Lise Berit Rugland

A Stochastic Modelling Technique for a Multi-Component Stormwater Management Facility

Master's thesis in Civil and Environmental Engineering
Supervisor: Sveinung Sægrov
June 2019

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Description of master thesis

TITLE:	**A stochastic modelling technique for a multi-component stormwater management facility**
SUBJECT:	**Stormwater modelling**
CANDIDATE:	**Lise Berit Rugland**
SUPERVISORS:	**Sveinung Sægrov (*Norwegian University of Science and Technology*)** **Ekaterina Sokolova (*Chalmers University of Technology*)** **Per Møller-Pedersen (*Storm Aqua AS*)**
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Background

Climate change and urbanization have resulted in an increase in runoff, causing a growing interest in well-functioning stormwater management systems. Efficient models to demonstrate the performance of sustainable urban drainage systems (SUDS) is of high interest to researchers, consultants and municipalities. Information extracted from such models are used in decision-making processes around the world, in a growing field of storm- and wastewater management. Modern drainage systems are increasing in complexity due to an expanded toolbox of available stormwater management solutions; introducing additional uncertainties in hydrological models. Quantifying a drainage system's performance is challenging as simulations often are run based on incomplete data sets, lacking information about parameters, and lacking resolution in time and space. Despite the wide range of uncertainties included in parameterization and conceptualization of drainage systems, deterministic methods are still very popular in the engineering practice due to its simplicity. While being computationally more efficient than continuous simulations, stochastic models have the potential to overcome major shortcomings to deterministic models and provide more robust and holistic estimations. Uncertainties of key input variables are inherited and represented in the final output, providing contractors and decision-makers with a confidence interval of expected performance. This study is testing the applicability of a stochastic model for a complex stormwater management pilot area.

The presented study is in collaboration with the Klima 2050 project (ww.klima2050.no), from which the partner company Storm Aqua has contributed by providing data and documentation.

Thesis format

Traditionally, a master thesis at NTNU is submitted as an extensive report on the chosen topic of study. However, upon the wish of the candidate and supervisor from NTNU, this master thesis is written in attempt to fulfill the requirements of a research article. The manuscript is rather extended for the purpose of the thesis submission and includes additional figures.

Sammendrag

Formålet med denne oppgaven er å teste applikasjonen av en hendelses-basert stokastisk modell for et fler-komponent overvannshåndterings system i Sørvest-Norge. Området har både infiltrasjonsflater og konvensjonelle komponenter. Triangulære hydrografer ble generert basert på en probabilistisk regn-til-avrenning modell og en estimert konsentrasjonstid. Hydrografene ble brukt som input til en kaskade av magasinrutinger. Magasinene er kummer med åpen bunn, hvor tilgjengelig volum er diktert av grunnvannstand. Startvolumet er definert av sannsynlighetsfordelingen for grunnvannstand, og implementert i modellen som en stokastisk variabel. Til slutt, ble sannsynlighetsfordelinger av maks utløp fra alle kummer beregnet. Resultatene fra casestudiet er diskutert i kontekst av modell oppsettet og parametersettingen av input variabler. Artikkelen foreslår tre hovedbegrensninger mot implementeringen av en stokastisk metode for et fler-komponent overvannshåndterings system: Modellene er ofte stedsspesifikke; den beregningsmessige effektivitet blir redusert når systemet har mange komponenter; og fordelene med resultat formatet fra en stokastisk modell er begrenset når systemet fungerer optimalt. Funnene i dette studiet påpeker nyttige forbehold som bør tas når man velger modelleringsteknikk for komplekse avrenningssystemer. Kombinering av konvensjonelle dreneringssystemer og lokal overvannsdisponering kommer til å bli mer vanlig i kommende år. Derfor er det av høy interesse å utforske forbedrede og mer effektive modelleringsalternativer for bruk i ingeniør praksis.

Prolog

This report is submitted for 30 ECTS credits for the course *"TVM4509 Water supply and wastewater systems, Master's thesis"* at the Norwegian University of Science and Technology (NTNU) during spring semester 2019. The thesis is submitted in partial fulfillment of the requirements for a Nordic Master of Science in Environmental Engineering, after following the study track *"Urban Water"* at Chalmers University of Technology and NTNU. The master thesis is a continuation of a preliminary study of the topic during fall 2018 in the 7.5 ECTS credits course: *"TVM4510 Water and wastewater engineering, Specialization project".* The framework for this study was provided by partner institutions from the Klima 2050 project: Storm Aqua (Skjæveland Group), SINTEF and NTNU. The scope of the study involves modelling the stormwater management facility at Stangeland Arena to evaluate the system performance and the applicability of the chosen modelling technique. The choice of topic was inspired by challenges met while producing an evaluation report on the implementation of SUDS as a summer intern in the water and wastewater division in Stavanger municipality. The idea of a stochastic approach to overcome these challenges was initiated from knowledge obtained during the course "*Risk assessment and decision support"* at Chalmers during spring 2018. I would like to express my gratitude to my supervisors Sveinung Sægrov, Ekaterina Sokolova, and Per Møller-Pedersen for providing support and feedback, participating in discussions, and for greeting my ideas with enthusiasm throughout the thesis work. I would also like to thank:

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Trondheim, June 11th, 2019

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A stochastic modelling technique for a multi-component stormwater management facility

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Abstract

This paper aims to test the application of an event-based stochastic model for a multi-component stormwater management facility located in the southwest of Norway. The facility contains both infiltration surfaces and conventional components. Triangular hydrographs are derived using a probabilistic rainfall-runoff model and an estimated time of concentration. The hydrographs are used as input to a cascade of storage-indication reservoir routings. Open-bottomed manholes are considered to be the reservoirs, for which the available storage level is dictated by the groundwater level. Initial storage level is defined by the probability distribution of the groundwater data and implemented in the model as a stochastic variable. Finally, probability distributions of peak discharge from all manholes are derived. The results of the case study are discussed in context of the model setup and parameterization of input variables. This paper suggests three main limitations to the implementation of a stochastic approach for multi-component drainage systems: Models are often highly site-specific; computational efficiency is reduced when the system contains several components; and the benefits of the output structure of a stochastic model are limited if the system is performing optimally. The findings in this study provides valuable considerations to have in mind when selecting a modelling technique for more complex drainage systems. Combining conventional and sustainable urban drainage systems is likely to become more common in following years. Therefore, it is of interest to explore improved and more efficient modelling alternatives for use in common engineering practice.

Keywords: Stormwater modelling, Sustainable urban drainage system, Runoff event analysis, Reservoir routing, Groundwater drainage

1 Introduction

Climate change and urban development pose several environmental and infrastructural challenges. These include higher flood risk, increased pollutant transport, increased streambed erosion and reduced groundwater recharge (Liu et al., 2014). Concerns over damage to properties, degradation of water quality and ecosystems are increasing the demand for incorporating sustainable urban drainage systems (SUDS) in urban development. SUDS are implemented to preserve predevelopment hydrology by keeping the natural elements of storage, infiltration and groundwater recharge (Liu et al., 2017). Combining natural elements and conventional components are increasing the complexity of modern drainage systems. This points toward a significant commercial interest to explore modelling alternatives to evaluate the performance of such multi-component systems. For the purpose of this paper, a multi-component drainage system is defined as a drainage facility including a variety of both conventional components and SUDS. The decision to implement SUDS is often highly influenced by local groundwater conditions and infiltration capacity. This paper attempts to incorporate the effect of changing groundwater level on the system performance. An event-based stochastic stormwater model is applied to a complex stormwater management facility with shallow groundwater drainage. Despite the extensive research carried out in this field, there seems to be limited attention paid to the use of stochastic modelling techniques for multi-component systems.

Peak discharge rates and runoff volumes estimated with hydrologic models have traditionally been used in planning and design of stormwater management facilities. The most widely implemented models applied in engineering practices are lacking both efficiency and holistic outputs. Stormwater models consist of representations of both hydrologic and hydraulic processes. There are three main approaches to urban stormwater modelling (Adams and Papa, 2000; Chen and Adams, 2007; Loveridge and Rahman, 2018): (1) the design storm event approach, which is based on design peak flow and hydrograph estimation methodology; (2) continuous simulation approach using continuous time series and an empirical derivation of runoff response; (3) derived probability distribution or stochastic approach computing the statistics of a system output from rainfall input.

The design storm approach has traditionally been used to design stormwater management facilities. This method is an efficient estimate, but it lacks insight in possible scenarios and uncertainties inherited from the conceptualization of the system and input variables. The design storm event approach uses fixed input values for rainfall intensity, duration and losses, and assumes that a design storm hyetograph and its resulting runoff hydrograph have the same, known return period or frequency (Loveridge and Rahman, 2018). It has been argued that such unique frequencies do not exist (e.g. Adams and Howard, 1986). Peak runoff can be generated by a variety of combinations of rainfall and catchment characteristics, questioning the validity of the design storm approach (Adams and Howard, 1986; Mirfenderesk et al., 2013). Other concerns include that the approach does not account for antecedent moisture conditions (Chen and Adams, 2007; Guo, 2018) and potential variability of storm pattern and dry-weather processes like recovery of soil infiltration (Adams and Papa, 2000). Using design storms without appropriately choosing durations and hyetographs, could result in peak discharges differing by 40-50 % (Guo, 2011). Point rainfall cannot represent the typical variation in rainfall intensity across a catchment, as the spatial variation of rainfall intensity will affect the shape of the runoff hydrograph (Adams and Howard, 1986). This issue may result in an uneven dimensioning of drainage systems, leaving two categories of suitable approaches: continuous simulation approach and the analytical probabilistic approach (Arnell, 1978; Balistrocchi et al., 2013; Guo, 2001; Wang and Guo, 2018).

Continuous simulation methods have proven to simulate observations with high accuracy; however, it is computationally expensive for use in preliminary system analyses (Guo et al., 2018). These models estimate generated flow through simulation of the wet and dry cycles of a catchment by employing long-term rainfall records (Boughton and Droop, 2003). Continuous models can thus recognize the cumulative effects of storms, where time-variant mathematical relationships are mimicking hydrologic processes (Adams and Papa, 2000). Continuous models are considered to be the most reliable as they can account for all runoff producing variables. Both historic time series or synthetic time series may be applied and run with high resolution. The main drawbacks from continuous simulations are that the data requirements are extensive, and it can be time-consuming to extract detailed system statistics from the simulation outputs (Chen & Adams, 2007).

Recently developed analytical probabilistic stormwater models (APSWM) have demonstrated to be a computationally efficient and compact alternative to continuous simulations (e.g. Guo and Adams, 1998a; Adams and Papa, 2000; Chen and Adams, 2007; Hassini and Guo, 2017), while eliminating some of the greatest shortcomings to the traditional design storm approach (e.g. Guo and Zhuge, 2008; Mirfenderesk et al., 2013; Hassini and Guo, 2017; Loveridge and Rahman, 2018). Benjamin and Cornell (1970) showed that the probability distribution of a dependent random variable may be derived from related independent random variables using functional relationships. Since then, there has been an increase in application of probabilistic approaches, also in water resources engineering. Eagleson (1972) was the first to use a statistical meteorological data analysis to provide the basis of inputs to an analytical probabilistic model for flood frequencies. Probability distributions were fitted to rainfall data and used to produce a probability distribution of peak flow based on a relationship between rainfall and catchment parameters. Eagleson (1978) further discussed storm properties and their mathematical representations and introduced the options of using a two-parameter gamma distribution for rainfall depths and representing interarrival times as a Poisson process. Howard (1976) first employed an analytical probabilistic approach to stormwater control facilities for modelling storage and treatment plant overflows. Guo and Adams (1998a) developed an event-based probabilistic model for surface runoff volume using exponential probability distributions for rainfall characteristics, which was further extended to derive a model for peak discharge rate by incorporating an estimated time of concentration (Guo and Adams, 1998b). Guo and Adams (1999a;1999b) proposed an analytical probabilistic approach to model detention facilities, by obtaining a routed probability distribution of peak outflow rate from a flood control facility.

APSWMs have been demonstrated to be practical for design and performance estimations for multiple stormwater management systems, including storage facilities (Bacchi et al., 2008; Balistrocchi and Bacchi, 2011; Guo and Baetz, 2007; Balistrocchi et al., 2017), green roofs (Zhang and Guo, 2012a), rain gardens (Zhang and Guo, 2012b) and permeable pavements (Guo et al., 2012; Zhang and Guo, 2014a). The application of APSWM has been extended to practical design cases with multiple sub-catchments (Quader and Guo, 2006), appropriately modelling effects of multiple detention ponds and flood peak attenuation effects of channel reaches (Guo and Zhuge, 2008), and routing reservoir sizing of both on- and off-line reservoirs (Balistrocchi et al., 2013). Most analytical probabilistic models still require simplifying assumptions about initial water content in reservoirs (Adams and Papa, 2000; Wang and Guo, 2018). A stationary probability distribution of initial storage has been concluded to be difficult to obtain (Chen and Adams, 2005; Zhang and Guo, 2014b), resulting in the two common assumptions that the reservoir is either full at the beginning of the preceding dry period (Guo and Baetz, 2007; Howard, 1976; Lognathan and Delleur, 1984); Zhang and Guo, 2012b) or empty at the end of the preceding dry period (Bacchi et al., 2008; Balistrocchi et al., 2009, 2013; Zhang and Guo, 2014b). Although challenging, a stationary probability distribution of initial capacity can in theory can be obtained (Chen and Adams, 2005; Zhang and Guo, 2014b). The assumption that storage is either full or empty at the beginning of a random dry period will lead to some level of under- or overestimation of performance (Wang and Guo, 2018). To overcome this limitation, Wang and Guo (2018) derived an analytical stochastic model (ASM) to obtain the probability density function (PDF) of long-term average storage level from rainfall characteristics.

The aim of this paper is to test the applications and limitations of an event-based stochastic modelling technique for a drainage facility consisting of multiple infiltration and detention components. The main goal of applying a stochastic approach is to achieve a comprehensive analysis of the system's performance, while both utilizing long-term meteorological data and incorporating hydrologic, hydraulic and design parameters in an efficient manner. In order to address the aim, a procedure consisting of three main steps was completed for the study area. First, a meteorological analysis was conducted on continuous precipitation data and used as input in a rainfall-runoff transformation. Second, the peak runoff volume was extracted and used to create multiple triangular hydrographs, which in turn were used as input to a cascade model for the underground detention components. The system is in dynamic interaction with a shallow groundwater aquifer; thus, it was hypothesized that the groundwater level affects the performance of the system. Initial groundwater level was included as a stochastic input variable. The distribution of initial groundwater level was determined directly from continuous groundwater data. Storage-indication reservoir routing was used to obtain the peak discharge from the detention volumes. Finally, different scenarios were run to test model applicability and system performance. The model was programmed using MATLAB R2017a.

This paper addresses the following research questions:

- How can such multi-component system be conceptualized for this procedure?
- How can initial groundwater level be implemented as a stochastic variable?
- Can a stochastic approach be considered an efficient modelling technique for preliminary analyses of complete drainage systems?

2 Material and methods

A scoping study (Arksey and O'Malley, 2005) was conducted using the online search engines Google Scholar, Oria and EBSCO Host to gain an overview of the application of analytical probabilistic models for stormwater drainage systems. Backward snowballing according to the prescriptions of Wohlin (2014) was used on relevant articles to retrieve the pioneering research in this field (e.g. Benjamin and Cornell, 1970; Howard, 1976; Eagleson 1972;1978; Adams and Papa, 2000; Guo and Adams, 1998a;1998b; Adams and Papa, 2000). Forward snowballing (Wohlin, 2014) was then used to find advances and more recent applications of the probabilistic rainfall-runoff transformations. References explaining the early development of the probabilistic stormwater models were studied in depth, while more recently published articles were studied more briefly with the intention of grasping the advancements in methodologies. Lastly, an author-oriented literature search was conducted on researchers that are perceived to be leading the development of this research field. In particular, the work of Yiping Guo has proved of significant importance to the rainfall-runoff transformation reported on in this paper.

2.1 The study area

The study area was constructed as a full-scale pilot facility for stormwater management and is located in the southwest of Norway. The local climate is coastal and temperate, with a high annual precipitation volume. The surface area of the catchment consists of an indoor soccer facility of plastic cladding material, an infiltration trench along the eastern wall and a parking lot of permeable interlocking concrete pavement (PICP), adding up to a total area of 5970 m^2 (Figure 1). The largest parking area has a 5 ‰ slope towards a shallow, egg-shaped stormwater pipe (ESSP) that has a telescopic connection to open surface grids. The ESSP is of standard dimensions as described by Gill (1987), and is intercepted perpendicularly by 9 drainpipes with open, downward-facing grids to distribute water over a greater area and facilitate more infiltration. Pipes and slot drains are collecting remaining runoff, leading water to 5 open-bottomed infiltration manholes. All excess water drains towards the northeastern corner of the site, where flow is measured before discharged through an emergency outlet. There is a rain gauge and a groundwater sensor located in the southeastern corner of the site, and an additional groundwater sensor in manhole 3 (Figure 1). Continuous data of one-minute and one-hour resolution have been logged at the site since it was constructed in October 2017. Infiltrated water is drained by a shallow moraine aquifer (~80 cm below the surface), which is observed to be highly responsive to rainfall events. Infiltration tests performed by contractors in adjacent moraine deposits have revealed that infiltration rate varies greatly over short distances.

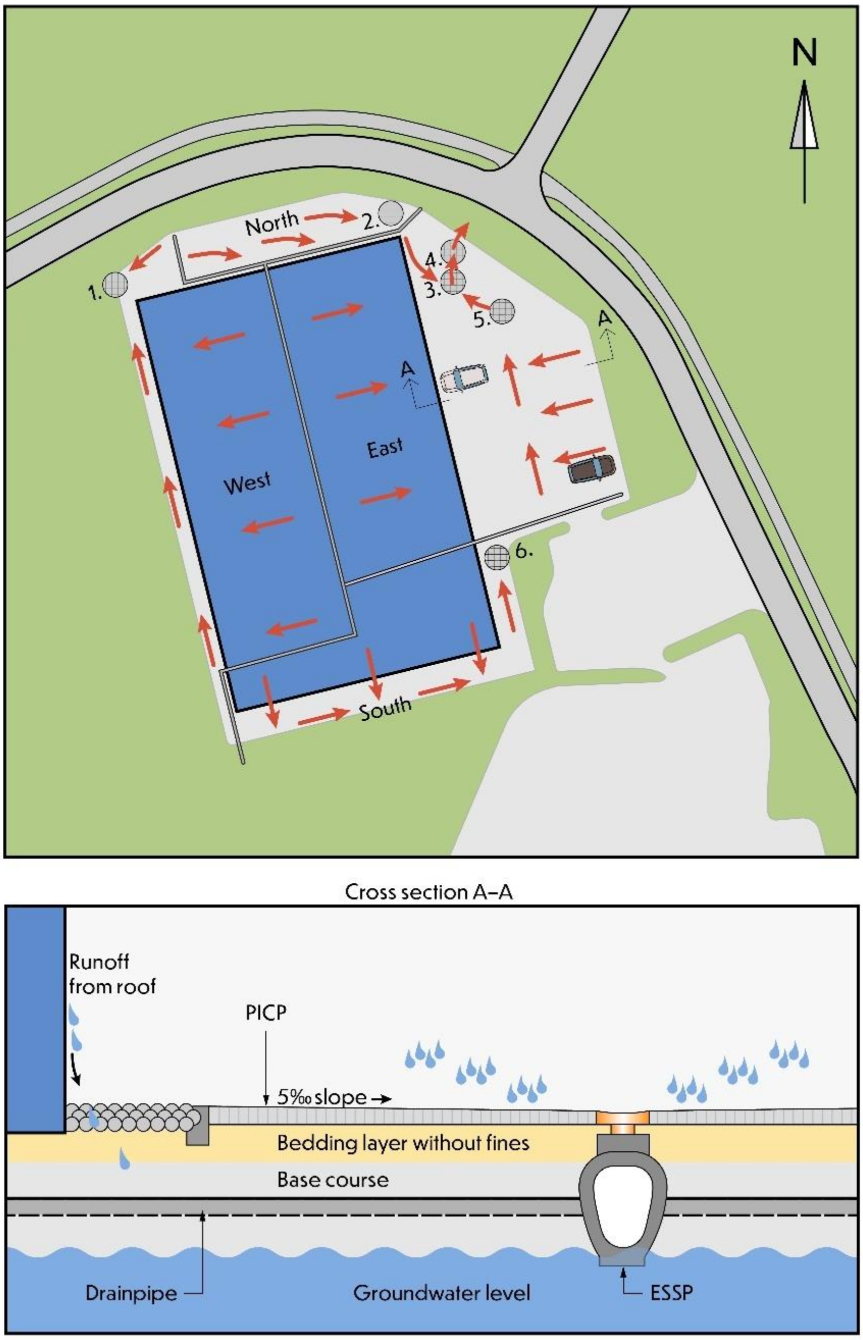

Figure 1. Bird view (top) and cross section (bottom) of study area.

2.2 Initial groundwater level

For this study area, the initial storage is determined by the groundwater level. An average gradient between the upstream and downstream logger was calculated from the data, and it was assumed that the shape of all the PDFs followed that of the downstream distribution. The gradient was assumed to be constant across the site and used to estimate initial water level in the manholes between the loggers. According to visual inspection of the groundwater data and precipitation data, the peaks in the two data sets align well (Appendix A). Due to the significant descend in water table during longer dry periods, it is evident that precipitation is a driver of the groundwater level. However, the relative magnitudes of the peaks are deviating substantially. Therefore, there are likely several processes preventing an apparent correlation structure to be found between groundwater level and precipitation data: The interevent time leading up to an event is key in draining the manholes before the onset of a new event. Also, the volume at the end of the previous event depends on the magnitude and duration. The lag time from the onset of the rain until the groundwater is perturbated may also vary according to antecedent conditions. As the combination of these factors is random, initial groundwater level was implemented as a statistically independent variable. The initial depths in the manholes were sampled according to a pseudorandom process to generate numbers from a bimodal gaussian distribution function.

2.3 Meteorological analysis

The meteorological analysis consisted of characterizing rainfall events by rainfall depth, duration and interevent time (Eagleson, 1978). Each characteristic was assumed to be a statistically independent random variable (Appendix B), adequately represented by exponential distributions (Adams et al., 1986; Bacchi et al., 2008; Balistrocchi et al., 2009; Eagleson, 1972; Howard, 1976; Guo and Baetz, 2007; Wang and Guo, 2018). With the advantage of being a single parameter distribution, the exponential distribution is simple to incorporate in calculations (Table 2.1). Rainfall events with depth $\leq$2 mm were omitted, to ensure that the exponential distributions would adequately represent the heavier rainfall events. Similarly, durations >50 h were also omitted to favor the high-volume, short-duration events that are more likely to trigger a discharge event.

Table 2.1. Probability density functions for rainfall characteristics based on 1.5 years of 1-hour interval continuous data.

	PDF	Expected value	Sample mean
Rainfall depth (mm)	$f(v) = \zeta e^{-\zeta v}$	$\zeta = \frac{1}{\bar{v}}$	$\bar{v} = 10.4$
Interevent time (h)	$f(b) = \psi e^{-\psi b}$	$\psi = \frac{1}{\bar{b}}$	$\bar{b} = 14.8$
Duration (h)	$f(t) = \lambda e^{-\lambda t}$	$\lambda = \frac{1}{\bar{t}}$	$\bar{t} = 14.1$

The rainfall data were separated both into independent characteristics, and discrete events. To perform these operations, an appropriate minimum interevent time (MIET) was applied. MIET can be selected in such way that the discrete rainfall events are considered statistically independent (Adams and Papa, 2000). There are mainly three suggested objective methods to select MIET: (1) using the autocorrelation coefficient of the rainfall pulses (e.g. Howard, 1976); (2) comparing the average annual number of rainfall events to the events obtained when varying MIETs (e.g. Nix ,1994); (3) selecting MIET to support the assumption of exponentially distributed interevent times, by setting a MIET that results in the coefficient of variance to be equal to unity (Restrepo-Posada and Eagleson, 1982). A new methodology using exponential function analysis to select an appropriate MIET in urban areas was recently proposed by Lee and Kim (2018). However, this procedure was concluded insufficient for small drainage areas with time of concentration less than an hour. Studies have suggested that the choice of MIET should be based on the intended application (Guo et al., 2012; Joo et al., 2014). To ensure a one-to-one correspondence between rainfall and runoff events, the MIET should be greater than the catchment response time. For smaller urbanized catchments, 1-6 hours are typically considered appropriate (Adams et al., 1986). Rainfall events separated by shorter MIET have more varied duration and higher peaks (Aris and Dan'azumi, 2010), capturing more of the possible scenarios and variability within the data. A subjective method was used to select MIET in this paper. Different values in the range 1-16 hours were tested and evaluated based on the resulting Pearson's product moment (r-value) for rainfall depth and duration (Figure 4). The value resulting in the lowest absolute r-value was chosen to support the assumption that the rainfall characteristics are statistically independent.

2.4 Rainfall-runoff transformation

An event-based rainfall-runoff transformation was applied in this paper, where rainfall reaching the ground may be stored in surface depressions, infiltrated into the ground, or generate runoff. Different levels of complexity have been developed for rainfall-runoff transformations. The simplest include runoff generation from surface depression exceedance, while it is more common to also account for infiltration excess flow (Guo and Adams, 1998a; Chen and Adams, 2007). Further advancements of models are also considering runoff generation from saturation excess flow (Guo et al., 2012) and initial storage and antecedent soil moisture conditions (Guo, 2018; Guo et al., 2018).

Although various rainfall-runoff transformation procedures are available, it is advantageous for a model to be as simple as possible while representing the system with adequate accuracy. To establish these criteria, the APSWM proposed by Guo and Adams (1998a) was used as a basis for the rainfall-runoff transformation. Similar notation is used in this paper for rapid recognition of procedures in listed references. The catchment was divided into an impervious (h) and pervious fraction (1-h), assigning values of surface depression storage (S_{dp}), initial soil wetting (S_{iw}), and long-term infiltration rate (f_c) for the pervious area. A function representing S_{iw} can be estimated empirically, however, it is often treated as a constant (Guo and Adams, 1998a). S_{dp} is a lumped constant representing both evaporation losses and the cumulative rainfall depth that may fill depressions on the surface. The total initial losses are therefore incorporated as one constant where $S_{il} = S_{iw} + S_{dp}$ (Eq. 1). The area-weighted initial losses of the pervious area (S_d) of the catchment is given by $S_d = (1 - h)S_{il}$ (Eq. 2).

Several infiltration models are available to represent the tendency of infiltration capacity of a soil to decrease over the duration of an event. Infiltration capacity is expected to stabilize at a certain value after some time. A conservative and simplifying assumption was applied, setting infiltration capacity as a constant equal to the ultimate infiltration rate of the soil (f_c). Both the use of Horton's infiltration model and a constant infiltration rate in the APSWM have demonstrated acceptable results (Guo and Guo, 2018). Surface infiltration rates of PICPs have been found anywhere between 10-216 mm/h (Borgwardt, 2015; Bean et al., 2007), suggesting that the saturated hydraulic conductivity (K_{sat}) of the soil is likely the limiting factor determining overall infiltration capacity of the system ($f_c \approx K_{sat}$). Recovery rates were calculated from peak to trough for all peaks in the one-minute resolution groundwater data and used as a proxy for f_c.

Runoff is immediately generated from the impervious area, whereas the rainfall depth must exceed the capacity of initial and infiltration losses before the pervious area is contributing to runoff (Eq. 3).

$$v_r = \begin{cases} 0 & v = 0 \\ hv & 0 < v \leq S_{il} + f_c t \\ v - S_d - f_c(1-h)t & v > S_{il} + f_c t \end{cases} \qquad \text{(Eq. 3)}$$

Cumulative density functions (CDF) or non-exceedance frequencies of runoff ($F_{V_R}(v_r)$) were calculated by integrating the joint PDF of event depth and duration (Appendix C). The regions of integration were bounded by runoff-generating thresholds. Detailed derivations to obtain $F_{V_R}(v_r)$ are presented in Guo and Adams (1998a). The runoff is expressed as water depth over catchment area (Eq. 4).

$$F_{V_R}(v_r) = \begin{cases} 1 & v_r = 0 \\ \exp\left(-\frac{\zeta}{h} v_r\right) & 0 < v_r \leq hS_{il} \\ \frac{\lambda}{\lambda + \zeta f_c - \zeta f_c h} \exp(-\zeta S_d - \zeta v_r) + \frac{\zeta f_c (1-h)}{\lambda + \zeta f_c - \zeta f_c h} \exp\left(\frac{\lambda}{f_c} S_{il} - \frac{1}{h}\left(\zeta + \frac{\lambda}{f_c}\right) v_r\right) & v_r > hS_{il} \end{cases}$$

(Eq. 4)

2.5 Generating triangular hydrographs

The catchment was divided into four sub-catchments; North, South, East, and West (Figure 1), and a distribution of runoff was calculated for each area using different values of *h*. Peak runoff was assumed to reach the nearest downstream manhole at the time of concentration (t_c). It has been argued that t_c is independent of the characteristics of the rainfall event, and thus specific to the catchment properties (Hassini and Guo, 2017). A constant t_c was estimated for each of the four sub-catchments using kinematic wave theory (Singh, 1988), $t_c = 0.116 \frac{L^{0.6} n^{0.6}}{i_e^{0.4} S^{0.3}}$ (Eq. 5), where L is the longest flow length [m], n is the area-weighted Manning's roughness coefficient, i_e is the effective rainfall intensity [mm/h] and S is the slope. t_c was estimated based on typical design values for smaller catchments; a 10-minute duration event with a reoccurrence interval of 20-years. To simplify computations, the common assumption of a triangular hydrograph was applied (e.g. Wycoff and Singh, 1976; Guo and Adams, 1999b; Balistrocchi et al., 2013). Although an unpolished assumption, the use of triangular hydrographs can be justified by the fact that the peak value for each event is of main concern in evaluating the system capacity. The hydrographs were estimated based on time to peak (t_c), time base (t_b=duration) and peak runoff ($q_p = \frac{2v_r}{t+t_c}$) (Eq. 6). The rising and recessing limbs of a triangular hydrograph were given by $\frac{q_p}{t_c}t$ (Eq. 7a) and $-\frac{q_p}{t-t_c}(t-t_b)$ (Eq. 7b), respectively. Implementing the triangular hydrograph assumption in the rainfall-runoff transformation, the peak runoff rate from a rainfall event can be expressed as:

$$q_p = \begin{cases} 0 & v = 0 \\ \frac{2hv}{t+t_c} & 0 < v \leq S_{il} + f_c t \\ \frac{2[v - S_d - f_c(1-h)t]}{t+t_c} & v > S_{il} + f_c t \end{cases} \qquad \text{(Eq. 8)}$$

2.6 Reservoir routing

Storage-indication reservoir routing was applied in this study, treating all manholes as a reservoir. The manholes are assumed to have a constant infiltration rate (f_c) and a random initial water level following the bimodal distribution of the groundwater. Logical statements were used to determine whether any overflow from the upstream manhole would proceed to the downstream system. If so, the routed hydrograph was superimposed with the runoff hydrograph and used as input for the downstream manhole. Hydrograph attenuation due to pipe flow was neglected for all pipes, as attenuation is assumed to be insignificant if the travel time (t_t) through the pipe is much smaller than the time base of the hydrograph (Petrucci and Tassin, 2015). Due to the relatively small catchment size and short pipes, the t_t's of peak discharges were found to be in the order of <10 seconds, while t_c's and t_b's are in the order of minutes and hours, respectively.

The Eastern drainage area is a unique case due to the ESSP and the attached drainpipes. As the ESSP and drainpipes are not sloped, the reservoir was considered to include these components as well as the downstream manhole. A set of critical depths was applied to predict which storage components would be activated at what volume (V). Geometric properties of a standard egg-shaped pipe developed by Gill (1987) along with hydraulics of partly full and full circular pipes were used to graphically derive an equation for storage fraction ($S_f(V)$). $S_f(V)$ is a set of third-degree polynomials describing how much of the total water entering the ESSP will be stored in the ESSP and the downstream manhole as a function of *V* for the different critical depth intervals. $S_f(V)$ was implemented in the reservoir routing of the sub-catchment to account for the volume lost to drainpipes (Figure 2).

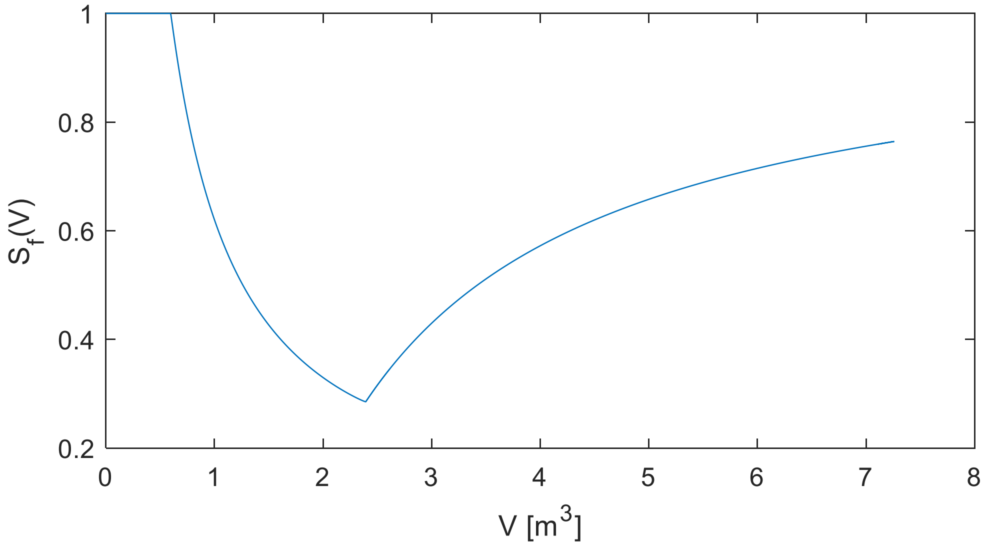

Figure 2. Storage fraction.

Two series of superimposed hydrographs meet in a larger infiltration manhole (3; Figure 1) in the northeastern corner of the study area. The large manhole (3) connects to a smaller closed-bottomed manhole (4) that contains a flowmeter and an overflow weir. Two routing steps were performed for each chamber of the final manhole. CDFs of the peak discharges were obtained for each of the manholes, the overflow weir, and the emergency outlet (Figure 3).

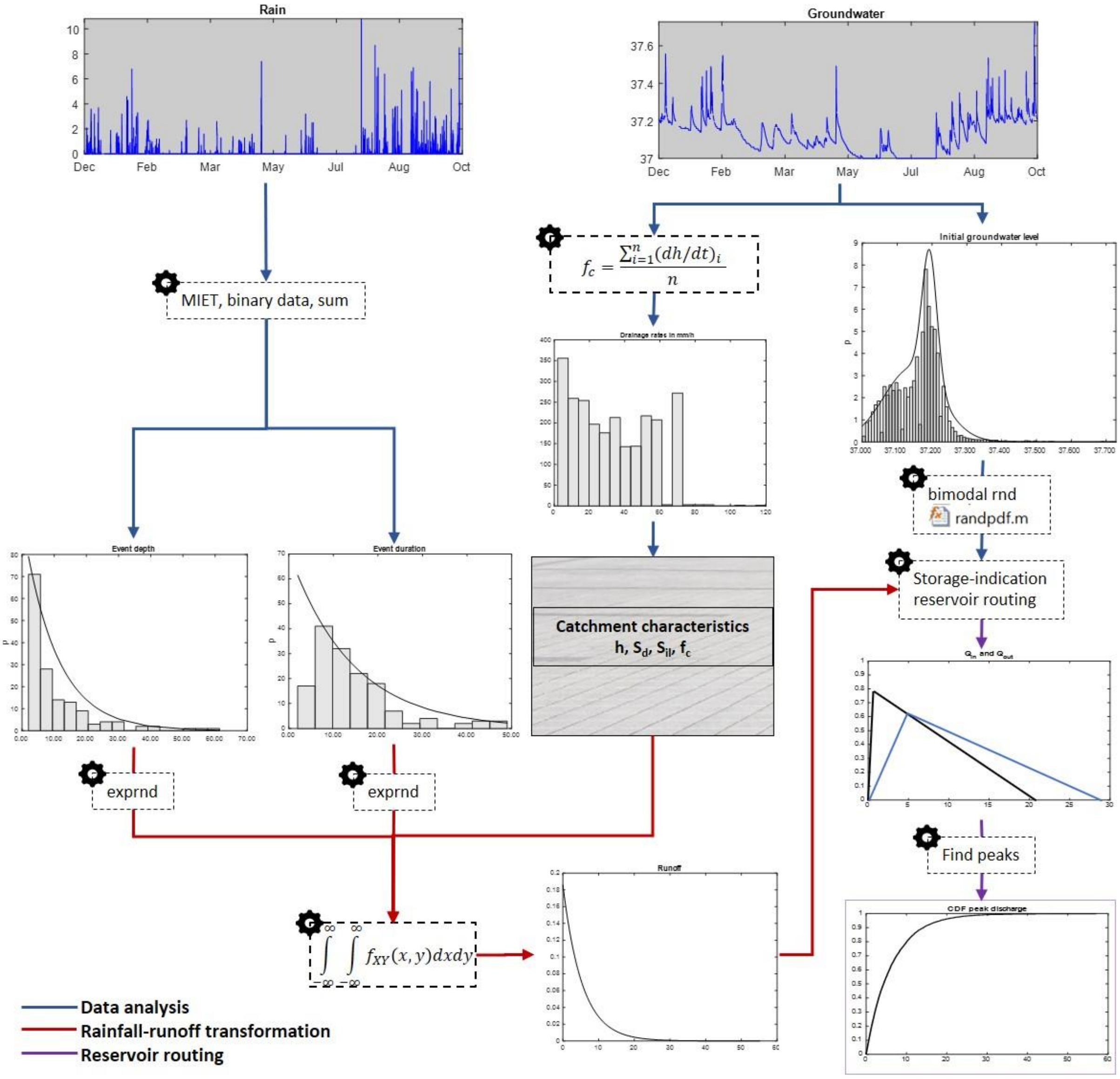

Figure 3. Flow chart of model setup and data flow. ***Note this is a simplified illustration; not all numbers are accurate, and formulas are not exhaustive.**

2.7 Scenario analysis and stress test

Based on observations and flow measurements at the outlet, the drainage facility is performing exceptionally well. The emergency outlet has only been in use at one occasion. Therefore, calibration of the model using outflow data from the system is not an option. A scenario analysis was conducted to test model sensitivity towards fixed key variables (f_c and t_c) and stresses to the system. These scenarios also demonstrate the flexibility of model application in a theoretical design phase. Surface depression storage and initial wetting are likely to have a minimal impact on the results as the relative magnitudes compared to a heavier rainfall event are small (Guo and Adams, 1998a). Therefore, parameter sensitivity was not tested for these. As little or no discharge is expected from the system based on observations, possible scenarios where input variables would be adjusted to enhance the performance of the system were disregarded (e.g. increasing f_c).

Aside from the base scenario, six additional scenarios (I-VI) were evaluated (Table 3.2), each representing plausible present or future conditions. As Eq. 5 suggests, t_c is not entirely a constant property of the catchment but a function of rainfall intensity (Eq. 5). Scenario I is evaluating the effect of shortening the t_c by one half, representing t_c during a heavy rain event. As precipitation in southwestern Norway is expected to increase by ~20-40 % throughout this century (Hanssen-Bauer et al., 2015), a stress test factor (stf) of 1.4 was applied to base conditions (II) and to a worst-case scenario (V). III simulates ageing of the PICP. According to field tests on 204 PICPs reported in Borgwardt (2015), clogging will cause the infiltration capacity of permeable pavements to decrease by 10-25 % of its original performance over the course of 8-12 years. f_c for III is therefore set to 10 % of the base scenario. To evaluate the potential of groundwater to affect the system, IV was run setting the initial groundwater level constant and equal to the maximum value. For V, all worst-case alternatives are combined to make an ultimate stress test of the system. Scenario VI is imagining that the entire catchment is completely impervious (h=1). Since the runoff is provided in mm depth over catchment area and the input variables are uniform, the runoff curve will look identical for all sub-catchments for VI (Appendix D). However, this scenario tested whether the pipe and manhole system would be sufficient without a permeable pavement; providing an idea of the dimensioning of the system, and contribution of the pavement to the overall performance.

3 Results

3.1 Groundwater levels and infiltration rates

General statistics for the two groundwater sensors are provided in Table 3.1. The average slope from the upstream sensor to the downstream sensor was -0.0065 m/m. The groundwater data approaches a normal distribution when divided into seasons, suggesting that the bimodality is caused by seasonal shifts in mean groundwater level. The data revealed recovery rates from peaks to troughs ranging from 2 to 120 mm/h, with a mean rate of 35 mm/h. This range of recovery rates corresponds well with table values for hydraulic conductivities of the presumed sub-grade sediment classes; moraine and silt. The proxy value of f_c was found to be higher than expected, thus it is uncertain whether the limiting layer for infiltration is the PIPC or the native soil.

Table 3.1. Groundwater statistics for bimodal gaussian distributions.

Logger	Minimum	Maximum	1st Mean	2nd Mean
Upstream (masl)	37.20	38.50	37.73	37.87
Downstream (masl)	37.02	37.28	37.14	37.19

3.2 Rainfall events and characteristics

325 discrete rainfall events were extracted from the data, based on a chosen MIET of 4 hours. Amongst the tested values, a MIET of 4 hours minimized the *r*-value between rainfall event depth and duration. 4 hours also corresponds well with the recommended range for small catchments. The returned *r*-values were 0.17, 0.06, and 0.60 for interevent time and rainfall depth, interevent time and duration, and rainfall depth and duration (Figure 4), respectively. Neither of the *r*-values suggest significant correlations between any of variables. Rainfall characteristics were fitted using both one-hour-interval data and one-minute-interval data. The differences in resulting rainfall characteristics, number of events and *r*-values using hour-resolution data compared to minute-resolution were negligible. Therefore, the model proceeded based on one-hour data input to decrease run time.

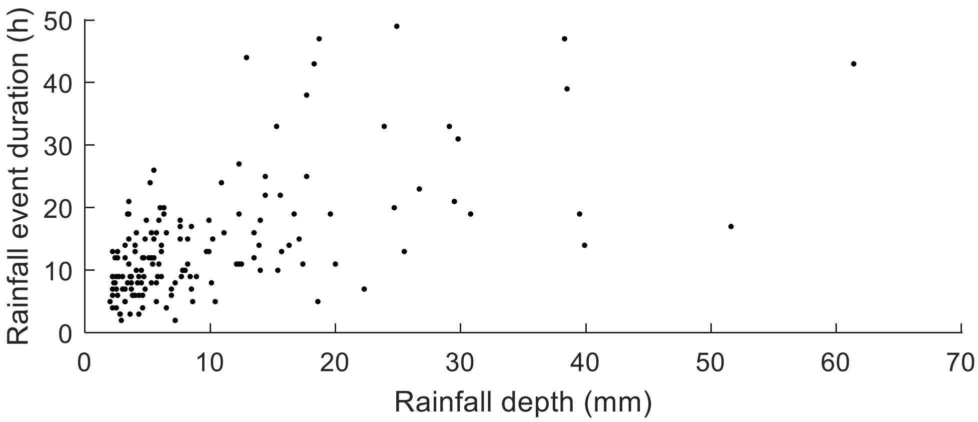

Figure 4. Scatter plot showing the association between the most critical variables; rainfall event depth and duration.

3.3 System capacity

Without initial content, the pipes and manholes have a total capacity of 36.2 m^3, which is quite substantial. The modeled results coincide with the observation that the system is high performing, with a very small probability of discharging any water. For the base scenario, the model predicts a zero-probability of discharge. This result may signify that: (1) the exact combination of variables causing a discharge event is not represented amongst the iterations; (2) discharge-producing variables are not adequately parameterized; (3) that antecedent conditions are driving factors in stressing the system to produce discharge. The observed discharge event released a total of 3.45 m^3, at a maximum rate of 3.24 m^3/h. The mean event rain depth of the 14 days leading up the discharge event was only 9 mm, which is less than the overall average (Table 2.1). However, the frequency of storms was 1.2 events/day and the average interevent time 12.9 hours compared to the overall mean frequency of 0.61 events/day and interevent time of 14.8 hours. Groundwater level was likely an important factor as it varied between 98-100 % of the detected maximum throughout these days.

All designed scenarios (Table 3.2) showed little variation from the base scenario, suggesting that the system is over-dimensioned. Changing the t_c (I) did not affect the results (Table 3.3), likely because the t_c is already so small compared to the event durations. Increasing precipitation (II) resulted in runoff increasing by ~40-56 %, but not enough for discharge to occur from any manholes. The increase was higher for the sub-catchments of lower h, suggesting that the significance of the permeable area becomes less important to performance once the pavement is under higher rain loads. Saturation excess could become a significant runoff generating process during extreme cases. The decreased infiltration rate (III) increased runoff by 56 % for the Northern catchment, while the change in maximum runoff for the Western sub-catchment was negligible due to the high h-value. Maximizing the groundwater level (IV) was the only test that resulted in discharge from some of the manholes. The same two catchments produced discharge for the worst-case scenario (V), only in greater magnitude. Assuming the catchment to be completely impervious (h=1), resulted in a greater maximum runoff, yet no discharge. From a service point of view, one could conclude that there is no need for the PICP to prevent discharge, or the pipes and manholes could be smaller. Nevertheless, it should be kept in mind that the PICP has several other benefits beyond runoff reduction (e.g. Liu et al., 2017).

The groundwater is facilitating swift drainage of the system. However, as the groundwater table is intercepting the manholes, it is also expected to occupy storage space at times. As the groundwater is recharged by precipitation events, the level is at its highest during longer wet periods when back-to-back rainfall events occur frequently. This is also when higher storage space is needed to prevent a discharge event from occurring, arguing that there are drawbacks to consider when constructing infiltration structures overlying shallow groundwater aquifers.

Table 3.2. Input variables for various scenarios (I-V) and sub-catchments. *groundwater level setting. **stochastically sampled.

Sub-catchment		Parameter	Base	I	II	III	IV	V
Common		S_{dp} (mm)	5	5	5	5	5	5
		S_{iw} (mm)	10	10	10	10	10	10
		f_c (mm/h)	35	35	35	**3.5**	35	**3.5**
		$*gw$	**s	s	s	s	***max***	***max***
		stf	1.0	1.0	**1.4**	1.0	1	**1.4**
West	$h = 0.80$	t_c (min)	13	**6.5**	13	13	13	**6.5**
North	$h = 0.00$	t_c (min)	2.8	**1.4**	2.8	2.8	2.8	**1.4**
South	$h = 0.60$	t_c (min)	11	**5.5**	11	11	11	**5.5**
East	$h = 0.52$	t_c (min)	10	**5.0**	10	10	10	**5.0**

Table 3.3. Probability of discharge ($1 - F_{V_R}(v_r)$), max event runoff ($v_{r,max}$) and peak manhole discharge values ($q_{p,max}$) from all sub-catchments and emergency outlet. Iterations=5,000.

Sub-catchment	Parameter	Base	I	II	III	IV	V	VI h=1
West	$v_{r,max}$ (mm)	75.9	75.9	106	76.4	75.9	115	95.4
	$P[q_p > 0]$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	$q_{p,max}$ (m^3/h)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
North	$v_{r,max}$ (mm)	43.4	43.4	66.7	67.7	43.7	99.4	95.4
	$P[q_p > 0]$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	$q_{p,max}$ (m^3/h)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
South	$v_{r,max}$ (mm)	57.1	57.1	81.9	71.1	57.1	103	95.4
	$P[q_p > 0]$	0.00	0.00	0.00	0.00	0.11	0.23	0.00
	$q_{p,max}$ (m^3/h)	0.00	0.00	0.00	0.00	1.951	11.25	0.00
East	$v_{r,max}$ (mm)	49.5	49.5	77.3	70.7	49.5	102	95.5
	$P[q_p > 0]$	0.00	0.00	0.00	0.00	0.001	0.010	0.00
	$q_{p,max}$ (m^3/h)	0.00	0.00	0.00	0.00	2.85	56.9	0.00
Emergency outlet	$P[q_p > 0]$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	$q_{p,max}$ (m^3/h)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

4 Discussion

4.1 Conceptualizing a multi-component system

The greatest challenge when modelling a complete drainage system of multiple components, is to make the appropriate simplifications and assumptions. For performance evaluation of a single component, a rather detailed analysis can be justified. However, for larger systems, balancing simplicity and accuracy is key. A clear vision of what the model output will represent should be determined before any assumptions and simplifications are made. The pilot area was built to demonstrate a configuration of a zero-discharge system. To evaluate such high-performing system, the focus needed to be on extreme cases and peak values.

Although the strengths of probabilistic model outputs for performance analyses are inevitable, these strengths are faded when applied to a system where no adverse events are expected. Neither of the scenarios run were able to produce a discharge event. A possible explanation could be that the model is not accounting for all necessary discharge-producing processes during extreme conditions. Equally, the number of iterations could be insufficient for representing the exact combinations that could lead to a discharge event. To obtain quantitative results for capacity exceedance of the presented study area, combinations of distribution tail values are likely of great importance. A major benefit of stochastic models is the ability to present uncertainties in the final output. However, for well-functioning, in-place systems, it can be difficult to retrieve detailed and meaningful results for extreme cases. A thorough understanding of the processes leading to an adverse event is needed. The beneficial output structure of stochastic models is more evident in the planning and design phase of projected systems, where a confidence interval of performance can be derived to adjust configurations of the drainage system. Where applicable, new systems could be designed according to an acceptable likelihood of discharge.

In terms of conceptualizing the system for the rainfall-runoff transformation, a decision was made to neglect the effect of antecedent moisture conditions and runoff generation due to saturation excess. Guo et al. (2018) found that antecedent moisture contents in permeable pavements are usually close to zero, which likely applies to a rather new construction like the PICP evaluated in this study. Antecedent moisture content may become a significant factor over time, as compaction or clogging of the pavement can cause the permeability to decrease; allowing water to retain in the soil layers longer (Yong et al., 2013). A second rainfall-runoff transformation accounting for saturation overflow (Guo et al., 2012), was tested for this catchment. A negligible number of events satisfied the conditions for which saturation overflow would occur, thus advancing the derivations to implement this process was considered not to pay off in terms of accuracy.

When dimensioning a multi-component system, it is necessary to know the magnitude of runoff that each component is likely to be subject to. As this catchment is small and $t_c << t_b$, the plotting resolution of the hydrograph must be very high to sufficiently represent the peak and rising limb in the routing procedure. This is slowing down the model significantly, as it affects every routing step, which in turn applies to every manhole. A simpler way of modelling the peak discharge would be to apply the more direct approach as proposed by Guo and Adams (1999b), using a simplified routing technique that only routes the peak outflow rates (Hall, 1984). This approach has proven very useful for single detention facilities and is extremely advantageous as an analytical equation can be derived. However, this approach would limit the opportunity of studying the stepwise functionality of a system in further detail. Also, previous studies have assumed an empty detention basin at the beginning of the event, which does not apply to the study area presented in this paper. Implementing the rapid peak routing in the APSWM requires that the relationship between maximum storage and peak outflow is known. If this relationship cannot be fitted with an analytical function, peak outflow can only be solved iteratively (Guo and Adams, 1999b). As the available storage capacity of this study area is highly dynamic and the detention components are taking several geometric shapes, deriving storage-discharge relationships for this system would be complex; favoring the use of a traditional routing technique. A possible solution that could decrease the number of needed time steps when $t_c << t_b$, would be to explore the option of a floating time step that is smaller for the rising limb than the recessing limb of the hydrograph.

4.2 Initial groundwater level as a stochastic variable

The hypothesis that the groundwater level would affect the system performance was supported by the case study results. No discharge is expected from any of the manholes unless the groundwater level is approaching its maximum. This is also consistent with the detected discharge event, for which the rain depth alone was not high enough to cause overflow. The high groundwater level combined with rain events occurring more frequently than usual, were likely the causes of this discharge event. Assumptions of full or empty initial storage, are often useful by providing lower and upper boundaries of performance of detention basins. However, due to the large dimensions of this system, the detention volumes are not expected to become full at any point in time, and due to the interception of the groundwater table, they are not expected to ever be completely empty either. This is a strong argument for accounting for initial storage in a different way, even if the implementation of groundwater as a stochastic variable is inhibiting the opportunity of deriving an analytical equation for peak discharge. The assumed gradient to estimate the groundwater levels in the manholes between the loggers may cause discrepancies. The variability of infiltration rates in adjacent sites suggests that the aquifer could be heterogenous, thus a constant gradient and distribution shape is not necessarily representative across the drainage area. For instance, the data from the upstream logger has a somewhat different distribution shape, as the variation is greater than at the downstream logger. A large portion of true values are still expected to be represented for all manholes due to the random sampling.

4.3 Stochastic approach for preliminary analyses of complete drainage systems

Stochastic and joint probability approaches have proven to be an excellent modelling alternative for several SUDS and stormwater detention facilities. Optimizing a framework for stochastic models for complete drainage systems could provide endless flexibility in a design phase. Ideally, each component of the drainage system could be evaluated in terms of its potential contribution as a stormwater barrier. Further, the components could be optimally dimensioned in accordance with probabilities of adjacent components to reach a desired overall performance level. Probability distributions of components could also be used to define the most critical point of the system and run sensitivity analyses in an efficient manner. Depending on the location, drainage systems may be constructed with different targets of performance. For instance, a drainage system in an urban area where strong monsoon seasons are common, handling short-duration, high-intensity events may be a priority. In other locations, long-duration, moderate-intensity events may be more critical. Probabilistic models can provide holistic input when deciding between different configurations to address these targets.

Although previous studies on applied stochastic stormwater models contain many similarities and a key framework (Loveridge and Rahman, 2018), the mathematical complexity to derive the results can vary greatly depending on the nature of the precipitation data and catchment properties. Several studies on stochastic stormwater models have discovered special attentions that need to be made depending on meteorological conditions, system and catchment characteristics. The effect of groundwater on the system presented in this paper is an excellent example. The rainfall-runoff transformation proposed by Guo and Adams (1998a), is easily implemented due to the analytical expression for the joint probability of rainfall depth and duration. However, when using the runoff output distribution as input to a cascade of downstream components, each requiring several mathematical operations, the computational burden increases significantly. If the drainage system of interest becomes large and complex enough, the advantage of applying a stochastic approach over a continuous simulation could diminish.

Although a closed-form expression was not obtained in this study, the methodology could apply to any catchment of multiple detention volumes given that meteorological parameters and initial storage assumptions are analogous. Nevertheless, a simplified analysis should be considered for larger drainage systems if the number of detention components are much higher. An option to speed up the analysis and simplify the approach, could be to derive a model that only computes a binary, qualitative output. Such model could for instance apply a simple volumetric comparison of runoff to available storage capacity and derive a distribution of overflow frequencies. The modelled results would not provide a quantitative insight in the relative contribution of individual stormwater barriers to overall performance. However, such analysis could be sufficient in preliminary analyses and perhaps determine where overflow of detention volumes is expected to occur. A more exhaustive model could then be applied for the critical components. When applying a complete reservoir routing for drainage areas of multiple components, efforts should be placed on implementing logical statements for threshold values early on in the program. Such filters should be used to determine whether the combination of input values for the given iteration is unlikely to result in a discharge event, and then skip to the next iteration instead of proceeding with the routing. Setting up a comprehensive filter requires a good system understanding but will contribute to decrease the computational burden significantly.

5 Limitations

This paper is focusing on the conceptual framework of using a stochastic model for a multi-component system, for which the parameterization of input variables is highly simplified. Advancing the representation of input variables and validation of the model is encouraged for further work. It is highly desirable to calibrate the model against a continuous model, as there is not sufficient real runoff data available. Further advances of the model could be considered if seen necessary after or during calibration. Such advances could include accounting for saturation excess flow (Guo et al., 2012), using a more adequate hydrograph representation (Ponce, 1989; Nadarajah, 2007), and accounting for cumulative effects of storms such as antecedent moisture conditions (Guo et al., 2018) and periods of higher groundwater level. As a discharge event could not be triggered from the scenario analysis, the effect of back-to-back events might play a bigger role than the assumptions applied in this model suggests. The marginal distribution shapes appeared to be more consistent on a seasonal basis for this study area. Running a season-separated model may improve accuracy if the continuous time series are long enough to cover several seasons. Otherwise, synthetic timeseries could be applied to extend the input data.

Although computationally more efficient and compact than a continuous simulation, the APSWM require a thorough analysis of input variables before application. The assumption that rainfall depth and duration is statistically independent is not valid for all study areas, inhibiting the opportunity to derive an analytical and universal equation that is applicable to various case studies. Rivera et al. (2005) analyzed this for a watershed in Santiago, Chile and Fort Collins, USA. A strong dependence was found between depth and duration in Santiago, whereas no apparent correlation was found in Fort Collins. Eagleson (1970) underlined that strong correlations were found for short-duration, high-intensity rain events and long-duration, low-intensity rain. Although not yet clearly understood, analytical models derived by neglecting variable dependences have proven to yield better and more conservative results (Adam and Papa, 2000). Accounting for associations amongst the random variables increases the complexity of the model setup, as the derivation of multivariate probability functions can be a troublesome task (Balistrocchi and Bacchi, 2011). The introduction of copula functions (Nelsen, 2006) to multivariate statistics have posed an opportunity to reduce these drawbacks and improve the accuracy of probabilistic models with strong variable dependencies (De Michele and Salvadori, 2003; Balistrocchi and Bacchi, 2011; Balistrocchi et al., 2017; Fu and Butler, 2014).

Another issue inhibiting the opportunity of making a universal framework for the APSWM, is that not all continuous rainfall data is adequately represented by an exponential distribution (Balistrocchi and Bacchi, 2011). Other distributions have been presented as more appropriate in other studies, such as gamma, log normal (Eagleson, 1978), Pareto (De Michele and Salvadori, 2003) or Weibull (Balistrocchi and Bacchi, 2011) distributions. The choice of an exponential distribution fit to the durations in this study is likely to cause an overrepresentation of short-duration events (Appendix B), thus it could be beneficial to test a different distribution type. The goal of an analytically derived joint distribution is to develop a closed-form mathematical expression. Some distributions are not integratable and can only lead to numerical solutions.

6 Conclusions

As a demonstration site for a zero-discharge stormwater management facility, the system is performing exceptionally well, with a high resilience against any extreme present and future conditions. From a general design point of view, the system is perceived to be over-dimensioned. The groundwater was found to affect the system significantly, which should be taken into consideration when constructing infiltration facilities that are overlaying a shallow groundwater aquifer. Incorporating natural elements of storage and infiltration in drainage models brings challenges in parameterization of input variables and additional uncertainties. One of the greatest strengths of a stochastic model, is that inherited uncertainties can be represented in the final output and provide contractors and decision-makers with valuable information. However, three main drawbacks were discovered when considering a stochastic modelling technique for a preliminary analysis of a multi-component stormwater facility: (1) The mathematical complexity in deriving the model can vary greatly form one watershed to the next, resulting in the potential of each model being highly site-specific; (2) the advantage of a stochastic approach to be computationally more compact and efficient than continuous simulation is weakened as the number of components increases; (3) high specificity of input variables and good system understanding is needed to produce meaningful results for high-performing stormwater management systems.

Further attention should be paid to which discharge-producing factors and processes are decisive to appropriately model a high-performing stormwater management facility under extreme conditions. Such factors are likely to include cumulative effects of storms. This is perceived to be a research area of growing interest, yet great potential for improvements. It can be concluded from both literature study and the case study reported on in this article, that the configuration of a stochastic stormwater model can vary greatly from one system or study area to the next. However, as the complexity of both drainage systems and modelling opportunities are increasing, research should continue to uncover new ways of including different system variables in closed-form analytical expressions. Such expressions can easily be implemented in common engineering practice and improve system analyses significantly.

Abbreviations

APSWM	Analytical probabilistic stormwater model
ASM	Analytical stochastic model
b	Interevent time
CDF	Cumulative density function
ESSP	Egg-shaped stormwater pipe
Eq	Equation
f_c	Ultimate infiltration rate
h	Fraction of impervious area of catchment
K_{sat}	Saturated hydraulic conductivity
PDF	Probability density function
PICP	Permeable interlocking concrete pavement
S_{di}	Surface depression storage impervious area
S_{dp}	Surface depression storage pervious area
$S_f(V)$	Storage fraction
S_{il}	Initial losses
S_{iw}	Initial soil wetting
t	Rainfall event duration
t_b	Hydrograph time base
t_c	Time of concentration
t_t	Travel time
v	Rainfall event depth
V	Total volume

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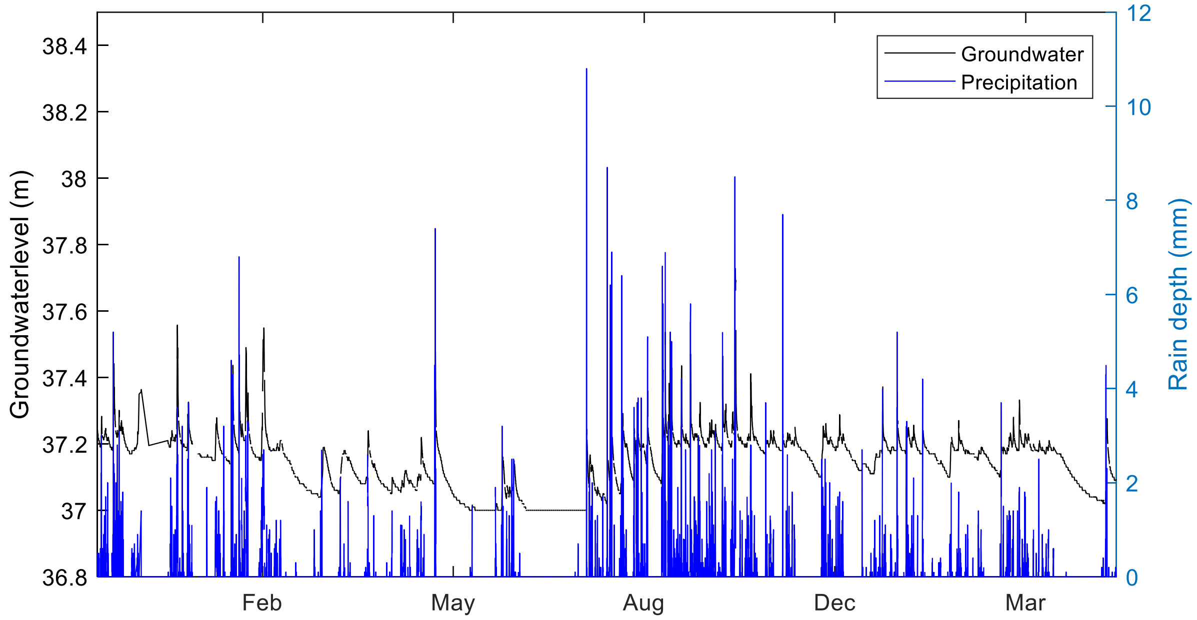
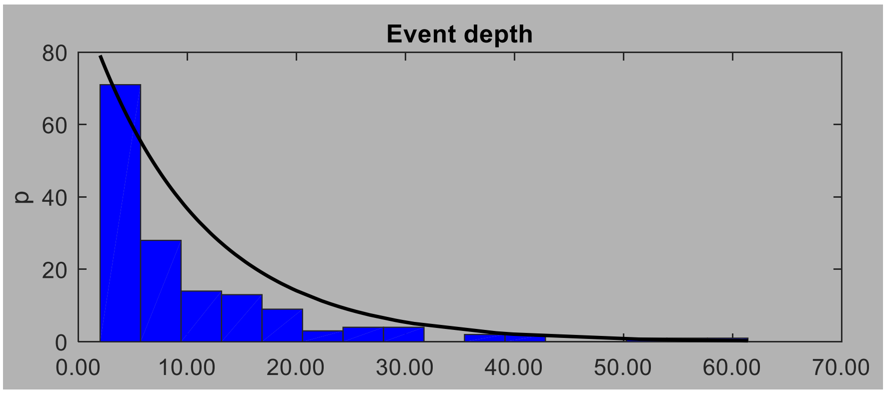
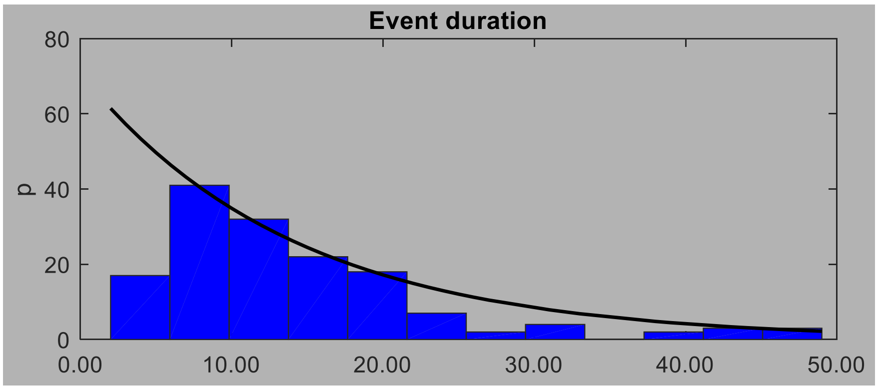
Appendix A – Precipitation and groundwater timeseries

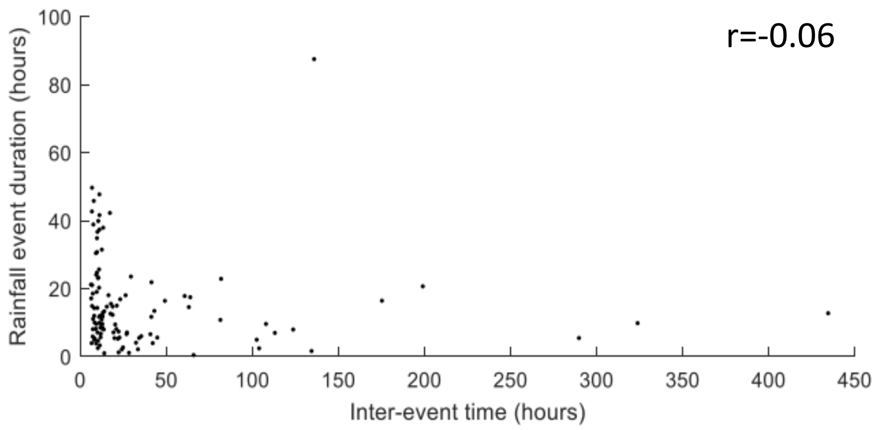
Data from the downstream sensor was used as a basis for the data analysis. Timeseries from this sensor along with precipitation is therefore presented below to show the alignment in peaks for the two data sets, yet the large deviations in relative magnitudes.

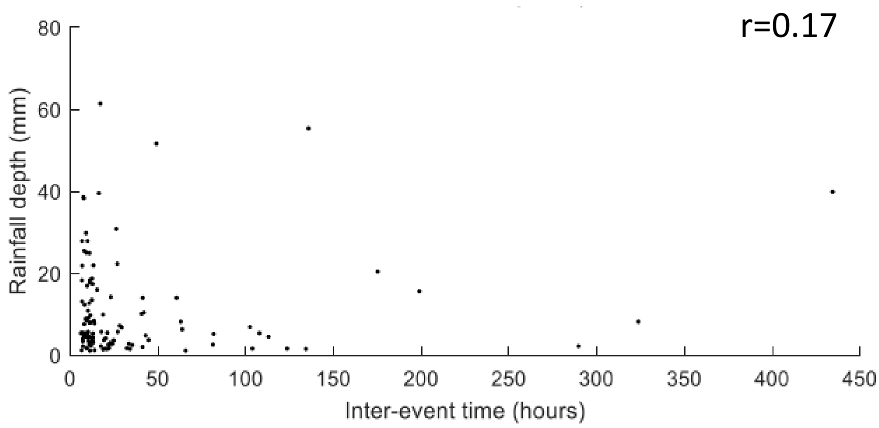


Appendix B – Meteorological input variables

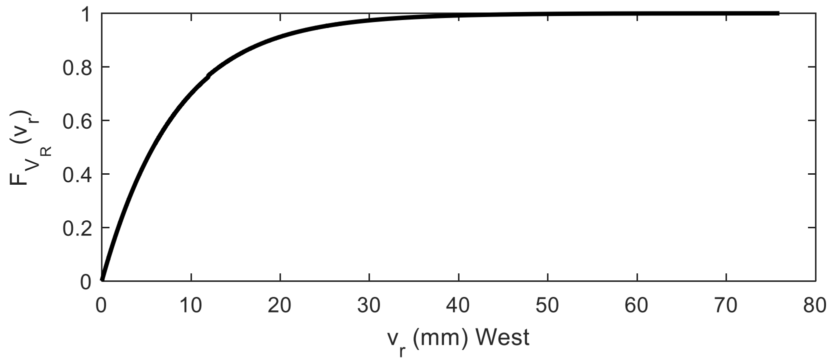


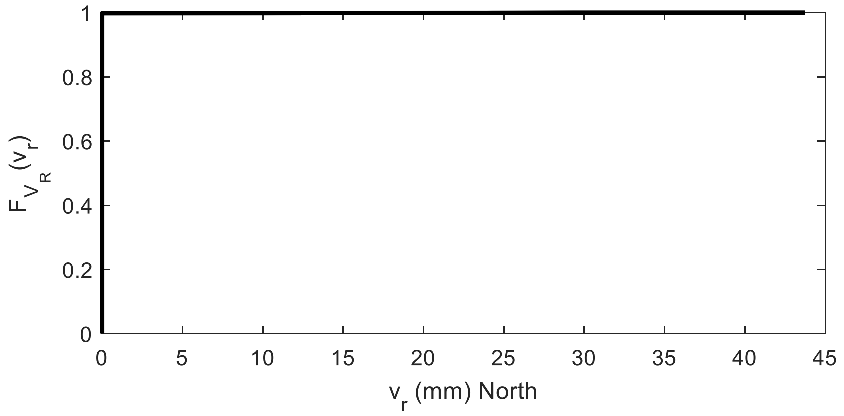


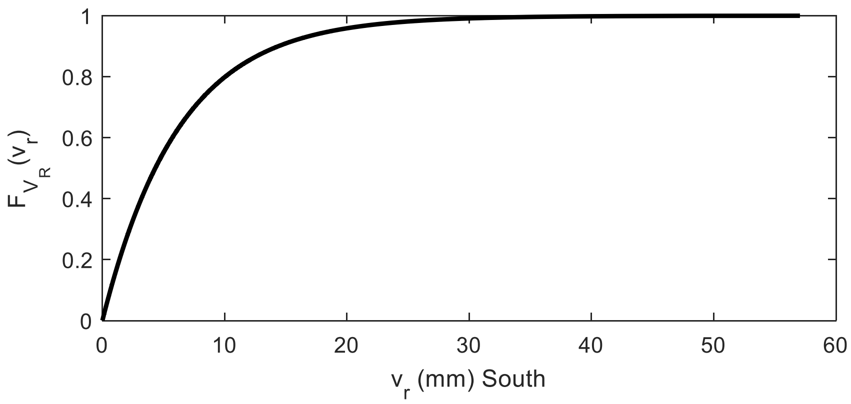


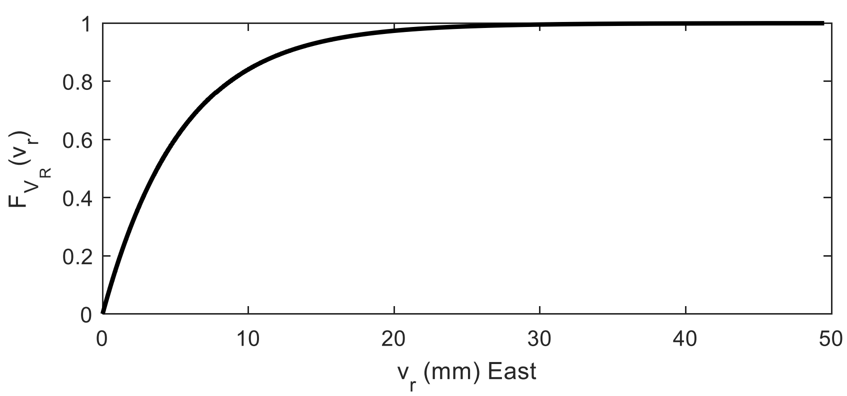


Appendix C – CDFs of base scenario runoff



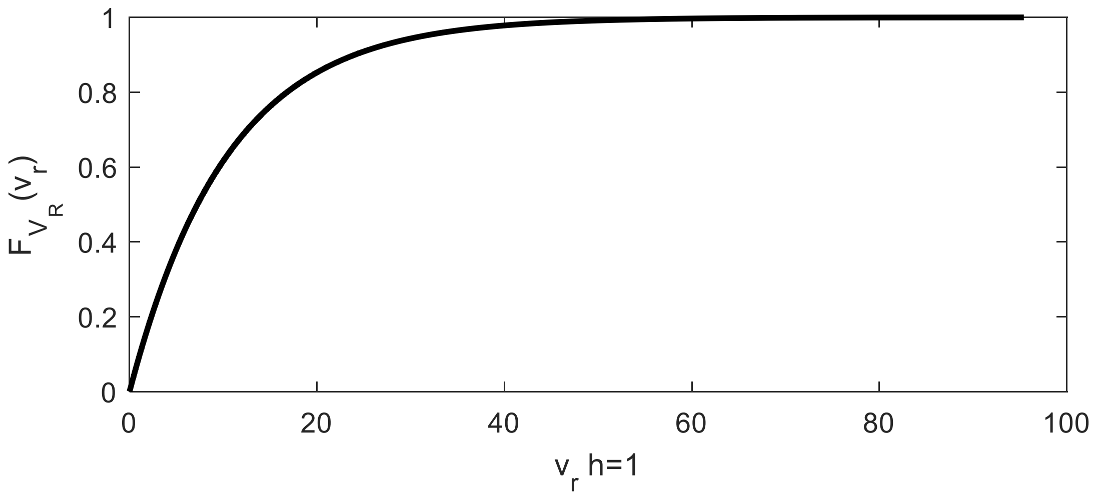






Appendix D – CDF for h=1

The impervious area fraction (h) is controlling the shape of the CDF as runoff is normalized over the area of the catchments. The CDF presented below is therefore representative for all sub-catchments when h=1.



Appendix E – Comparing expected runoff to rational method

To evaluate the general magnitude of the results from the rainfall-runoff transformation using the APSWM, the results were compared to a typical deterministic analysis (Table C.1.) using the rational method (Eq. C.1). As the PICP is quite new and has not been subject to extensive loading or clogging yet, a runoff coefficient of 0.3 was assumed. A design rain of 183.6 L/s*ha was used, which corresponds to a 10-minute duration event with a 20-year reoccurrence interval. The area-weighted runoff coefficients used for the rational formula (C_{RM}) were compared to the average fraction of runoff volume to rainfall volume from the rainfall-runoff transformation using the APSWM (C_{APSWM}). The theoretical design event runoff depths from all sub-catchments (Q_{RM}) were compared to the expected runoff derived by the APSWM (Q_{APSWM}).

$Q_{RM} = C_{RM} iA$ *(Eq. C.1) i is the rainfall intensity and A is the area of the sub-catchment.*

Table C.1: Comparing results from APSWM to analysis performed using rational method.

Sub-catchment	C_{RM}	Q_{RM} (mm/event)	C_{APWSM}	Q_{APSWM} (mm/event)
West	0.86	9.61	0.80	8.26
North	0.30	3.35	0.00	0.11
South	0.72	8.05	0.60	6.23
East	0.66	7.36	0.52	5.42

Both the weighted runoff coefficients and estimated runoff from the deterministic method were higher than the expected values computed using the APSWM, with a root-mean-square error (RMSE) of 2.2 (Eq. C.2). The greatest discrepancy was found for the northern catchment, where the use of a traditional runoff coefficient is underestimating the infiltration capacity. The choice of an appropriate runoff coefficient is very important when applying the rational method and is often resulting in a conservative estimate and an oversized stormwater management system.

$$RMSE = \sqrt{\frac{\sum(Q_{APSWM} - Q_{RM})^2}{4}} \quad \textit{(Eq. C.2)}$$

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