.Sc. Civil Engineer, Department of Transports and Projects and Process Technology, Civil Engineering School, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain.

[3] Ph.D. M.Sc. Civil Engineer, Professor, Dept. of Water Science and Technology, Civil Engineering School, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain.

[4] Ph.D. M.Sc. Civil Engineer, Professor, Department of Transports and Projects and Process Technology, Civil Engineering School, Universidad de Cantabria, Av. de los Castros 44, 39005, Santander, Spain.

*E-Mail: rodrighj@unican.es; Tel.: +34-942-20-39-43; Fax: +34-942-20-17-03.

Abstract

Hydrological behavior of pervious pavements during rainfall events is a complex process that is affected by many factors such as surface type, aggregates nature, layer thickness, rainfall height, rainfall intensity and the preceding dry period. In order to determine the influence of construction materials on the runoff attenuation capacity of pervious pavements sixteen laboratory models were created with four different cross sections obtained by combining two pervious surfaces and two sub-base aggregate materials. Successive rainfall simulations were applied over the laboratory models measuring lag times, retained rainfalls, times to peak and peak outflows were registered for the simulated rainfalls. The results obtained were grouped depending on the materials used and statistically analysed in order to compare their stormwater retention and runoff attenuation capacities. Both surface type and sub-base aggregate characteristics were proven to influence the attenuation capacity of pervious pavements. While sub-base aggregate materials highly influence the hydrological performance during the first rainfall simulations, the permeable surface affects the hydrological behavior during the final rainfall events and the retention capacity variation over time.

Keywords: Permeable pavement; Porous asphalt; Interlocking concrete blocks; BMP; SuDS.

Introduction

Rainfall water is a fundamental resource for urban settlement development, being essential for refilling reservoirs and aquifers. Nonetheless, the massive waterproofing of natural land in urban areas has disturbed the natural processes of water drainage (Dolz and Gómez 1994), generating flooding problems, loss of serviceability of urban infrastructures and water pollution. For this reason, stormwater runoff was normally treated as an undesirable waste in urban areas, being drained as fast as possible from impervious surfaces and piped into the surrounding environment or sewage systems (Castro-Fresno et al. 1994). Conventional drainage systems have been widely used to manage stormwater runoff, but the progressive growth of urban centers has enlarged impervious areas (Swan

2010) and caused increasing runoff volumes (Ferguson 2005). In lowland urbanized areas, this situation leads to flooding problems for surpassing the drainage capacity of conventional systems. The sustainable flood risk management approach is gaining ground worldwide and the integration of control measures for runoff management in urban development is becoming increasingly important to mitigate the problems related to stormwater management (Dietz 2007).

One of the main solutions to reduce runoff volumes in urbanized areas is the substitution of impervious surfaces by permeable ones (Sañudo-Fontaneda et al. 2014a), allowing runoff to infiltrate into the ground. In fact, McBride and Knapton (2006) pointed out that the use of pervious surfaces in new urban development allows the permeability levels of natural land to be maintained. Moreover, retrofitting of impervious areas in urban centers, replacing them with permeable surfaces, helps control runoff directly in the origin, increasing the amount of infiltrated water and reducing runoff volumes (Sañudo-Fontaneda et al. 2014b). Specifically, permeable surfaces, which can resist traffic loads, have been widely used to mitigate runoff volumes and pollutants in urban areas (Scholz and Grabowiecki 2007). The main advantage of using pervious pavements is the reduction of the runoff volume that flows into sewage systems (Schlüter and Jefferies 2002). Moreover, the application of these techniques provides peak flow reductions in the range of 40%-60% (Mullaney and Lucke 2014) and sometimes, with light rainfall intensities, the complete disappearance of runoff (Brattebo and Booth 2003; Collins et al. 2008).

The hydrological performance of pervious pavement systems is complex due to the different factors that determine their behavior over time. Pratt *et al* (1989, 1995) found that outflow intensities from permeable pavements were 30% lower than rainfall intensities, delaying the outflow and prolonging it after the end of the rainfall event. They observed delays in the range of 5-10 min between the start of the rainfall event and the beginning of the outflow. The variability found in those results was mainly related to the sub-base aggregates used in the construction of pervious pavements (Bond et al. 1999) and other hydrological parameters such as rainfall intensity, rainfall volumes and length of dry period between rainfall events (Pratt et al. 1995).

Some studies (Andersen et al. 1999) showed that, depending on the materials used, permeable pavement systems provide different stormwater retention capacities in terms of lag time and retained rainfall volumes. Other studies (Gomez-Ullate et al. 2011) showed statistical differences in the rainwater harvesting capacity of permeable pavements depending on the surface type, indicating some influence of the infiltration behavior on the hydrological performance of the systems. The different infiltration processes between permeable surfaces and porous surfaces (Pratt et al. 2002) along with the different nature of the aggregates can lead to different hydrological performances depending on the materials used. With the aim of analyzing the influence of the surface and sub-base materials on the stormwater retention and the runoff attenuation capacity of pervious pavements over time, a long-term laboratory study was developed. Successive rainfall simulations were applied to different permeable pavement cross sections registering the lag times, retained rainfalls, times to peak and peak outflows, in order to study the differences in their hydrological performance depending on the materials used. Therefore, for assessing only the materials' influence, no clogging effects were studied in the present research, limiting the applicability of the results obtained to the field, where the surface characteristics can affect the clogging influence on the hydrological behavior of permeable pavements.

Materials and Methods

Two sub-base aggregate materials, with different characteristics were used: limestone and recycled aggregate from construction and demolition debris. The gradations used were quite similar for both aggregates (Fig.1a), resulting in similar air void content. The water absorption capacities according to UNE-EN 1097-6 were 1.6% for limestone and 9.4% for recycled aggregates; while the particle densities were 2702 kg/m³ for limestone and 2554 kg/m³ for recycled aggregates.

In order to study the influence of the different infiltration processes induced by porous and permeable surfaces, two different surfaces were selected:

- Interlocking Concrete Blocks (ICB) with dimensions 100x200x100 mm and 4 permeable semi-elliptical slots of 100 mm².
- Porous Asphalt with a nominal maximum aggregate size of 12 mm made with limestone aggregates and polymer-modified bituminous binder, resulting in a mixture with 20±1% of total air voids.

Four permeable pavement cross sections were obtained by combining the two permeable surfaces with the two aggregate materials (Fig. 1b), and four replicas of each cross section were tested. All laboratory models include a base layer of limestone aggregate (5-6.35 mm) under the permeable surface, and a plastic cell with 53 mm of thickness under the sub-base layer. Finally, two geotextile layers were used: a separation geotextile between base and sub-base, and a retention geotextile under the sub-base in order to avoid the scouring of the fine aggregates. Both geotextiles have the same characteristics: non-woven polypropylene-based geotextiles with 0.15 mm in thickness, 0.11 mm of opening size and vertical permeability of $5 \cdot 10^{-2}$ cm/s.

The simulated rainfall events were 50 mm in height and lasted 1 hour, resulting in a similar rainfall intensity used in previous studies (Rodriguez-Hernandez et al. 2012; Sañudo-Fontaneda et al. 2013; Sañudo-Fontaneda et al. 2014b). In order to reduce the influence of one simulated rainfall on the following one, the dry period between successive simulations was fixed at two weeks. Four different rainfall simulators were constructed in order to test simultaneously the four replicas of each cross section. The rainfall simulators were built using cylindrical containers with droppers at their bottom. The surface covered by the droppers was 0.05m² so filling the containers with 2500ml a 50 mm of rainfall height was simulated. By modifying the number of droppers, different rainfall durations can be obtained. The preliminary tests had shown that by using 18 droppers, the simulated rainfall events lasted 1 hour, fulfilling the experimental design requirements. The droppers were placed covering a circular area slightly lower than the tested surface area in order to reduce possible edge effects and distilled water was used for simulating rainfall in order to avoid the progressive clogging of the droppers, which can affect the simulated rainfall characteristics. During the monitoring period, three control tests were carried out for each rainfall simulator, measuring the cumulated rainfall volumes during the simulated rainfall events. The data obtained was mathematically modelled by polynomial distributions reaching determination coefficients higher than 0.9. By using the mathematical models obtained, the 5-minutes interval rainfall intensity was calculated for each rainfall simulator, and the results obtained are shown in Fig. 2a.

Sixteen laboratory models of pervious pavements, corresponding to the four different cross sections were constructed in cylindrical containers. The containers were perforated at the bottom, allowing the collection of the water drained through the cross section. The surface layer was peripherally sealed with polyurethane foam in order to minimize the possible edge effects attributable to the container walls, providing an effective surface area of 0.05 m^2.. The rain simulators were mounted on support structures placed 50cm above the permeable surface and a funnel was placed under each laboratory model in order to collect the infiltrated water. The outflow was conducted to little rain gauges that were used to register the cumulated volumes with a precision of 7.2 ml. Each rain gauge was placed inside a plastic bucket which was weighed after the rainfall simulation in order to verify the total outflow volume. The experimental setup used can be seen in Fig. 2b.

After the laboratory models were mounted, 32 rainfall simulations were applied to the permeable pavement structures over 64 weeks resulting in 1600mm of rainfall applied to each laboratory model. For all the rainfall simulations two different stormwater retention parameters were measured:

•Lag Time: time elapsed between the beginning of the rainfall and the beginning of the outflow from the permeable pavement.

•Retained Rainfall: difference between the cumulated outflow 48 hours after finalizing the rainfall simulation and the rainfall volume simulated.

Moreover, every 8 weeks the cumulated outflow volumes from the different laboratory models were registered during the simulated rainfalls with a maximum frequency interval of 5 minutes. These volumes were mathematically modelled and the 5-minute interval outflow intensities were calculated for each cross section in order to obtain the main indicators of the runoff attenuation capacity:

- The Peak Outflow, defined as the maximum 5-minute outflow intensity from the permeable pavement structure during the rainfall simulation.

- The Time to Peak, or the time passed between the beginning of the rainfall event and the occurrence of the Peak Outflow.

Finally, the obtained data was divided into two groups: a first group that enables the study of the short-term performance of the cross sections tested, in which the first 16 rainfall simulations were considered; and a second group in which the last 16 rainfall simulations were studied. Moreover, as was necessary, the obtained results were statistically analyzed by using SPSS software in order to enable valid interpretation of the results. All the statistical analysis were performed at 95% of confidence level, accepted as a standard value for statistical analysis.

Results and Discussion

Lag Time and Retained Rainfall

The average values of Lag Time and Retained Rainfall for the four replicas of each cross section are shown in Fig. 3. It can be observed that during the initial rainfall simulations, high Lag Time and Retained Rainfall values were observed probably due to the initial washing of fine particles and the higher water absorption of the dry aggregates. The initial performance of permeable pavements was mainly conditioned by the sub-base aggregate nature, with higher Lag Time and Retained Rainfall values for recycled aggregates probably due to the higher content in fine particles and the higher water retention capacity of this material. As the number of rainfall simulations increases, a continuous downward trend was observed in cross sections with ICB surface, such that at the end of the experimental program the values obtained were grouped by the surface type, with lower Lag Time and Retained Rainfall results for BR and BL cross sections.

The values of Lag Time and Retained Rainfall obtained were grouped and statistically analyzed in order to compare the different cross sections during the two stages into which the monitoring period was divided. The box plots of the average results obtained by the four replicas of each cross section tested during each stage and the outlier values of the data distributions are shown in Fig. 4. It can be observed that the outliers of the Lag Time data distribution correspond to the values obtained in the first rainfall events showed in Fig. 3. These values, although considered extreme from the statistical point of view, were also representative of the materials influence in the short term, and for this reason were included in the further analysis.

The statistical analysis showed non-normal distributions for Lag Time values of BR and PR cross sections during Stage 1, so non parametric statistical analysis was performed in order to assess the significance of the observed differences. Specifically a Kruskal-Wallis H-test was performed, testing the null hypothesis of equality of populations, and showing there were significant differences in the results obtained for Lag Time (Sig=0.000) and Retained Rainfall (Sig=0.001) depending on the cross section. Moreover, multiple pairwise Mann-Whitney U-Tests were performed among the Lag Time and Retained Rainfall results of the different cross sections in order to verify whether there are significant differences in their mean values. The results of the analyses showed significantly higher Lag Time values for recycled aggregate sub-bases (Sig<0.001), while the differences observed between the different permeable surfaces were not significant (Sig>0.108). On the other hand, higher Retained Rainfall values were observed in cross sections with recycled aggregate sub-bases, especially in PR cross section which showed significantly higher Retained Rainfall values than permeable pavements with limestone sub-base (Sig<0.001). Interestingly, Retained Rainfall values in PR cross section also proved to be significantly higher than those observed in BR one (Sig=0.033), while no significant differences were observed between BR, BL and PL laboratory models.

These results indicate that, during the first stage, Lag Time and Retained Rainfall values were mainly conditioned by the sub-base aggregate nature. During the first rainfall simulations, the sub-base aggregates were not fully saturated and the residual fine particles of the aggregates were not totally washed so the aggregate characteristics had more influence on the starting results. The highest Lag Time and Retained Rainfall values were observed for recycled aggregate sub-bases due to the higher water absorption capacity of recycled aggregates and their slightly higher content in fine particles. Especially PR cross section showed the highest initial values of Retained Rainfall, indicating some influence of the permeable surface. In porous asphalt surfaces, water infiltrates through the connected air voids spread over the entire surface and some rainfall water can be retained in the air voids. Moreover, this infiltration behavior resulted in dispersed water flows inside the pavement structures and increased the water contact with the sub-base aggregates. The higher water absorption capacity of recycled aggregates as well as the infiltration performance of porous surfaces resulted in higher values of Retained Rainfall for the PR cross section.

In order to study whether there are statistical differences between the results obtained for each cross section over time, the Mann-Whitney U-Test was applied to the Lag Time and Retained Rainfall values registered for each cross section for the two stages into which the experimental period was divided. The results obtained showed that Lag Time and Retained Rainfall values were significantly lower in the second stage for BR and BL cross sections ($Sig<0.048$), while the PL cross section showed significantly higher values of Lag Time during the second stage ($Sig=0.020$).

As the number of simulations increases Lag Time and Retained Rainfall values tend to decrease for BR and BL cross sections while for PR and PL remained similar or showed a little upward tendency. This indicates the influence of the permeable surface on the variation of these parameters over time. The different infiltration behavior of the permeable surfaces can explain the observed differences. While ICB surfaces infiltrate the water through the permeable joints, leading to concentrated water flows, in porous asphalt the water infiltrates through connected air voids spread over the entire surface. The concentrated water flows through the permeable joints of the ICB surfaces increase the erosive power of the infiltrated water, leading to the progressive development of preferential paths, progressively reducing Lag Time values for BR and BL cross sections. This fact also reduces the water contact with the sub-base aggregates, progressively reducing the water retained by the sub-base aggregates in cross sections with ICB surfaces. On the other hand, the higher dispersion of the infiltrated water inside the pavement structure for PL and PR cross sections reduced the erosive power of the water flows resulting in more homogeneous performance over time.

Finally, during Stage 2, it can be observed that Lag Time and Retained Rainfall values were grouped by the surface type, with higher values for cross sections with porous asphalt surfaces. Moreover, for the same surface type, higher values of Lag Time and Retained Rainfall were observed for the recycled aggregate sub-base. In order to analyze the statistical significance of these differences, and considering the normal and homoscedastic data distribution for the different cross sections, parametric statistics were used. Specifically, the ANOVA test with Tukey HSD correction was applied to the results obtained in order to assess the statistical significance of the differences among the mean scores of Lag Time and Retained Rainfall for the different cross sections tested. The results of this analysis showed that porous asphalt surfaces provide significantly higher runoff attenuation capacity, significant differences existing between the PR and BR cross section, and between the PL and BL for Lag Time and Retained Rainfall values (Sig<0.001). Similarly to the first stage, depending on the surface type, the sub-base aggregate can influence the performance, significant differences existing in Retained Rainfall and Lag Time results between PR and PL cross sections (Sig=0.013), but not between BR and BL (Sig=0.061).

The progressive downward trend of Retained Rainfall and Lag Time observed in BR and BL cross sections together with the homogeneous performance observed in PR and PL resulted in final results grouped by the surface type. Higher values of Retained Rainfall and Lag Time were observed for cross sections with porous asphalt surfaces as a result of the dispersed water flows provided by porous asphalt surfaces and the lower erosive power of the infiltrated water. Some influence of the sub-base aggregate was also observed during the second stage, with higher values of Lag Time and Retained Rainfall for recycled aggregate sub-bases. Similarly to the first stage, the PR cross section showed the highest attenuation capacity in terms of Lag Time and Retained Rainfall values due to the interaction of the dispersed water flows provided by porous surfaces with the higher water absorption capacity of recycled aggregates.

Peak Outflow and Time to Peak

Every eight weeks the outflow volumes during a single rainfall event from each cross section were monitored and mathematically modelled. Polynomial distributions were used to fit the obtained data, reaching determination coefficients higher than 0.95 in all cases. The 5-minute interval outflow intensities were calculated from the regression models. The hydrographs obtained are shown in Figs. 5 and 6.

These hydrographs showed higher Time to Peak and lower Peak Outflow values for recycled aggregate sub-bases in both stages. The lower water absorption capacity of limestone aggregates along with its slightly lower content of fine particles in relation to recycled aggregates resulted in the lower Time to Peak and the higher Peak Outflow values observed in the BL and PL cross sections. The second stage showed lower Time to Peak and slightly higher Peak Outflow for all cross sections. The progressive wash off of the fine particles reduces the Time to Peak values, while the progressive clogging of the bottom geotextile reduced the Peak Outflow, explaining the observed performance.

It can be observed that, depending on the surface type, sub-base aggregates can increase their influence on the Peak Outflow values. While for PR and PL cross sections the Peak Outflow results were quite similar, cross sections with ICB surfaces presented important differences depending on the sub-base aggregates. As discussed previously, the concentrated water flows through the permeable joints of ICB surfaces progressively developed preferential paths. The fine particles were progressively washed off by the infiltrated water until they reached the bottom geotextile at the end of the preferential paths. Finally, these particles were retained by the bottom geotextile progressively clogging the end of the preferential paths, increasing the influence of the aggregate nature in the Peak Outflow values. For the BA cross section, the slightly lower content of fine particles and the lower absorption capacity of the aggregates lead to higher Peak Outflow. On the other hand, in BR cross sections the higher content of fine particles increases the clogging level at the end of the preferential paths and the higher water absorption capacity of the aggregates reduced the Peak Outflow values resulting in the observed differences between these cross sections.

Conclusions

After 32 rainfall simulations, both surface type and sub-base aggregates have proven to influence the attenuation and retention capacity of permeable pavements. In the short term after construction, sub-base aggregate characteristics had more influence than the infiltration behavior of the permeable surface on the overall attenuation capacity. Recycled aggregate sub-bases showed the lowest Peak Outflow results and highest values of Lag Time, Retained Rainfall and Time to Peak due to the higher water absorption capacity of this material and the slightly higher content of fine particles.

The infiltration behavior of the permeable surfaces tested proved to be an important factor in the variation of the stormwater retention capacity of permeable pavements over time. The concentrated water flows provided by ICB surfaces led to the progressive development of preferential paths for the infiltrated water, progressively reducing Lag Time and Retained Rainfall results, while the dispersed water flows provided by porous surfaces resulted in a more stable performance over time.

In the long term, the progressive downward tendency of Retained Rainfall and Lag Time for ICB surfaces resulted in higher Lag Time and Retained Rainfall values for permeable pavements with porous asphalt surfaces. Some influence of the sub-base aggregates was also observed for the same surface type, recycled aggregates showing the highest attenuation capacity in terms of Lag Time, Retained Rainfall, Peak Outflow and Time to Peak.

The combination of the porous asphalt surface with the recycled aggregate sub-base showed the highest stormwater retention capacity during the whole experimental program, with a Lag Time of 5±1 minutes and a Retained Rainfall of 6±1 mm of rainfall height after a dry period of two weeks. On the other hand, the combination of ICB surface with recycled aggregate sub-base provided the highest runoff attenuation capacity in terms of Time to Peak and Peak Outflow.

These conclusions are limited to the laboratory conditions described in the methodology section, avoiding factors that can affect the long-term hydrological performance of permeable pavements. Further investigation is needed in order to assess the hydrological behavior of permeable pavements in field conditions, analyzing the factors that influence performance over time such as salting and icing in cool climates, clogging dynamics, and the influence of the pavement geometrical conditions and the usage patterns.

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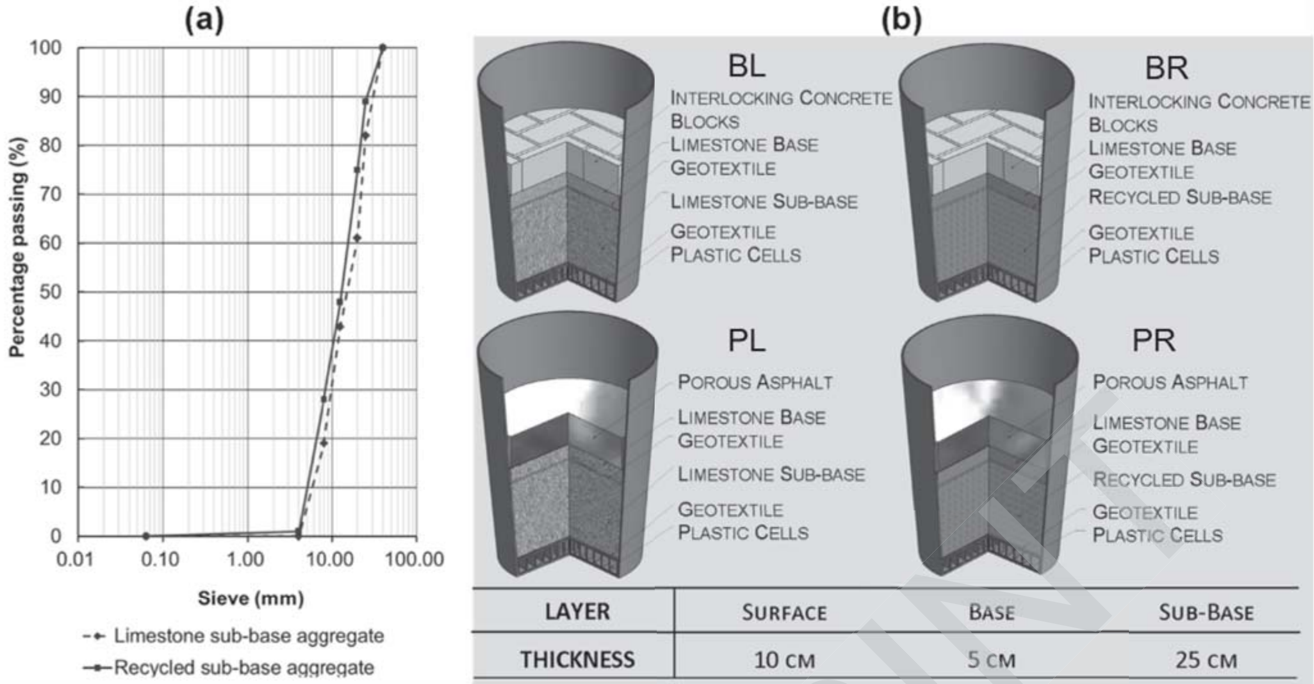

Fig. 1 (**a**) Gradation of the sub-base aggregates; (**b**) Cross sections tested

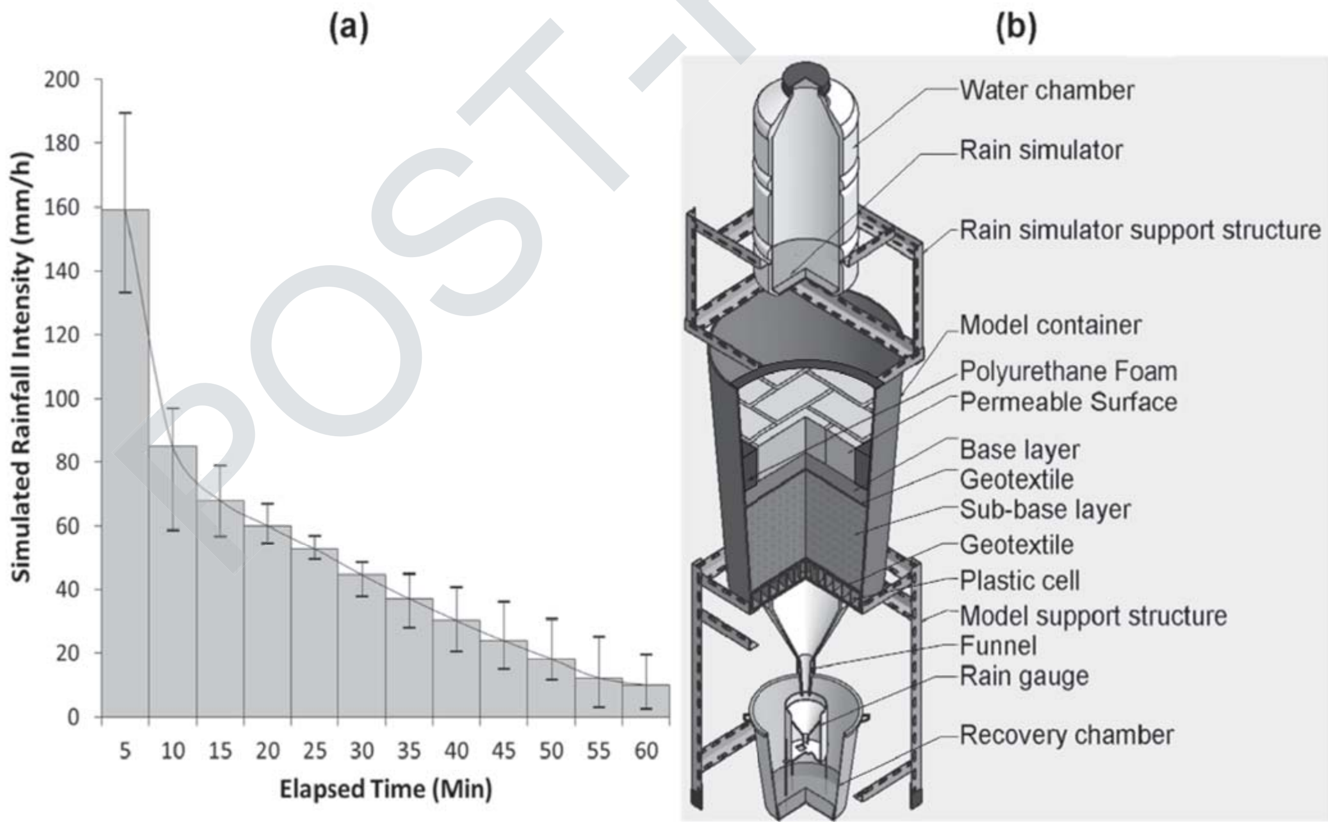

Fig. 2 (**a**) Average simulated rainfall intensity (N=12); (**b**) Rainfall simulation experimental set up

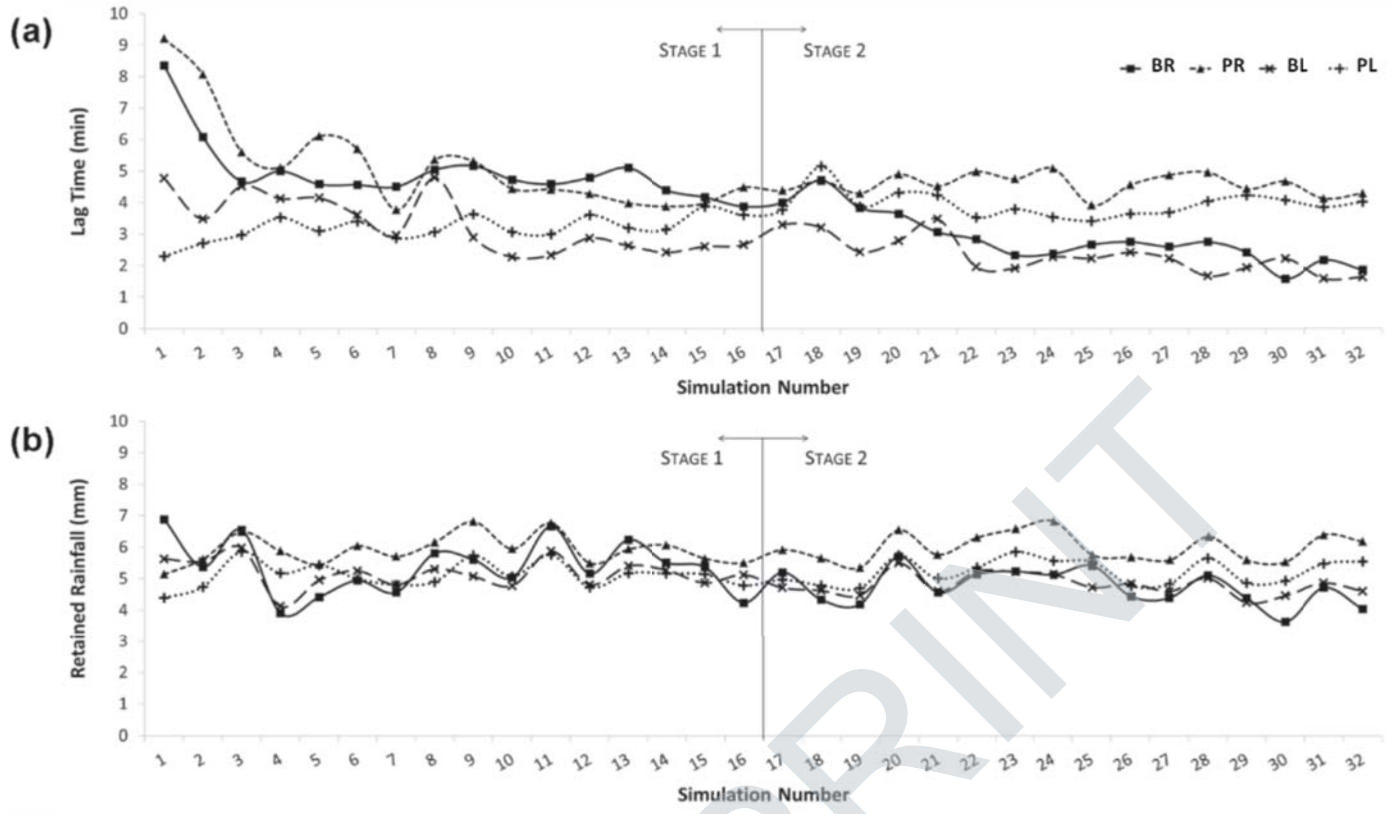

Fig. 3 (a) Lag Time and **(b)** Retained Rainfall during rainfall simulations

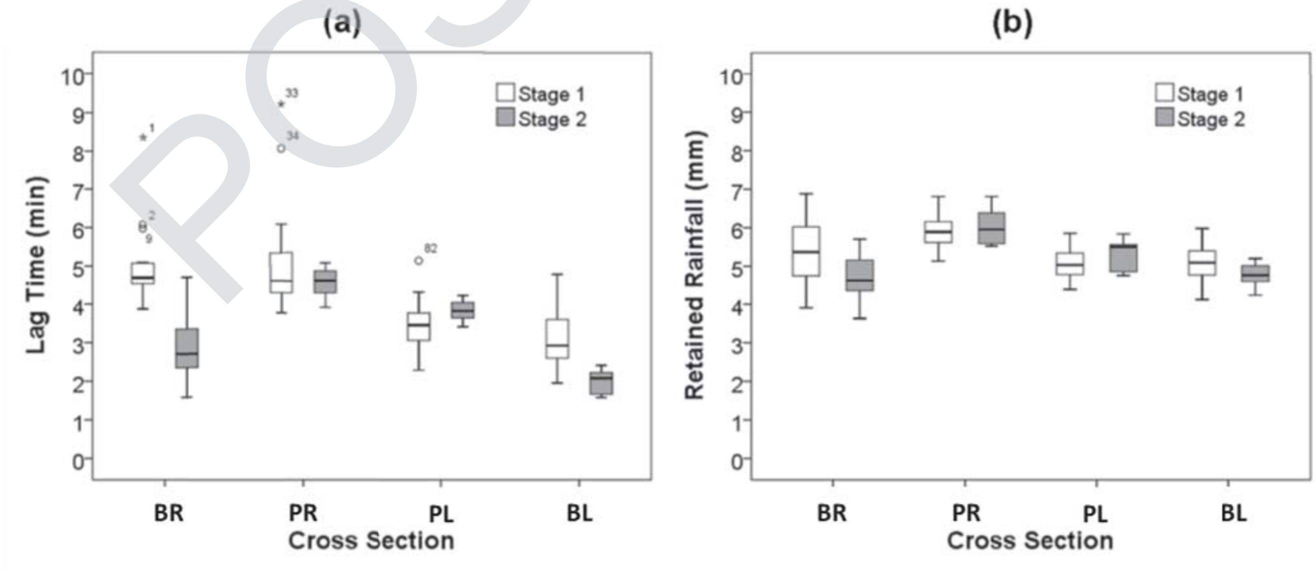

Fig. 4 Box-Plots of the average **(a)** Lag Time and **(b)** Retained Rainfall (N=16)

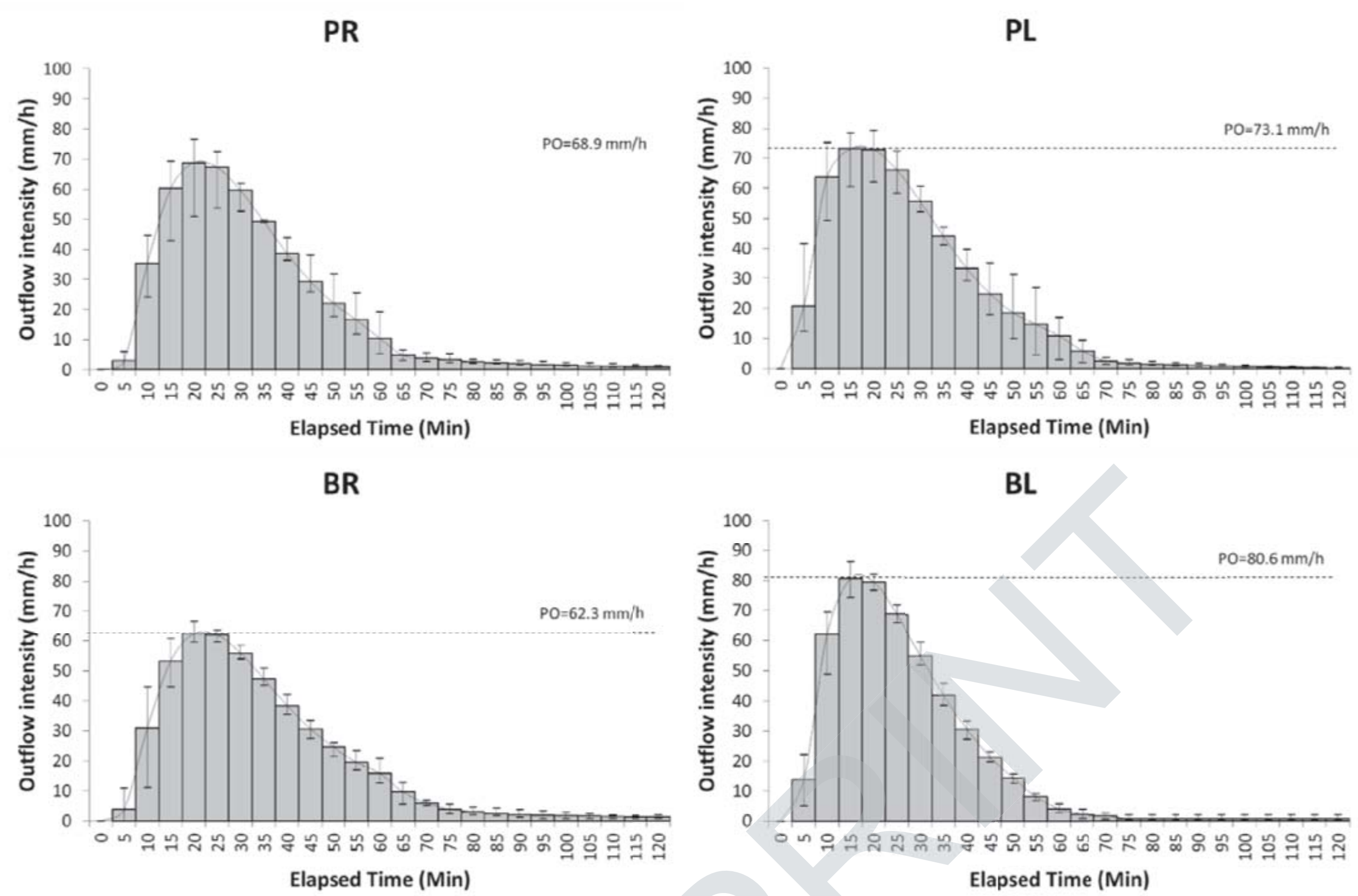

Fig. 5 Five-minute interval outflow hydrographs for the first stage (N=16, PO: Peak Outflow)

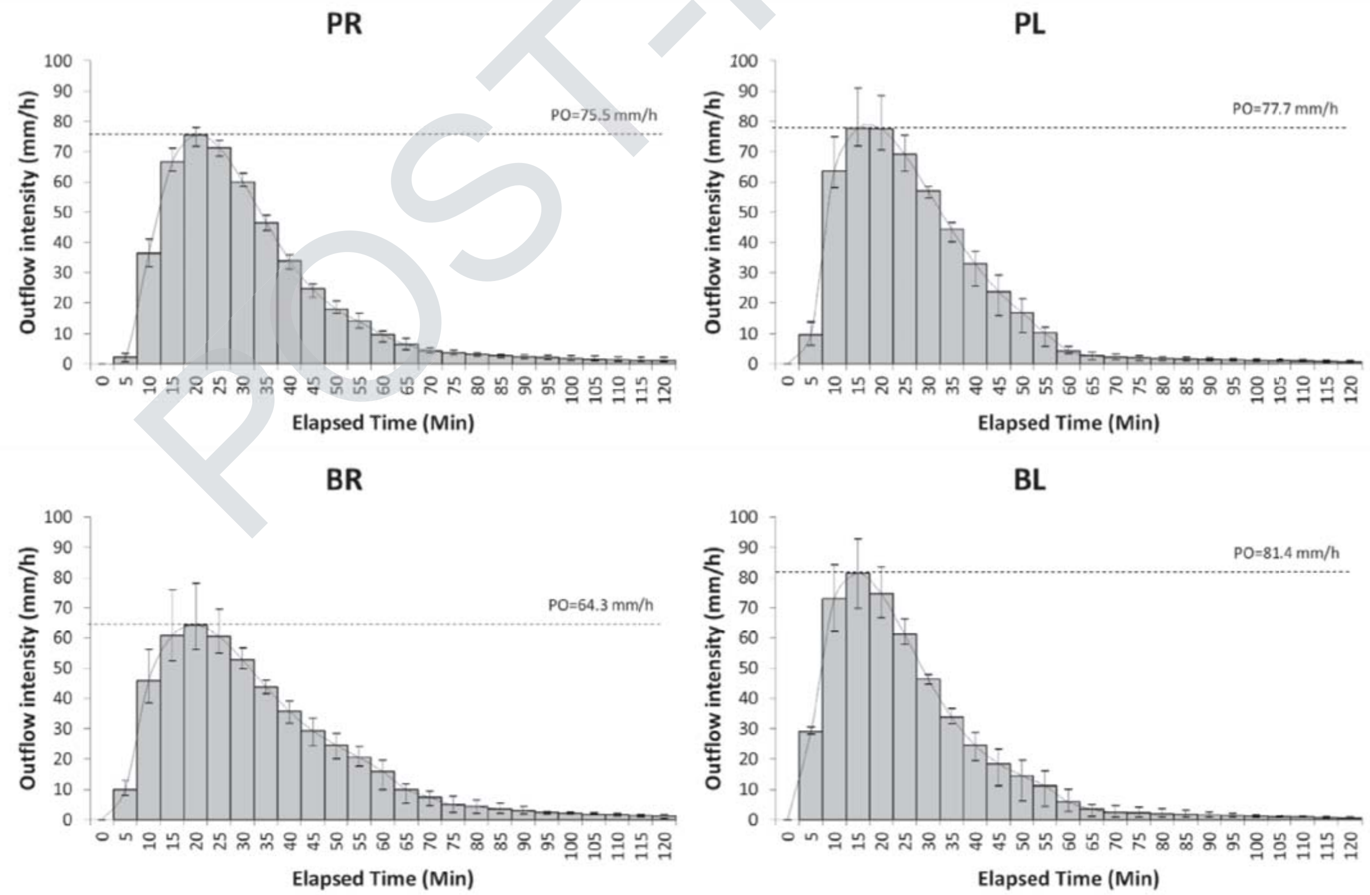

Fig. 6 Five-minute interval outflow hydrographs for the second stage (N=16, PO: Peak Outflow)