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Modelling Runoff from Permeable Surfaces in Urban Areas

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Background

The urban landscape is made up of both impermeable and permeable surfaces. Permeable surfaces are increasingly viewed as important for stormwater management, leading to an increasing use in urban areas. We need to extend our understanding of the contribution of permeable surface to the runoff.

In the context of alternatives to pipe-based systems for urban drainage, green areas and their hydrologic function receive increasing attention. Hydrological models can represent permeable areas, but research about the models' accuracy of modelling in-soil processes of permeable surfaces is needed. In addition, little attention has been given to model structure uncertainty in hydrological models. This is however especially relevant when models are used as a planning tool, as lack of measurements often precludes calibration. The infiltration methods represented in hydrological models are typically designed for non-urban areas. Are these methods suitable for urban permeable surfaces as well?

Climate change leads to more extreme weather, where both droughts and extreme weather is a threat. Site specific climatic factors can affect the infiltration process, since both the initial conditions before a storm event and evapotranspiration are affecting the soil. Are infiltration methods able to account for the site-specific climatic factors in their performance?

The research questions that this thesis aims to answer are:

1) How does initial moisture affect the permeable surface runoff contribution in SWMM and STORM using the Horton, Holtan and Green-Ampt infiltration method?
2) What are the most important parameters for the methods? How sensitive are the

methods to changes in soil infiltration parameters?

3) To what extent are the methods able to account for compaction changes in urban soils in the infiltration process?

Collaboration partners: TU Berlin, Engineering bureau Prof. Sieker mbh

Location: The project thesis will be conducted at the Engineering bureau Prof. Sieker mbh in cooperation with TU Berlin.

Advisors: Tone Merete Muthanna, Heiko Sieker

Preface

This report is the result of the course "*TVM4905 - Water Supply and Wastewater Systems, Master's Thesis*" at Norwegian University of Science and Technology (NTNU). The aim of the thesis is to evaluate hydrological infiltration methods' ability to simulate runoff in urban pervious areas and evaluate the methods' ability to account for initial soil moisture content.

This thesis was conducted as part of a cooperation between NTNU, The Technical University of Berlin (TU Berlin), and Engineering bureau Prof. Sieker mbh. I am very grateful for the opportunity to work within the cooperation between the universities and would like to thank everyone involved in this process.

I would like to thank my supervisor at TU Berlin, Professor Dr. Eng. Heiko Sieker, and other employees at Engineering bureau Prof. Sieker mbh, who has given me access to data, and helped me during the process of this thesis. I would like to express my deepest gratefulness to Dip. Geographer Stephan Bandermann for his expertise and interesting conversations throughout the study. In addition, I would like to thank my supervisor Assoc. Prof. Tone Merete Muthanna for her support, guidance, and advices during the semester.

Berlin, July 18, 2018

Frida Parnas

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Thesis structure

This thesis is presented as a scientific paper, which is planned to be submitted to the International Water Association (IWA) journal Water Science and Technology. The framework of this report is therefore based on their guidelines of making a research paper, where the goal is to make a manuscript of the paper; “Modelling Runoff from Permeable Surfaces in Urban Areas”. Additional data and results can be found in the appendix.

The work of this thesis has been accepted to the Nordic Water conference 2018 taking place in Bergen 13th to 15th of August, where an oral presentation of the thesis will be presented.

Sammendrag

Urbanisering, klimaendringer og utfordringer med kombinerte overløp har ført til et større fokus på å implementere og bevare permeable flater i byer. Ved prosjektering av overvannsystemer har disse overflatene tradisjonelt blitt ignorert i avrenningssituasjoner, men flere studier viser til at dette ikke er tilfelle. I tillegg er urban jord påvirket av eksterne faktorer som for eksempel komprimering, tilførsel eller fjerning av organisk materiale eller forurensning av konstruksjonsrester, som fører til forskjellig jordkarakteristikk enn rural jord. Det har blitt utviklet en rekke ulike forenklede matematiske representasjoner for å modellere infiltrasjon. Disse er typisk laget for rural jord. Flere studier nevner viktigheten av å identifisere disse metodenes usikkerheter og antagelser når det kommer til å modellere infiltrasjon fra urban jord.

I dette studiet har Green-Ampt og Horton infiltrasjonsmetode blitt evaluert i SWMM og Holtan infiltrasjonsmetode i STORM. Målet med dette studiet er følgende; (1) å evaluere hvordan jordfuktigheten i begynnelsen av en nedbørshendelse påvirker avrenningsbidraget fra permeable overflater ved bruk av infiltrasjonsmetodene, (2) finne de viktigste parameterne som påvirker oppførselen til metodene og hvor sensitive metodene er til endring av disse parameterne, og (3) evaluere metodenes evne til å ta for seg komprimeringsendringer i urban jord i infiltrasjonsprosessen. For å svare på dette er metodene blitt brukt på tre forskjellige urbane sandige jordprøver fra felt. Deretter er det utført en sensitivitetsanalyse for en av lokasjonene. Til slutt er det utført en evaluering av metodenes evne til å ta for seg varierende jordfuktighet ved bruk av kontinuerlige simuleringer.

Resultatene viser at Holtan infiltrasjonsmetode sin evne til å ta for seg både tilgjengelig porevolum for vann og maksimum infiltrasjonsrate gjør at denne metoden er mer troverdig, men metoden krever mer inputdata enn både Green-Ampt- og Horton infiltrasjonsmetode som kan være vanskelig å få tak i fra feltmålinger. Green-Ampt- og Holtan infiltrasjonsmetode i SWMM tar ikke for seg evapotranspirasjon i regenerering av jordfuktigheten som gjør at metodene kan over- eller underestimere avrenningskarakteristikkene, avhengig av klimaet i studieområdet. Holtan infiltrasjonsmetode er bedre egnet for kontinuerlige simuleringer på grunn av evnen den har til å ta for seg evapotranspirasjon i tørre perioder.

Under mettede jordfuktighetsforhold er metodene mest sensitive til mettet infiltrasjonsrate. For tørre jordfuktighetsforhold spiller også de andre jordinfiltrasjonsparameterne en viktig rolle. Green-Ampt infiltrasjonsmetode er mest sensitive til mettet hydraulisk konduktivitet, etterfulgt av tilgjengelig porevolum for vann og sugehøyde under tørre jordforhold. Horton er mest

sensitiv til minimum infiltrasjonsrate, etterfulgt av maksimum infiltrasjonsrate og forfallskoeffisient under tørre forhold. Holtan infiltrasjonsmetode er mest sensitiv til maksimum infiltrasjonsrate, etterfulgt av porøsitet og jordfuktighet i begynnelsen av nedbørshendelsen.

For å oppnå nøyaktige resultater for komprimerte urbane jordtyper ved bruk av disse forenklede infiltrasjonsmetodene, er feltmålinger av infiltrasjonsrate essensielle. Denne studien fremhever tre grunner til dette: (1) Resultatene viser store forskjeller i feltmålinger for forskjellige urbane sandige jordtyper som fører til forskjellige avrenningskarakteristikker, (2) metodene har høy sensitivitet til endringer av infiltrasjonsrate, som betyr at små endringer i input fører til store endringer i avrenningskarakteristikkene, og (3) litteratur viser til at komprimering fører til en betydelig reduksjon i infiltrasjonsrate. Bruk av parametere fra en annen urban jord eller fra litteratur kan dermed føre til feil estimering av avrenningskarakteristikker.

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Abbreviations

ADWP	Antecedent dry weather period
ET	Evapotranspiration
IDF	Intensity Duration Frequency
SWMM	Stormwater Management Model

Modelling Runoff from Permeable Surfaces in Urban Areas

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Abstract

Climate change and urbanization increases the pressure on combined sewer systems in urban areas resulting in increased combined sewer overflows, degraded water quality in receiving waters, and changing stream flows. Permeable surfaces are increasingly used to combat the challenges regarding runoff to combined sewer systems. The variation in urban soil characteristics, and the initial conditions before a rainfall event are important factors affecting the infiltration process and consequently runoff characteristics. In this study SWMM and STORM are used to evaluate the Green-Ampt, Horton, and Holtan infiltration method. Three different urban sandy soils were compared based on field measurements. A sensitivity analysis was carried out to get an improved understanding of the consequences of choosing the incorrect parameter values for urban soils. In addition, long-term simulations were conducted to evaluate the methods' ability to account for initial soil moisture content. The results showed that Holtan infiltration method's ability to account for both available storage capacity and maximum infiltration rate gives the method more confidence calculating runoff behavior, but more input data is needed as compared to Green-Ampt and Horton infiltration method. The method is also able to account for evapotranspiration in the regeneration process of the soil moisture, which makes it suitable for long-term simulations. The various results from the different urban sandy soils with different infiltration rate at saturation, together with a high sensitivity to this parameter indicates that field measurements of infiltration rate at saturation are needed to model accurate results from compacted urban sandy soils with these methods.

Keywords: Hydrological Modelling, Initial Soil Moisture, Permeable Surfaces, STORM, SWMM, Urban Soils

Introduction

In urban areas, it is commonly known that impervious areas contribute to increased runoff (Bøyum et al. 1997; Redfern et al. 2016). In recent years, it has therefore become an increasing focus on preserving existing, and implementing new green areas (Jiang et al. 2018; Law et al.

2009), hence, it is important to increase the knowledge about these areas. In design of urban green infrastructure, it has been common practice to only count impervious surfaces as contributing to runoff (Leandro et al. 2016). However, several recent publications have focused on pervious surfaces contribution to stormwater runoff (Redfern et al. 2016; Becker 2016; Davidsen et al. 2018). Becker (2016) investigated the runoff from urban pervious areas with the use of measured soil data, where the results showed significant amount of runoff from some of the urban green surfaces. Davidsen et al. (2018) study showed that pervious areas have a significant contribution to runoff with the use of rain events with return period larger than 5 to 10 years.

Soils in urban areas have different characteristics than natural soils due to various factors. Among these, the most common factors include; 1) degree of compaction during construction; 2) amount of organic matter; 3) contamination of construction debris (Gregory et al. 2006; Pitt et al. 2008; Wang et al. 2017; Morel et al. 2005; Pitt et al. 1999). These factors make it difficult to classify urban soils in the normal soil taxonomy groups. Law et al. (2009) highlight the fact that hydrological models might underestimate surface runoff from urban soils, with the use of published soil characterization data. A study by Gregory et al. (2006) showed that compaction of soils in urban areas due to vehicles that are commonly used in urban construction and compaction treatments could lead to 70-99% reduction in infiltration rates. The initial moisture conditions in the soil has additional effects on the soil behavior (Davidsen et al. 2018; Redfern et al. 2016; Pitt et al. 1999). Davidsen et al. (2018) showed that the infiltration capacity before an event is significantly reduced, due to the initial conditions in the urban soil, leading to more surface runoff.

In design and planning for urban stormwater management, knowing the portion of precipitation that infiltrates is essential, especially in planning and designing blue green infrastructure. Engineers and hydrologists use various simplified mathematical representation methods to model infiltration. Two of the most commonly used methods include the Green-Ampt method developed by Green and Ampt in 1911, and the Horton method (Horton 1941). The Green-Ampt infiltration method is based on a saturated upper layer, called wetted zone, where the water is percolated to an un-wetted zone with an initial soil moisture content, θ_i. Darcy's law gives the infiltration velocity, f_p, through saturated wetted zone, as shown in equation [1] and [2].

$$f_p = K_{sat}\left(\frac{\psi_s\,\theta_d}{F} + 1\right) \qquad [1]$$

$$F = K_{sat} + \psi_s \theta_d \, ln\left(1 + \frac{F}{\psi_s \, \theta_d}\right) \qquad [2]$$

Where K_{sat} is the saturated hydraulic conductivity, ψ_s is the suction head, θ_d is the difference in moisture content at saturation and initial soil moisture, and F is the cumulative infiltration. These equations are only valid for saturated conditions. Before saturation, a common procedure is to assume that infiltration velocity is equal to the rainfall intensity (Rossman & Huber 2016). The Horton approach introduced by Horton (1941) is divided into two parts. By the following equation, it calculates the infiltration capacity into the soil for the precipitation events;

$$f_p = f_{min} + (f_{max} - f_{min})e^{-k_d t} \qquad [3]$$

Where t is the time since the beginning of the storm, f_p is the infiltration capacity into the soil, f_{min} is the minimum infiltration rate when $t = \infty$, f_{max} is the initial infiltration rate, and k_d is the decay coefficient during precipitation. Secondly, Horton calculates the recovery during dry periods by the following equation;

$$f_p = f_{max} - (f_{max} - f_{min})e^{-k_r(t - t_w)} \qquad [4]$$

Where k_r is the decay coefficient for recovery, and t_w is the hypothetical projected time at which $f_p = f_\infty$ on the recovery curve. In general, Horton and Green-Ampt show good results in non-urban soils (Bauwe et al. 2016; Haghighi et al. 2010; Esteves et al. 2000). However, previous studies have shown poor results modelling urban soils with these methods (Wang et al. 2017; Pitt et al. 1999). Wang et al. (2017) highlights that infiltration methods can have distinctive variation in their performance with large uncertainties modelling urban soils. This indicates that a better understanding of the changes in input parameters for urban soils is needed.

Another method introduced by Holtan (1961) is the Holtan infiltration method, which is based on some of the most important soil storage parameters (Holtan & Lopez 1971). The infiltration rate, f_p, after modifications by Holtan & Lopez (1971) is given by the following equation;

$$f_p = GIa((\theta_s - \theta_i)d)^{1.4} + f_c \qquad [5]$$

Where GI is the growth index of crop in percent of maturity, a is an index of surface connected porosity, f_c is the minimum infiltration rate, θ_s is the saturated water content of the soil, θ_i is the actual volumetric water content of the soil, and d is the depth of the surface layer.

Sensitivity analysis are used to achieve an awareness of the models' uncertainties, optimize its' functions, and identify the key parameters that affect the models' output (Loosvelt et al. 2013; Song et al. 2015). Given the high range of input parameter values given in literature (Pitt et al. 1999), it is important to know which parameters are most sensitive. To obtain better modelling results, the parameters for which if an assumed value is chosen that differs from the true value of these parameters in the field would result in significant change in output, are thereby the parameters which would be most beneficial to be measured in the field. However, this is limited only to parameters where field measurements are possible, which is not the case for all parameters. Previous studies have shown that Green-Ampt infiltration method is sensitive to saturated hydraulic conductivity (Bauwe et al. 2016) and Horton infiltration method is sensitive to minimum infiltration rate (Liong et al. 1991). Davidsen et al. (2018) highlight the importance of making appropriate assumptions for initial infiltration conditions, when modelling runoff from urban areas. A better understanding of the infiltration methods' assumptions and its' uncertainties modelling urban permeable areas is needed (Redfern et al. 2016; Law et al. 2009).

In this study the Stormwater Management Model (SWMM) with Horton and Green-Ampt infiltration method options, maintained by the United States Environmental Protection Agency (EPA); and the hydrological rainfall runoff model STORM (Engineering Bureau Prof. Sieker) with Holtan infiltration method, are evaluated with the use of urban soil measurements. This paper seeks to answer the following research questions;

1) How does initial moisture affect the permeable surface runoff contribution in SWMM and STORM using the Horton, Holtan and Green-Ampt infiltration method?
2) What are the most important parameters for the methods? How sensitive are the methods to changes in soil infiltration parameters?
3) To what extent are the methods able to account for compaction changes in urban soils in the infiltration process?

Study area and data

Soil data

Measured data, part of previous studies for urban sandy soils from three different places in Norway; Oslo, Trondheim and Sandnes, were used to evaluate urban soils. Table 1 shows the obtained data from field measurements and previous studies of these areas. A sensitivity analysis and evaluation of initial soil moisture content were conducted with the use of data from Sandnes.

Table 1 parameter values for urban sandy soils obtained from measurements and studies

Parameters		Unit	Oslo	Trondheim	Sandnes
Saturated hydraulic conductivity	K_{sat}	mm/h	104.64	31.88	14.05
Porosity	ϕ	-	0.34	0.34	-
Soil moisture content	θ_i	-	0.26	0.30	-
Source			Becker (2015; 2016)	Becker (2015; 2016)	Bandermann et al. (2013)

Climate data

A design storm of 120 min duration and 5-year return period from Blindern in Oslo, constructed by the symmetric hyetograph method (Bøyum et al. 1997) from an IDF-curve in the period of 1968-2017 obtained by Norwegian Centre for Climate Services (NCCS) (2018, 04.04.2018), was used for Oslo, Trondheim and Sandnes to compare the urban soils. The total precipitation for the event is 28.52 mm, as shown in the hyetograph in Figure 1. The chosen event is based on step one in the three-steps strategy described by Lindholm et al. (2008), where the main goal is to intercept and infiltrate the rain water. The evaporation in Norway vary from approximately 50 mm/year in mountain areas to 500 mm/year in lower areas (Hanssen-Bauer et al. 2009).

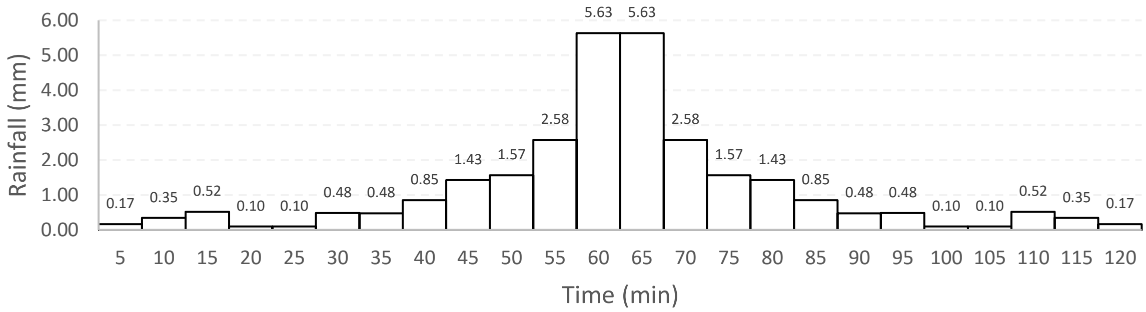


Figure 1 Design storm with 5-year return period and duration of 120 min

Methods

Green-Ampt and Horton infiltration method are evaluated in SWMM, and Holtan infiltration method is evaluated in STORM. The study is divided into three steps; (1) using the methods for urban sandy soils from three different locations in Norway; (2) sensitivity analysis is carried out; (3) long-term simulations with different initial conditions are conducted. The first step is conducted with measured data from Oslo, Trondheim, and Sandnes, while the sensitivity analysis and the long-term simulations are conducted with data from Sandnes.

Model setup

In order to evaluate the different infiltration methods, a simplified watershed with a 100% pervious area of 100 m^2, and a depression storage, d_s, for grassed urban surfaces of 2.5 mm (Rossman & Huber 2016), was created in SWMM and STORM. A width of 20 m, a slope, S, of 1%, and a Manning's roughness coefficient, n, of 0.075 (Rossman & Huber 2016) was used in SWMM, and a soil depth of 1 m was used in STORM. The evaporation is set to 1 mm/day in both models, based on the average evaporation rate in Norway (Hanssen-Bauer et al. 2009).

Urban soils analysis

Single-event simulations were conducted on the three different urban sandy soils in Norway to evaluate the infiltration methods' response to different urban sandy soils, with the use of the rainfall event shown in Figure 1. First the simulations were done with initial soil moisture measured in field (wet conditions), then the simulations were done with initial soil moisture content set to 70% of field capacity (dry conditions). A summary of the input values is given in Table 2.

Table 2 Input values for the infiltration methods

Method	Parameters		Unit	Oslo	Trondheim	Sandnes
Green-Ampt	Saturated hydraulic conductivity	K_{sat}	mm/h	104.64*	31.88*	14.05*
	Suction head[1)]	ψ_s	mm/h	51.68	76.31	99.84
	Initial deficit, wet[2)]	θ_d	-	0.080	0.040	0.036
	Initial deficit, dry[2)]			0.260	0.258	0.220
Horton	Minimum infiltration rate	f_{min}	mm/h	104.64*	31.88*	14.05*
	Maximum infiltration rate, wet[3)]	f_{max}	mm/h	130.99	35.90	15.82
	Maximum infiltration rate, dry[3)]			190.02	57.75	25.00
	Decay coefficient[4)]	k_d	h^{-1}	4.0	4.0	4.0
Holtan	Minimum infiltration rate	f_{min}	mm/h	104.64*	31.88*	14.05*
	Maximum infiltration rate[5)]	f_{max}	mm/h	209.28	63.76	28.10
	Wilting point[6)]	WP	-	0.050	0.050	0.050
	Field capacity	FC	-	0.115[7)]	0.117[7)]	0.117[8)]
	Porosity	ϕ	-	0.340*	0.340*	0.302[9)]
	Initial soil moisture, wet	θ_i	-	0.260*	0.300*	0.266[10)]
	Initial soil moisture, dry			0.081	0.082	0.082

*See Table 1

1) Based on relationship between K_{sat} and ψ_s described in the SWMM technical manual (Rossman & Huber 2016).
2) The difference between porosity and initial soil moisture content.
3) Adjusted values to account for initial soil water content. It is set to the infiltration rate, when the initial soil moisture percentage of porosity is taken away from the infiltrated water above f_{min} within 2 hours, based on equation [1] (see Appendix A).
4) From recommendation by SWMM technical manual (Rossman & Huber 2016).
5) Maximum infiltration rate is assumed to be double the minimum infiltration rate, where the values are within the measured values for compacted sandy soils by Pitt et al. (1999).
6) Based on values from Wang et al. (2017).
7) Calculated based on measured values and method described by Becker (2016).
8) Assumed the same as for Trondheim.
9) Khan et al. (2012) showed that the porosity of sandy soils can be significantly reduced due to compaction. A 31% reduction to the recommended typical porosity for sandy sand from Rossman & Huber (2016) was used.
10) Initial soil moisture percentage of porosity is assumed the same as in Trondheim, due to high amount of rainy days in both locations (NCCS 2018).

Sensitivity analysis

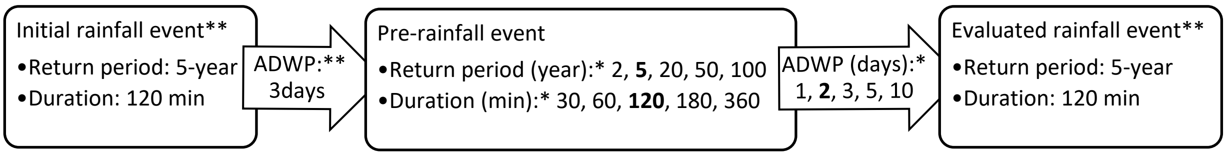
A sensitivity analysis for single event simulations was performed for Sandnes in both wet and dry condition to identify the parameters that influence the method performance most. An approach described by Jewell et al. in 1978 (Rosa et al. 2015) was used, where the initial parameter values were changed within ±50%, while the other parameters were unchanged. The sensitivity to changes in the peak runoff, total runoff volume, peak delay, time to start of runoff, and runoff duration were calculated. The rainfall event shown in Figure 1 is used in the sensitivity analysis. The sensitivity of the change of parameters were compared using the following equation;

$$Sensitivity = \left(\frac{\partial R}{\partial P}\right)\left(\frac{P}{R}\right) \qquad [6]$$

Where ∂R is the difference between the output in the initial state and after changed parameter value, ∂P is the difference between the original and adjusted parameter, R is the original model output, and P is the original parameter value.

Initial moisture content

To compare the methods' ability to account for different initial conditions in the soil, long-term simulations with three rainfall events, initial rainfall, pre-rainfall, and evaluated rainfall are simulated for the urban sandy soil in Sandnes. The initial rainfall event, the evaluated rainfall event and the antecedent dry weather period (ADWP) between initial rainfall event and pre-rainfall event are constant, while the magnitude and return period of the pre-rainfall is changed, as well as the ADWP between the pre-rainfall and evaluated rainfall. The schematic procedure of the long-term simulations is shown in Figure 2.



** Return period, duration and ADWP are changed one at a time to evaluate the effect on the evaluated rainfall event. Highlighted values correspond to base values that are used when other rainfall characteristics are changed.*
*** Constant*

Figure 2 Schematic representation of the long-term simulations

A table of the storm events used as pre-rainfall obtained by symmetric hyetograph method (Bøyum et al. 1997) from IDF-curve from Blindern in Oslo in the period of 1968-2017 (NCCS, 2018, 04.04.2018), is shown in Appendix C. The values under 1 mm rainfall in 5 min were changed to 1 mm, in order to obtain continuing rainfall within the storm event. To obtain higher intensities for shorter durations, the symmetric hyetographs were made with different time steps, but the hyetographs with lesser time step than 5 min, were adjusted to 5 min in STORM, due to minimum time step of 5 min is possible in the model. The simulations were conducted with evaporation equal 1 mm/day and 7 mm/day, to evaluate the method's ability to account for this. The drying time in Horton is set to 4.20 days based on the embedded formula used in Green-Ampt, where the drying time is based on the K_{sat}-value (Rossman & Huber 2016). The maximum infiltration rate is set to double the minimum infiltration rate. For Holtan, the initial soil moisture is set to 70% of field capacity. For Green-Ampt, the initial deficit is set equal to the porosity, to make the method consider the whole spectre of available storage for water.

Results and discussion

Urban soils analysis

The design event did not generate surface runoff in Oslo since the rainfall intensity never reaches the infiltration rate at saturation. It is generated more surface runoff for Sandnes than for Trondheim, as expected, due to the soil characteristics, shown in Table 2. There is a large difference in peak runoff, runoff volume, and runoff duration between the different urban sandy soils as seen in Table 3, which confirms the difficulty of classifying an urban soil. It is important to notice that there is a difference in the model setup in SWMM and STORM. SWMM routes the surface runoff to an outlet, while STORM is simulated without routing, which makes a different runoff distribution for the two models.

Table 3 Runoff characteristics for urban sandy soils in Sandnes and Trondheim.

	Sandnes						Trondheim					
	Wet conditions			Dry conditions			Wet conditions			Dry conditions		
	G-A	Horton	Holtan	G-A	Horton	Holtan	G-A	Horton	Holtan	G-A	Horton	Holtan
Peak (l/s)	1.46	1.45	1.45	0.42	1.40	1.18	0.81	0.78	0.91	0.00	0.45	0.29
Volume (m3)	1.01	0.99	1.23	0.10	0.88	0.80	0.27	0.25	0.54	0.00	0.10	0.17
Peak delay (min)	65	65	60	65	65	65	65	65	65	-	65	65
Start time (min)	56	56	45	62	57	55	60	60	60	-	62	60
Duration (min)	30	30	40	11	29	20	13	13	10	0	9	10
Runoff (mm)	10.08	9.89	12.25	1.03	8.76	8.03	2.74	2.54	5.44	0.00	1.02	1.69

Note that Holtan is simulated with 5 min time step and is not routed to an outlet as in Green-Ampt (G-A) and Horton.

The different methods generate similar results for wet conditions, compared to dry conditions for both Sandnes and Trondheim. It appears that the methods are more similar closer to saturation, since the infiltration rate at saturation is the same in all methods, corresponding to the location. The varying results between the methods for dry conditions, indicate that the methods behave different in the process from a dry to a saturated condition. This is an important finding with respect to the choice of method. If saturated conditions are assumed as a conservative measure, it is less important which method is chosen for infiltration. However, if saturated conditions are not assumed, the selection of method will have a large influence on the result.

The runoff hydrograph, shown in Figure 3, is approximately equal for Green-Ampt and Horton for wet conditions. For the dry condition in Sandnes, the peak runoff and runoff volume for Green-Ampt is only 30% and 11%, respectively, of the peak runoff and runoff volume for Horton. In Horton it is assumed a maximum infiltration rate. Since the soil capacity is filled up during the first lower intensities, the highest infiltration rate reached in Horton for dry condition is 18.65 mm/h in Sandnes. Green-Ampt, also consider the cumulative amount of infiltrated water, but since the method is based on the available pores for water storage, the highest infiltration rate is almost three times as high as in Horton. Since Green-Ampt is not depending on a maximum infiltration rate, the method will not generate any surface runoff if there is storage available for water in the soil. Horton generate almost similar results in dry and wet conditions in Sandnes. The reason for this is that maximum infiltration rate is the only parameter that distinguishes wet and dry conditions. This is governed by the second part of equation [3], where the difference in maximum and minimum infiltration rate is the driver. For Trondheim, there is a larger difference between these values than for Sandnes, hence more difference in runoff characteristics between wet and dry conditions is shown for Trondheim. It can be seen that, as the maximum infiltration rate gets closer to minimum infiltration rate, the difference between the runoff characteristics between a wet and dry condition will decrease for Horton. This principal difference in how Green-Ampt and Horton generate surface runoff from a dry soil should be evaluated when choosing infiltration method in SWMM to obtain the most realistic runoff behaviour for a specific soil.

The third method, the Holtan method used in STORM is based on continuously calculating the soil moisture content. For a soil moisture content between wilting point and field capacity, the infiltration decreases continuously from a maximum infiltration rate. Reaching soil porosity, the infiltration rate is set to a minimum. Exfiltration starts at a slow rate when the soil moisture content is 70% of field capacity, before it reaches minimum infiltration rate when the soil moisture content reaches the soil porosity. In addition to maximum infiltration rate, Holtan also considers available soil storage at a specific time, as such, allows for more water to infiltrate compared to Horton, due to still available storage capacity in the soil. Holtan’s ability to account for both maximum infiltration rate, and available storage gives the method more confidence. Nevertheless, the reader should be aware that the method requires more available soil data than Green-Ampt and Horton, which often is not available, and difficult to obtain.

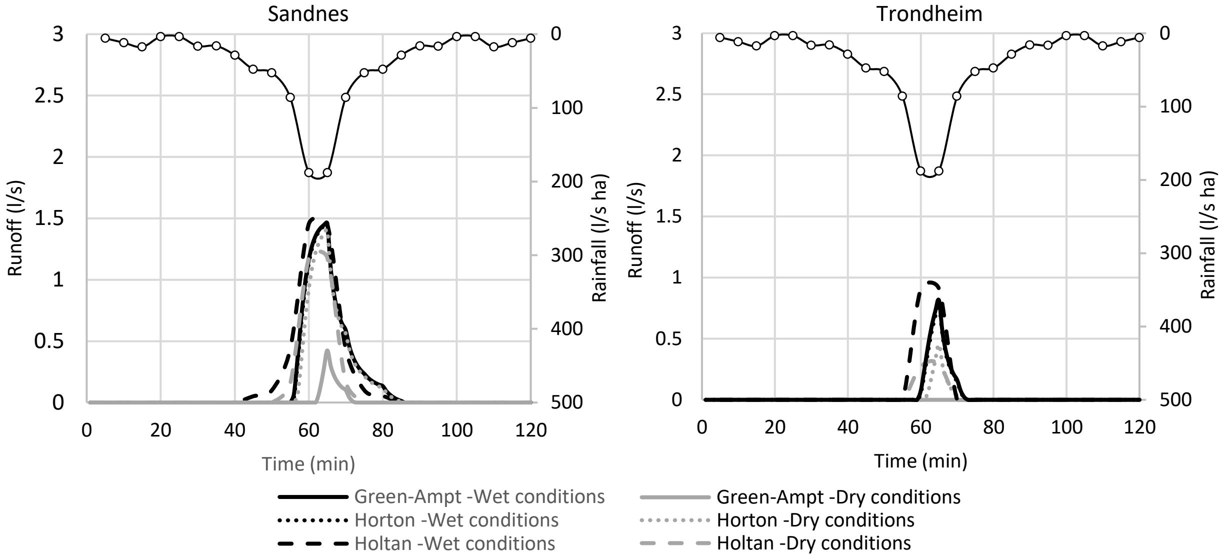


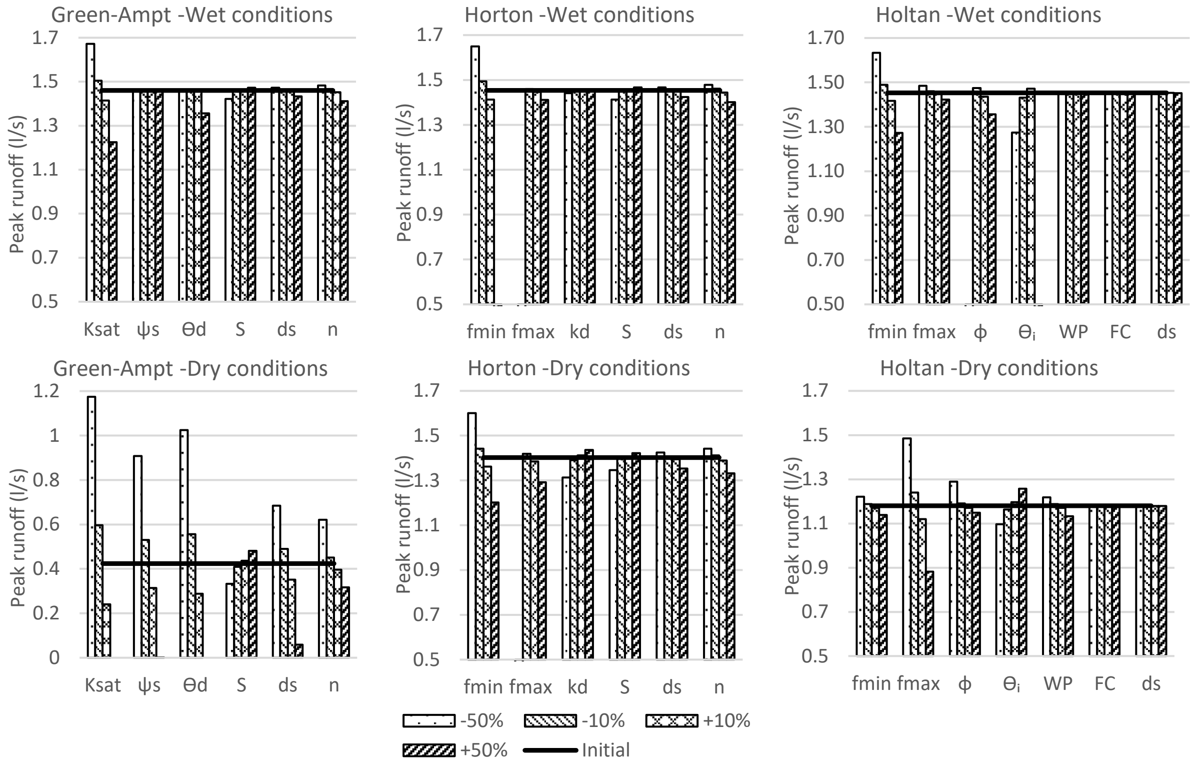
Figure 3 Runoff hydrographs for Sandnes (left) and Trondheim (right). Note that due to model-setup, the runoff from Green-Ampt and Horton in SWMM is routed to an outlet, whereas the runoff from Holtan in STORM is simulated without routing. Horton and Green-Ampt is approximately same for wet conditions, hence the graph is not visible.

From Figure 3, it is shown that there is a difference in peak runoff between dry and wet condition, but with varying difference between the methods. For design purposes, it is therefore important to evaluate the runoff characteristics for both wet and dry conditions based on the site-specific weather conditions.

Sensitivity analysis

The sensitivity analysis was conducted for the urban sandy soil in Sandnes to evaluate the methods' sensitivity in changes of parameter values. The sensitivity to change of parameter values for the different infiltration methods with respect to the runoff characteristics are shown in Table 4 for wet condition and in Table 5 for dry condition.

In Green-Ampt, the governing parameters are saturated hydraulic conductivity, suction head, and initial deficit. For both wet and dry conditions, saturated hydraulic conductivity is the most sensitive parameter. A 50% reduction of this parameter leads to more than 50% decrease in runoff volume for a wet condition. In literature it is shown that an even bigger reduction than 50% can be the case for compacted urban soils (Gregory et al. 2006). Thus, it is important to have a high degree of confidence in chosen value for this parameter. As can be seen in Figure 4, all the governing parameters in Green-Ampt are essential for dry condition. For a wet condition the most sensitive parameter is saturated hydraulic conductivity, followed by increasing initial deficit, while there are no changes in runoff characteristics when changing the suction head. Assuming worst case scenario, saturated condition, for design practices, this indicates that saturated hydraulic conductivity is the essential parameter to be considered. For dry conditions, on the other hand, all parameters should be considered.



Ksat=Saturated hydraulic conductivity, ψs=Suction head, θd=Initial deficit, S=Slope, ds=Depression storage, n=Manning's roughness, fmin=Minimum infiltration rate, fmax=Maximum infiltration rate, kd=Decay coefficient, ϕ=Porosity, θ_i=Initial soil moisture, WP=Wilting point, FC=Field capacity

Figure 4 Input parameters' sensitivity to peak runoff

Horton method is most sensitive to the minimum infiltration rate for wet conditions. For dry conditions the method is also most sensitive to minimum infiltration rate, followed by maximum infiltration rate and decreasing the decay coefficient. For dry conditions, the sensitivity of maximum infiltration rate is observed to be slightly higher than for wet conditions. This might be an explanation for the relatively small difference between wet and dry conditions for Sandnes using Horton, compared to the other methods. Holtan, on the other hand, shows the highest degree of sensitivity for maximum infiltration rate under dry conditions, while it is most sensitive to minimum infiltration rate under wet conditions. By increasing the maximum infiltration rate by 10% in Horton for a dry condition, the peak runoff decreases only by 1.3%. The corresponding value for Holtan is a 5.1% change in peak runoff. Holtan's ability to continuously calculating the soil moisture content in the soil leads to a higher sensitivity in the parameters; maximum infiltration rate, initial soil moisture content and porosity, especially for dry soil conditions. Measurements of compacted sandy soils showed that maximum infiltration rate (Pitt et al. 1999) and porosity (Khan et al. 2012) can be significantly reduced due to compaction. Hence, field measurements for these parameters are also important when conducting single-event simulations on urban soils with Holtan. Whereas for Horton, the minimum infiltration rate is more important for both conditions, but also maximum infiltration rate should be considered with simulations for dry conditions.

In general, the sensitivity analysis shows that as accurate value for the infiltration rate as possible is needed to generate accurate results with the infiltration methods. As shown in the results of urban sandy soils in Norway, the runoff characteristics from different urban sandy soils show a large variation in infiltration rate. The use of standard values or values from compacted soils from another field can lead to a wrong estimation, since a small change in input value can lead to a big change in output value. This is in agreement with what Pitt et al. (1999) and Law et al. (2009) reported. In addition, compacted urban soils lead to a decrease in infiltration rate (Gregory et al. 2006). Based on this, the methods can underestimate the surface runoff, leading to an underestimation of design practices with the use of data from non-urban soils.

Table 4 Sensitivity of parameters where the initial parameter values are changed from -50% to +50% for wet conditions.

	-50%					-10%					+10%					+50%				
	Peak runoff	Runoff volume	Peak delay	Time to start	Runoff duration	Peak runoff	Runoff volume	Peak delay	Time to start	Runoff duration	Peak runoff	Runoff volume	Peak delay	Time to start	Runoff duration	Peak Runoff	Runoff volume	Peak delay	Time to start	Runoff duration
Green-Ampt Infiltration method -Wet conditions																				
K_{sat}	**-0.29**	**-1.05**	0.00	**0.14**	**-1.00**	**-0.30**	**-0.93**	0.00	0.00	**-0.67**	**-0.31**	**-0.91**	0.00	0.00	**-0.33**	**-0.32**	**-0.75**	0.00	**0.07**	**-0.47**
ψ_s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
θ_d	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**-0.15**	**-0.43**	0.00	**0.04**	**-0.14**
S	**0.05**	**0.03**	0.00	0.00	**-0.13**	**0.03**	**0.02**	0.00	0.00	**-0.33**	**0.02**	**0.02**	0.00	0.00	0.00	**0.02**	**0.01**	0.00	0.00	0.00
d_s	**-0.02**	**-0.25**	0.00	**0.11**	**-0.20**	**-0.02**	**-0.25**	0.00	0.00	0.00	**-0.03**	**-0.25**	0.00	0.00	0.00	**-0.04**	**-0.25**	0.00	**0.04**	**-0.07**
n	**-0.03**	**-0.04**	0.00	0.00	**0.07**	**-0.05**	**-0.04**	0.00	0.00	0.00	**-0.06**	**-0.04**	0.00	0.00	**0.31**	**-0.07**	**-0.04**	0.00	0.00	**0.13**
Horton Infiltration method -Wet conditions																				
f_{min}	**-0.27**	**-0.90**	0.00	**0.11**	**-0.93**	**-0.27**	**-0.81**	0.00	0.00	**-0.67**	**-0.28**	**-0.78**	0.00	0.00	**-0.33**	*	*	*	*	*
f_{max}	*	*	*	*	*	**-0.04**	**-0.17**	0.00	0.00	0.00	**-0.05**	**-0.19**	0.00	0.00	0.00	**-0.06**	**-0.20**	0.00	**0.04**	**-0.07**
k_d	**0.02**	**0.05**	0.00	0.00	0.00	**0.01**	**0.03**	0.00	0.00	0.00	**0.01**	**0.03**	0.00	0.00	0.00	**0.01**	**0.02**	0.00	0.00	0.00
S	**0.06**	**0.03**	0.00	0.00	**-0.07**	**0.03**	**0.02**	0.00	0.00	**-0.33**	**0.02**	**0.02**	0.00	0.00	0.00	**0.02**	**0.02**	0.00	0.00	0.00
d_s	**-0.02**	**-0.25**	0.00	**0.11**	**-0.20**	**-0.03**	**-0.26**	0.00	0.00	0.00	**-0.03**	**-0.26**	0.00	0.00	0.00	**-0.04**	**-0.25**	0.00	**0.07**	**-0.13**
n	**-0.03**	**-0.04**	0.00	0.00	**0.07**	**-0.05**	**-0.04**	0.00	0.00	0.00	**-0.06**	**-0.04**	0.00	0.00	**0.31**	**-0.07**	**-0.04**	0.00	0.00	**0.13**
Holtan infiltration method -Wet conditions																				
f_{min}	**-0.25**	**-0.73**	0.00	0.00	**-0.25**	**-0.25**	**-0.71**	0.00	0.00	0.00	**-0.25**	**-0.70**	0.00	0.00	0.00	**-0.25**	**-0.50**	**0.17**	**0.44**	**-1.00**
f_{max}	**-0.04**	**-0.13**	0.00	0.00	0.00	**-0.05**	**-0.13**	**-0.83**	0.00	0.00	**-0.04**	**-0.13**	**0.83**	0.00	0.00	**-0.04**	**-0.13**	**0.17**	0.00	0.00
ϕ	*	*	*	*	*	**-0.15**	**-0.41**	**-0.84**	0.00	0.00	**-0.12**	**-0.36**	**0.84**	0.00	0.00	**-0.13**	**-0.34**	**0.17**	**0.44**	**-0.75**
θ_i	**0.25**	**0.50**	**-0.17**	**-0.44**	**1.00**	**0.15**	**0.45**	**-0.85**	0.00	0.00	**0.13**	**0.37**	0.00	0.00	0.00	*	*	*	*	*
WP	**0.00**	**0.00**	0.00	0.00	0.00	0.00	**0.00**	0.00	0.00	0.00	0.00	**-0.01**	**0.83**	0.00	0.00	**0.00**	**-0.03**	0.00	**0.22**	**-0.25**
FC	**-0.01**	**-0.02**	0.00	0.00	0.00	**-0.01**	**-0.02**	0.00	0.00	0.00	**-0.01**	**-0.02**	0.00	0.00	0.00	**-0.01**	**-0.02**	0.00	0.00	0.00
d_s	**0.01**	**0.02**	0.00	0.00	0.00	**0.01**	**0.02**	0.00	0.00	0.00	**0.01**	**0.02**	0.00	0.00	0.00	**0.01**	**0.02**	**0.17**	0.00	0.00

** Not possible. Initial soil moisture content cannot be higher than porosity. Minimum infiltration rate cannot be higher than maximum infiltration rate.*

K_{sat}=Saturated hydraulic conductivity, ψ_s=Suction head, θ_d=Initial deficit, S=Slope, d_s=Depression storage, n=Manning's roughness, f_{min}=Minimum infiltration rate, f_{max}=Maximum infiltration rate, k_d=Decay coefficient, ϕ=Porosity, θ_i=Initial soil moisture, WP=Wilting point, FC=Field capacity

Table 5 Sensitivity of parameters where the initial parameter values are changed from -50% to +50% for dry conditions

	-50%					-10%					+10%					+50%				
	Peak runoff	Runoff volume	Peak delay	Time to start	Runoff duration	Peak runoff	Runoff volume	Peak delay	Time to start	Runoff duration	Peak runoff	Runoff volume	Peak delay	Time to start	Runoff duration	Peak Runoff	Runoff volume	Peak delay	Time to start	Runoff duration
Green-Ampt Infiltration method -Dry conditions																				
K_{sat}	**-3.54**	**-9.27**	0.00	**0.10**	**-2.73**	**-4.10**	**-6.79**	0.00	0.00	**-1.82**	**-4.31**	**-5.61**	0.00	**0.16**	**-1.81**	**	**	**	**	**
ψ_s	**-2.29**	**-4.68**	0.00	**0.06**	**-1.27**	**-2.51**	**-3.89**	0.00	0.00	**-0.91**	**-2.58**	**-3.43**	0.00	**0.16**	**-1.82**	**-2.00**	**-2.00**	0.00	**0.10**	**-1.82**
θ_d	**-2.83**	**-6.30**	0.00	**0.10**	**-2.00**	**-3.12**	**-4.92**	0.00	0.00	**-0.91**	**-3.20**	**-4.20**	0.00	**0.16**	**-1.82**	**	**	**	**	**
S	**0.43**	**0.26**	0.00	0.00	**-0.18**	**0.34**	**0.19**	0.00	0.00	0.00	**0.32**	**0.17**	0.00	0.00	0.00	**0.27**	**0.14**	0.00	0.00	0.00
d_s	**-1.23**	**-2.28**	0.00	**0.06**	**-0.55**	**-1.57**	**-2.21**	0.00	0.00	0.00	**-1.71**	**-2.09**	0.00	**0.16**	**-0.91**	**-1.72**	**-1.80**	0.00	**0.10**	**-0.91**
n	**-0.95**	**-0.46**	0.00	0.00	**0.18**	**-0.70**	**-0.38**	0.00	0.00	0.00	**-0.62**	**-0.35**	0.00	0.00	0.00	**-0.50**	**-0.31**	0.00	0.00	**0.18**
Horton Infiltration method -Dry conditions																				
f_{min}	**-0.28**	**-0.91**	0.00	**0.04**	**-0.76**	**-0.29**	**-0.80**	0.00	0.00	**-0.35**	**-0.29**	**-0.74**	0.00	0.00	**-0.34**	**-0.29**	**-0.62**	0.00	**0.04**	**-0.41**
f_{max}	*	*	*	*	*	**-0.12**	**-0.35**	0.00	0.00	0.00	**-0.13**	**-0.34**	0.00	0.00	0.00	**-0.16**	**-0.36**	0.00	**0.04**	**-0.14**
k_d	**0.13**	**0.29**	0.00	**-0.04**	**0.21**	**0.09**	**0.22**	0.00	0.00	0.00	**0.07**	**0.19**	0.00	0.00	0.00	**0.05**	**0.14**	0.00	0.00	0.00
S	**0.08**	**0.04**	0.00	0.00	**-0.07**	**0.05**	**0.02**	0.00	0.00	0.00	**0.04**	**0.02**	0.00	0.00	0.00	**0.03**	**0.02**	0.00	0.00	0.00
d_s	**-0.03**	**-0.28**	0.00	**0.04**	**-0.07**	**-0.04**	**-0.29**	0.00	0.00	0.00	**-0.05**	**-0.29**	0.00	0.00	0.00	**-0.07**	**-0.29**	0.00	**0.04**	**-0.07**
n	**-0.06**	**-0.05**	0.00	0.00	**0.14**	**-0.08**	**-0.05**	0.00	0.00	0.00	**-0.09**	**-0.05**	0.00	0.00	0.00	**-0.10**	**-0.04**	0.00	0.00	**0.07**
Holtan infiltration method -Dry conditions																				
f_{min}	**-0.07**	**-0.12**	0.00	0.00	0.00	**-0.07**	**-0.12**	0.00	0.00	0.00	**-0.08**	**-0.12**	0.00	0.00	0.00	**-0.07**	**-0.12**	0.00	0.00	0.00
f_{max}	**-0.52**	**-1.24**	**0.15**	**0.36**	**-2.00**	**-0.51**	**-0.91**	0.00	0.00	0.00	**-0.51**	**-0.90**	0.00	0.00	0.00	**-0.51**	**-0.69**	0.00	**0.18**	**-1.00**
ϕ	**-0.18**	**-0.32**	0.00	0.00	0.00	**-0.09**	**-0.16**	0.00	0.00	0.00	**-0.08**	**-0.13**	0.00	0.00	0.00	**-0.05**	**-0.09**	0.00	0.00	0.00
Θ_i	**0.14**	**0.24**	0.00	0.00	0.00	**0.15**	**0.25**	0.00	0.00	0.00	**0.14**	**0.25**	0.00	0.00	0.00	**0.13**	**0.23**	0.00	0.00	0.00
WP	**0.00**	**-0.01**	0.00	0.00	0.00	0.00	**-0.01**	0.00	0.00	0.00	**-0.01**	**-0.01**	0.00	0.00	0.00	**0.00**	**0.00**	0.00	0.00	0.00
FC	**-0.06**	**-0.11**	0.00	0.00	0.00	**-0.07**	**-0.13**	0.00	0.00	0.00	**-0.08**	**-0.13**	0.00	0.00	0.00	**-0.08**	**-0.14**	0.00	0.00	0.00
d_s	**0.01**	**0.01**	0.00	0.00	0.00	0.00	**-0.01**	0.00	0.00	0.00	**-0.01**	**-0.01**	0.00	0.00	0.00	**-0.01**	**-0.01**	0.00	0.00	0.00

** Not possible. Minimum infiltration rate cannot be higher than maximum infiltration rate.*

*** No runoff.*

K_{sat}=Saturated hydraulic conductivity, ψ_s=Suction head, θ_d=Initial deficit, S=Slope, d_s=Depression storage, n=Manning's roughness, f_{min}=Minimum infiltration rate, f_{max}=Maximum infiltration rate, k_d=Decay coefficient, ϕ=Porosity, θ_i=Initial soil moisture, WP=Wilting point, FC=Field capacity

Initial moisture content

Long-term simulations for the soil in Sandnes were conducted to evaluate the methods' ability to account for initial soil moisture content in the soil before a precipitation event. An essential role of this is the way the methods are modelling the regeneration of soil moisture content from a saturated soil to a dry soil. The methods' response to changes in return period of pre-rainfall, antecedent dry weather period (ADWP) after pre-rainfall, and duration of pre-rainfall are shown in Figure 5. Note that the evaluated rainfall is constant.

The runoff characteristics of the evaluated rainfall are minimally affected by changes in the return period of the pre-rainfall for any of the methods. Return periods between 2 and 100 years were used, where the peak rainfall intensity is higher than the minimum infiltration rate for the soil in Sandnes. This indicates that the soil reaches a saturated condition during pre-rainfall, hence no difference in soil conditions at the evaluated rainfall event is expected.

Green-Ampt is highly affected by changes in ADWP after pre-rainfall between 1 and 5 days. Horton shows a smaller change in runoff characteristics by changing ADWP between 1 and 3 days. This indicates that Green-Ampt reaches a dry condition after 5 days, whereas Horton reaches a dry condition after 3 days. This can be an explanation for the differences in the methods' reaction to changes in duration of pre-rainfall. Green-Ampt is more affected by changes in the pre-rainfall's duration than Horton. The slope of the graph at ADWP equal 2 days in Green-Ampt (Figure 5.1B) is higher than for Horton (Figure 5.2B). This in turn indicates that a longer duration has a larger effect on the surface runoff for Green-Ampt, due to a longer duration of pre-rainfall leads to rainfall closer to the evaluated rainfall.

SWMM calculates evapotranspiration (ET) only when there is surface water available. This happens as a part of the recovery of depression storage, and when water is available on the surface, but it is not part of the recovery of soil moisture (Rossman & Huber 2016). This leads to approximately no difference when changing the ET-value for Green-Ampt and Horton, as seen in Figure 5.1 and 5.2. A study by Seneviratne et al. (2010) showed the complexity of factors contributing to changes in soil moisture content, where ET has various effect on the soil depending on the climate. Norway has a large temporal, and geographical variation in climate (Hanssen-Bauer et al. 2009). Ignoring ET in the soil moisture recovery calculation, may lead to an overestimation of runoff in summers and underestimation of runoff in winters. This indicates that long-term simulations of catchments with significant permeable areas in SWMM can be unsuitable for climates with changing characteristics, especially where the ET-value is low, due to the fast recovery time from saturated to dry condition.

Holtan shows a large difference when changing the ET-value (Figure 5.3). The main source of soil water loss in STORM is exfiltration and ET. Exfiltration starts when soil moisture content is equal to 70% of field capacity, and ET takes place as long as the soil moisture content is more than the wilting point. The difference between the output for the two ET values when changing the return period and duration of pre-rainfall is approximately constant (Figure 5.3A and 5.3C) since there is the same number of ADWP before the evaluated rainfall. As the number of ADWP after pre-rainfall is increasing, the difference between the output-values when changing ET-value increases (Figure 5.3B). This makes Holtan suitable for long-term simulations for study sites with changing climate during a year since the method gives the option of annual changes in ET.

The largest difference between the methods are their responses to changes in ADWP after the pre-rainfall (Figure 5.1B, 5.2B, and 5.3B). For Green-Ampt, SWMM uses a simplified method where the recovery time is a function of saturated hydraulic conductivity, and by keeping track of the initial deficit value. In this way a typical clayey soil with low saturated hydraulic conductivity has a longer drying time than a sandy soil with high saturated hydraulic conductivity (Rossman & Huber 2016). As shown in the study of urban soils in Norway, urban sandy soils can have a large variation in runoff characteristics. This simplification should therefore be considered with care and should be a part of the calibration process of saturated hydraulic conductivity if Green-Ampt is used for long-term calculations.

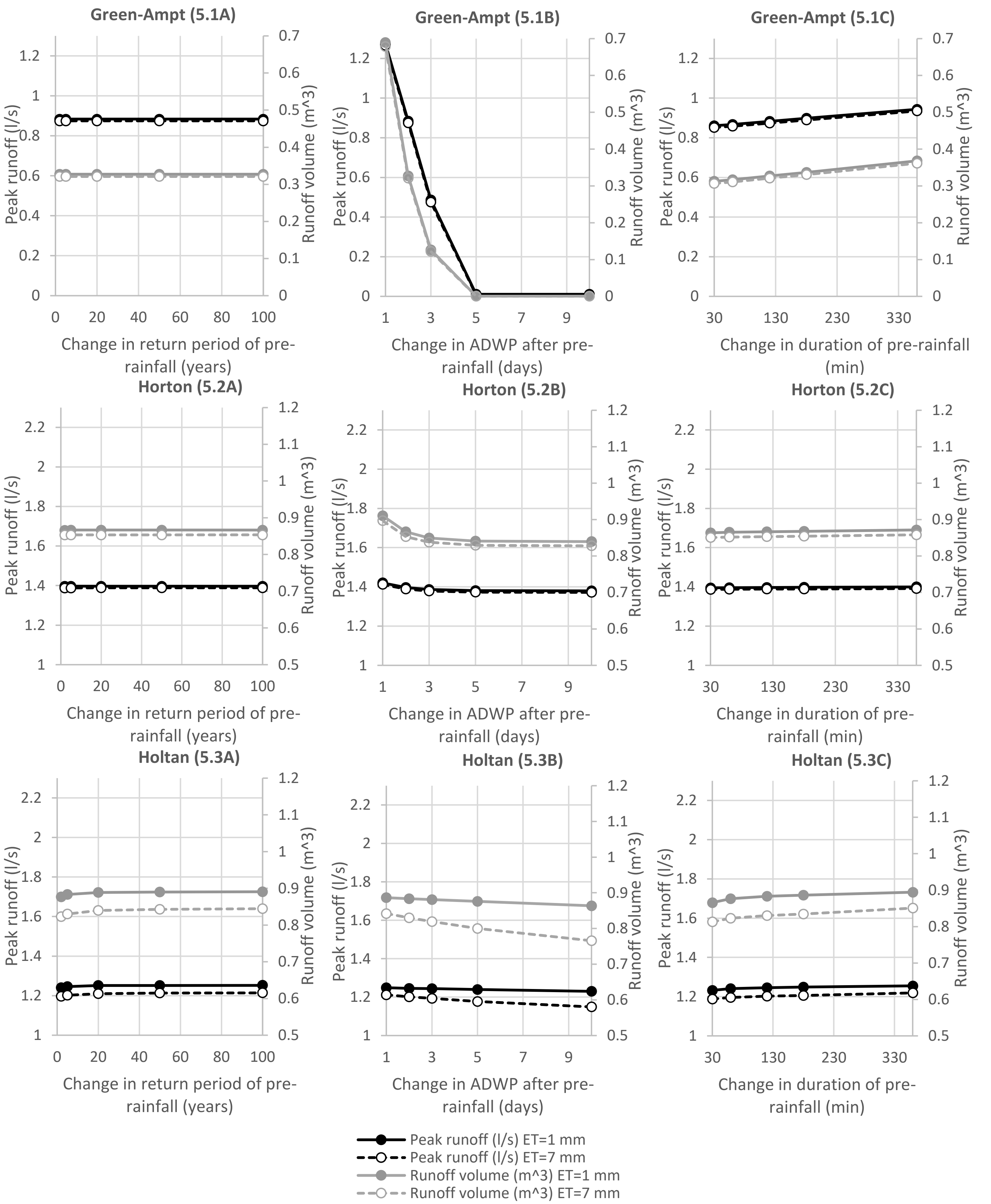


Figure 5 Green-Ampt (1), Horton (2), and Holtan (3) infiltration method response to changes in return period of pre-rainfall (A), ADWP after pre-rainfall (B), and duration of pre-rainfall (C).

Horton gives the option of a user-specified value for regeneration of infiltration capacity. The value for this in Figure 5.2 is based on the embedded formula in SWMM used for Green-Ampt. Horton goes faster towards dry condition than with the use of Green-Ampt, due to the models' procedure of calculating the recovery process (Rossman & Huber 2016). The sensitivity of drying time-value was not included in the conducted sensitivity analysis. In order to investigate this, the sensitivity of changing this parameter ±50% from the initial value, 4.20 days, with changing ADWP, and maximum infiltration rate (f_{max}) were performed to evaluate the effect on peak runoff. The results show that drying time is more sensitive if the maximum infiltration rate is larger (Figure 6). With maximum infiltration rate equal to two times minimum infiltration rate, there is almost no change when changing the drying time and ADWP. This indicates that the drying time-parameter should be evaluated if there is a larger difference between the minimum infiltration rate and maximum infiltration rate. However, the regeneration time to a dry state is relatively fast, which suggests that Horton is better suited for single-event simulation or if it is known that the soil changes rapidly from saturated to dry condition.

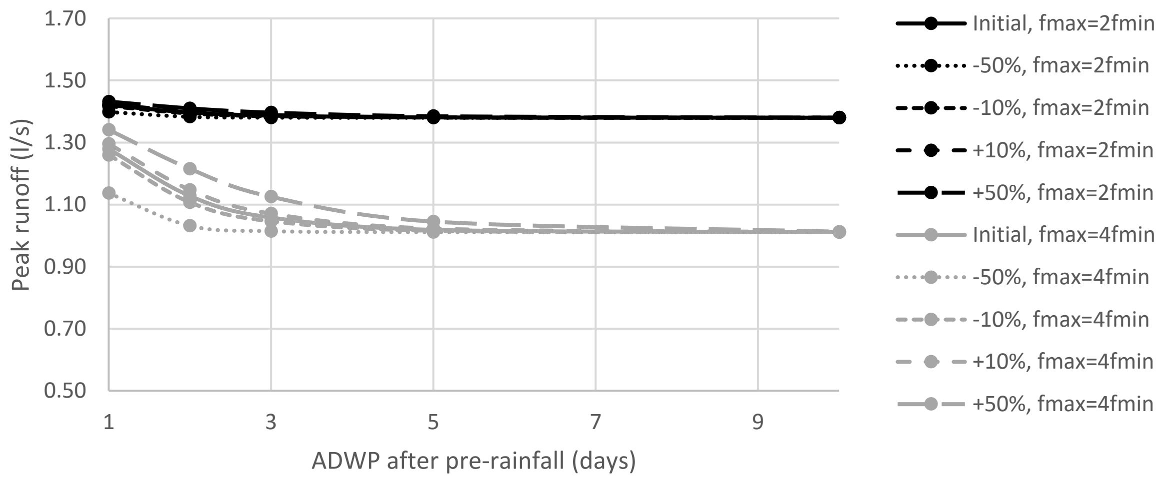


Figure 6 Horton's sensitivity to changing drying time ±50% with maximum infiltration rate equal to two times and four times minimum infiltration rate.

Conclusions

In this study Green-Ampt, Horton, and Holtan infiltration methods in the SWMM and STORM model have been used to evaluate the methods' performance in modelling infiltration for urban permeable surfaces.

There are different parameters that account for the initial soil moisture in different infiltration methods. Green-Ampt infiltration method takes the available storage for water into account, while for Horton a user specified maximum infiltration rate is needed. Holtan method accounts for both these parameters, giving the method more confidence, but it requires more input data than the other two methods. If dry initial conditions are assumed, the selection of method should be based on the available field data. However, if saturated conditions are assumed as a conservative measure for design practices, it is less important which method is chosen for infiltration. Green-Ampt's and Horton's lack of accounting for evapotranspiration in the regeneration of soil moisture makes it less suitable for long-term simulations. For design purposes, the use of these methods will likely overestimate or underestimate the surface runoff depending on the variation in climate. Holtan infiltration method is more suitable for long-term simulations, due to its ability to account for evapotranspiration.

The methods are most sensitive to changes in infiltration rate at saturation under saturated conditions. Additional soil infiltration parameters in the methods are more important for dry soil conditions. Green-Ampt is most sensitive to saturated hydraulic conductivity, followed by initial deficit and suction head for dry condition. Horton is most sensitive to minimum infiltration rate, followed by maximum infiltration rate and decreasing the decay coefficient in dry conditions. Holtan method is most sensitive to maximum infiltration rate, followed by porosity and initial soil moisture content for dry condition.

To obtain accurate results for urban compacted sandy soils with the simplified infiltration methods used in this study, field measurement of infiltration rate is essential. This study highlights three reasons for this; (1) There is a big variance in field measurements from different compacted urban sandy soils leading to different runoff characteristics, (2) the methods show a high sensitivity to infiltration rate, implying that a small change in the parameter, leads to a big change in runoff characteristics, (3) literature shows that compaction can lead to a significant reduction in infiltration rate. The use of parameter values from a different urban sandy soil or standard soil data from literature, can lead to wrong estimations of runoff characteristics.

The represented methods in this study are easy to use, but due to their simplification, there are many limitations for the use on urban soils. Urban soils have various additional parameters that can affect the infiltration procedure, which these methods are not accounting for. Hence, field measurements are important. Future studies should focus on a classification system of urban soils, in order to describe the complexity of urban soils' characteristics. Furthermore, the hydrological models should be adjusted to account for parameters that are typical for urban soils.

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References

Bandermann, S., Potrawiak, J. & Sommer, H., 2013. *Feasibility study -Flood Mitigation by on-site stormwater management (SUDS) -Preplanning of SUDS in Sandnes City*,

Bauwe, A., Kahle, P. & Lennartz, B., 2016. Hydrologic evaluation of the curve number and Green and Ampt infiltration methods by applying Hooghoudt and Kirkham tile drain equations using SWAT. *Journal of Hydrology*, 537, pp.311–321. Available at: http://dx.doi.org/10.1016/j.jhydrol.2016.03.054.

Becker, M.A., 2016. *Assessment of Downspout Disconnection by Modeling Infiltration Potential in Urban Areas*. Norwegian University of Science and Technology (NTNU). Available at: http://hdl.handle.net/11250/2433619.

Becker, M.A., 2015. *Beregning av mettet hydraulisk konduktivitet ved bruk av MPD-infiltrometer, for vurdering av frakopling av taknedløp (Calculation of saturated hydraulic conductivity using MPD infiltrometer to investigate the effect of disconnecting roof drains)*. Norwegian University of Science and Technology (NTNU).

Bøyum, Å. et al., 1997. Anvendt Urbanhydrologi (Applied Urban Hydrology). *The Norwegian Water Resources and Energy Directorate (NVE)*. Available at: https://www.nve.no/hydrologi/urbanhydrologi/.

Davidsen, S. et al., 2018. Initial conditions of urban permeable surfaces in rainfall-runoff models using Horton's infiltration. *Water Science and Technology*, 77(3), pp.662–669. Available at: http://wst.iwaponline.com/lookup/doi/10.2166/wst.2017.580.

Esteves, M. et al., 2000. Overland flow and infiltration modelling for small plots during unsteady rain: numerical results versus observed values. *Journal of Hydrology*, 228(3–4), pp.265–282. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0022169400001554.

Gregory, J. et al., 2006. Effect of urban soil compaction on infiltration rate. *Journal of Soil and Water Conservation*, 61(3), pp.117–124. Available at: http://www.jswconline.org/content/61/3/117.abstract.

Haghighi, F. et al., 2010. Evaluation of some infiltration models and hydraulic parameters. *Spanish Journal of Agricultural Research*, 8(1), pp.210–217. Available at: http://revistas.inia.es/index.php/sjar/article/view/1160.

Hanssen-Bauer, I. et al., 2009. Klima i Norge 2100 Bakgrunnsmateriale til NOU Klimatilplassing (Climate in Norway 2100 Background material for NOU Climate adaptation). *Norwegian Centre for Climate Services (NCCS)*. Available at: http://hdl.handle.net/11250/117195.

Holtan, H.N., 1961. A concept for infiltration estimates in watershed engineering. *United States Dept. of Agriculture*, 41–51.

Holtan, H.N. & Lopez, N.C., 1971. USDAHL-70 model of watershed hydrology. *United States Department of Agriculture*. Available at: http://purl.umn.edu/171863.

Horton, R.E., 1941. An Approach Toward a Physical Interpretation of Infiltration-Capacity1. *Soil Science Society of America Journal*, 5(C). Available at: https://www.soils.org/publications/sssaj/abstracts/5/C/SS00500C0399.

Jiang, Y., Zevenbergen, C. & Ma, Y., 2018. Urban pluvial flooding and stormwater management: A contemporary review of China's challenges and "sponge cities" strategy. *Environmental Science and Policy*, 80, pp.132–143. Available at:

https://doi.org/10.1016/j.envsci.2017.11.016.
Khan, S.R., Abbasi, M.K. & Hussan, A.U., 2012. Effect of Induced Soil Compaction on Changes in Soil Properties and Wheat Productivity under Sandy Loam and Sandy Clay Loam Soils: A Greenhouse Experiment. *Communications in Soil Science and Plant Analysis*, 43(19), pp.2550–2563. Available at: http://www.tandfonline.com/doi/abs/10.1080/00103624.2012.711877.
Law, N.L., Cappiella, K. & Novotney, M.E., 2009. The Need for Improved Pervious Land Cover Characterization in Urban Watersheds. *Journal of Hydrologic Engineering*, 14(4), pp.305–308. Available at: https://doi.org/10.1061/(ASCE)1084-0699(2009)14:4(305).
Leandro, J., Schumann, A. & Pfister, A., 2016. A step towards considering the spatial heterogeneity of urban key features in urban hydrology flood modelling. *Journal of Hydrology*, 535, pp.356–365. Available at: http://dx.doi.org/10.1016/j.jhydrol.2016.01.060.
Lindholm, O. et al., 2008. Veiledning i klimatilpasset overvannshåndtering (Guidance on climate adapted stormwater management). *Norsk Vann*, 162.
Liong, B.S.Y., Chan, W.T. & Lum, L.H., 1991. Knowledge-Based System for SWMM Runoff Component Calibration. , 117(5), pp.507–524. Available at: https://doi.org/10.1061/(ASCE)0733-9496(1991)117:5(507).
Loosvelt, L. et al., 2013. Local sensitivity analysis for compositional data with application to soil texture in hydrologic modelling. *Hydrology and Earth System Sciences*, 17, pp.461–478. Available at: https://doi.org/10.5194/hess-17-461-2013.
Morel, J.L. et al., 2005. Urban Soils. In *Encyclopedia of Soils in the Environment*. pp. 202–208. Available at: https://doi.org/10.1016/B0-12-348530-4/00305-2%0A.
NCCS, 2018. Norwegian Centre for Climate Services (NCCS). Available at: https://klimaservicesenter.no/ [Accessed April 4, 2018].
Pitt, R. et al., 2008. Compaction's Impacts on Urban Storm-Water Infiltration. *Journal of Irrigation and Drainage Engineering*, 134(5), pp.652–658. Available at: https://doi.org/10.1061/(ASCE)0733-9437(2008)134:5(652).
Pitt, R. et al., 1999. Infiltration Through Disturbed Urban Soils and Compost- Amended Soil Effects on Runoff Quality and Quantity Research Report Infiltration Through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity. *Environmental Protection Agency*, (EPA/600/R-00/016).
Redfern, T.W. et al., 2016. Current understanding of hydrological processes on common urban surfaces. *Progress in Physical Geography*, 40(5), pp.699–713. Available at: http://journals.sagepub.com/doi/10.1177/0309133316652819.
Rosa, D.J., Clausen, J.C. & Dietz, M.E., 2015. Calibration and Verification of SWMM for Low Impact Development. *Journal of the American Water Resources Association*, 51(3), pp.746–757. Available at: http://doi.wiley.com/10.1111/jawr.12272.
Rossman, L. & Huber, W., 2016. Storm Water Management Model Reference Manual Volume I – Hydrology. *US EPA Office of Research and Development*, (EPA/600/R-15/162A). Available at: http://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100NYRA.txt.
Seneviratne, S.I. et al., 2010. Investigating soil moisture-climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3–4), pp.125–161. Available at: http://dx.doi.org/10.1016/j.earscirev.2010.02.004.
Song, X. et al., 2015. Global sensitivity analysis in hydrological modeling: Review of concepts, methods, theoretical framework, and applications. *Journal of Hydrology*, 523, pp.739–757. Available at: http://dx.doi.org/10.1016/j.jhydrol.2015.02.013.
Wang, X. et al., 2017. Performance of two prevalent infiltration models for disturbed urban soils. *Hydrology Research*, 48(6), pp.1520–1536. Available at: http://hr.iwaponline.com/lookup/doi/10.2166/nh.2017.217.

Appendix

Appendix A Calculation of maximum infiltration rate for Horton infiltration method

Table A1 Infiltration rates to find maximum infiltration rate for wet and dry condition for Horton infiltration method

	Oslo				Trondheim				Sandnes			
Time (min)	f_p (mm/h)	f_p, above f_{min} (mm/h)	*V*, above f_{min} (mm)	*Cum V*, above f_{min} (mm)	f_p (mm/h)	f_p, above f_{min} (mm/h)	*V*, above f_{min} (mm)	*Cum V*, above f_{min} (mm)	f_p (mm/h)	f_p, above f_{min} (mm/h)	V, above f_{min} (mm)	*Cum V*, above f_{min} (mm)
0	209.28	104.64	1.744	1.744	63.76	31.88	0.531	0.531	28.10	14.05	0.234	0.234
1	202.53	97.89	1.632	3.376	61.70	29.82	0.497	1.028	27.19	13.14	0.219	0.453
2	196.22	91.58	1.526	4.902	59.78	27.90	0.465	1.493	26.35	12.30	0.205	0.658
3	**190.31**	85.67	1.428	**6.330**	**57.98**	26.10	0.435	**1.928**	**25.55**	11.50	0.192	**0.850**
4	**184.79**	80.15	1.336	**7.665**	**56.30**	24.42	0.407	**2.335**	**24.81**	10.76	0.179	**1.029**
5	179.62	74.98	1.250	8.915	54.72	22.84	0.381	2.716	24.12	10.07	0.168	1.197
6	174.78	70.14	1.169	10.084	53.25	21.37	0.356	3.072	23.47	9.42	0.157	1.354
7	170.26	65.62	1.094	11.178	51.87	19.99	0.333	3.405	22.86	8.81	0.147	1.501
8	166.03	61.39	1.023	12.201	50.58	18.70	0.312	3.717	22.29	8.24	0.137	1.638
9	162.07	57.43	0.957	13.158	49.38	17.50	0.292	4.009	21.76	7.71	0.129	1.767
10	158.36	53.72	0.895	14.053	48.25	16.37	0.273	4.282	21.26	7.21	0.120	1.887
11	154.90	50.26	0.838	14.891	47.19	15.31	0.255	4.537	20.80	6.75	0.112	1.999
12	151.66	47.02	0.784	15.675	46.20	14.32	0.239	4.776	20.36	6.31	0.105	2.105
13	148.63	43.99	0.733	16.408	45.28	13.40	0.223	4.999	19.96	5.91	0.098	2.203
14	145.79	41.15	0.686	17.094	44.42	12.54	0.209	5.208	19.58	5.53	0.092	2.295
15	143.13	38.49	0.642	17.735	43.61	11.73	0.195	5.403	19.22	5.17	0.086	2.381
16	140.65	36.01	0.600	18.335	42.85	10.97	0.183	5.586	18.89	4.84	0.081	2.462
17	138.33	33.69	0.561	18.897	42.14	10.26	0.171	5.757	18.57	4.52	0.075	2.537
18	136.16	31.52	0.525	19.422	41.48	9.60	0.160	5.917	18.28	4.23	0.071	2.608
19	134.12	29.48	0.491	19.914	40.86	8.98	0.150	6.067	18.01	3.96	0.066	2.674
20	**132.22**	27.58	0.460	**20.373**	40.28	8.40	0.140	6.207	17.75	3.70	0.062	2.736
21	**130.44**	25.80	0.430	**20.803**	39.74	7.86	0.131	6.338	17.51	3.46	0.058	2.793
22	128.78	24.14	0.402	21.206	39.23	7.35	0.123	6.461	17.29	3.24	0.054	2.847
23	127.22	22.58	0.376	21.582	38.76	6.88	0.115	6.575	17.08	3.03	0.051	2.898
24	125.77	21.13	0.352	21.934	38.32	6.44	0.107	6.683	16.89	2.84	0.047	2.945
25	124.40	19.76	0.329	22.264	37.90	6.02	0.100	6.783	16.70	2.65	0.044	2.989
26	123.13	18.49	0.308	22.572	37.51	5.63	0.094	6.877	16.53	2.48	0.041	3.031
27	121.94	17.30	0.288	22.860	37.15	5.27	0.088	6.965	16.37	2.32	0.039	3.069
28	120.82	16.18	0.270	23.130	36.81	4.93	0.082	7.047	16.22	2.17	0.036	3.106
29	119.78	15.14	0.252	23.382	36.49	4.61	0.077	7.124	16.08	2.03	0.034	3.139
30	118.80	14.16	0.236	23.618	36.19	4.31	0.072	7.196	15.95	1.90	0.032	3.171
31	117.89	13.25	0.221	23.839	**35.92**	4.04	0.067	**7.263**	**15.83**	1.78	0.030	**3.201**
32	117.03	12.39	0.207	24.045	**35.66**	3.78	0.063	**7.326**	**15.71**	1.66	0.028	**3.229**
33	116.23	11.59	0.193	24.239	35.41	3.53	0.059	7.385	15.61	1.56	0.026	3.255
34	115.49	10.85	0.181	24.419	35.18	3.30	0.055	7.440	15.51	1.46	0.024	3.279
35	114.79	10.15	0.169	24.589	34.97	3.09	0.052	7.491	15.41	1.36	0.023	3.301
36	114.13	9.49	0.158	24.747	34.77	2.89	0.048	7.539	15.32	1.27	0.021	3.323
37	113.52	8.88	0.148	24.895	34.59	2.71	0.045	7.585	15.24	1.19	0.020	3.343
38	112.95	8.31	0.138	25.033	34.41	2.53	0.042	7.627	15.17	1.12	0.019	3.361
39	112.41	7.77	0.130	25.163	34.25	2.37	0.039	7.666	15.09	1.04	0.017	3.379

40	111.91	7.27	0.121	25.284	34.10	2.22	0.037	7.703	15.03	0.98	0.016	3.395
41	111.44	6.80	0.113	25.397	33.95	2.07	0.035	7.738	14.96	0.91	0.015	3.410
42	111.00	6.36	0.106	25.503	33.82	1.94	0.032	7.770	14.90	0.85	0.014	3.424
43	110.59	5.95	0.099	25.603	33.69	1.81	0.030	7.800	14.85	0.80	0.013	3.438
44	110.21	5.57	0.093	25.695	33.58	1.70	0.028	7.828	14.80	0.75	0.012	3.450
45	109.85	5.21	0.087	25.782	33.47	1.59	0.026	7.855	14.75	0.70	0.012	3.462
46	109.51	4.87	0.081	25.863	33.36	1.48	0.025	7.880	14.70	0.65	0.011	3.473
47	109.20	4.56	0.076	25.939	33.27	1.39	0.023	7.903	14.66	0.61	0.010	3.483
48	108.91	4.27	0.071	26.010	33.18	1.30	0.022	7.924	14.62	0.57	0.010	3.492
49	108.63	3.99	0.067	26.077	33.10	1.22	0.020	7.945	14.59	0.54	0.009	3.501
50	108.37	3.73	0.062	26.139	33.02	1.14	0.019	7.964	14.55	0.50	0.008	3.510
51	108.13	3.49	0.058	26.197	32.94	1.06	0.018	7.981	14.52	0.47	0.008	3.518
52	107.91	3.27	0.054	26.252	32.88	1.00	0.017	7.998	14.49	0.44	0.007	3.525
53	107.70	3.06	0.051	26.303	32.81	0.93	0.016	8.014	14.46	0.41	0.007	3.532
54	107.50	2.86	0.048	26.350	32.75	0.87	0.015	8.028	14.43	0.38	0.006	3.538
55	107.31	2.67	0.045	26.395	32.69	0.81	0.014	8.042	14.41	0.36	0.006	3.544
56	107.14	2.50	0.042	26.437	32.64	0.76	0.013	8.054	14.39	0.34	0.006	3.550
57	106.98	2.34	0.039	26.476	32.59	0.71	0.012	8.066	14.36	0.31	0.005	3.555
58	106.83	2.19	0.036	26.512	32.55	0.67	0.011	8.077	14.34	0.29	0.005	3.560
59	106.69	2.05	0.034	26.546	32.50	0.62	0.010	8.088	14.33	0.28	0.005	3.564
60	106.56	1.92	0.032	26.578	32.46	0.58	0.010	8.097	14.31	0.26	0.004	3.569
61	106.43	1.79	0.030	26.608	32.43	0.55	0.009	8.107	14.29	0.24	0.004	3.573
62	106.32	1.68	0.028	26.636	32.39	0.51	0.009	8.115	14.28	0.23	0.004	3.576
63	106.21	1.57	0.026	26.662	32.36	0.48	0.008	8.123	14.26	0.21	0.004	3.580
64	106.11	1.47	0.024	26.687	32.33	0.45	0.007	8.130	14.25	0.20	0.003	3.583
65	106.01	1.37	0.023	26.710	32.30	0.42	0.007	8.137	14.23	0.18	0.003	3.586
66	105.92	1.28	0.021	26.731	32.27	0.39	0.007	8.144	14.22	0.17	0.003	3.589
67	105.84	1.20	0.020	26.751	32.25	0.37	0.006	8.150	14.21	0.16	0.003	3.592
68	105.76	1.12	0.019	26.770	32.22	0.34	0.006	8.156	14.20	0.15	0.003	3.594
69	105.69	1.05	0.018	26.787	32.20	0.32	0.005	8.161	14.19	0.14	0.002	3.597
70	105.62	0.98	0.016	26.804	32.18	0.30	0.005	8.166	14.18	0.13	0.002	3.599
71	105.56	0.92	0.015	26.819	32.16	0.28	0.005	8.171	14.17	0.12	0.002	3.601
72	105.50	0.86	0.014	26.833	32.14	0.26	0.004	8.175	14.17	0.12	0.002	3.603
73	105.45	0.81	0.013	26.847	32.13	0.25	0.004	8.179	14.16	0.11	0.002	3.605
74	105.39	0.75	0.013	26.859	32.11	0.23	0.004	8.183	14.15	0.10	0.002	3.606
75	105.35	0.71	0.012	26.871	32.09	0.21	0.004	8.187	14.14	0.09	0.002	3.608
76	105.30	0.66	0.011	26.882	32.08	0.20	0.003	8.190	14.14	0.09	0.001	3.609
77	105.26	0.62	0.010	26.893	32.07	0.19	0.003	8.193	14.13	0.08	0.001	3.611
78	105.22	0.58	0.010	26.902	32.06	0.18	0.003	8.196	14.13	0.08	0.001	3.612
79	105.18	0.54	0.009	26.911	32.04	0.16	0.003	8.199	14.12	0.07	0.001	3.613
80	105.15	0.51	0.008	26.920	32.03	0.15	0.003	8.201	14.12	0.07	0.001	3.614
81	105.11	0.47	0.008	26.927	32.02	0.14	0.002	8.204	14.11	0.06	0.001	3.616
82	105.08	0.44	0.007	26.935	32.01	0.13	0.002	8.206	14.11	0.06	0.001	3.617
83	105.05	0.41	0.007	26.942	32.01	0.13	0.002	8.208	14.11	0.06	0.001	3.617
84	105.03	0.39	0.006	26.948	32.00	0.12	0.002	8.210	14.10	0.05	0.001	3.618
85	105.00	0.36	0.006	26.954	31.99	0.11	0.002	8.212	14.10	0.05	0.001	3.619
86	104.98	0.34	0.006	26.960	31.98	0.10	0.002	8.214	14.10	0.05	0.001	3.620
87	104.96	0.32	0.005	26.965	31.98	0.10	0.002	8.215	14.09	0.04	0.001	3.621
88	104.94	0.30	0.005	26.970	31.97	0.09	0.002	8.217	14.09	0.04	0.001	3.621
89	104.92	0.28	0.005	26.975	31.96	0.08	0.001	8.218	14.09	0.04	0.001	3.622
90	104.90	0.26	0.004	26.979	31.96	0.08	0.001	8.220	14.08	0.03	0.001	3.622
91	104.88	0.24	0.004	26.983	31.95	0.07	0.001	8.221	14.08	0.03	0.001	3.623
92	104.87	0.23	0.004	26.987	31.95	0.07	0.001	8.222	14.08	0.03	0.001	3.624
93	104.85	0.21	0.004	26.990	31.94	0.06	0.001	8.223	14.08	0.03	0.000	3.624
94	104.84	0.20	0.003	26.994	31.94	0.06	0.001	8.224	14.08	0.03	0.000	3.624

95	104.83	0.19	0.003	26.997	31.94	0.06	0.001	8.225	14.07	0.02	0.000	3.625
96	104.81	0.17	0.003	27.000	31.93	0.05	0.001	8.226	14.07	0.02	0.000	3.625
97	104.80	0.16	0.003	27.002	31.93	0.05	0.001	8.227	14.07	0.02	0.000	3.626
98	104.79	0.15	0.003	27.005	31.93	0.05	0.001	8.227	14.07	0.02	0.000	3.626
99	104.78	0.14	0.002	27.007	31.92	0.04	0.001	8.228	14.07	0.02	0.000	3.626
100	104.77	0.13	0.002	27.009	31.92	0.04	0.001	8.229	14.07	0.02	0.000	3.627
101	104.76	0.12	0.002	27.012	31.92	0.04	0.001	8.229	14.07	0.02	0.000	3.627
102	104.76	0.12	0.002	27.014	31.92	0.04	0.001	8.230	14.07	0.02	0.000	3.627
103	104.75	0.11	0.002	27.015	31.91	0.03	0.001	8.231	14.06	0.01	0.000	3.627
104	104.74	0.10	0.002	27.017	31.91	0.03	0.001	8.231	14.06	0.01	0.000	3.628
105	104.74	0.10	0.002	27.019	31.91	0.03	0.000	8.232	14.06	0.01	0.000	3.628
106	104.73	0.09	0.001	27.020	31.91	0.03	0.000	8.232	14.06	0.01	0.000	3.628
107	104.72	0.08	0.001	27.021	31.91	0.03	0.000	8.232	14.06	0.01	0.000	3.628
108	104.72	0.08	0.001	27.023	31.90	0.02	0.000	8.233	14.06	0.01	0.000	3.628
109	104.71	0.07	0.001	27.024	31.90	0.02	0.000	8.233	14.06	0.01	0.000	3.629
110	104.71	0.07	0.001	27.025	31.90	0.02	0.000	8.234	14.06	0.01	0.000	3.629
111	104.70	0.06	0.001	27.026	31.90	0.02	0.000	8.234	14.06	0.01	0.000	3.629
112	104.70	0.06	0.001	27.027	31.90	0.02	0.000	8.234	14.06	0.01	0.000	3.629
113	104.70	0.06	0.001	27.028	31.90	0.02	0.000	8.234	14.06	0.01	0.000	3.629
114	104.69	0.05	0.001	27.029	31.90	0.02	0.000	8.235	14.06	0.01	0.000	3.629
115	104.69	0.05	0.001	27.030	31.89	0.01	0.000	8.235	14.06	0.01	0.000	3.629
116	104.69	0.05	0.001	27.031	31.89	0.01	0.000	8.235	14.06	0.01	0.000	3.629
117	104.68	0.04	0.001	27.031	31.89	0.01	0.000	8.235	14.06	0.01	0.000	3.629
118	104.68	0.04	0.001	27.032	31.89	0.01	0.000	8.236	14.06	0.01	0.000	3.630
119	104.68	0.04	0.001	27.033	31.89	0.01	0.000	8.236	14.06	0.01	0.000	3.630
120	104.68	0.04	0.001	27.033	31.89	0.01	0.000	8.236	14.05	0.00	0.000	3.630

Where f_p is infiltration rate with the use of equation [3] with respective site-specific data, f_p above f_{min} is the infiltration rate minus minimum infiltration rate, V above f_{min} is the volume infiltrating minus the minimum infiltrated volume, and cum V above f_{min} is the cumulative infiltrated volume above minimum infiltrated volume.

Highlighted values correspond to the values that are used for maximum infiltration rate based on the values in Table A2

Table A2 Parameters needed to calculate maximum infiltration rate at the specific initial soil moisture content, and the maximum infiltration rate used for wet and dry conditions

	Unit	Oslo	Trondheim	Sandnes
Minimum infiltration rate, f_{min}	mm/h	104.64	31.88	14.05
Maximum infiltration rate, f_{max}	mm/h	209.28	63.76	28.10
Decay coefficient, k_d	min	0.067	0.067	0.067
Water content, wet*	-	0.76	0.88	0.88
Water content, dry*	-	0.24	0.24	0.27
Infiltrated volume after 2h	mm	27.033	8.236	3.630
Amount away, wet**	mm	20.672	7.267	3.203
Amount away, dry**	mm	6.401	1.984	0.984
Maximum infiltration rate, wet	**mm/h**	**130.99**	**35.90**	**15.82**
Maximum infiltration rate, dry	**mm/h**	**190.02**	**57.75**	**25.00**

** Water content percentage of porosity (Initial soil moisture/porosity)*
*** Volume that are infiltrated based on the initial soil moisture content (Water content*Total volume after 2h above minimum infiltrated water volume)*

Maximum infiltration rate was found by following steps:

1. Calculating infiltration rate with site-specific parameters for the corresponding locations within 2 h with the use of equation [3],
2. Calculating the cumulative volume of water infiltrated minus the minimum volume of infiltrated water,
3. Finding the percentage of water that are assumed infiltrated at the specific initial soil moisture content (Initial soil moisture/porosity),
4. Taking this percentage of the total cumulative water above minimum infiltrated water after 2 h to find the total water that are infiltrated with the specific initial soil moisture content,
5. Using Table A1 to find this amount of water at a specific time with corresponding infiltration rate which is set to maximum infiltration rate.

Appendix B Input -Sensitivity Analysis

Table B Input parameters for the sensitivity analysis

Method	Parameters		Unit	Initial	-50%	-10%	+10%	+50%
Green-Ampt	Saturated hydraulic conductivity	K_{sat}	mm/h	14.05	7.03	12.65	15.46	21.08
	Suction head	ψ_s	mm/h	99.84	49.92	89.86	109.83	149.77
	Initial deficit, wet	θ_d	-	0.036	0.018	0.032	0.039	0.053
	Initial deficit, dry			0.220	0.110	0.198	0.242	0.330
	Slope	S	%	2.50	1.25	2.25	2.75	3.75
	Depression storage	d_s	mm	1.0	0.5	0.9	1.1	1.5
	Manning's roughness	N	-	0.075	0.038	0.068	0.083	0.113
Horton	Minimum infiltration rate	f_{min}	mm/h	14.05	7.03	12.65	15.46	21.08
	Maximum infiltration rate, wet	f_{max}	mm/h	15.82	7.91	14.24	17.40	23.73
	Maximum infiltration rate, dry			25.00	12.50	22.50	27.50	37.50
	Decay coefficient	K_d	h^{-1}	4.0	2.0	3.6	4.4	6.0
	Slope	S	%	2.50	1.25	2.25	2.75	3.75
	Depression storage	d_s	mm	1.0	0.5	0.9	1.1	1.5
	Manning's roughness	N	-	0.075	0.038	0.068	0.083	0.113
Holtan	Minimum infiltration rate	f_{min}	mm/h	14.05	7.03	12.65	15.46	21.08
	Maximum infiltration rate	f_{max}	mm/h	28.10	14.05	25.29	30.91	42.15
	Wilting point	WP	-	0.050	0.025	0.045	0.055	0.075
	Field Capacity	FC	-	0.117	0.059	0.105	0.129	0.176
	Porosity	ϕ	-	0.302	0.151	0.272	0.332	0.453
	Initial soil moisture, wet	θ_i	-	0.266	0.133	0.240	0.293	0.400
	Initial soil moisture, dry			0.082	0.041	0.074	0.090	0.123
	Depression storage	d_s	mm	2.50	1.25	2.25	2.75	3.75

Appendix C Design rainfalls

Table C Design rainfall used for the long-term simulations

														Adjusted timestep for STORM		
	5-year		5-year		5-year		5-Year		2-Year	5-year	20-year	50-year	100-year		5-Year	5-year
	30 min		60 min		180 min		360 min		120 min	120 min	120 min	120 min	120 min		30 Min	60 min
Time	**Rain**	**Time**	**Rain**	**Time**	**Rain**	**Time**	**Rain**	**Time**	**Rain**	**Rain**	**Rain**	**Rain**	**Rain**	**Time**	**Rain**	**Rain**
(min)	**(mm)**	**(min)**	**(mm)**	**(min)**	**(mm)**	**(min)**	**(mm)**	**(min)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(mm)**	**(min)**	**(mm)**	**(mm)**
1	0.18	**2.5**	0.16	**10**	0.21	**15**	0.30	**5**	0.18	0.17	0.10	0.10	0.10	**5**	2.24	0.64
2	0.25	**5.0**	0.32	**20**	0.58	**30**	0.30	**10**	0.30	0.35	0.10	0.10	0.10	**10**	3.40	0.74
3	0.31	**7.5**	0.48	**30**	0.96	**45**	0.30	**15**	0.42	0.52	0.10	0.10	0.10	**15**	9.63	1.66
4	0.38	**10.0**	0.37	**40**	0.51	**60**	0.57	**20**	0.10	0.10	0.36	0.38	0.39	**20**	2.59	1.99
5	0.45	**12.5**	0.60	**50**	0.20	**75**	0.93	**25**	0.15	0.10	0.82	0.93	1.01	**25**	1.93	2.86
6	0.39	**15.0**	0.83	**60**	0.51	**90**	1.29	**30**	0.44	0.48	1.28	1.48	1.62	**30**	0.89	7.53
7	0.48	**17.5**	0.57	**70**	1.33	**105**	0.45	**35**	0.35	0.48	0.66	0.76	0.83	**35**		3.73
8	0.49	**20.0**	0.99	**80**	2.99	**120**	1.30	**40**	0.54	0.85	1.24	1.50	1.68	**40**		2.30
9	0.53	**22.5**	1.15	**90**	8.21	**135**	1.04	**45**	0.93	1.43	2.06	2.47	2.77	**45**		1.14
10	0.68	**25.0**	1.43	**100**	8.21	**150**	0.30	**50**	1.10	1.57	2.18	2.57	2.86	**50**		1.20
11	0.52	**27.5**	1.87	**110**	2.99	**165**	2.75	**55**	1.71	2.58	3.70	4.41	4.94	**55**		0.96
12	0.82	**30.0**	3.77	**120**	1.33	**180**	9.77	**60**	4.19	5.63	7.49	8.68	9.56	**60**		0.32
13	1.03	**32.5**	3.77	**130**	0.51	**195**	9.77	**65**	4.19	5.63	7.49	8.68	9.56			
14	1.34	**35.0**	1.87	**140**	0.20	**210**	2.75	**70**	1.71	2.58	3.70	4.41	4.94			
15	1.93	**37.5**	1.43	**150**	0.51	**225**	0.30	**75**	1.10	1.57	2.18	2.57	2.86			
16	1.93	**40.0**	1.15	**160**	0.96	**240**	1.04	**80**	0.93	1.43	2.06	2.47	2.77			
17	1.34	**42.5**	0.99	**170**	0.58	**255**	1.30	**85**	0.54	0.85	1.24	1.50	1.68			
18	1.03	**45.0**	0.57	**180**	0.21	**270**	0.45	**90**	0.35	0.48	0.66	0.76	0.83			
19	0.82	**47.5**	0.83			**285**	1.29	**95**	0.44	0.48	1.28	1.48	1.62			
20	0.52	**50.0**	0.60			**300**	0.93	**100**	0.15	0.10	0.82	0.93	1.01			
21	0.68	**52.5**	0.37			**315**	0.57	**105**	0.10	0.10	0.36	0.38	0.39			
22	0.53	**55.0**	0.48			**330**	0.30	**110**	0.42	0.52	0.10	0.10	0.10			
23	0.49	**57.5**	0.32			**345**	0.30	**115**	0.30	0.35	0.10	0.10	0.10			
24	0.48	**60.0**	0.16			**360**	0.30	**120**	0.18	0.17	0.10	0.10	0.10			
25	0.39															
26	0.45															
27	0.38															
28	0.31															
29	0.25															
30	0.18															
SUM	**19.56**		**25.08**		**31.00**		**38.60**		**20.82**	**28.52**	**40.18**	**46.96**	**51.92**		**20.68**	**25.07**

Appendix D Sensitivity to runoff volume and runoff duration for wet condition

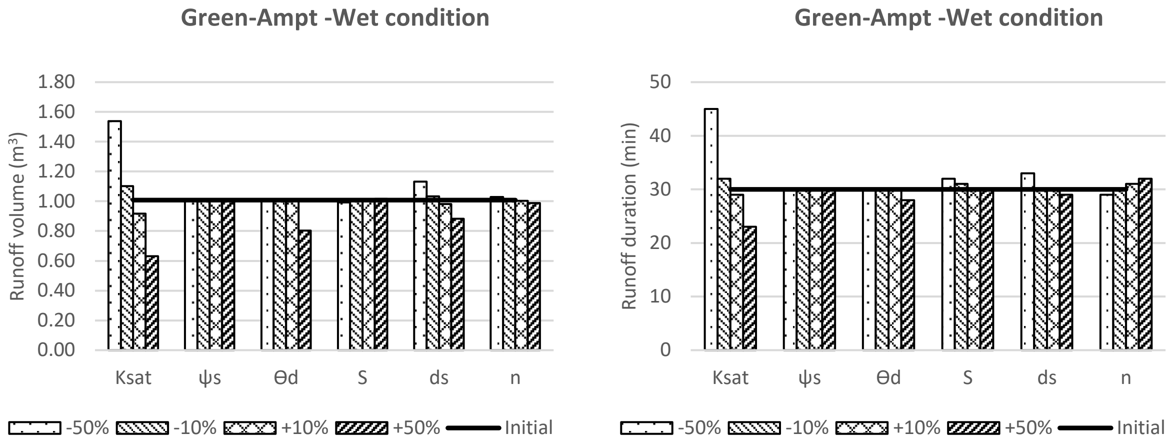

Figure D1 Input parameters' sensitivity to runoff volume and runoff duration for Green-Ampt

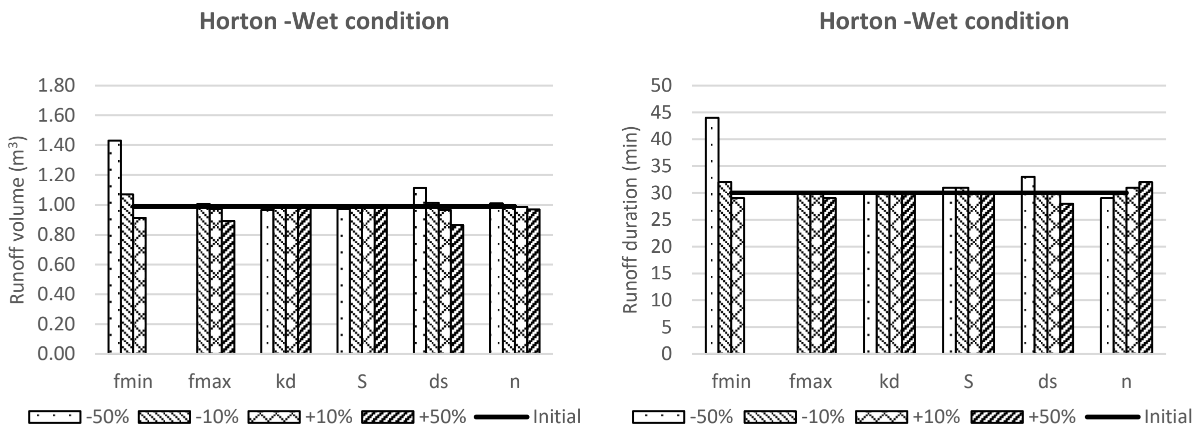

Figure D2 Input parameters' sensitivity to runoff volume and runoff duration for Horton

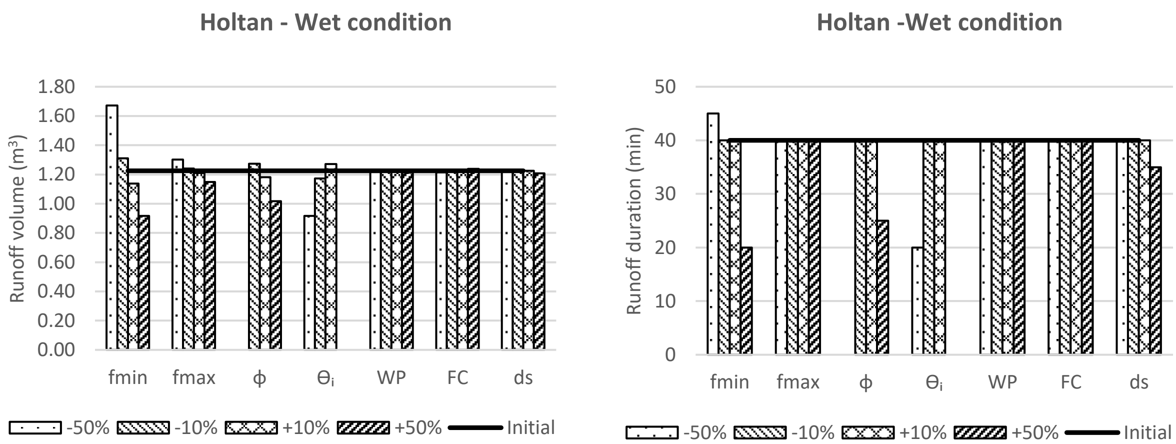

Figure D3 Input parameters' sensitivity to runoff volume and runoff duration for Holtan

Appendix E Sensitivity to runoff volume and runoff duration for dry condition

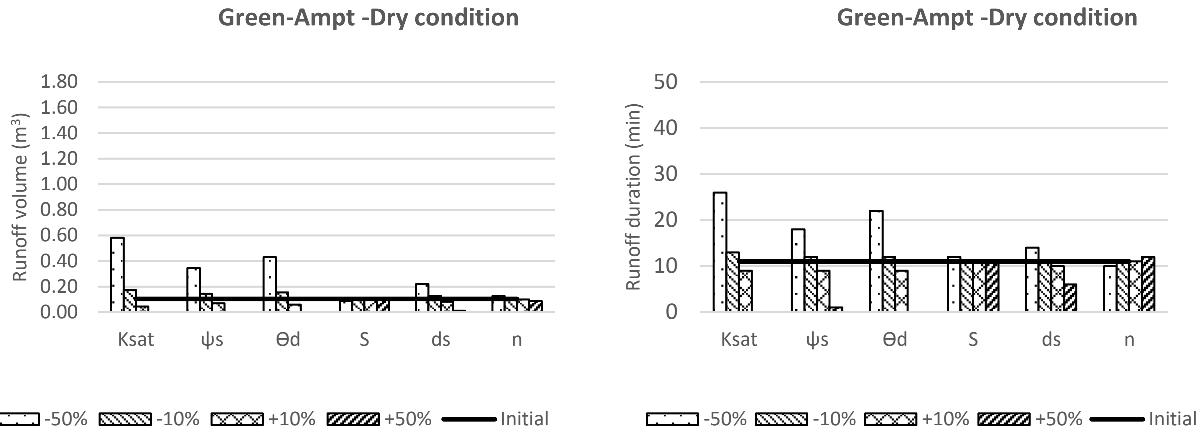

Figure E1 Input parameters' sensitivity to runoff volume and runoff duration for Green-Ampt

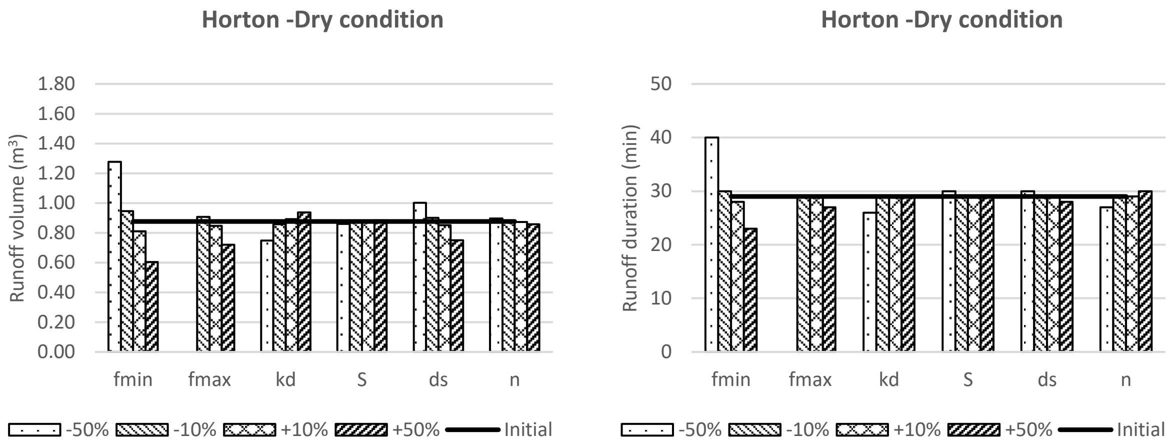

Figure E2 Input parameters' sensitivity to runoff volume and runoff duration for Horton

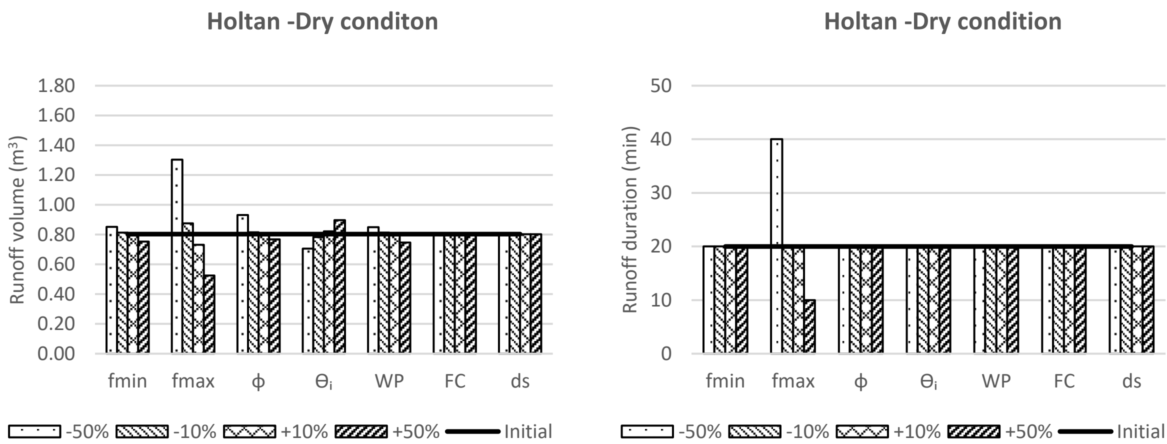

Figure E3 Input parameters' sensitivity to runoff volume and runoff duration for Holtan

Appendix F Tables of results from changing pre-rainfall

Table F1 Changes in runoff characteristics of the evaluated rainfall when the return period of pre-rainfall, the ADWP after pre-rainfall, and duration of pre-rainfall is changed for Green-Ampt infiltration method with ET=1 mm and ET=7 mm

	Green-Ampt -Change of ADWP after pre-rainfall with ET=1 mm					Green-Ampt -Change of return period of pre-rainfall with ET=7 mm				
Return period (years)	**2**	**5**	**20**	**50**	**100**	**2**	**5**	**20**	**50**	**100**
Peak runoff (l/s)	0.884	0.884	0.884	0.884	0.884	0.875	0.875	0.875	0.875	0.875
Runoff volume (m^3)	0.327	0.327	0.327	0.327	0.327	0.321	0.321	0.321	0.321	0.321
Peak delay (min)	66	66	66	66	66	66	66	66	66	66
Time to start (min)	61	61	61	61	61	61	61	61	61	61
Duration (min)	17	17	17	17	17	17	17	17	17	17
Runoff (mm)	3.273	3.273	3.273	3.273	3.273	3.212	3.212	3.212	3.212	3.212

	Green-Ampt -Change of ADWP after pre-rainfall with ET=1 mm					Green-Ampt -Change of ADWP after pre-rainfall with ET=7 mm				
ADWP (days)	**1**	**2**	**3**	**5**	**10**	**1**	**2**	**3**	**5**	**10**
Peak runoff (l/s)	1.274	0.884	0.487	0.010	0.010	1.265	0.875	0.476	0.007	0.007
Runoff volume (m^3)	0.689	0.327	0.126	0.001	0.001	0.679	0.321	0.122	0.000	0.000
Peak delay (min)	66	66	66	66	66	66	66	66	66	66
Time to start (min)	59	61	63	70	70	59	61	63	70	70
Duration (min)	26	17	11	1	1	25	17	11	1	1
Runoff (mm)	6.894	3.273	1.264	0.006	0.006	6.787	3.212	1.218	0.004	0.004

	Green-Ampt -Change of duration of pre-rainfall with ET=1 mm					Green-Ampt -Change of duration of pre-rainfall with ET=7 mm				
Duration (min)	**30**	**60**	**120**	**180**	**360**	**30**	**60**	**120**	**180**	**360**
Peak runoff (l/s)	0.861	0.868	0.883	0.898	0.944	0.852	0.859	0.874	0.889	0.935
Runoff volume (m^3)	0.313	0.317	0.327	0.337	0.368	0.306	0.311	0.321	0.331	0.362
Peak delay (min)	66	66	66	66	66	66	66	66	66	66
Time to start (min)	61	61	61	61	61	61	61	61	61	61
Duration (min)	17	17	17	18	19	17	17	17	17	18
Runoff (mm)	3.125	3.169	3.270	3.368	3.681	3.065	3.108	3.208	3.305	3.616

Table F2 Changes in runoff characteristics of the evaluated rainfall when the return period of pre-rainfall, the ADWP after pre-rainfall, and duration of pre-rainfall is changed for Horton infiltration method with ET=1 mm and ET=7 mm

	Horton -Change of return period of pre-rainfall with ET=1 mm					Horton -Change of return period of pre-rainfall with ET=7 mm				
Return period (years)	**2**	**5**	**20**	**50**	**100**	**2**	**5**	**20**	**50**	**100**
Peak runoff (l/s)	1.397	1.397	1.397	1.397	1.397	1.389	1.389	1.389	1.389	1.389
Runoff volume (m^3)	0.866	0.866	0.867	0.867	0.867	0.853	0.853	0.854	0.854	0.854
Peak delay (min)	66	66	66	66	66	66	66	66	66	66
Time to start (min)	58	58	58	58	58	58	58	58	58	58
Duration (min)	29	29	29	29	29	29	29	29	29	29
Runoff (mm)	8.663	8.665	8.666	8.666	8.666	8.533	8.534	8.536	8.536	8.536

	Horton -Change of ADWP after pre-rainfall with ET=1 mm					Horton -Change of ADWP after pre-rainfall with ET=7 mm				
ADWP (days)	**1**	**2**	**3**	**5**	**10**	**1**	**2**	**3**	**5**	**10**
Peak runoff (l/s)	1.420	1.397	1.387	1.381	1.380	1.412	1.389	1.379	1.373	1.372
Runoff volume (m^3)	0.911	0.866	0.850	0.841	0.840	0.897	0.853	0.838	0.830	0.828
Peak delay (min)	66	66	66	66	66	66	66	66	66	66
Time to start (min)	58	58	58	58	58	58	58	58	58	58
Duration (min)	29	29	29	29	29	29	29	29	29	29
Runoff (mm)	9.107	8.665	8.497	8.411	8.396	8.969	8.534	8.377	8.295	8.280

	Horton -Change of duration of pre-rainfall with ET=1 mm					Horton -Change of duration of pre-rainfall with ET=7 mm				
Duration (min)	**30**	**60**	**120**	**180**	**360**	**30**	**60**	**120**	**180**	**360**
Peak runoff (l/s)	1.395	1.396	1.397	1.398	1.400	1.387	1.388	1.389	1.389	1.392
Runoff volume (m^3)	0.864	0.865	0.866	0.868	0.872	0.851	0.852	0.853	0.854	0.858
Peak delay (min)	66	66	66	66	66	66	66	66	66	66
Time to start (min)	58	58	58	58	58	58	58	58	58	58
Duration (min)	29	29	29	29	29	29	29	29	29	29
Runoff (mm)	8.636	8.652	8.665	8.678	8.717	8.507	8.522	8.533	8.544	8.583

Table F3 Changes in runoff characteristics of the evaluated rainfall when the return period of pre-rainfall, the ADWP after pre-rainfall, and duration of pre-rainfall is changed for Holtan infiltration method with ET=1 mm and ET=7 mm

	Holtan -Change of return period of pre-rainfall with ET=1 mm					Holtan -Change of return period of pre-rainfall with ET=7 mm				
Return period (years)	**2**	**5**	**20**	**50**	**100**	**2**	**5**	**20**	**50**	**100**
Peak runoff (l/s)	1.240	1.246	1.251	1.251	1.252	1.196	1.202	1.210	1.213	1.214
Runoff volume (m^3)	0.876	0.883	0.889	0.890	0.891	0.823	0.830	0.840	0.843	0.844
Peak delay (min)	65	65	65	65	65	65	65	65	65	65
Time to start (min)	55	55	55	55	55	55	55	55	55	55
Duration (min)	20	20	20	20	20	20	20	20	20	20
Runoff (mm)	8.762	8.835	8.887	8.896	8.906	8.226	8.299	8.398	8.430	8.445

	Holtan -Change of ADWP after pre-rainfall with ET=1 mm					Holtan -Change of ADWP after pre-rainfall with ET=7 mm				
ADWP (days)	**1**	**2**	**3**	**5**	**10**	**1**	**2**	**3**	**5**	**10**
Peak runoff (l/s)	1.249	1.246	1.244	1.240	1.230	1.212	1.202	1.193	1.177	1.149
Runoff volume (m^3)	0.886	0.883	0.881	0.876	0.864	0.842	0.830	0.819	0.800	0.766
Peak delay (min)	65	65	65	65	65	65	65	65	65	65
Time to start (min)	55	55	55	55	55	55	55	55	55	55
Duration (min)	20	20	20	20	20	20	20	20	20	20
Runoff (mm)	8.863	8.835	8.809	8.757	8.636	8.419	8.299	8.191	7.999	7.656

	Holtan -Change of duration of pre-rainfall with ET=1 mm					Holtan -Change of duration of pre-rainfall with ET=7 mm				
Duration (min)	**30**	**60**	**120**	**180**	**360**	**30**	**60**	**120**	**180**	**360**
Peak runoff (l/s)	1.232	1.241	1.246	1.249	1.255	1.188	1.196	1.202	1.206	1.219
Runoff volume (m^3)	0.866	0.877	0.883	0.886	0.894	0.813	0.823	0.830	0.835	0.851
Peak delay (min)	65	65	65	65	65	65	65	65	65	65
Time to start (min)	55	55	55	55	55	55	55	55	55	55
Duration (min)	20	20	20	20	20	20	20	20	20	20
Runoff (mm)	8.658	8.767	8.835	8.865	8.944	8.130	8.230	8.299	8.346	8.506