CHALMERS

The Effect of Conventional Block Pavement (CBP) on Surface Runoff

A Simulation Study

Master of Science Thesis in the Master's Programme Infrastructure and Environmental Engineering

EMILY DAUBNEY

Department of Civil and Environmental Engineering
Division of Water Environment Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014

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Cover:
Picture of a gutter surrounded by conventional block pavement.

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ABSTRACT

As cities continue to grow, the amount of impermeable surfaces increase. This in turn increases the risk of local flooding. However, there are solutions that deal with this problem. One solution is to replace impermeable surfaces with so called conventional block pavement (CBP) which allows water to infiltrate into the ground. The surface runoff will be reduced as well as the problems of local flooding. The aim of this study is to quantify the effect of an entire CBP-structure on runoff characteristics such as frequency, duration, volume and peak flow. This has been conducted by simulating long-term rainfall runoff for 16 years in the software EPA-SWMM 5.0.022. First, a literature review was carried out in order to find relevant input data to the model. Second, the model was run and several sensitivity analyses were performed where different parameters related to the CBP-structure were varied within a reasonable range to see their effect on runoff. The following parameters were altered; resolution of infiltration rates, initial losses, surface slope, void ratio of the storage layer, height of the storage layer and finally conductivity of the native soil below the storage layer. It was seen that the resolution of infiltration rates only had little effect on peak flows, runoff volume and duration. Parameters that showed a great impairment to the runoff characteristics were a reduction in storage height or a change in initial losses. The most dramatic effect was seen using a very low conductivity corresponding to clay. This resulted in an increase of all runoff characteristics; frequency, duration, peak flows and total runoff. When changing from a conductivity corresponding to silt to a conductivity of sand, the total runoff was reduced by 11%. A recommendation followed by this consequence is to always use a drainage pipe at the bottom of the storage layer to enable a faster drainage and thereby reduce runoff from the CBP-structure.

Key words: urbanisation, conventional block pavement, surface runoff, peak flows, total runoff, runoff duration, sensitivity analysis

Plattsatt Marks Effekt på Ytavrinning

En Simulationsstudie

Examensarbete inom Infrastructure and Environmental Engineering

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SAMMANFATTNING

När städerna växer ökar även de hårdgjorda ytorna. Detta i sin tur ökar risken för lokala översvämningar, men det finns lösningar som behandlar detta problem. En lösning är att ersätta täta ytor med plattsatt mark, vilket gör att vatten kan infiltrera ner i marken. Detta leder till att ytavrinningen minskar, likaså problemen med lokala översvämningar. Syftet med denna studie är att kvantifiera effekten som en hel plattsatt struktur har på ytavrinningen. Avrinningsparametrar som har undersökts är frekvens, varaktighet, volym och maxflöden. Detta har utförts genom att simulera avrinning från en regntidsserie på 16 år i mjukvaran EPA - SWMM 5.0.022 . Först genomfördes en litteraturstudie för att hitta relevanta indata till modellen. I nästa steg kördes modellen och flera känslighetsanalyser utfördes där olika parametrar relaterade till den plattsatta strukturen varierades inom rimliga intervall för att se deras effekt på ytavrinning. Följande parametrar varierades; upplösning av infiltrationshastigheter, inledande ytförluster, ytans lutning, porositet hos magasinsvolymen, höjd för magasinsvolymen och slutligen konduktiviteten hos den ursprungliga marken under magasinsvolymen. Upplösningen av infiltrationshastigheter visade sig ha relativt liten effekt på maxflödet från ytan, mängden avrinning samt varaktighet. Parametrar som visade sig ge en stor ökning av alla avrinningsparametrar var en minskning av magasinsvolymens höjd samt inledande ytförluster. Den i särklass största effekten uppvisades vid användning av en mycket liten konduktivitet motsvarande lera. Detta resulterade i en ökning av samtliga avrinningsparametrar; frekvens, varaktighet, maxflöden och total avrinning. Vid byte från en konduktivitet motsvarande silt till en konduktivitet motsvarande sand, minskade den totala avrinningen med 11%. En rekommendation blir följaktligen att alltid använda dräneringsrör i botten av magasinsvolymen (framförallt när ursprunglig mark har låg konduktivitet) för att möjliggöra en snabbare tömning av magasinet och därigenom minska avrinningen från plattsatt mark.

Nyckelord: urbanisering, plattsattt mark, ytavrinning, maxavrinning, total ytavrinning, avrinningens varaktighet, känslighetsanalys

Contents

Preface

This Master's Thesis was commenced in the spring of 2013, paused during late summer and winter, and resumed again in the spring of 2014. It was written in cooperation with the department of Civil and Environmental Engineering at Chalmers University of Technology, Göteborg, Sweden and the Institute for Sanitary Engineering, Water Quality and Solid Waste Management at Stuttgart University, Stuttgart, Germany as a part of a Double Master's degree exchange from the Master's programs Infrastructure and Environmental Engineering (Chalmers) and Water Resources Engineering and Management (Stuttgart). The supervisors during the project have been Dr.-Ing. Ulrich Dittmer at Stuttgart University and Professor Britt-Marie Wilén at Chalmers University of Technology. Their guidance and support throughout the work has been greatly appreciated.

Dipl. -Ing. David Bendel at the University of Stuttgart has also contributed with valuable support, since he programmed an Excel sheet used for presenting data obtained from the simulations.

I would also like to thank the company WSP for providing me with a work-place at their office in Göteborg, during the completion of my Master's Thesis.

Göteborg, April 2014

Emily Daubney

1 Introduction

The degree of paving increased in our cities along with industrialisation, since it improved the working environment and facilitated transportation of goods. This, in turn, had effects on the amount of generated stormwater and increased the risk of flooding. As awareness of this increased, the interest for solutions dealing with local flooding grew. One solution is to imitate the natural water cycle, enabling water to infiltrate into the ground, by implementing permeable ground covers.

When designing stormwater systems in urban areas, paved surfaces are generally considered impermeable, meaning more or less all rainfall is converted to runoff. However, operational experience shows that rainfall-runoff volumes in many cases are over-estimated (Dittmer 2013). In other words, certain pavements do allow water to infiltrate to a greater extent than presumed, through gravel layers as well as through joints in flagstone or block pavements. Today, when determining runoff amounts and characteristics, only the surface's effects are studied. The surface of partially permeable pavement is assigned a so called 'runoff coefficient' that describes the share of the area contributing to runoff. For an impermeable surface, the runoff coefficient is equal to one, whereas for partially permeable ground covers it is less than one. Normal values for conventional block pavement (CBP), which is one of the most common types of partially permeable pavements, is roughly estimated as being between 0.70-0.85 (Iowa State University 2009). Illgen (2009b) has shown that the annual mean runoff coefficient for conventional block pavement (CBP) is below ten percent (Dittmer 2013).

Determining the magnitude of the infiltration capacity is still an issue since it can vary largely, even over a small area. For CBP the infiltration capacity can vary from 0.72mm/hr to 216mm/hr (Illgen 2008), which is partly due to the degree of clogging. This parameter, however, is not easily determined. The wide variation in infiltration capacity results in major uncertainties with respect to characteristics of surface runoff.

Other parameters describing the properties of CBP structures can also vary over a large range, which results in an even greater uncertainty of the runoff characteristics. It is of great interest to find out which parameters affect the runoff characteristics the most and to what extent, in order to facilitate the design of urban drainage systems.

In addition, single rain events are currently considered in design as opposed to an entire time series (Berggren-Clausen 2014). However, by studying a longer time series, there is a possibility to see how the frequency of rainfall affects the runoff. This is interesting because the structure of interest might not have had time to dry before a following rain event and consequently will fill up more rapidly.

1.1 Aim

The aim of the study is to quantify the effect of an entire CBP structure on surface runoff characteristics such as frequency, duration, volume and peak flows, by simulating long-term rainfall runoff in the software EPA-SWMM v. 5.0.022.

1.2 Method

First a literature review was carried out in order to find the most important input vales to a water cycle and for a CBP structure. More details on this can be found in chapter 2. The model was created in the software EPA-SWMM v.5.0.022. A plausibility control was performed in order to evaluate the reasonability of the results. This was conducted by simulating block rainfall (see section 2.1.1) for a rainfall duration of 20 minutes with different rainfall intensities ranging from 9mm/hr (25l/s*ha) to 108 mm/hr (300l/s*ha). Since the software uses the unit mm/hr, this unit is used in the report. The output values, such as total precipitation reaching the surface, total runoff and total evaporation, obtained after each simulation seemed reasonable. Therefore the model is assumed to be correct.

After the plausibility control, actual rain data recorded over 16 years was used. The rain data originates from a weather station in Holzgerlingen in the south of Germany and was recorded from 1977-1992. The input values for the CBP structure, such as layer thickness and surface characteristics, were in the long-term simulations varied within a reasonable range to see how each parameter affected the behavior of the runoff. This is explained more in detail in section 3.2.

2 Theory

This chapter will first give a short overview of precipitation and possible pathways such as evaporation, surface runoff and infiltration. Second, the properties and structure of CBP will be presented.

2.1 Precipitation and its pathways

In urban hydrology, rainfall is the most frequent form of precipitation, which is why it is the dominating factor when designing urban storm drainage facilities for flood prevention (Akan & Houghtalen 2003 see Illgen 2009a). When rain reaches the ground surface it will take different paths, depending on the surface and ground conditions. Figure 1 shows different flows in a rural (natural ground cover) and an urban environment (75%-100% impervious surface) respectively.

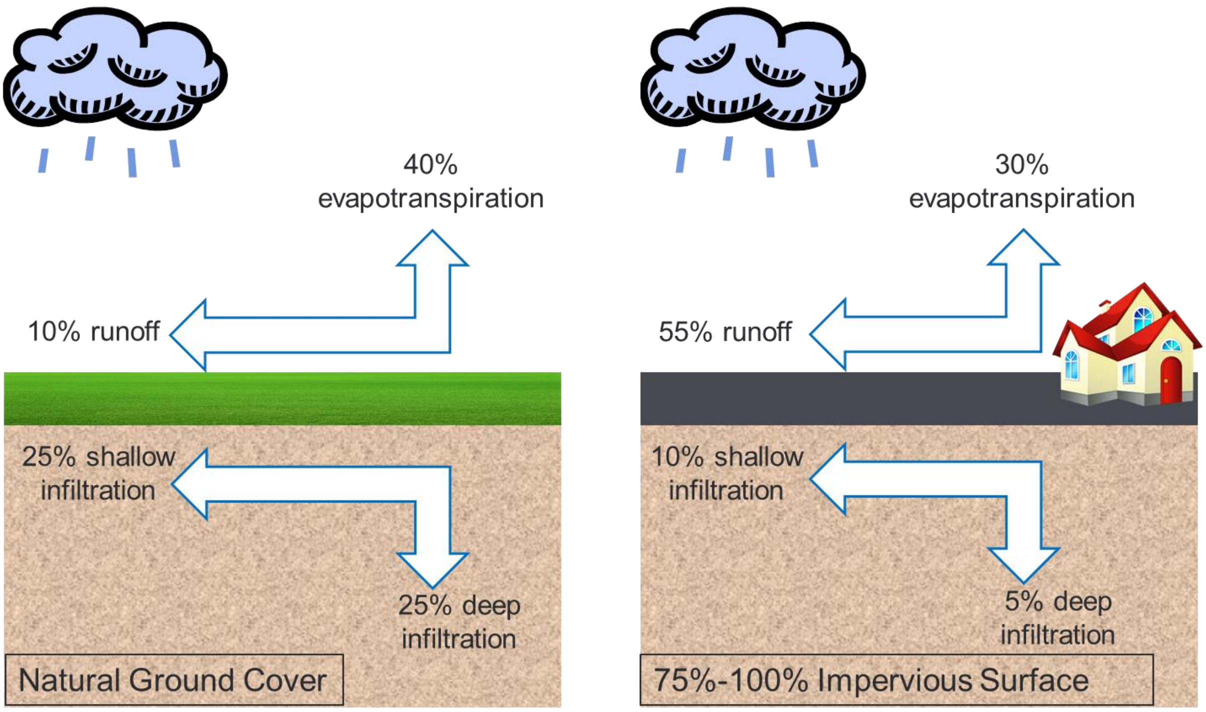

Figure 1. A comparison between flows in a natural environment and an urban environment. (Inspired by Ruby).

Figure 1 shows that an increase in the amount of impervious surfaces affects the distribution between the different pathways for precipitation, which gives rise to new challenges. The infiltration capacity is clearly reduced, resulting in increased runoff. In order to deal with these challenges, methods to reduce the negative impacts have been implemented. Permeable pavements enable an increased infiltration and thereby also recharge groundwater. CBP as permeable pavement will be discussed more in detail in section 2.2.

2.1.1 Precipitation

Rain is, as previously stated, the most common form of precipitation and is usually measured in l/(s*ha) or mm/hr. To convert from l/(s*ha) to mm/hr the former is simply multiplied by 0.36.

Precipitation can be described by using different models. Usually the precipitation is presented in intensity (mm/hr) or volume (mm) with respect to a certain time series showing how the intensity or volume varies within a certain period of time. This generates a hyetograph showing the shape of the rain event (Svenskt Vatten 2011). The hyetograph can have different shapes, depending on where in the world the rainfall occurs. Simpler models employ block shaped rains (see figure 2) where the rain intensity is assumed to be constant throughout the entire rain event.

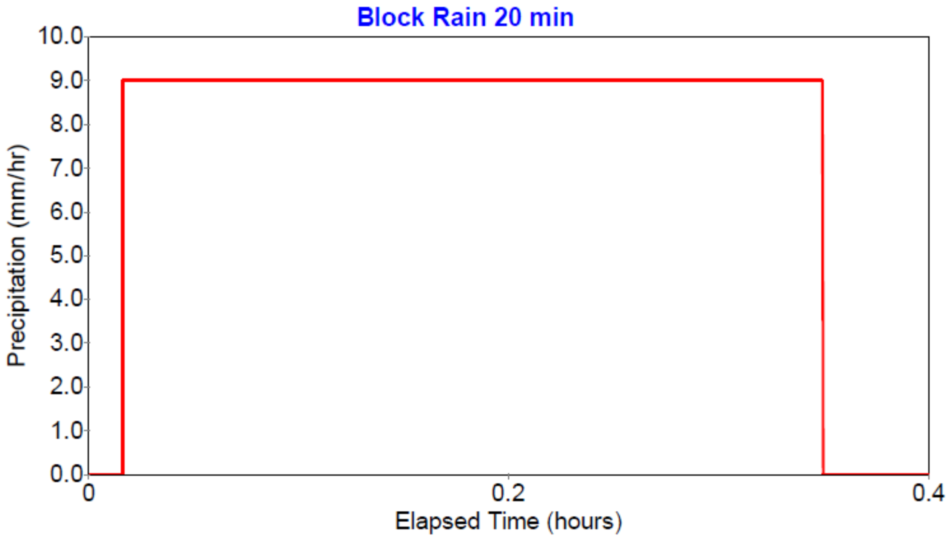

Figure 2. A block rain lasting for 20min with a constant intensity of 9mm/hr.

Figure 2 only displays a short-term rain event lasting for 20min (0.33 hours). However, in order to get results closer to reality, real-life measurements of rain data during a longer time period should be employed. This gives a hyetograph closer to reality and provides a more reasonable input to a hydrological model. Figure 3 shows a hyetograph for one day with real measurements. The shape of real rain events are, in other words, not really block shaped, but for shorter periods this assumption can be applicable, although it is preferable to use the actual shape and intensity that can be expected.

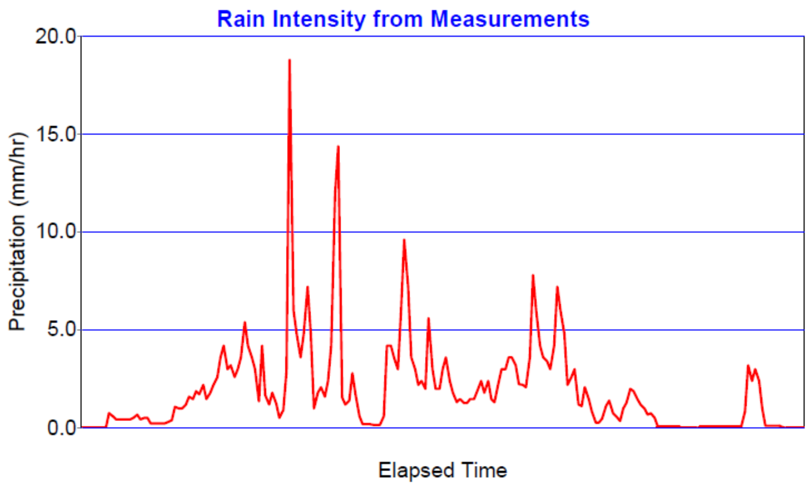

Figure 3. Rain intensities measured during one day in Holzgerlingen, Germany.

2.1.2 Interception and depression storage

Interception (mm) is the process where rainfall is collected and retained by vegetation, which is why it is relatively small in urban areas (Butler & Davies 2006). For impervious ground cover, it can even be below 1mm. Therefore, it is often neglected or combined with depression storage.

Depression storage, d_p, (mm) describes the amount of rainwater temporarily stored in depressions in the surface layer (see profile of surface in figure 4). As soon as the water depth, d, exceeds the depression storage, there will be an overflow, Q. Consequently, the depression storage increases in accordance with the surface roughness and planarity. Common values for d_p are 0.5-2mm for impervious areas, 2.5-7.5mm for flat roofs and up to 10mm for gardens (Butler & Davies 2006). In computer models, depression storage usually includes interception and all wetting losses. As can be concluded by the figure, the water stored in depressions will eventually infiltrate or evaporate depending on the conditions at hand.

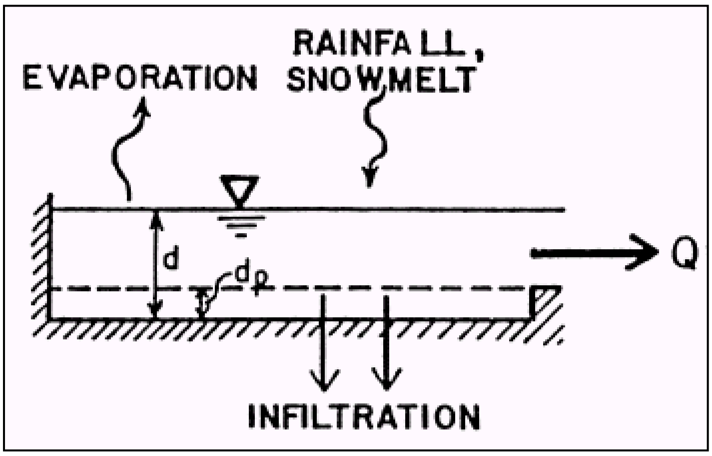

Figure 4. Profile and water balance over a surface (Rossman 2010).

2.1.3 Evapotranspiration

Evapotranspiration is the combined process of evaporation and transpiration where liquid water is converted to vapor (Dingman 2002, see Illgen 2009a). Evaporation is simply water vaporising from any surface, whereas transpiration is water released in gaseous form from vegetation. Consequently, transpiration increases along with the amount of vegetation. Evaporation depends on air temperature, humidity, air movement and solar radiation (Illgen 2009a). In other words it can vary a great deal, even just over the course of one day due to fluctuating weather conditions. Thus, it is difficult to determine an exact value.

According to Illgen (2009a) evapotranspiration during a rain event plays a minor role and is usually neglected in event-based cases. Nevertheless, evaporation should be considered when looking at long-term simulations, since it can contribute to almost 70% of the water loss from annual precipitation. A common way of describing evaporation is by using potential evaporation which is the evaporation that would take place if the soil would be continuously moist (Addison et. al 2008). An example of the daily average value for potential evaporation for the UK during the summer months is 2-3mm (Butler & Davies 2006). However, since soil is not usually continuously moist, the value is smaller in reality (Addison et. al 2008). Consequently, since it is a very small value, it is sometimes included in the depression storage along with interception.

2.1.4 Runoff generation

The runoff from a surface occurs when the retention capacity (the depression storage) of the surface is exceeded. Due to the retention capacity, the initial runoff volume during a rain event is low (Illgen 2009a). This lag time, before runoff is initiated, also depends on the rain intensity (mm/hr). If the intensity is high, the lag time will be shorter.

Figure 4 in section 2.1.2 shows the surface runoff, Q, which can be calculated by solving Manning's equation (see equation 1). Depth of water, d, over the catchment is continuously updated with time by solving numerically a water balance equation over the catchment (U.S EPA 2010). Inflow comes from precipitation and outflows consist of infiltration, evaporation, and surface runoff.

Figure 5 shows a subcatchment consisting of a partially impervious and pervious area. It shows how the different parameters affecting the surface outflow are oriented as seen from above.

$$\boldsymbol{Q = \frac{W}{n} \times (d - d_p)^{5/3} \times S^{1/2}} \qquad (1)$$

(U.S EPA 2010**)**

W = characteristic width of subcatchment, perpendicular to runoff (m)
S = surface slope (perpendicular to width) ()
n = Manning's roughness value ($s/m^{1/3}$)
d_p = depression storage (m)
d = water depth (m)

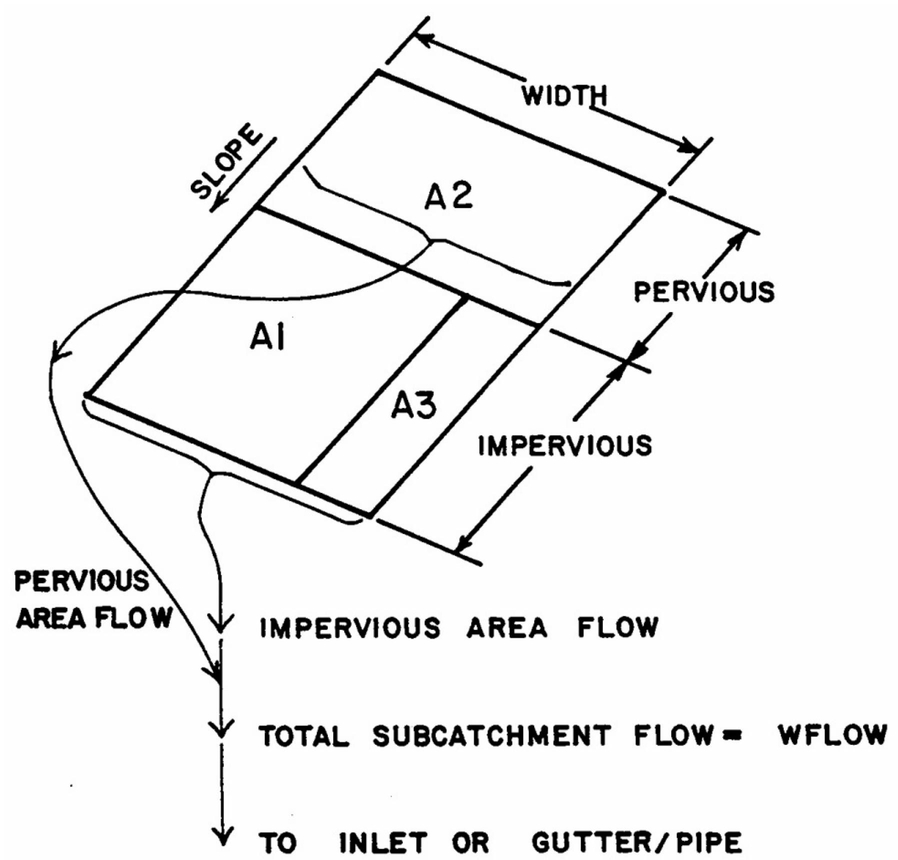

Figure 5. Various runoff flows from the different surfaces straight to an inlet or gutter/pipe (Dickinson & Hudson 1992). Area A3 represents an LID control which will be explained in chapter 3.

Figure 5 shows that runoff from the surfaces are directed to an inlet, gutter or pipe system.

The rate at which runoff occurs can be presented in a hydrograph showing the amount of runoff reaching an inlet with respect to time. This looks similar to the hyetograph, but it will have a certain delay since it takes time for the runoff to reach the inlet. Also, the amount of water has been reduced on its way to the inlet due to depression storage, evaporation and infiltration.

Flow routing within conduit links

Runoff leaves the surface via a gutter and is transported through a conduit link to a wastewater treatment plant or to a near water course where it is discharged.

There are three different methods used for flow routing within a conduit link in SWMM: Steady Flow Routing, Kinematic Wave Routing and Dynamic Wave Routing (Rossman 2010). All of the routing methods employ the Manning equation to relate flow rate to flow depth and bed (or friction) slope (U.S EPA 2010). The Manning equation is solved for every time step assigned to the model.

The first modelling option assumes, as the name indicates, a steady and uniform flow. It should only be used for preliminary analysis using long-term continuous simulations (Rossman 2010). The method is insensitive to the applied time step and does not account for channel storage, backwater effects, entrance/exit losses, flow reversal or pressurised flow.

Kinematic Wave routing, on the other hand, is sensitive to the applied time step (Rossman 2010). Still, fairly large time steps can be used, ranging from five to 15 minutes, without jeopardising the numerical stability. The routing method considers spatial and temporal variability within a conduit by solving the continuity equation and a simplified form of the momentum equation (where the water surface has to be equal to the slope of the conduit). Any excess flow entering an inlet node is either lost from the system or can pond in the inlet node until there is enough available capacity in the conduit. The method does not account for backwater effects, entrance/exit losses, flow reversal or pressurised flow. Essentially, the method works better for long-term simulations and should only be used for dendritic networks.

The third possible routing method in SWMM is Dynamic Wave Routing, which produces the theoretically most accurate result (Rossman 2010). The method solves the complete one-dimensional Saint Venant flow equations, consisting of the continuity and momentum equations for conduits, and a volume continuity equation at nodes. As opposed to the previous methods, the Dynamic Wave Routing accounts for channel storage, backwater effects, entrance/exit losses, flow reversal and pressurised flow. However, a much smaller time step is required, usually less than one minute. The method is suitable for any system and should be used when significant backwater effects, due to downstream flow restrictions, are expected.

2.1.5 Infiltration

Water that does not evapotranspirate nor become run off will infiltrate into the ground structure. The infiltration rate (mm/hr) varies over time and is dependent on the capacity of the ground structure and the rate at which water is applied to the surface, i.e. the intensity (Iowa State University 2009). During the first few minutes of a storm event the wide pores in the mineral aggregates in the joints of pavement structures are filled with water, resulting in a higher initial infiltration rate (see figure 6) (Illgen 2008). The infiltration capacity (mm/hr) is the maximum rate at which water can infiltrate into a soil under a given set of conditions.

Figure 6 shows that if the rain intensity exceeds the infiltration capacity of the formation, water will pond, become runoff or evaporate (the shaded area). The saturated infiltration rate (steady state) is in the figure called K_S and is usually reached after 5-10 minutes in the joints of CBP (Illgen 2008). In other words, the duration of a rain event affects the final expected infiltration rate. If the rain duration is longer than 10 minutes, the final infiltration rate can be approximated as the saturated infiltration rate.

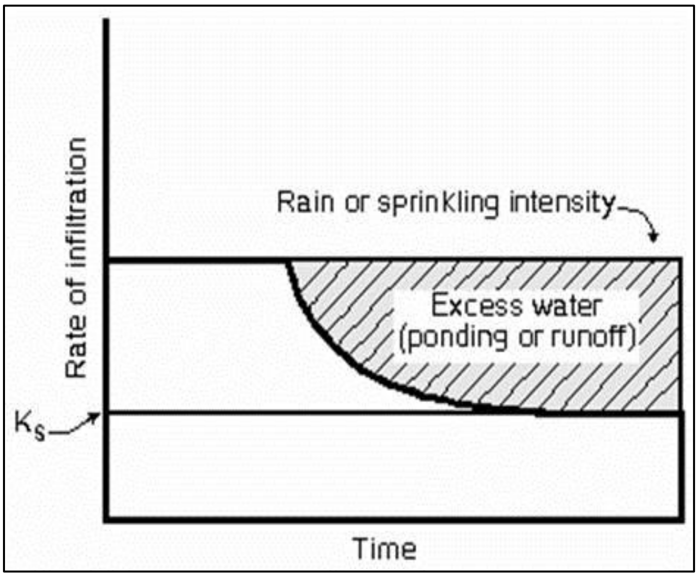

Figure 6. Profile of infiltration rate (Iowa State University 2009).

When the rainfall intensity is less than the infiltration capacity, all of the water reaching the ground can infiltrate (Iowa State University 2009). However, if the rainfall intensity exceeds the infiltration capacity, infiltration will occur only at the infiltration capacity rate and water in excess of that capacity will be stored in depressions, become surface runoff or evaporate.

The different parameters that affect the infiltration capacity for CBPs according to Illgen (2008) are

- Degree of clogging (depending on traffic load, degree of utilisation and age of the structure)
- Mechanical impacts (compaction)
- Opening ratio of joints
- Grain size distribution of the joint aggregates
- Surface slope
    - An increase of surface slope from 2.5% to 5% reduces the infiltration capacity with 5-20%. Tests have confirmed that the reduction in infiltration capacity due to change of slope, is more distinct for low permeable pavements such as CBP than for highly permeable eco-pavements

With respect to the mentioned parameters (especially the degree of clogging) it is very difficult to determine the infiltration capacity to be expected for CBP. Illgen (2008) has taken part in generating an extensive data base where results from numerous infiltration tests have been gathered for CBP and other common pavements. All in all, 90 infiltration tests on existing pavements were conducted, as well as an aggregation of 260 former infiltration tests and also long-term monitoring of runoff from parking lots (Illgen 2008). In addition, data from over 140 lab tests were analysed with respect to surface runoff and infiltration and percolation rates. Accumulated frequency curves for the final infiltration rates were constructed for five major types of pavements and it was found that the infiltration rate can vary largely. For CBP and interlocking pavement (IP), with sand filled joints and an opening ratio of less than 6%, the final infiltration rate can vary from as much as 216mm/hr to as little as 0.72mm/hr (see figure 7).

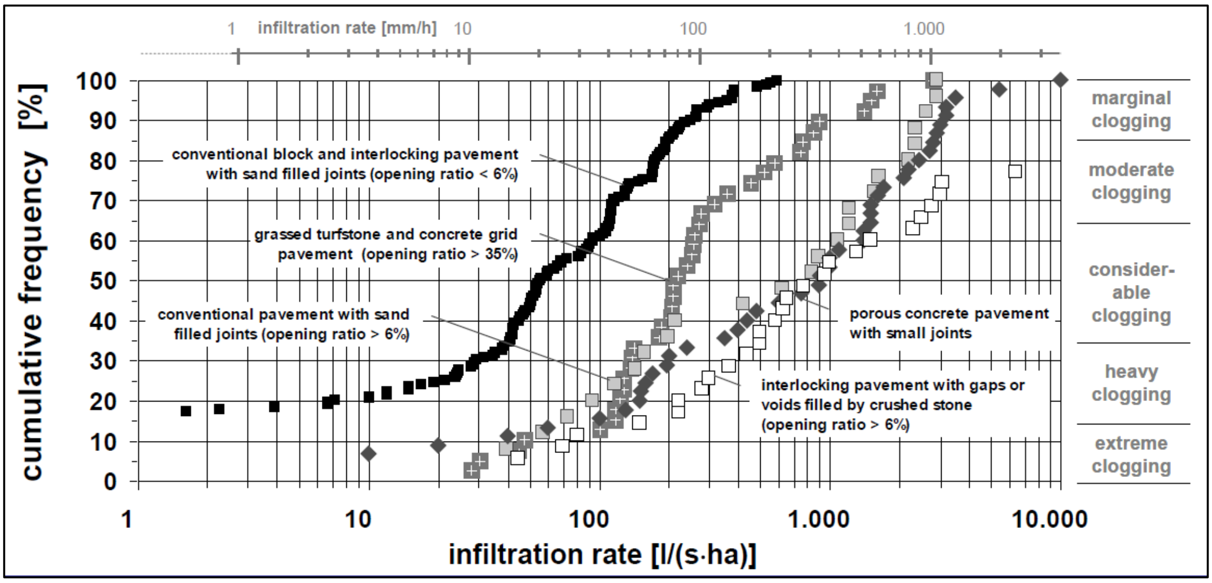

Figure 7. Accumulated frequency curves for measured final infiltration rates for different pavement types (Illgen 2008).

The data which the frequency curve is based on has been obtained from a multitude of sites with different boundary conditions and it is therefore considered to be representative for each particular pavement.

In present modeling, only one runoff coefficient is applied to each type of surface. This can be translated into one final infiltration rate for one kind of pavement; however, this is a very rough estimation since the final infiltration rate varies to a great extent. In order to account for this wide variation, Illgen (2008) suggests that more than one infiltration rate should be assigned to the area: at least 3-6 different classes of infiltration rates. Figure 8 shows how the frequency curve would be divided into 1, 2, 3, 5 or 10 different infiltration classes. The y-axis shows the final infiltration rates in l/(s*ha) and the x-axis shows the accumulated percentage of all performed tests.

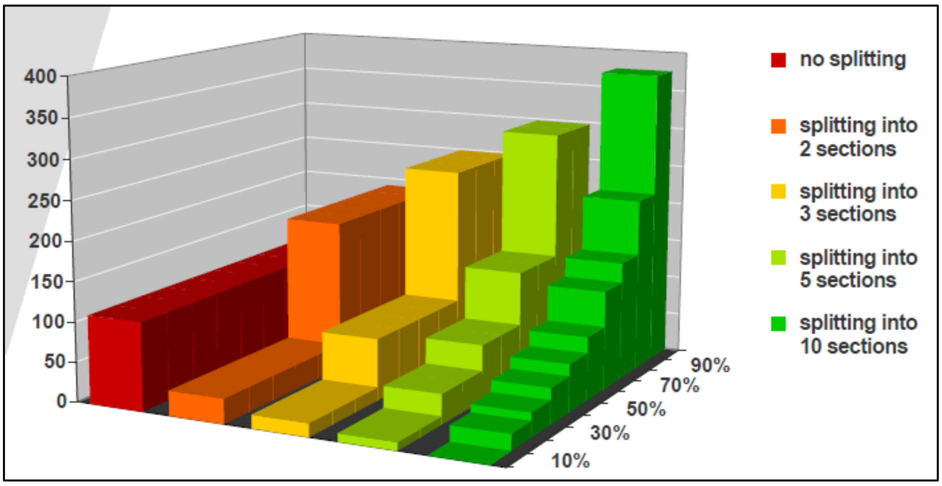

Figure 8. Conceptual idea of how to divide the accumulated frequency curve into blocks for permeable pavements (Illgen 2008).

Table 1 shows the final infiltration rates recommended by Illgen for each block (for CBP), with respect to applied number of infiltration classes; 1, 3, 5 or 10.

Table 1. Various distributions of infiltration rates for CBP and the corresponding infiltration rate for each block (Illgen 2009b).

<table>
<tr><td>Share of permeable subcatchment area (%)</td><td>10</td><td>10</td><td>10</td><td>10</td><td>10</td><td>10</td><td>10</td><td>10</td><td>10</td><td>10</td></tr>
<tr><td>Infiltration rates, 10 classes (mm/hr)</td><td>0</td><td>5.4</td><td>9</td><td>14.4</td><td>18</td><td>25.2</td><td>39.6</td><td>48.6</td><td>72</td><td>126</td></tr>
<tr><td>Infiltration rates, 5 classes (mm/hr)</td><td colspan="2">2.7</td><td colspan="2">11.7</td><td colspan="2">21.6</td><td colspan="2">44.1</td><td colspan="2">99</td></tr>
<tr><td>Infiltration rates, 3 classes (mm/hr)</td><td colspan="3">4.8</td><td colspan="4">24.3</td><td colspan="3">82.2</td></tr>
<tr><td>Infiltration rate, 1 class (mm/hr)</td><td colspan="10">35.8</td></tr>
</table>

Still, the accumulated frequency curve only applies to the final infiltration rates. The next question is how to account for the higher initial infiltration rate. Figure 9 shows the difference between initial and final infiltration rates for block pavement within the same parking lot (Illgen 2008). As the picture shows, the initial infiltration rate is much higher than the final infiltration rate in all cases. In additon, the infiltration rates (initial and final) are much lower for the area where the tires are usually situated compared to the central parts of a parking space, which is due to clogging from rubber particles and dirt. This is why one needs to consider different classes of infiltration rates even though the same type of pavement is used.

Illgen (2008) came to the conclusion that, in order to account for the higher initial infiltration rate shown in figure 6 and 9, the depression storage should be increased. The value suggested by Illgen is 2.5mm for CBP where the opening ratio is less than 6% (Illgen 2009b).

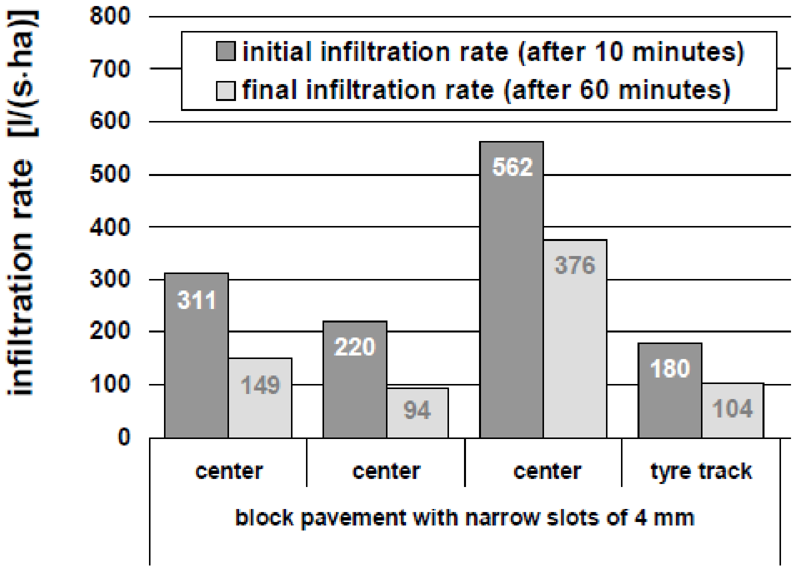

Figure 9. Temporal variation of infiltration rates (Illgen 2008).

2.2 Conventional block pavement (CBP)

CBP (see figure 10) is not permeable through the block itself, but through the joints in between the blocks (Interpave 2010). The infiltration capacity through the pavement consequently depends on the conductivity of the filling material in the joints. However, the final infiltration rates given in the accumulated frequency curve in table 1 is with respect to the entire area constructed with CBP, which is why this final infiltration rate should be considered an average value for the entire surface and not only for the joints.

Figure 10. Top view of an area with CBP.

The surface is not the only part contributing to CBP as a means to reduce surface runoff. The entire structure plays an important role in the reduction. The profile of the structure can be seen in figure 11.

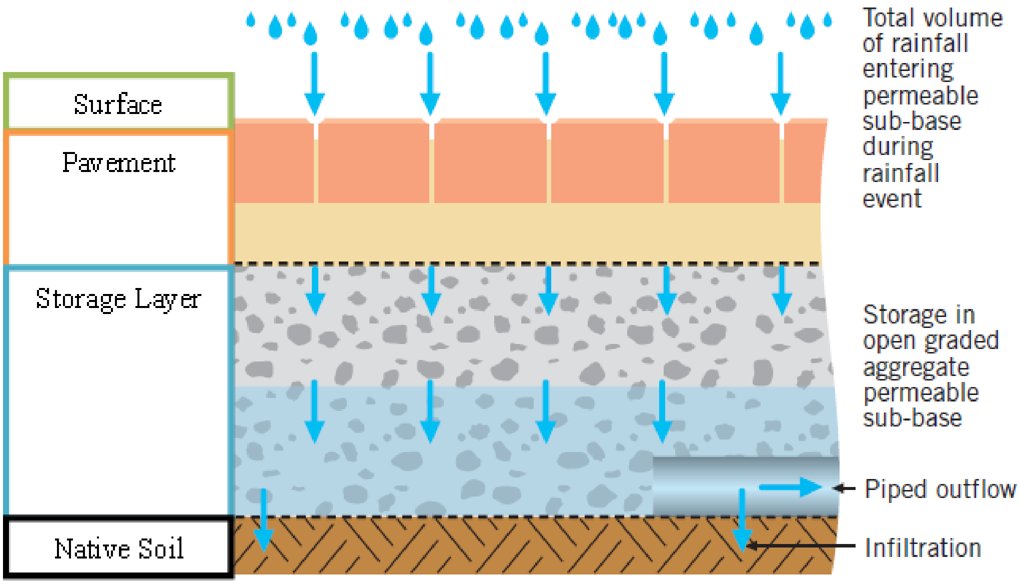

Figure 11. Profile of a CBP-structure with a drainage pipe (Interpave 2010).

The following paragraphs describe the most important elements of the structure in detail. The different layers that play a part are the surface, pavement, storage layer, presence or absence of an underdrain and the native soil.

2.2.1 Surface

The parameters needed to describe the surface layer in a hydrological model are surface slope, surface roughness (Manning's n, see equation 1), depression storage and vegetation volume fraction.

A surface with block pavement should have a surface slope of at least 1-2cm/m, in other words an inclination of 1-2% (Benders 2012). According to Larm (1994, see Ritzman 2013) the slope on permeable pavements should not exceed 5% in order for it to work efficiently, since the steeper it is, the faster water flows and the less time the water has to infiltrate. This was also stated by Illgen (2008), see section 2.1.5 about infiltration.

Common values for surface roughness (Manning's n) is 0.010-0.020 for concrete (Butler & Davies 2006). For smooth concrete it is about 0.012. The surface roughness also affects the previously described depression storage. Illgen (2009b) recommends to use the value 2.5mm for depression storage for CBP (with an opening ratio <6%) in order to account for the higher infiltration capacity at the beginning of rain events. By increasing the depression storage, the use of a constant infiltration rate (the final infiltration rate) is enabled throughout the entire infiltration period.

The vegetation volume fraction is the fraction of the volume within the storage depth filled with vegetation (U.S EPA 2010). This volume can often be ignored, but may be as high as 0.1 to 0.2 in case of very dense vegetative growth.

2.2.2 Pavement

The parameters describing the pavement layer are the thickness of the block, impervious surface fraction, void ratio (=voids/solids), permeability (mm/hr) and the clogging factor ().

Blocks of CBP (see figure 12) can have a wide variety of dimensions, depending on the manufacturer. The thickness of the block depends on the landuse; the bigger the load, the thicker the block. For pedestrian walkways and bicycle lanes the thickness of the block should be at least 40mm (S:t Eriks 2012). A block suitable for parking areas could be in the range 50-100mm (S:t Eriks 2012)(Widén 2013).

Figure 12. Possible appearance of a block of CBP.

The impervious surface fraction is 0 for continuously permeable pavements (porous pavements), since the entire surface is considered permeable. For modular systems such as CBP the fraction is more than 0 but less than 1 since only the joints are permeable. However, when using the accumulated frequency curve for CBP, the infiltration rates have been determined on the basis of l/(s*ha) where a mean value has been obtained for the entire surface area, meaning that the fraction should also be set to 0, just as in the case of continuously porous pavements.

The void ratio for permeable pavement systems typically ranges from 0.12-0.21 and is calculated as follows,

$$VoidRatio = \frac{Porosity}{1-Porosity} \qquad (2)$$

The void ratio describes the storage capacity in the pavement layer. Thus, only the open pores available for conducting water are of interest. In other words, the drainage porosity (effective porosity) should be used in the calculation, (Brady & Kunkel 2003).

For modular systems such as conventional block pavement, the void ratio of the filling material in the joints should be used. However, in this case, only 6% of the block pavement is considered to contribute to storage, which is why the void ratio is multiplied by 0.06, leaving 0.0072-0.0126, a very small value, without any significant contribution to storage in the system.

The permeability is the permeability of the concrete or asphalt used in continuous systems or the hydraulic conductivity of the joint fill material (gravel or sand) used in modular systems. The permeability of new porous concrete or asphalt is very high (e.g. hundreds of mm/hr) but can drop off over time due to clogging by fine particulates in the runoff (U.S EPA 2010). In this study the permeability is set to the final infiltration rates obtained from the accumulated frequency curve (see figure 7 and table 1 in section 2.1.5), where clogging is already considered, which is why the clogging factor is set to 0.

Between the pavement layer and the storage layer, there is usually a layer of sand, which can be seen in figure 11. The thickness of this layer is usually around 30mm (Widén 2013). However, SWMM does not contain a layer of this type, why the effect of this is neglected.

2.2.3 Storage layer

The storage layer, also called the base layer, usually consists of crushed stone and gravel and the height typically ranges from 150-450mm for permeable pavements (U.S EPA 2010). A typical height of the storage layer for a pedestrian walkway with CBP which is supposed to be able to support an occasional car crossing, where the main idea is to support the load applied to the surface and not to store water, is around 400mm (Widén 2013). According to Interpave (2010) the storage height can be between 250-450mm for permeable pavements, depending on the load.

Other input data required for this layer is the void ratio (=voids/solids) which describes to what extent the storage layer can store water. Common values for gravel beds used for permeable pavements are 0.5-0.75 (U.S EPA 2010).

2.2.4 Underdrain

An underdrain (see figure 11) transports the infiltrated water from the storage layer and thereby enables the storage layer to receive more infiltration water.

According to Larm (1994, see Ritzman 2013) a construction with permeable pavement should always contain underdrain piping. However, Bäckström and Forsberg (1998) claim that this is only necessary if the underlying soil has low infiltration capacity.

2.2.5 Native soil

The native soil is site specific and should be considered when designing the CBP-structure. The native soil can have a range of different conductivities, from clay to coarser gravel. Appendix II shows possible conductivities for each soil type.

3 The SWMM Model – Input Data and Assumptions

This chapter will show how the input data was chosen and applied to the virtual model in SWMM. All assumptions are based on the information given in chapter 2.

The function used in SWMM to consider the effect of permeable pavements is called LID (Low Impact Development) control. The LID control is an area that is applied to the catchment and displaces requested amount of ground cover. If several LIDs are assigned to the area, they will be placed in parallel and the runoff from each LID runs directly to the gutter (see area A3 in figure 5 in section 2.1.4, which shows how an LID displaces the impermeable area). Figure 13 shows the conceptual model in SWMM for permeable pavements and different inputs and outputs that are accounted for. During a simulation SWMM performs a moisture balance that keeps track of how much water moves between and is stored within each LID layer (U.S EPA 2010).

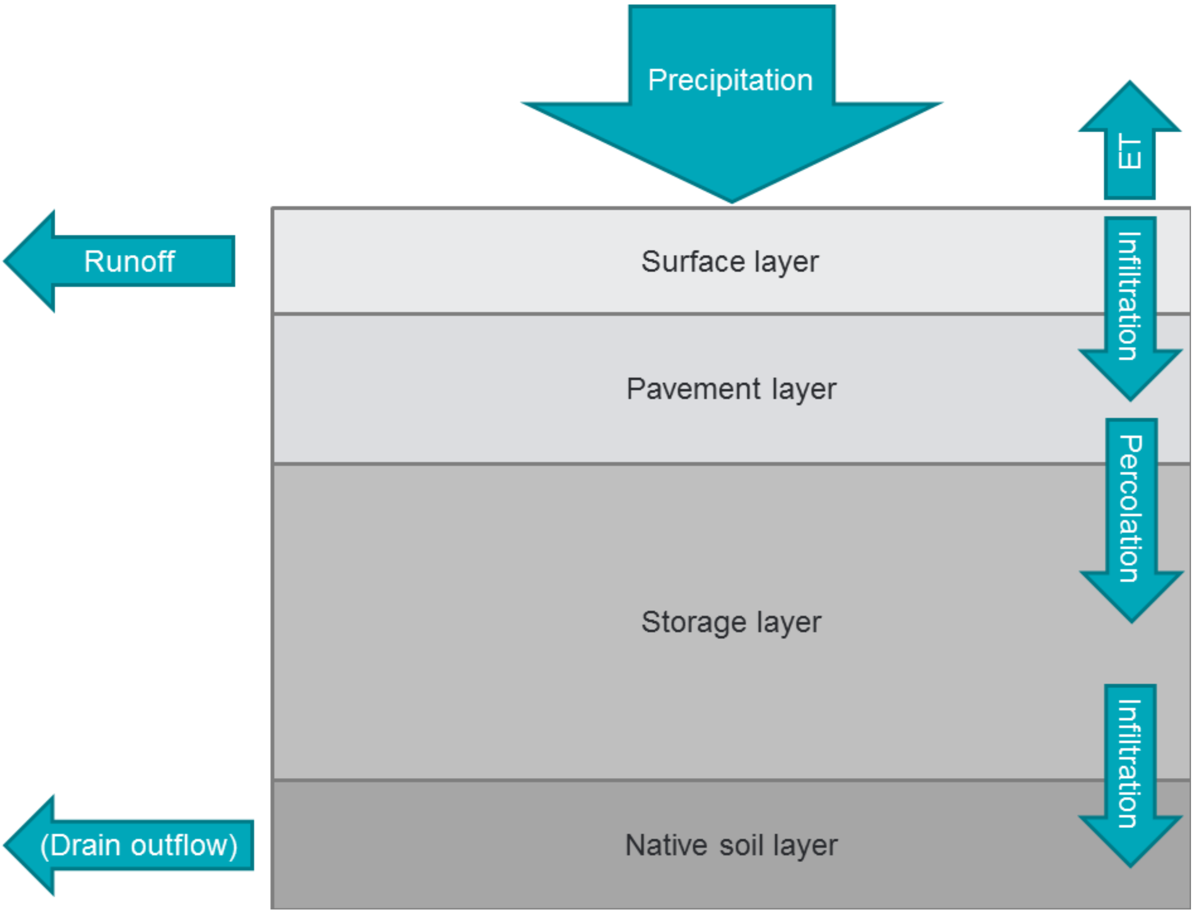

Figure 13. Conceptual model for permeable pavements in SWMM. ET stands for evapotranspiration. (Inspired by Rossman 2010).

3.1 General assumptions

The following sections will present assumptions made for all subcatchments used in the model. The area of interest consists of 10ha in total, where 70% is impermeable and 30% permeable with CBP (or ICP).

3.1.1 Rain data

First, different rain intensities were tested in the model in order to validate it and make sure that the results were reasonable with respect to water balances. The following intensities were tested: 9, 18, 27, 36, 45, 54, 72, 90 and 108 mm/hr. Block rain was used since it is the simplest model and appropriate for this purpose. The rain duration was set to 20min since a constant infiltration rate should have been reached at this time, according to Illgen (2008).

After simulating short-term rain data with satisfying results, long-term rain data (16 years=5840days) was used to make a sensitivity analysis. This data was obtained from real measurements in five minute intervals from 1977-1992 in Holzgerlingen, Germany. Figure 14 shows how the rain intensity varied during this time series. During the first days of the time series, no realistic data was produced, which is why there seems to be no precipitation during these days in figure 14.

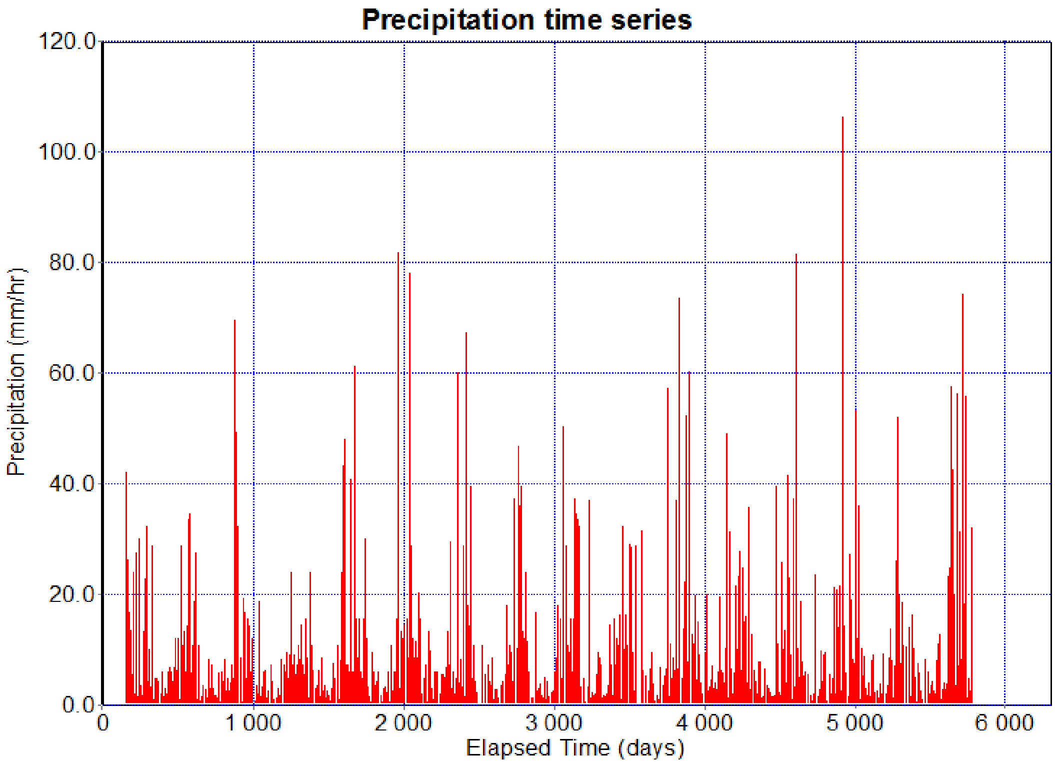

Figure 14. Rain intensities (mm/hr) between 1977-1992 for Holzgerlingen, Germany (Bendel 2013).

3.1.2 Evaporation rate

Starke et. al (2010) has proved that the evaporation rates from pervious concrete block pavements are 16% higher compared to water-impermeable pavements, and that the evaporation rates are more stable and evenly distributed over time (Starke et. al 2009, see Starke et. al 2010). The reason for the higher evaporation rates for pervious concrete block pavements are believed to be due to the water retained in the pore matrix of the paving stone as well as the joints (Starke et. al 2010).

Starke et. al (2010) performed tests on six different water permeable pavement systems to see what parameters affect the evaporation. The results obtained from these tests are presented in appendix III. The measurements took place during six different periods; rainy days, drying days (the two days following a rain event) and dry days.

Area 2.1 (see appendix III) is the common way of constructing pervious concrete block pavements according to the German standard DIN-EN, why it was used to calculate a reasonable evaporation rate for this study. An average value was calculated, and reduced with 16% in order to get a value corresponding to an impervious ground cover. This is because the models in this study consist of non-permeable concrete blocks and therefore mainly consist of impermeable surfaces. A constant value was chosen since Starke et. al (2009) claims that water permeable pavements have a more constant evaporation rate over time, compared to impermeable surfaces. By decreasing the evaporation rate, on the one hand, and at the same time considering a constant evaporation rate over time, both the permeable and the impermeable part of the pavement is considered. The value obtained from calculations was 0.33 mm/day (see appendix III) and was used as input data for the short-term and the long-term simulation in SWMM. This value may seem pretty low compared to the potential evaporation value mentioned in section 2.1.3 (2-3mm), but it gives conservative results, since more water will infiltrate (or become runoff). Moreover, the majority of the surfaces are impermeable.

3.1.3 Routing method and time steps

The routing method used was Kinematic Wave. Since this project only represents a virtual catchment, where parameters could be chosen such that backflow, pressurised flow and flow reversals could be avoided and thereby neglected, the use of Kinematic Wave was justified. SWMM requires four time steps to be specified before the simulations can be run and calculations can be made: a flow routing time step, a reporting time step, and runoff time steps for wet weather and dry weather.

The flow routing time step should never be larger than the wet weather time step or the reporting time step. It should be between 1-5 minutes or less when using Kinematic Wave (Gironás et. al 2009). In this case 30 seconds was used in order to reduce the error.

The reporting time step was set to 9 minutes, since this was the smallest applicable time step with respect to handling the output data in Microsoft Excel.

The wet weather time step should be less than the precipitation recording interval (Gironás et. al 2009). In other words, in this case it should not exceed 5 minutes. The wet weather and dry weather time steps were consequently set to 2 minutes respectively since this also gave small continuity errors (less than 1%) for every simulation.

3.1.4 Neglected parameters

All precipitation in the model is assumed to occur in the form of rainfall. No snow or other type of precipitation is accounted for.

The effect of groundwater has been neglected, in other words, the groundwater table is presumed to be at a level where it does not affect the flow balance calculations in SWMM.

An underdrain is not used since the underdrain outflow in SWMM leads to the same outlet as the surface runoff. This would result in difficulties to differentiate between flows originating from surface runoff and flows originating from the underdrain. Moreover, by excluding an underdrain from the model, the hypothesis of Bäckström and Forsberg (1998) that an underdrain is needed only if the underlying soil layer has a low percolation capacity, can be tested.

3.2 Virtual catchment – modelling layout

The following paragraphs describe the different setups used for each simulation and the purpose of the simulations. In the first step, simulations were run to see the effect of CBP and the number of infiltration classes for CBP on runoff characteristics. The next step was to evaluate the effect of vertical properties for CBP on runoff.

3.2.1 Sensitivity analysis – number of infiltration classes

The first simulation was run with two subcatchments of 10 ha (7 and 3 ha respectively) where 100% of the surface was considered impermeable. Figure 15 shows the layout of the system.

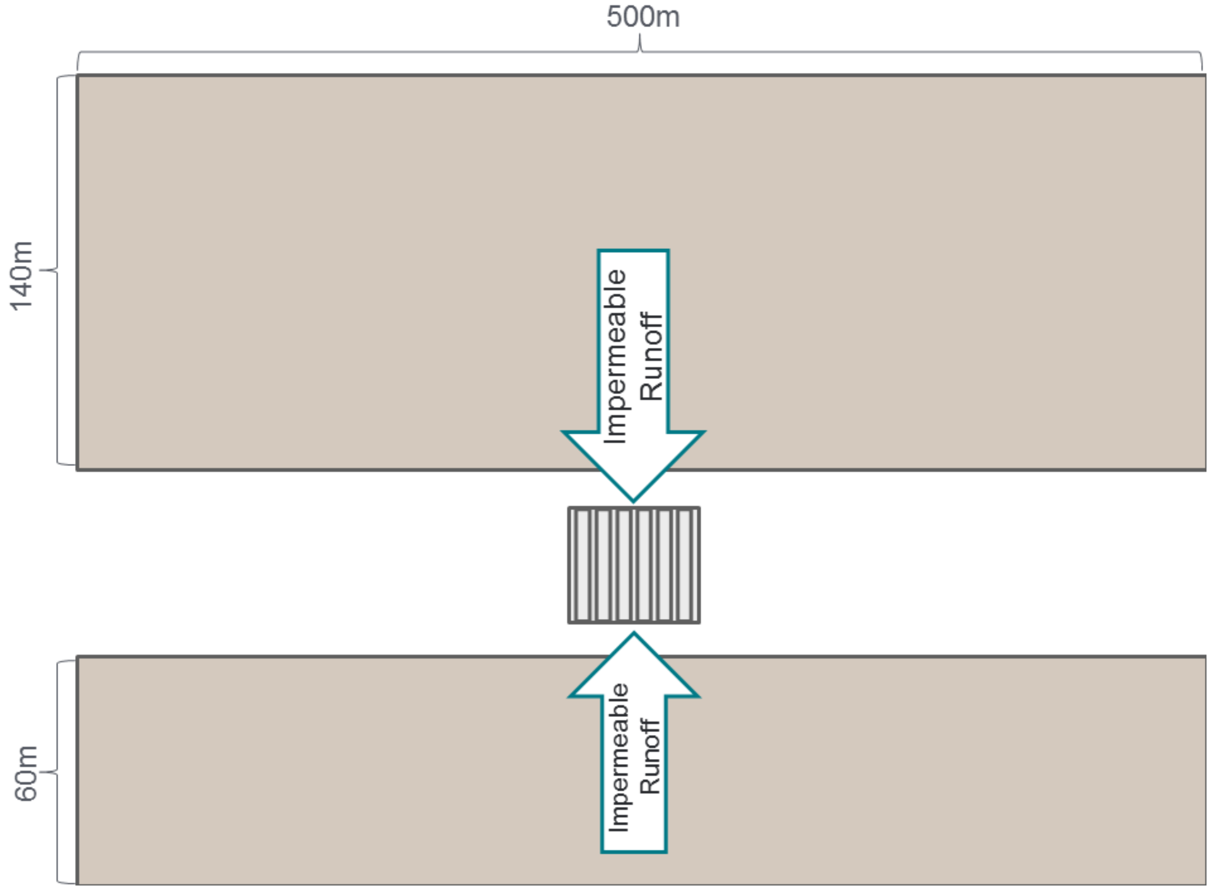

Figure 15. Layout of the virtual model with 100% impermeable ground cover in SWMM.

The generated runoff data for this simulation was used as a reference when evaluating the effect of adding CBP to the area. According to Dittmer (2013), 30% is a common share of permeable surfaces in an urban area, which is why the following simulations employ this share for CBP. In other words, the subcatchment of 7 ha is kept impermeable and the subcatchment of 3 ha is replaced with CBP.

The input data used for the impermeable subcatchments were chosen in accordance with table 2.

Table 2. Subcatchment properties for an impermeable area for two situations: 10ha impermeable or 7ha impermeable and 3ha CBP.

Subcatchment properties for impermeable area

Surface

Area [ha]	7 or 10 (=7+3)
Overland flow width [m] (see figure 5)	500
Slope [%]	2.5
Imperviousness [%]	100
Depression storage [mm]	0.5 (Butler & Davies 2006)

According to Illgen (2008) models should consider the probabilistic distribution of every pavement, since the final infiltration rate can vary extensively (see figure 7, section 2.1.5). He suggested that one type of permeable pavement should be subdivided into at least 3-6 classes with varying parameter sets, in order to avoid a too rough estimation of the properties. Table 3 describes how the subdivision was made in this study, with respect to the frequency curve given for CBP (and IP), with an opening ratio below 6% (See also section 2.1.5). Table 3 shows four different resolutions, with a subdivision into 10, 5, 3 or 1 class/es. The different infiltration rates given in the table are with respect to the entire area with CBP (or IP), in other words not only for the joints in the pavement.

Table 3. Various distributions of infiltration rates for CBP-blocks corresponding to a share of the area (Dittmer 2013).

Share of CBP-area [%]	10	10	10	10	10	10	10	10	10	10
Infiltration rates, 10 classes [mm/hr]	0	5.4	9	14.4	18	25.2	39.6	48.6	72	126
Infiltration rates, 5 classes [mm/hr]	2.7		11.7		21.6		44.1		99	
Infiltration rates, 3 classes [mm/hr]	4.8			24.3				82.2		
Infiltration rate, 1 class [mm/hr]	35.8									

Figure 16 shows a schematic picture of the geometry for the simulation with 3 different infiltration classes. The same idea is used for the other infiltration classes, only now the CBP-area is divided into finer or coarser segments, depending on the number of classes. Figure 16 also shows the infiltration rates for each segment of CBP in the case of 3 infiltration classes.

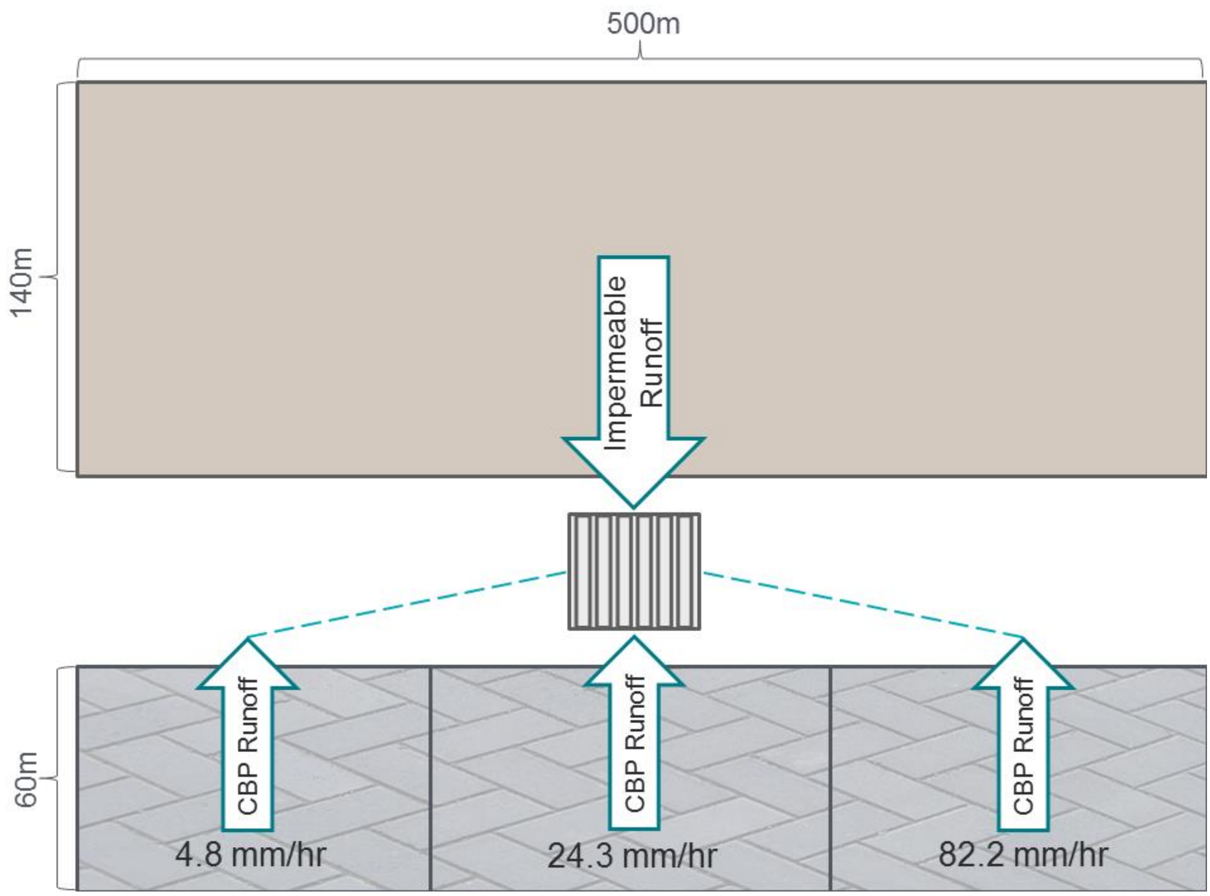

Figure 16. Modeling layout for 7ha impermeable surfaces and 3ha of CBP divided into 3 infiltration classes.

The generated runoff data obtained from these simulations were then compared to the 100% impermeable surfaces to see how CBP affects the runoff generation, as well as how the distribution of infiltration rates for CBP affects the runoff. The question at hand is whether a low number of infiltration classes will give an acceptable result or if a more detailed model is needed in order to get results closer to reality. It is of interest to know how much that is gained by applying a very detailed model.

When using Illgens approach with a constant infiltration rate over time, the depression storage should be increased in order to account for the higher initial infiltration rate. As was stated previously in section 2.1.5, Illgen suggests the value of 2.5mm in the case of CBP with an opening ratio <6% (Illgen 2009b).

The rest of the CBP structure was assigned values considered to serve as average values for CBP structures, based on the information presented in chapter 2. Table 4 shows the input data used.

Table 4. Properties for the subcatchment of 3ha with CBP.

<u>Subcatchment properties for CBP</u>

Surface

Area [ha]	3 (distributed between number of classes) 10 classes á 0.3 5 classes á 0.6 3 classes á 1 1 class á 3
Overland flow width [m], see figure 5	500 (distributed between number of classes) 10 classes á 50 5 classes á 100 3 classes á 166.67 1 class á 500
Storage Depth [mm]	2.5 (Illgen 2009b)
Vegetation Volume Fraction	0
Surface Roughness [Manning's n] [$s/m^{1/3}$]	0.012 (smooth concrete Butler & Davies 2006)
Surface Slope [%]	2.5

Pavement

Thickness [mm]	100
Void Ratio (=Voids/Solids) 0.12-0.21, recommended values by SWMM for porous pavement. Since only 6% of the entire LID area contributes to storage, the void ratio should be multiplied by 0.06.	0.0072-0.0126 → ~ 0.01 In other words, the storage capacity for the pavement layer is very limited.
Impervious Surface Fraction	0, since the measured infiltration rates are with respect to the entire area of block pavement
Permeability [mm/hr], according to table 3	10 classes: 0/5.4/9/14.4/18/25.2/39.6/48.6/72/126 5 classes: 2.7/11.7/21.6/44.1/99 3 classes: 4.8/24.3/82.2 1 class: 35.8
Clogging Factor	0, since Illgens model already considers clogging

Storage

Height [mm]	350 (Interpave 2010)
Void Ratio (=Voids/Solids) (see appendix I)	0.33
Conductivity [mm/hr] (for native soil layer), see Appendix II	0.42(silt)
Clogging Factor	0, since Illgens model already considers clogging

Underdrain

Drain Coefficient, C [mm/hr]	0 (no underdrain)
Drain Exponent, n	0
Drain Offset Height [mm]	0 (height above bottom of storage layer)

3.2.2 Sensitivity analysis – vertical parameters

For these simulations only runoff from the CBP area (3ha) was considered. The CBP area was divided into 5 infiltration classes on the recommendation that at least 3-6 infiltration classes should be used (Illgen 2008). Figure 17 shows the model layout. The values underneath the arrows in the figure represent the infiltration capacity of each block with CBP.

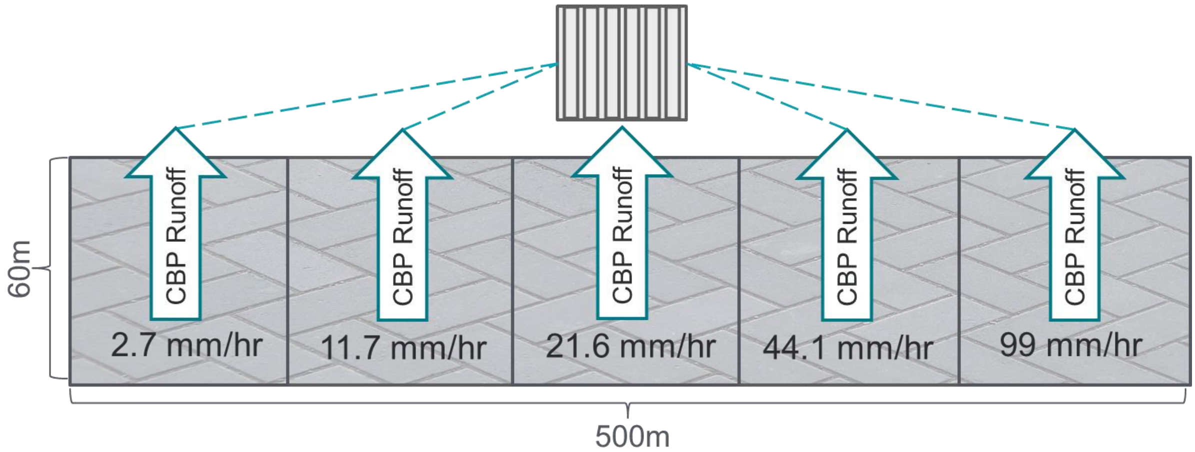

Figure 17. Top view of 3ha of CBP divided into 5 infiltration classes. The infiltration rates for each block are shown below the arrows in the figure.

The main purpose was to determine to what extent vertical parameters affect the runoff characteristics from CBP. Consequently, parameters were varied within a reasonable range during different simulations to see their effect on runoff characteristics.

Parameters assumed to have a significant effect on runoff characteristics were chosen for the simulations. The altered parameters were:

- Initial losses (storage depth) [mm]
- Surface slope [%]
- Height of storage layer [mm]
- Void ratio of storage layer []
- Conductivity of underlying soil [mm/hr]

The selected values for the impermeable subcatchment are presented in table 5.

Table 5. Properties for impermeable area for two situations: entirely impermeable or entirely CBP.

Subcatchment properties for impermeable area

Surface

Area [ha]	3 or 0
Overland flow width [m]	500
Slope [%]	2.5
Imperviousness [%]	100
Depression storage [mm]	0.5 (Butler & Davies 2006)

The selected values for the subcatchment with CBP are shown in table 6. The table is based on the SWMM interface and shows the input parameters used for CBP. Figure 11 explains the different layers mentioned in table 6. Since there is a range within which certain parameters can be varied, different values within this range were tested in the model to see their influence on runoff characteristics. When three values are presented in the table and they are separated by a dash (/), they are assumed to represent the minimum/average/maximum values, with reference to chapter 2. They were all tested in the model in a sensitivity analysis.

Table 6. Properties for the CBP area of 3ha divided into 5 classes.

Subcatchment properties for CBP

Surface

Area [ha]	3 (distributed evenly between 5 classes)
Overland flow width [m], see figure 5	500 (distributed evenly between 5 classes)
Storage Depth [mm]	0.5/2.5 (Illgen 2009b)/5
Vegetation Volume Fraction	0
Surface Roughness [Manning's n]	0.012 (smooth concrete Butler & Davies 2006)
Surface Slope [%]	1/ 2.5 /5

Pavement

Thickness [mm]	100
Void Ratio (=Voids/Solids) Void Ratio 0.12-0.21, recommended values by SWMM for porous pavement. Since only 6% of the entire LID area contributes to storage, the void ratio should be multiplied by 0.06.	0.0072-0.0126 →~ 0.01 In other words, the storage capacity for the pavement layer is very limited.
Impervious Surface Fraction	0, since the measured infiltration rates are with respect to the entire area of block pavement
Permeability [mm/hr], according to table 3	2.7/11.7/21.6/44.1/99
Clogging Factor	0, since Illgens model already considers clogging

Storage

Height [mm]	150/350/550 (Interpave 2010)
Void Ratio (=Voids/Solids) (see appendix I)	0.18/0.33/0.54
Conductivity [mm/hr] (for native soil layer), (see appendix II) Clay: $4.2x10^{-7}$ - 0.042 Silt, loess: 0.042 - 420 Silty sand: 4.2 - 420 Clean sand: 42 - 4,200 Gravel: 4,200 - 420,000	0.00042(clay)/0.42(silt)/420(sand)
Clogging Factor	0, since Illgens model already considers clogging

Underdrain

Drain Coefficient, C [mm/hr]	0 (no underdrain)
Drain Exponent, n	0
Drain Offset Height [mm]	0 (height above bottom of storage layer)

4 Results and Analysis

The following paragraphs will present and analyse the results obtained from the simulations. First, the entire system of 10 ha will be studied when studying the effect of adding 30% CBP (in different number of classes). Second, focus will be solely on the CBP-area, when studying the effect of changing vertical parameters within the CBP-structure.

4.1 Sensitivity analysis – number of infiltration classes

The first simulation was run with an entirely impermeable surface of 10 ha (7 and 3 ha). For the second simulation the 3 ha area was assigned CBP consisting of 1 infiltration class. The third simulation was run with 3 infiltration classes. The vertical properties were all assigned the average values according to table 4 in section 3.2.1.

Figure 18 shows the distribution of runoff rates with respect to the total amount of hours with runoff or with respect to the entire runoff volume per year (for 16 years). The runoff data was recorded for every 9min and was used to determine the number of hours with runoff. Runoff is only recorded if it exceeds 0.01 l/s. Each curve in figure 18 represents one simulation. The solid lines represent 100% impermeable surfaces, the dotted lines represent 30% CBP with 1 infiltration class and the dashed lines show 30% CBP with 3 infiltration classes. The total amount of runoff hours for the 100% impermeable case is used as reference for the curves for each class. In the same way the yearly runoff volume for the 100% impermeable curve is used as reference for the classes' volume curves. In other words, the data from the 100% impermeable case is used to normalise the data obtained from the simulations run with different classes of CBP.

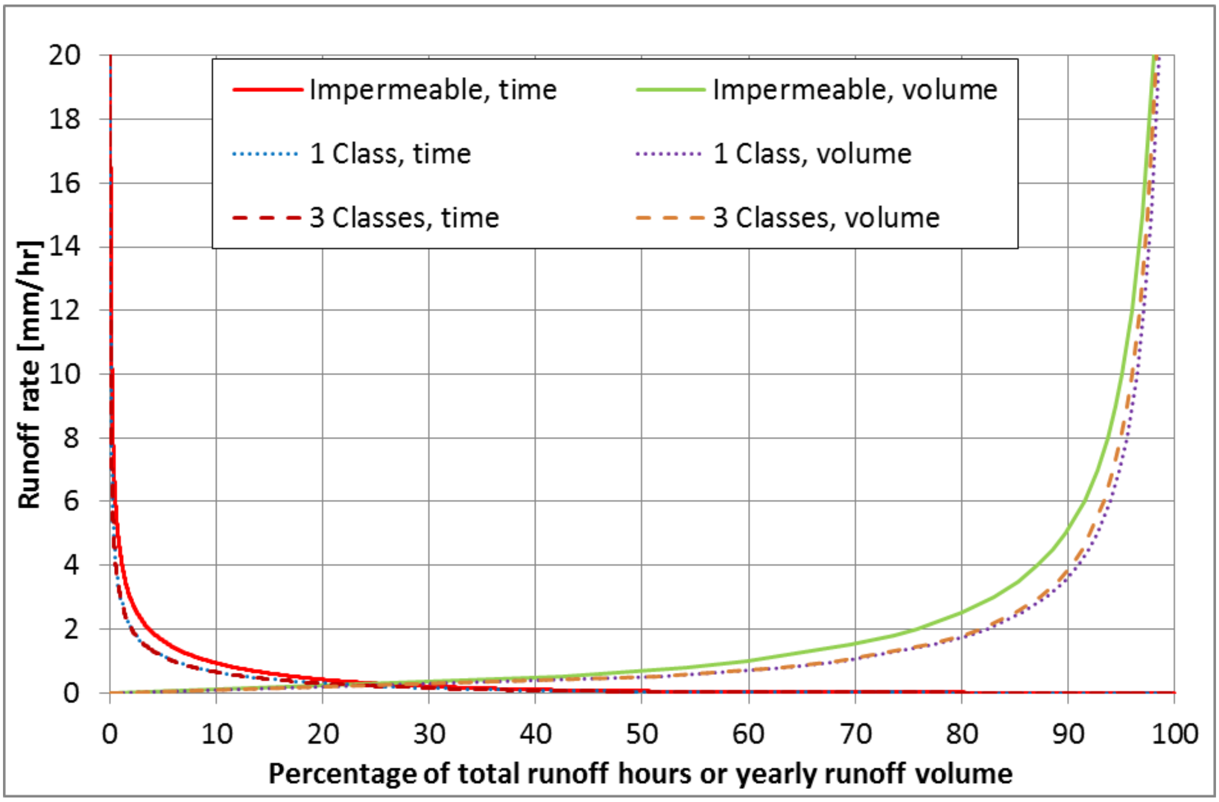

Figure 18. Comparison of the distributions of runoff rates when using a 100% impermeable surface, 1 class of CBP or 3 classes of CBP. The curve for 1 class and the curve for 3 classes are both normalised with data from the impermeable case.

Figure 18 shows that adding 30% CBP to an area will change the distribution of runoff rates, irrespective of whether 1 or 3 infiltration classes are used. When studying the time curves it can be seen that there will generally be runoff at lower rates for a longer duration of time when using CBP than for the 100% impermeable case.

When studying the volume curves in figure 18 both situations with infiltration classes show that CBP generally results in more of the runoff volume occurring at lower rates. For instance, in the impermeable case, 90% of the runoff volume occurs at rates below 5mm/hr, whereas for the case of adding CBP to the system, 90% of the runoff volume occurs at rates below 4mm/hr. It is important to be aware of the fact that the curves are relative and always based on the runoff volume from the impermeable case. In other words, a greater share of the runoff volume occurs at lower rates when using CBP, than when not using it. However, 1 class and 3 classes do not present identical results, especially not for the higher runoff rates. The remaining 10% that exceeds a runoff rate of 4mm/hr show the greatest difference. One can see that when using 1 infiltration class, the effect of CBP is slightly over-estimated, since the share of runoff rates above 4mm/hr is lower than when using 3 classes. The runoff characteristics are studied more in detail in table 7.

Since 1 and 3 infiltration classes not give identical results, there is a need to refine the resolution further. Figure 19 shows a graph similar to the one in figure 18, but now 5 and 10 infiltration classes are presented along with the curves for the 100% impermeable area.

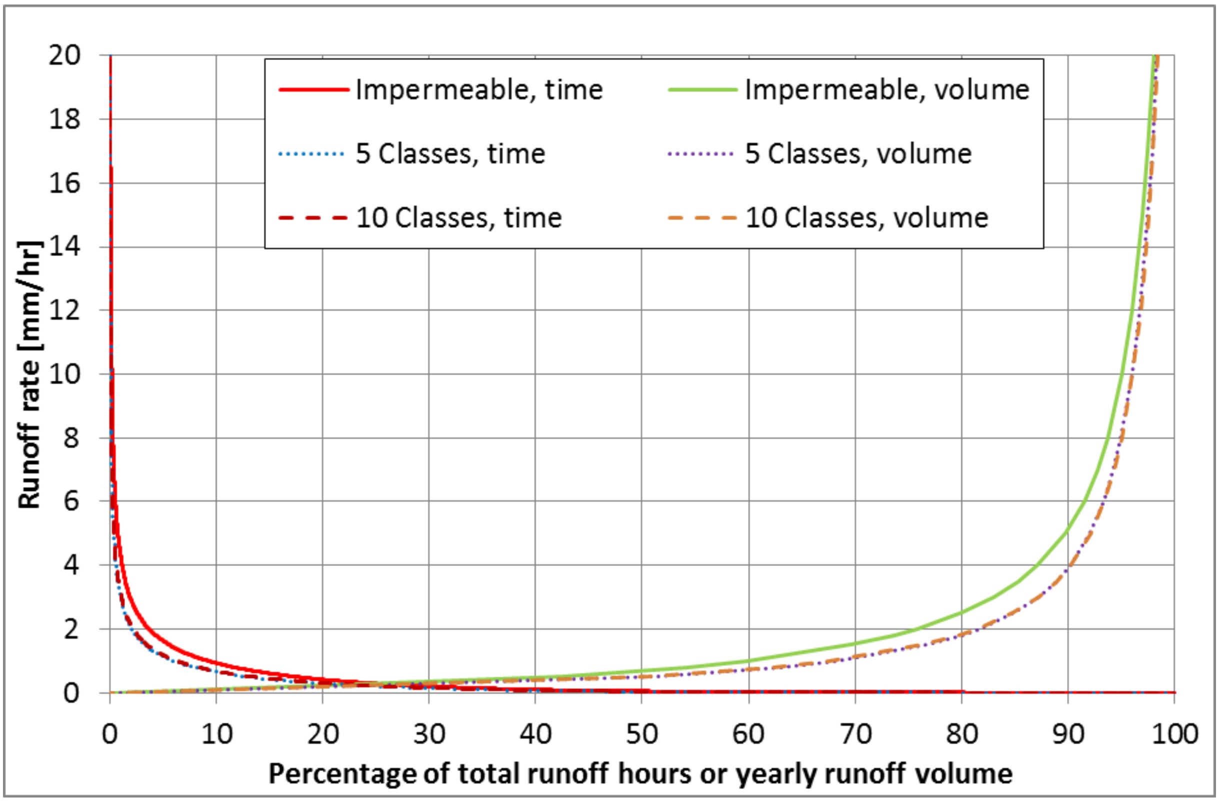

Figure 19. Comparison of the distributions of runoff rates when using a 100% impermeable surface, 5 classes of CBP or 10 classes of CBP. The curve for 5 classes and the curve for 10 classes are both normalised with data from the impermeable case.

The time curves are identical when looking at 5 or 10 classes. Also when looking at the volume curves the curve for 5 infiltration classes (dotted line) coincides with the curve showing 10 infiltration classes (dashed line). In other words, not much information is gained by refining the resolution further than 5 classes.

When comparing 3 and 5 infiltration classes (see figure 20) one can see that the graph looks identical to the graph in figure 19. The conclusion is that there is no need to use 10 or 5 classes, 3 classes are enough.

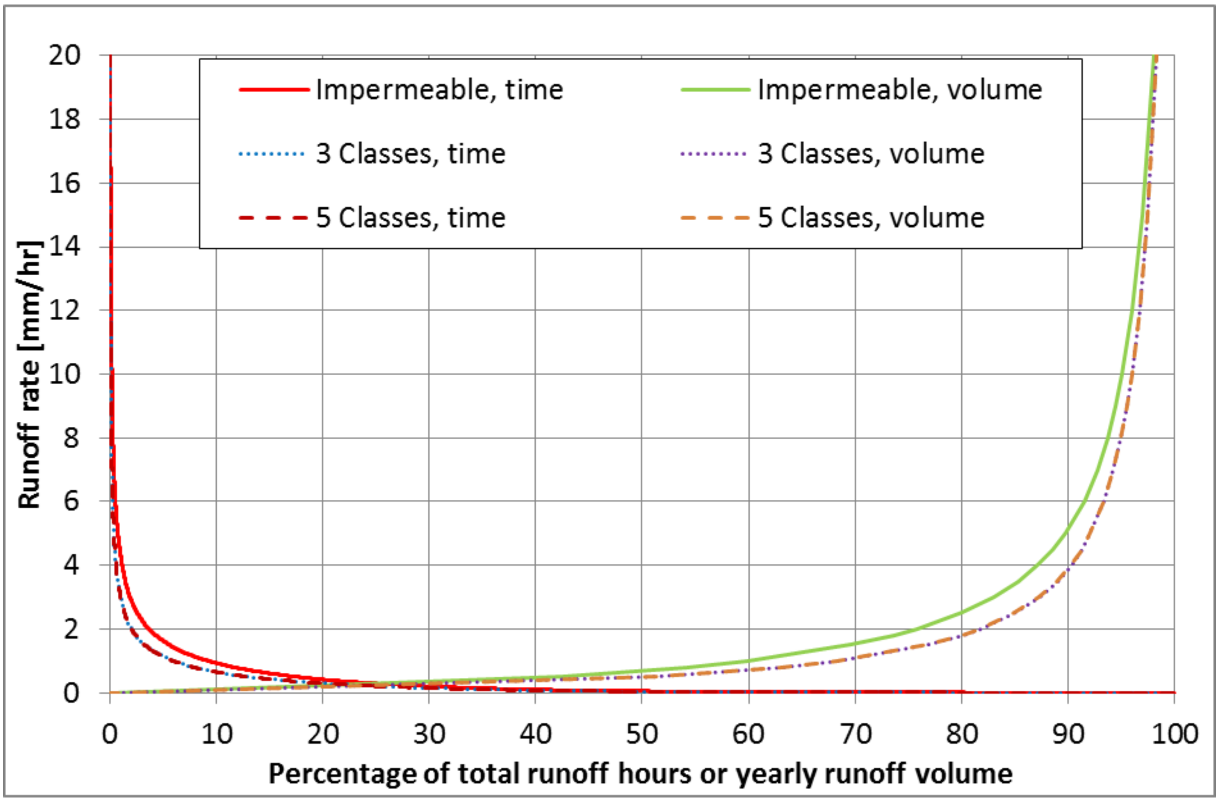

Figure 20. Comparison of the distributions of runoff rates when using a 100% impermeable surface, 3 classes of CBP or 5 classes of CBP. The curve for 3 classes and the curve for 5 classes are both normalised with data from the impermeable case.

However, when studying the data more in detail for every simulation (see table 7) one can see a clearer difference between the classes.

Table 7. Summary of the peak flows, total runoff and time with runoff for a 10ha impermeable surface and for 30% CBP divided into different number of classes. The differences and errors are shown in percent. Ref stands for reference and is used when calculating the percentages shown in the table.

	Peak flow [mm/hr]	Difference [%]	Error [%]	Total runoff [mm]	Difference [%]	Error [%]	Time with runoff [hr]	Difference [hr]
Impermeable	92	Ref	-	10,351	Ref	-	28,145.3	Ref
1Class	81	-12	-5%	7,283	-30	-4%	28,142.7	-2.55
3Classes	88	-4	+4%	7,335	-29	-3%	28,142.7	-2.55
5Classes	84	-9	-1%	7,347	-29	-3%	28,142.7	-2.55
10Classes	85	-9	Ref	7,595	-27	Ref	28,142.7	-2.55

Table 7 shows that when adding CBP to the system, the peak flow is reduced. Yet, this number depends on number of infiltration classes. When using only 1 class, the peak flow is reduced by 12%. However, this is an over-estimation, since the usage of 10 classes gives a reduction of only 9%. When only studying the peak flow, 5 classes seem to represent a fine enough resolution, since both 10 and 5 classes give the same reduction in percent. The column showing the error shows how inconsistent the peak flow is compared to the case of 10 classes. It can be seen that 5 classes only would give an error of 1%. Nevertheless, using 1 infiltration class only gives an error of 5%. Not a very big difference in other words.

When studying the total runoff from the entire surface, it can be seen that 30% CBP can reduce the runoff by almost 30%. However, even here there is a difference between the number of classes, where all classes fewer than 10 over-estimate the performance of CBP. When determining total runoff volume, 10 classes is the most accurate choice. However, if a lower resolution is wanted, 3 classes works almost as well as 5 classes with a reduction of the total runoff with 29% and a corresponding error of 3%. Even in this case, using a resolution of 1 infiltration class would only produce an error of 4%.

Adding CBP to the system reduces time with runoff with more than 2.5 hours. Still, this is not very significant with respect to the entire time series (16 years). The reason for the low reduction is that runoff from the impermeable surface of 7ha is lead directly to a gutter, and consequently the CBP will not be able to reduce time with runoff to such a great extent. However, if the runoff from the impermeable area would be lead across the CBP-area before reaching the gutter, the number of runoff hours would be reduced further. In table 8 in section 4.2 the number of runoff hours can be seen when replacing an impermeable surface of 3ha entirely with CBP.

The number of runoff hours does not increase when increasing the number of classes. This seems surprising because the use of more classes gives areas with lower infiltration capacities. This means that even rain events of lower intensities should result in runoff. However, when studying a histogram for the precipitation data (see appendix IV) it can be seen that around 95% of the precipitation occurs at rates below 5mm/hr. In addition, the exceedance frequency for a rain intensity of 2.7mm/hr (which was one of the lowest infiltration capacities for the CBP when using 5 classes) was only a little over 2%. In other words, the effect of the lower resolution and lower infiltration rates is not very significant since most of the rain can still infiltrate.

4.2 Sensitivity analysis – vertical parameters

In the following simulations only the CBP-area of 3ha was considered. First it was run with 100% impermeable surfaces and then it was replaced entirely by CBP. The simulation was run with 5 infiltration classes of CBP and average values as stated in table 6 in section 3.2.2 in table 6. The following simulations were run altering one parameter at a time, in order to see the effect of this change. Table 8 shows a summary of the peak flows, total runoff and time with runoff, obtained from the simulations. The four greatest values (+ and -) for each parameter are in bold. The results will be studied in more detail in the following paragraphs.

Table 8. Summary of the peak flows, total runoff and time with runoff for an entirely impermeable area of 3ha and subsequently entirely covered with CBP. Each row with data represents one simulation. The data refers to the values shown in table 6.

	Peak flow [mm/hr]	Difference [%]	Total runoff [mm]	Difference [%]	Time with runoff [hr]	Difference [%]
100% Impermeable	104	-	10,362	-	23,630	-
100% CBP						
Average	*75*	*Ref*	*350*	*Ref*	*234*	*Ref*
Min initial loss	88	**+17**	602	**+72**	540	**+31**
Max initial loss	62	**-17**	208	**-41**	125	**-47**
Min slope	74	-1	336	-4	258	+10
Max slope	98	**+31**	359	+3	221	-6
Min height SL	75	0	440	**+26**	268	**+15**
Max height SL	75	0	350	0	234	0
Min void ratio SL	82	+9	383	+9	243	+4
Max void ratio SL	75	0	351	0	234	0
Min conductivity	94	**+25**	9,389	**+2,583**	20,430	**+8,631**
Max conductivity	75	0	310	-11	234	0

The simulations show that adding CBP to an area has a great effect on the system. In every case with CBP, peak runoff, total runoff, and time with runoff is reduced. For the average case, peak runoff is reduced by 28% compared to the 100% impermeable area (from 104 mm/hr to 75 mm/hr). When adding CBP to the area also the total runoff is reduced, by as much as 97% (from 10,362mm to 350mm)! Moreover, the time with runoff is reduced by 99% (from 23,630hrs to 234hrs)! The subsequent simulations show the influence of changing *one* parameter at a time for CBP.

4.2.1 Initial losses

Table 9 shows how the runoff characteristics were changed when altering the initial losses. The initial losses had a great effect on peak flow, total runoff and time with runoff. The peak flow increased with 17% when the initial losses were low, and decreased with 17% when the initial losses were high. For the total runoff, a small initial loss gave an increase of 72% whereas a greater initial loss gave a reduction with 41%. The initial losses also had a great effect on time with runoff, with an increase of 306hrs for the case of low initial losses and a reduction of 109hrs for higher initial losses.

Table 9. Summary of the peak flows, total runoff and time with runoff when altering the initial loss.

Average initial loss 2.5mm	Peak flow [mm/hr]	Difference [%]	Total runoff [mm]	Difference [%]	Time with runoff (>0.01 LPS) [hr]	Difference [%]
Min initial loss 0.5mm	88	**+17**	602	**+72**	540	**+31 (+306hrs)**
Max initial loss 5mm	62	**-17**	208	**-41**	125	**-47 (-109hrs)**

The initial losses represent the capability of the surface to hold water. As soon as this capacity is exceeded, there will be an overflow. When the CBP has higher initial losses it will take a rain event of higher intensity (or low intensity and longer duration) to fill up the surface storage. Evidently the opposite applies for the case with lower initial losses. The water stored in depressions will either evaporate, or infiltrate into the CBP-structure over time. However, since the processes of evaporation and infiltration take time, the effect of surface storage is not relevant if rain events occur frequently during a short period of time. This is due to the fact that the surface storage will never have time to empty and therefore will stay full.

The peak flow is increased for the case of low initial losses since the rain of the highest intensity occurs when the surface storage is full. The opposite applies for the high initial loss, in other words it is not full when the peak flow occurs, which is why the peak flow is lower than for the average case.

The reason why total runoff is affected by the magnitude of initial losses is due to the increased/decreased possibility of infiltration and evaporation. As stated previously, water stored in depressions will either infiltrate or evaporate. Consequently, more rain can take these paths, instead of becoming runoff, if the initial loss is high.

Both cases also alter the time with runoff. For a low initial loss, there will be more time with runoff since even low rain intensities can make the depressions in the surface overflow. For a high initial loss, on the other hand, generally a rain of higher intensity will be needed in order to produce runoff.

Figure 21 shows a more detailed view of how the runoff rates vary over time, or with respect to the total runoff volume.

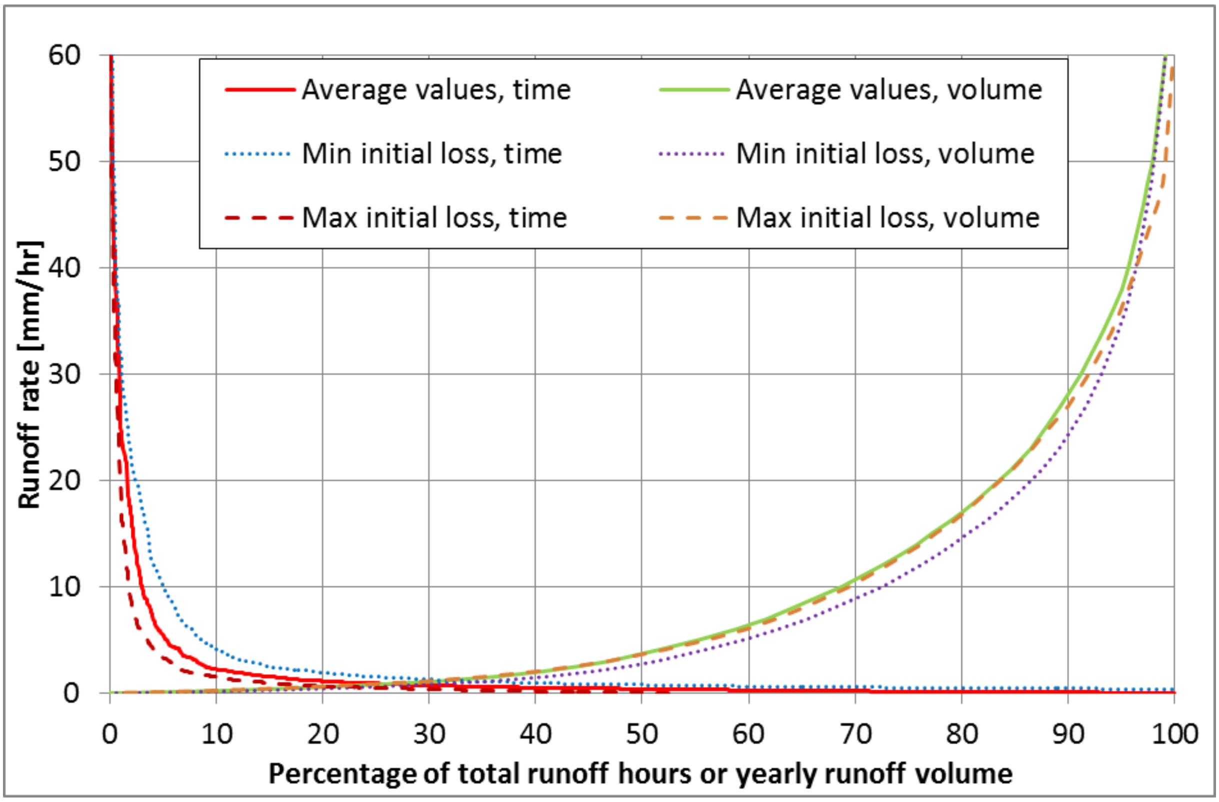

Figure 21. Comparison of the distributions of runoff rates for the average case with an initial loss of 2.5mm, 0.5mm (min initial loss) and 5mm (max initial loss) for CBP. The curves are all relative to the average case.

The solid lines represent the runoff from the CBP-structure with average values and show the distribution of runoff rates with respect to the total runoff hours or with respect to the yearly runoff volume. The solid line “Average values, time” that decreases with increasing percentage shows the distribution of runoff rates with respect to the total runoff hours. For instance, it shows that during 10% of the runoff time, runoff occurs at rates above 2mm/hr, which is relatively infrequent. The curve “Average values, volume” shows the distribution of runoff rates with respect to yearly runoff volume. For instance, 70% of the volume occurs at rates below 11mm/hr.

The effect of altering initial losses is studied with the average curves as reference. In other words, for the curves displaying runoff rates with respect to runoff hours, the max and min curves are normalised with the runoff hours for the average case. In the same way the max and min curves showing runoff rates with respect to yearly runoff volume are normalised with the runoff volume for the average case.

Earlier, it was shown that when decreasing the initial losses, the number of runoff hours increased. Figure 21 shows that runoff occurs at higher rates for a longer period of time, compared to the average case, which is because the surface is not able to hold as much water and when it is full, the runoff occurs as if there were no surface storage. The opposite is shown for the higher initial loss, where most of the time the runoff occurs at lower rates than in the average case.

It was previously stated that a decrease in the initial loss resulted in more total runoff. When studying the volume curves, it can be seen that a low initial loss results in more of the runoff volume occurring at lower rates, than for the average case. The reason for this is that even a rain event of fairly low intensity can fill the depression storage and contribute to runoff at low rates. The difference between the higher initial loss and the average case is not very large, not until higher runoff rates are reached. The dashed line “Max initial loss, volume” diverges from the solid line “Average values, volume” at approximately 88% of the volume. This means that less of the runoff volume occurs at very high rates, which also is connected with the reduced peak flow for a higher initial loss. In other words, when there is a heavy rain event the surface storage has had time to drain or evaporate to a certain extent, enabling more water to be stored before runoff occurs.

4.2.2 Surface slope

The surface slope had the greatest effect on the peak flow of all parameters, at least when increasing the slope. Table 10 shows that the peak flow increased with as much as 31% if the slope was steep, and decreased with 1% if the slope was small. It did however, not have a significant effect on the total runoff. A smaller slope gave a decrease of 4%, whereas a greater incline gave an increase of 3%. The slope also had some effect on total time with runoff, with an increase of 24hrs for the case of a smaller slope and a reduction of 13hrs for a steeper slope.

Table 10. Summary of the peak flows, total runoff and time with runoff when altering the slope.

Average slope 2.5%	Peak flow [mm/hr]	Difference [%]	Total runoff [mm]	Difference [%]	Time with runoff (>0.01 LPS) [hr]	Difference [%]
Min slope 1%	74	-1	336	-4	258	+10 (+24hrs)
Max slope 5%	98	**+31**	359	+3	221	-6 (-13hrs)

In section 2.1.5 Illgen (2008) claims that an increase of the surface slope from 2.5% to 5% reduces the infiltration capacity with 5-20% and this is more distinct for low permeable pavements such as CBP. The runoff will also increase due to a decreased storage volume since water will always flow to the lowest point – as shown in figure 22 (Interpave 2008).

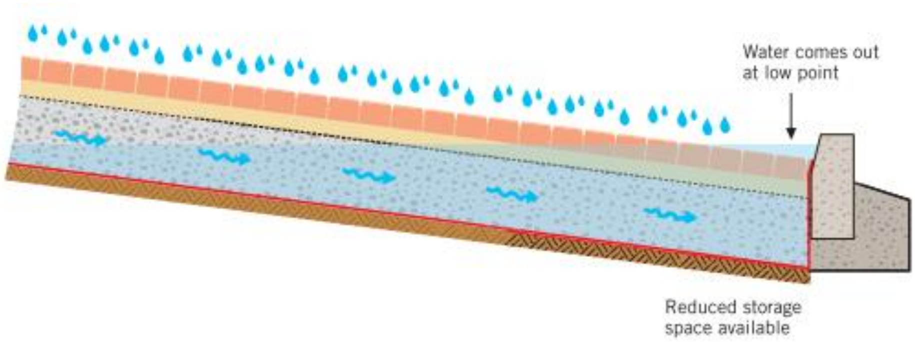

Figure 22. The effect of a steep slope on the available storage volume and consequently the runoff (Interpave 2008).

However, the results in this study suggest that the produced runoff will only increase with 3%. The reason might be the fact that the infiltration capacity and storage volume that was assigned as input to the model should have also been altered before running the simulations with a change in slope. Still, Illgen (2008) claims that the statistical model already considers many different boundary conditions since the measurements have been done at a multitude of sites.

When altering the slope, water will flow faster or slower across the surface on its way to the outlet. When using a slope with a smaller incline, it takes longer time for the runoff to reach the outlet. Consequently, there will be runoff for a longer period of time at lower rates. The slower runoff process results in the possibility of more infiltration leading to a reduction in total runoff (which can be seen under total runoff in table 10 where the runoff is reduced by 4%).

When studying figure 23 showing the distribution of runoff rates with respect to runoff hours, one can see that runoff occurs at similar rates for all three slopes. When using a smaller slope, it can be seen that the runoff rates are generally slightly smaller than in the average case; however, the difference is barely noticeable. This can be related to the time with runoff shown in table 10. Since the total runoff and time with runoff did not change to such a great extent, the curves will basically coincide.

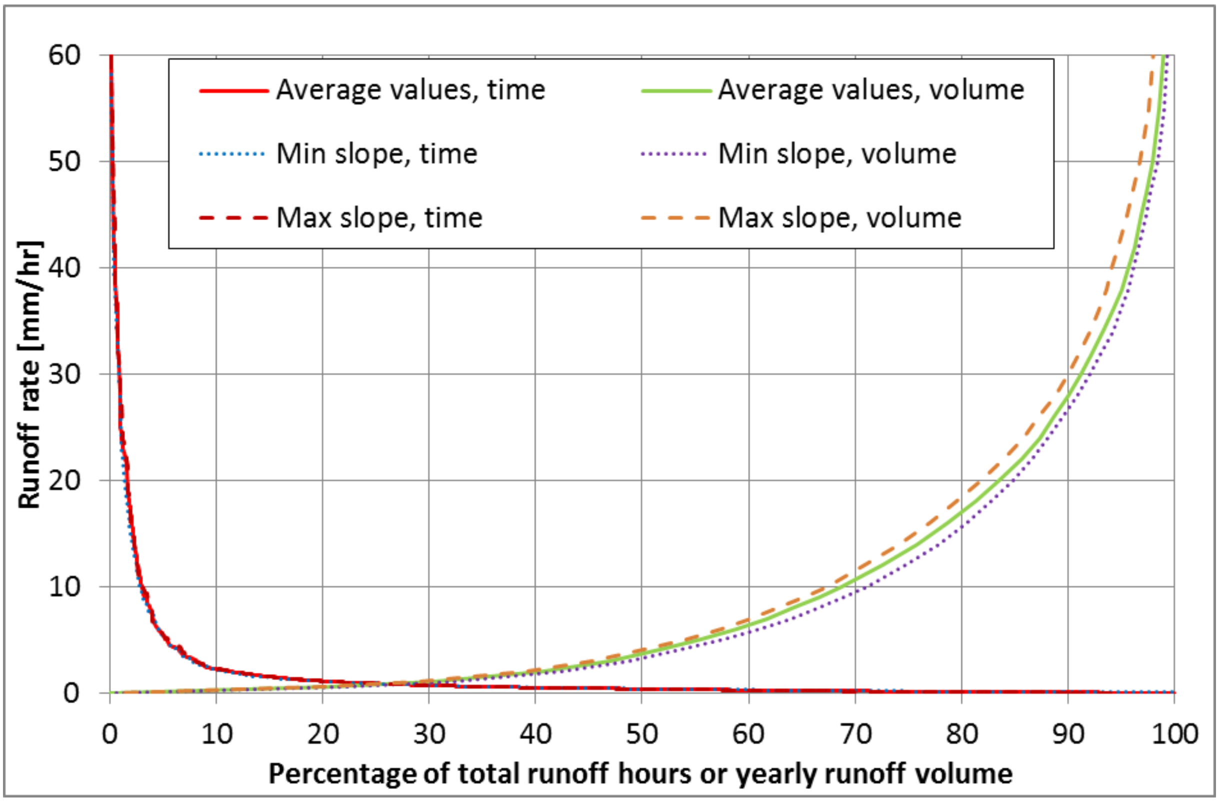

Figure 23. Comparison of the distributions of runoff rates for the average case with a slope of 2.5%, a slope of 1% (min slope) and a slope of 5% (max slope) for CBP. The curves are all relative to the average case.

On the other hand, when studying the volume curves in figure 23, it can be seen that a smaller slope results in more volume occurring at lower rates, than for the average case. This is because the water runs slowly across the surface and therefor has more time to infiltrate. The opposite applies for the case with a steeper slope.

4.2.3 Height of storage layer

Table 11 shows that increasing the storage height did not have any effect on runoff. Only a reduction of the storage height resulted in a change, where the total runoff was increased by 26% and the time with runoff increased by 34hrs.

Table 11. Summary of the peak flows, total runoff and time with runoff when altering the height of the storage layer.

Average height SL 350mm	Peak flow [mm/hr]	Difference [%]	Total runoff [mm]	Difference [%]	Time with runoff (>0.01 LPS) [hr]	Difference [%]
Min height SL 150mm	75	0	440	**+26**	268	**+15 (+34hrs)**
Max height SL 550mm	75	0	350	0	234	0 (0hrs)

When reducing the storage height, the volume available to hold water is also reduced and thereby runoff can occur more easily, as soon as the structure is full. When studying the distribution of runoff rates in figure 24, the time curve for a lower storage height (dotted line) shows that there are higher runoff rates compared to the average case. It means that for a longer period of time, compared to the average case, there will be runoff at higher rates. However, the peak flow is not changed when reducing the storage height, which is due to the fact that the storage volume is not full when the peak flow (highest rain intensity) occurs.

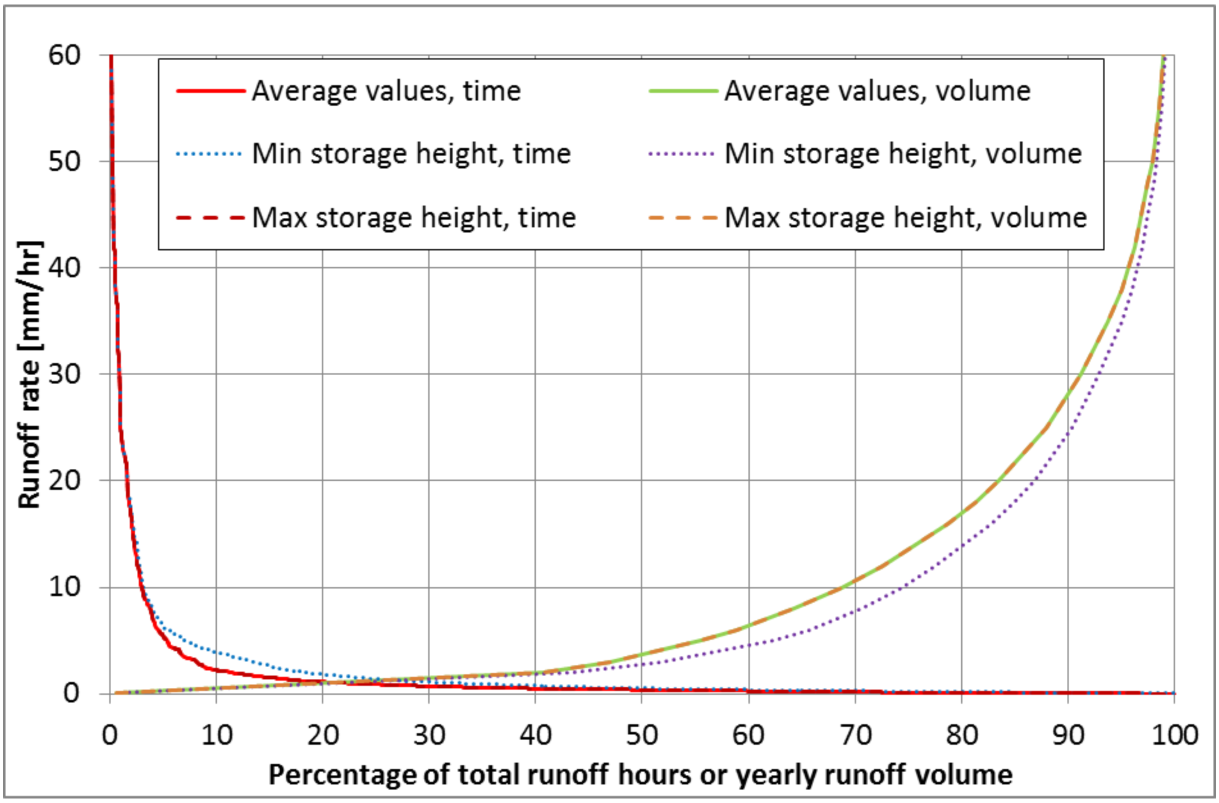

Figure 24. Comparison of the distributions of runoff rates for the average case with a storage height of 350mm, a storage height of 150mm (min storage height) and a storage height of 550mm (max storage height) for CBP. The curves are all relative to the average case.

When studying the volume curves in figure 24, it is clearly shown that an increase in storage height had no effect, which is also confirmed in table 11. This is due to the fact that the chosen storage height for the average case is already capable to deal with the applied rainfall from the time series. In other words, nothing is gained by increasing the storage height to more than average. When looking at the volume curve for a decrease in storage height (dotted line)it is shown that more of the volume occurs at lower rates than for the average case, which has to do with the fact that a rain event of low intensity can result in runoff provided that the storage volume is full. The risk of the storage volume being full is increased with a lower storage height. This can also be connected with the fact that the time with runoff is increased (see table 11), which means that runoff will occur more frequently.

4.2.4 Void ratio of storage layer

Table 12 shows that only a decrease of the void ratio has an effect for this case. Both peak flow and total runoff increased with 9%, whereas the time with runoff increased with 9hrs.

Table 12. Summary of the peak flows, total runoff and time with runoff when altering the void ratio of the storage layer.

Average void ratio SL 0.33	Peak flow [mm/hr]	Difference [%]	Total runoff [mm]	Difference [%]	Time with runoff (>0.01 LPS) [hr]	Difference [%]
Min void ratio SL 0.18	82	+9	383	+9	243	+4 (+9hrs)
Max void ratio SL 0.54	75	0	351	0	234	0

The void ratio indicates how much water the storage layer can store. By reducing it, also the storage volume is reduced. It can be seen that the peak flow is increased which is because the storage volume is full when the heaviest rain event occurs.

When studying the distribution of the runoff rates in figure 25 it can be seen that a smaller void ratio results in runoff occurring at higher rates for a longer period of time, compared to the average case. Table 12 also confirms this, since the total runoff as well as runoff hours are increased. In addition, when studying the volume curves, it can be seen that with a smaller void ratio more of the volume occurs at lower rates than for the average case, which has to do with the fact that even small rain events result in runoff if the storage volume is full. In other words, runoff will occur more frequently and at lower intensities.

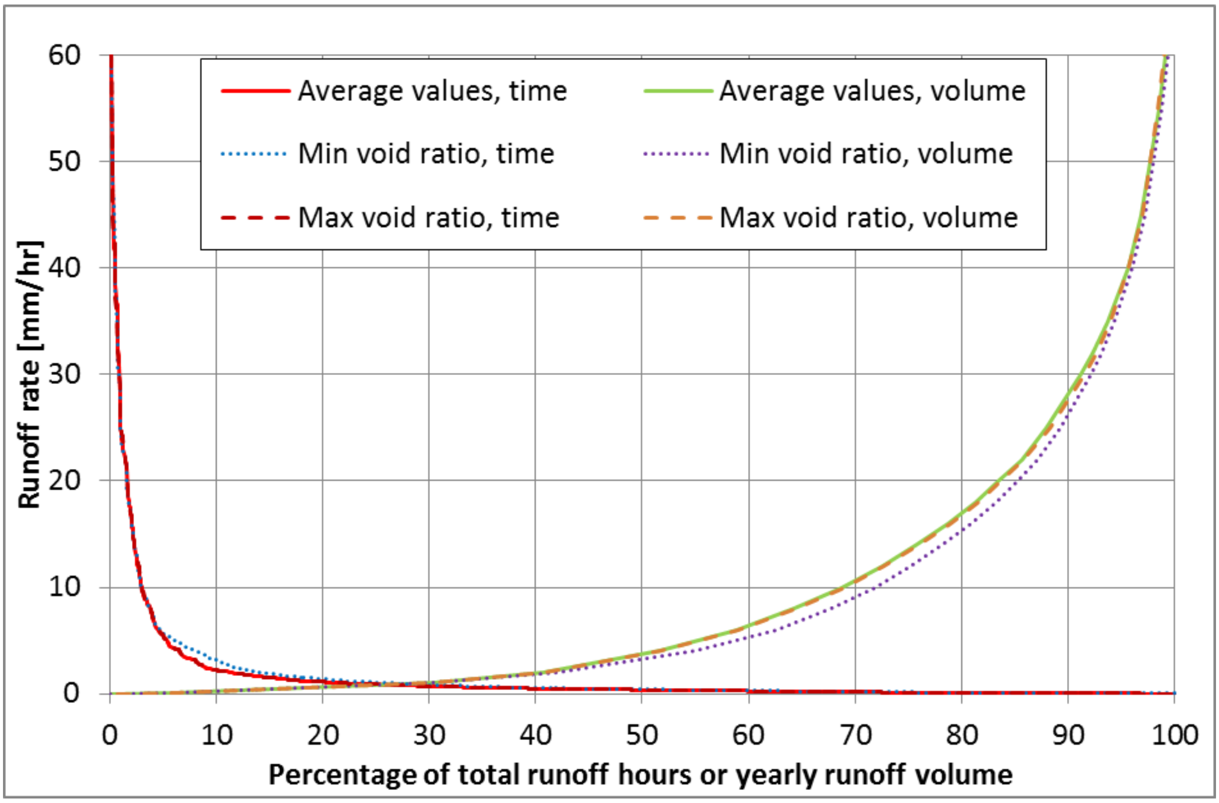

Figure 25. Comparison of the distribution of runoff rates for the average case with a void ratio of 0.33, a void ratio of 0.18 (min void ratio) and a void ratio of 0.54 (max void ratio) for CBP. The curves are all relative to the average case.

4.2.5 Conductivity of native soil

A decrease in conductivity showed an effect on all three parameters (see table 13). An increased conductivity, on the other hand only had an effect on the total runoff.

Table 13. Summary of the peak flows, total runoff and time with runoff when altering the conductivity of the native soil.

Average conductivity 0.42mm/hr (silt)	Peak flow [mm/hr]	Difference [%]	Total runoff [mm]	Difference [%]	Time with runoff (>0.01 LPS) [hr]	Difference [%]
Min conductivity 0.00042mm/hr (clay)	94	**+25**	9,389	**+2,583**	20,430	**+8,631 (+20,196hrs)**
Max conductivity 420mm/hr (sand)	75	0	310	-11	234	0

Lowering the conductivity of the native soil had by far the greatest influence on total runoff of all properties, with an increase of 2,583% compared to the average case! This is closer to a 100% impermeable surface and corresponds to only a 9% reduction of the surface runoff. The reason for the increase in runoff is due to the fact that the storage layer fills up faster than it can be drained by the native soil layer (or dry out through the surface). When studying a time series of rainfall, as in this case, it becomes very clear how the frequency of rainfall affects runoff when the conductivity of the native soil is very low. There can be runoff even during a rain event with fairly low intensity provided that there have been many rain events prior to this event. This means that the slightest rain event can result in runoff, depending on the recent rain history. In figure 26 it can be seen that more of the runoff volume occurs at low rates compared to the average case, which is due to the fact that even the slightest rain event can result in runoff if the storage volume is full.

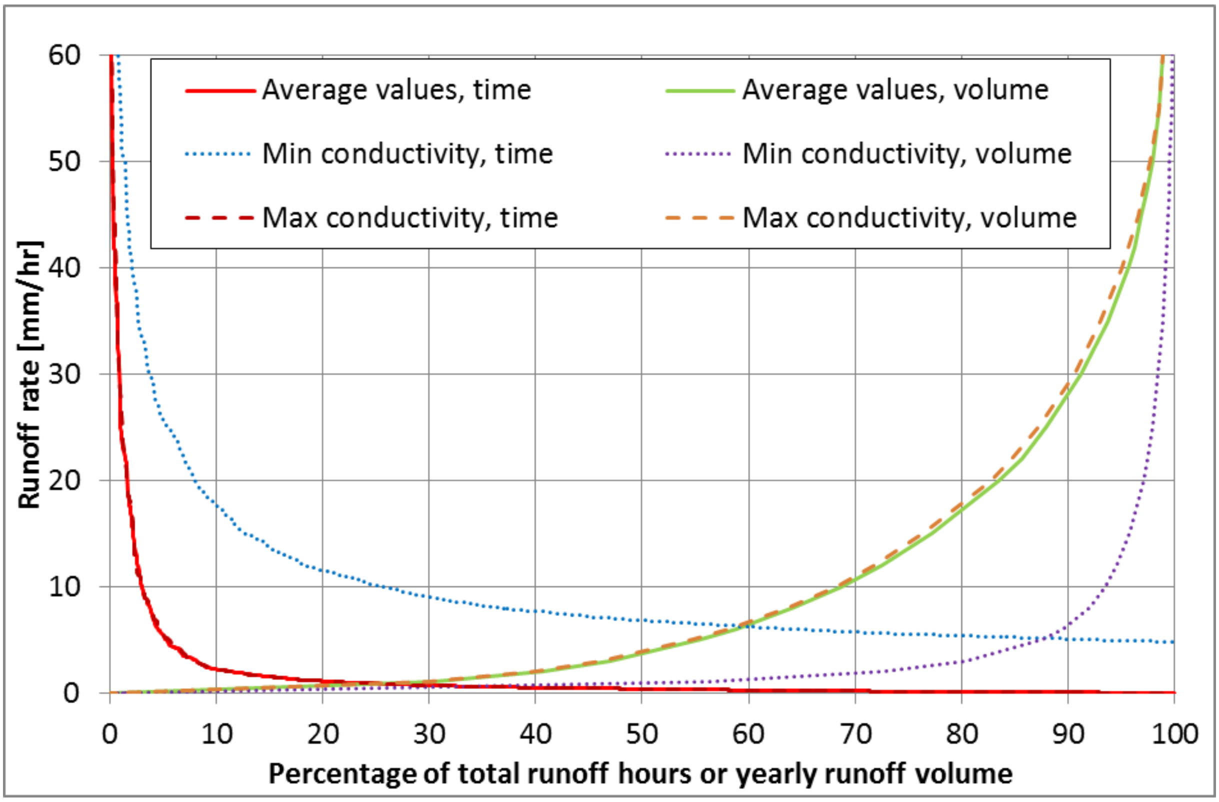

Figure 26. Comparison of the distribution of runoff rates for the average case with a conductivity of 0.42mm/hr (silt), a conductivity of 0.00042mm/hr (clay)(min conductivity) and a conductivity of 420mm/hr (sand)(max conductivity) for CBP. The curves are all relative to the average case.

Also, as stated previously, the peak flow increases with low conductivity of the native soil layer, which will occur if the storage layer becomes full during (or right before) the heaviest rain event.

When studying the distribution of runoff rates with respect to runoff time for a low conductivity (dotted line), it can be seen that there are higher runoff rates for a longer period of time than for the average case, which means that the storage volume is full for a longer period of time, therefore there will be a longer duration of runoff with higher rates. The dotted line also shows that the time with runoff is much longer than for the average case, which is the reason why the dotted line continues beyond 100% in figure 26.

When studying the effects of an increased conductivity, table 13 shows that it only has effect on the total runoff volume, where it was reduced with 11%. With a higher conductivity the storage volume drains faster and is not full when the average volume is full, thus the rain can drain rather than becoming runoff. The reason why the curve for a high conductivity in figure 26 (dashed line), showing the distribution of runoff rates with respect to the runoff volume, lies above the average curve is not because it results in higher runoff rates in total, but because a rain of higher intensity is usually needed in order to produce runoff, and the total runoff for the high conductivity case is less than for the average case. In other words, a larger portion of the runoff rates occur at high rates in relation to the total volume for a high conductivity compared to a lower conductivity.

5 Summary and Conclusions

In the following chapter the main findings will be presented along with recommendations on how to apply them in common practices today. The closing section suggests possible future investigations on the subject.

5.1 Peak runoff

When evaluating the influence of the number of infiltration classes of CBP on peak runoff, it was found that the use of only 1 class will overestimate the performance of CBP and consequently result in an underestimated peak flow. Instead, the simulations imply that 5 classes should be used, since they produce almost identical results as 10 classes. The error would only be 1%.

When studying how peak runoff was influenced by adding 30% CBP (in 5 classes) to an initially impermeable area, it was seen that it could reduce the peak flow by approximately 9%. Moreover, when an area of 3ha was replaced entirely with CBP (in 5 classes) the simulations suggest that the peak flow can be reduced by as much as 28%! Since the previous paragraph implies that 5 classes of CBP should be used to produce satisfying results for peak flows, the results obtained are relevant.

The four vertical parameters that showed the biggest effect on peak flow were low initial losses (+17%) as well as high initial losses (-17%), a steep slope of the surface (+31%) or a low conductivity of the native soil layer (+25%). One parameter that showed very little influence on the peak runoff was to reduce the slope (-1%).

5.2 Runoff volume

The total runoff volume was decreased by approximately 30% for the case with 30% CBP. Moreover, when replacing 3ha of impermeable surface solely with CBP (of 5 classes), the runoff volume was reduced by as much as 97%!

The difference between the number of classes was not very distinct, however, using a resolution that is too rough will result in an overestimation of the infiltration performance. When using 10 classes, the reduction in total runoff was only 27% whereas for 1 class it was 30%. Both 3 and 5 classes gave a reduction of 29%. In other words, when studying the total runoff, 10 classes give the best approximation. The error would be a little over 3% if 3 or 5 classes are used and 4% if 1 class is used.

The following simulations for vertical parameters were only run with 5 classes, even if this was shown to produce a slight error. Nevertheless, they give an indication of how the properties of a CBP-structure affect runoff.

The four vertical parameters that showed the most significant effect on total runoff were low initial losses (+72%) as well as high initial losses (-41%), reduced storage height (+26%) and a low conductivity (+2,583%).

5.3 Runoff duration

When adding 30% CBP to an area of 10ha, the time with runoff was reduced by 2.55hrs, irrespective of how many classes were used.

The four vertical parameters (for 5 classes of CBP) that showed the most significant effect on the runoff duration were low initial losses (+31%) as well as high initial losses (-47%), reduced storage height (+34%) and a low conductivity (+8,631%).

5.4 Distribution of runoff rates

When studying how the distribution of runoff rates was changed by adding 30% CBP to the area, it was seen that the rates were lowered irrespective of the applied number of classes. In other words, 30% CBP resulted in a larger time ratio with lower rates as well as a larger volume ratio occurring at lower rates, compared to an impermeable surface.

The distribution of runoff rates with respect to time was identical for all number of classes. However, the runoff rates with respect to volume for 1 class were not identical to 10 classes (which are assumed to represent the most accurate result). This implies that a finer resolution should be used. When comparing the output from all of the different classes, it was seen that 3 classes would give sufficiently detailed results.

The following results from the vertical analysis with 5 classes, shows sufficiently detailed results, using the assumption that 3 classes provides sufficient results as well.

The variations of the vertical parameters that had an effect on the distribution of runoff rates (for 5 classes of CBP) were an increase or decrease in the initial losses, an increase or decrease in the surface slope, a reduction of the storage volume (storage height or void ratio), and a reduction in the conductivity of the native soil layer. However, reducing the conductivity had the by far greatest influence on the CBP-structures' performance, where the time ratio with higher runoff rates increased, as well as the frequency of runoff. The runoff frequency increased since runoff occurred even during low intensity rain events because of the storage volume being full, due to insufficient drain capacity from the native soil.

The general idea for the case of a lower conductivity or a smaller storage volume was that runoff occurred even at low intensity rain events, resulting in a larger ratio of the runoff volume occurring at low rates. It also resulted in longer durations of higher runoff, since rain events of higher intensities would produce more runoff than for the average case.

5.5 Recommendations

The results from this study imply that when studying runoff from CBP surfaces it would be preferable to use 5 infiltration classes, if the peak flow is the most important factor. However, if the total runoff is more important, 10 classes will produce a more reasonable result. Nevertheless, the difference in peak flow, total runoff or time with runoff between the number of classes does not appear to be very great. If 1 class is used the error will be approximately 5% for the peak flow and 4% for the runoff volume. When using 3 or 5 classes the error will be no more than 4% or 1% for the peak flow and 3% for the runoff volume.

When studying the time with runoff, there was no difference between the number of classes, which is why 1 class could be used to get an idea of the performance of CBP with respect to runoff time.

The biggest effect CBP has in general is reducing the distribution of runoff rates, reducing peak flow and total runoff. Since CBP has shown to contribute a great deal to reducing surface runoff, more effort should be put in to designing structures of this kind not only to be sufficient for the applied traffic load, but also to store water. The design height and the void ratio of the storage layer should be chosen with respect to both of these factors. In the United Kingdom, this is already being done (Interpave 2008).

In addition, blocks with a rough surface should be used since this would increase the depression storage. The initial losses showed to have great effect on the overall performance of the CBP-structure, which is why it can be very beneficial to use block paving of this kind.

Conductivity of the native soil had an even greater effect on runoff, why it would be preferable to have a drainage pipe when the conductivity ranges from clay to silt. This could reduce all parameters of runoff; peak, volume, time and frequency for a long-term simulation.

One must note that the absolute values obtained from these situations only apply for the time series used in this specific case; nevertheless, it shows how important it is to study the entire structure of CBP, since the vertical properties show a great variety in both appearance and resulting runoff.

5.6 Further investigations

The simulations in this report have only been analysed with long-term rain data, however it would be interesting to make a similar analysis of an extreme event to see if the model will give similar indications for the number of classes. It would also be interesting to see the required storage volume.

Two parameters that have been neglected in this study are snowfall and groundwater. Nevertheless, it would be interesting to add groundwater as a parameter and also to see how snowfall would influence the results.

Moreover, it would be interesting to make a similar analysis for a real-world scenario and compare the model to this in order to validate the results further.

A next step could be to investigate how the runoff results obtained in this study affect the overflow activity of combined sewers.

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Appendix I – Determining void ratio from effective porosity

In order to calculate the void ratio, the available volume to store water is needed, i.e. the effective porosity. The effective porosity can be approximated by the specific yield[1]. The grain size for joints in structures with block pavement has been said to be approximately 2mm([2]). Figure 27([3]) shows that this corresponds to a specific yield of approximately 30%.

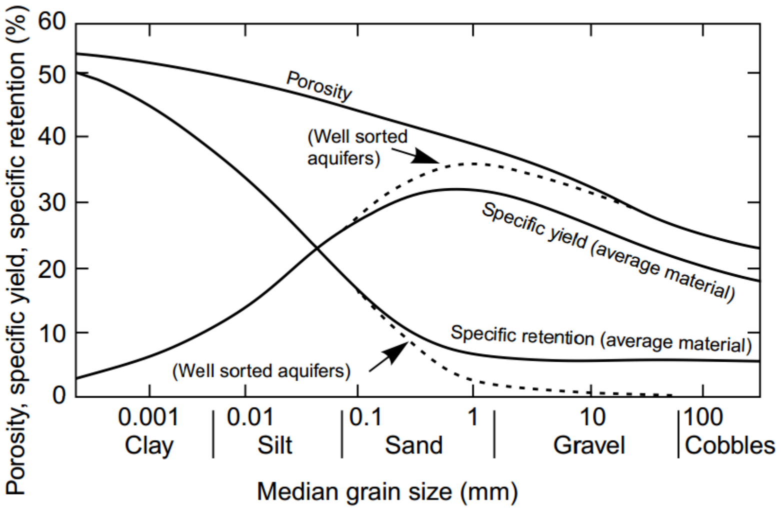

Figure 27. Relationship between median grain size and water-storage properties of alluvium[3].

The porosities for the simulations were estimated with reference to the figure above. The curve specific yield (average material) was used since this shows the capability to hold water. The porosities used in the model were 15% (silt), 25% (sandy silt) and 35% (sand), which translates to 0.18, 0.33 and 0.54 for the void ratio. It was calculated according to the following formula obtained from the software SWMM

$$Porosity = \frac{VoidRatio}{1 + VoidRatio} \quad \rightarrow \quad VoidRatio = \frac{Porosity}{1 - Porosity}$$

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Appendix II – Hydraulic conductivities for different soil types

Figure 28 from Heath (1983)[1] shows the (saturated) hydraulic conductivity for some rock and soil types.

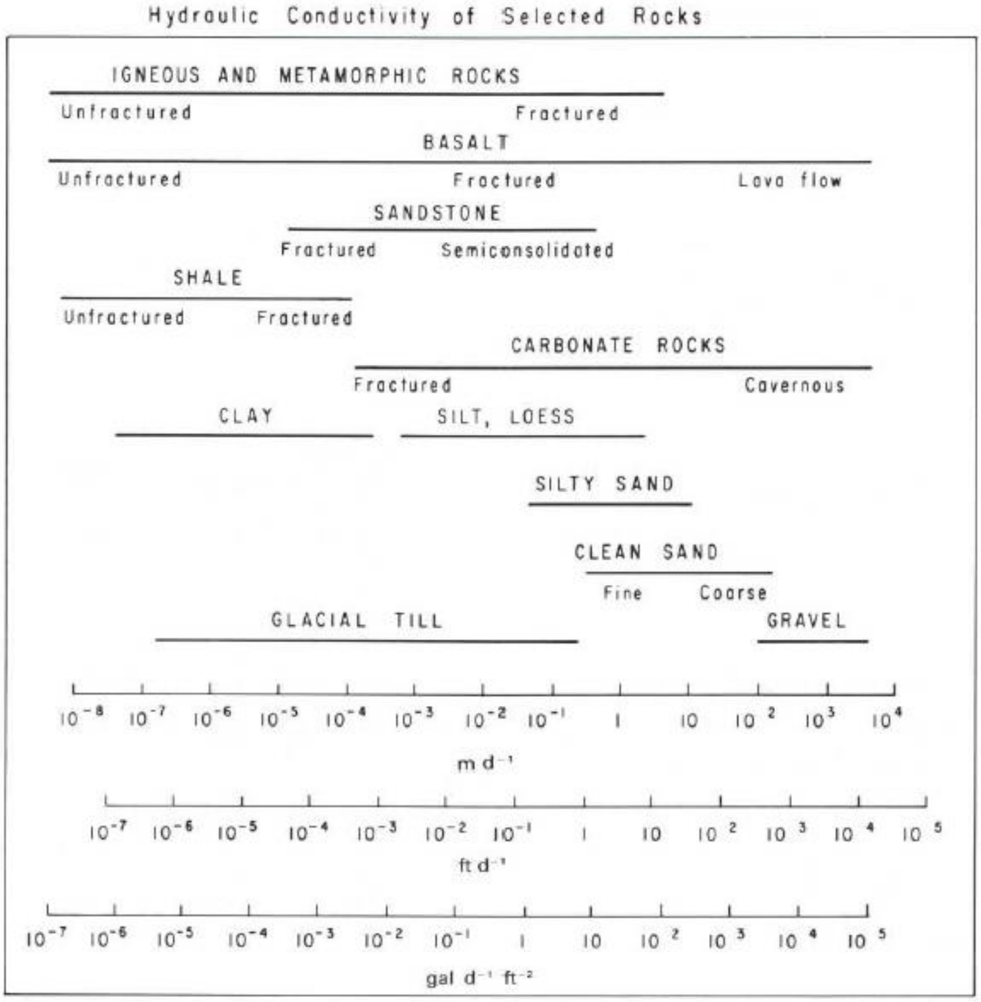

Figure 28. Saturated hydraulic conductivities for some rock and soil types.

Saturated hydraulic conductivity

	m/day	mm/hr
Clay	10^{-8} - 10^{-3}	4.167×10^{-7} - 0.04167
Silt, loess	0.001 - 10	0.04167 - 416.7
Silty sand	0.1 - 10	4.167 - 416.7
Clean sand	1 - 100	41.67 - 4167
Gravel	100 - 10000	4167 - 4.167×10^{5}

[1] Heath, R. C. (1983). Basic ground-water hydrology, U.S. Geological Survey Water-Supply Paper 2220. Available at: http://pubs.usgs.gov/wsp/2220/report.pdf [2013-06-20]

Appendix III – Calculation of evaporation rate for CBP

Figure 29[1] below was used to calculate the average evaporation rate for the study area used in this report. Area 2.1 in the table is constructed according to German standards (DIN EN-standard) for pervious concrete blocks with an opening ratio of 5.9% and a pavement thickness of 80mm. The average evaporation rate (Et_s) was estimated for different weather conditions during warm and cold days; rainy, drying and dry.

			Warm days			Cold days		
			Rainy	Drying	Dry	Rainy	Drying	Dry
Area 2.1	Measuring period	date	27.05.08-29.05.08	29.05.09-30.05.09	19.09.08-21.09.08	14.11.09-16.11.09	23.10.09-24.10.09	18.03.09-20.03.09
	Average *J*	°C	19.40	24.2	17.5	9.2	12.0	11.0
	Min./max. *J*	°C	12.8/28.1	16.5/29.6	7.5/26.4	5.5/11.7	8.2/17.4	3.0/19.3
	Average *rF*	%	53.3	35.0	53.6	92.1	82.2	49.0
	Average Et_s	mm/h	0.057	0.014	0.005	0.003	0.013	0.005
	Min/max Et_s	mm/h	0.013/0.147	0.005/0.04	0/0.181	0/0.023	0/0.032	0/0.014
Area 2.2	Measuring period	date	27.05.08-29.05.08	29.05.09-30.05.09	19.09.08-21.09.08		In measuring	
	Average *J*	°C	19.40	24.2	17.5			
	Min./max. *J*	°C	12.8/28.1	16.5/29.6	7.5/26.4			
	Average *rF*	%	53.3	35.0	53.6			
	Average Et_s	mm/h	0.037	0.019	0.006			
	Min/max Et_s	mm/h	0/0.087	0.012/0.034	0/0.189			
	Et_{cum} % of area 2.1	%	65.2	73.2	108.4			
Area 2.3	Measuring period	date	09.06.09-11.06.09	12.06-13.06	04.08.09-06.08.09	29.09.08-30.09.08	01.10.08-02.10.08	03.10.08-05.10.08
	Average *J*	°C	18.2	22.6	32.1	12.7	12.0	10.7
	Min./max. *J*	°C	12.0/26.6	14.3/29.5	20.1/39.8	9.3/18.4	8.2/17.4	5.4/15.4
	Average *rF*	%	72.2	38.4	31.4	85.6	82.2	74.8
	Average Et_s	mm/h	0.046	0.046	0.021	0.013	0.061	0.025
	Min/max Et_s	mm/h	0/0.307	0.006/0.104	0.026/0.045	0/0.05	0/0.275	0/0.178
	Et_{cum} % of area 2.1	%	101.7	144.8	-	117.1	158.4	159.4
Area 2.4	Measuring period	date	20.06.09-21.06.09	22.06.09-23.06.09	24.06.09-26.06.09	14.03.09-15.03.09	16.03.09-17.03.09	18.03.09-20.03.09
	Average *J*	°C	19.6	23.7	24.1	6.3	9.5	11.0
	Min./max. *J*	°C	13.7/27.1	13.7/27.1	15.5/34.0	4.9/8.0	2.9/18.7	3.0/19.3
	Average *rF*	%	56.6	46.3	52.9	90.7	57.2	49.0
	Average Et_s	mm/h	0.058	0.019	0.018	0.008	0.012	0.009
	Min/max Et_s	mm/h	0.006/0.184	0.004/0.036	0.001/0.035	0/0.021	0/0.046	0/0.033
	Et_{cum} % of area 2.1	%	117.3 % of $Et_{cum\,area2.5}$	76.5 % of $Et_{cum\,area2.5}$	112.9 % of $Et_{cum\,area2.5}$	76.1	130.6	161.1

Figure 29. Measured evaporation rates during days with different weather conditions.

The area used in the simulations in this report is similar to area 2.1 (opening ratio and pavement thickness), why this area was used to estimate the evaporation rate. First an average was calculated since the simulations in this study are run for a time series with varying weather conditions.

Average evaporation rate (Et_s) for pervious concrete blocks:

$(0.057+0.014+0.005+0.003+0.013+0.005)/6 \approx 0.016$ mm/hr

Starke et. al (2010) states that the evaporation rate for permeable areas is 16% higher than the evaporation rate for impermeable areas. Since the majority of the area in this study is impermeable (>94%), the evaporation rate was reduced accordingly:

Average evaporation rate for impermeable surface (corresponds to at least 94% of the area):

$0.016/1.16 = 0.014$ mm/hr → $0.014*24 =$ <u>0.33mm/day</u>

[1] Starke, P., Göbel, P., Coldeway, W.G. (2010). Effects of different water-permeable pavement designs on evaporation rates. Novatech

Appendix IV – Histogram of rain events

Figure 30 shows the distribution of precipitation recorded between 1977-1992 in Holzgerlingen, Germany.

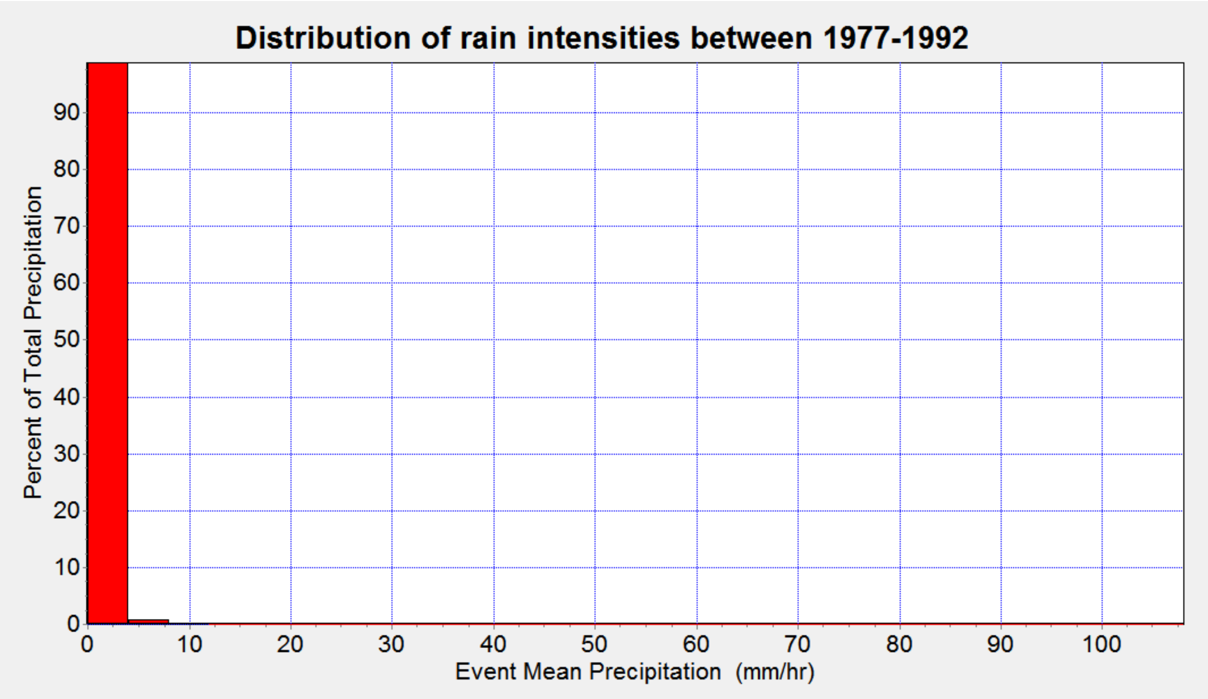

Figure 30. Distribution of rain intensities between 1977-1992 in Holzgerlingen, Germany.