Evaluating three commonly used infiltration methods for permeable surfaces in urban areas using the SWMM and STORM

Frida E. Å. Parnas, Elhadi M. H. Abdalla and Tone M. Muthanna

ABSTRACT

Climate change and urbanization increase the pressure on combined sewer systems in urban areas resulting in elevated combined sewer overflows, degraded water quality in receiving waters, and changing stream flows. Permeable surfaces offer infiltration potential, which can contribute to alleviate the runoff to combined sewer systems. The variation in urban soil characteristics and the initial moisture conditions before a rainfall event are important factors affecting the infiltration process and consequently runoff characteristics. In this study, the urban hydrological models SWMM and STORM are used to evaluate the Green-Ampt, Horton, and Holtan infiltration methods for three urban sandy soils. A sensitivity analysis was carried out on a set of key parameter values. In addition, long-term simulations were conducted to evaluate the ability to account for initial soil moisture content. The results showed that the Holtan method's ability to account for both available storage capacity and maximum infiltration rate, as well as evapotranspiration in the regeneration of infiltration capacity, gave the best result with regard to runoff behaviour, especially for long-term simulations. Furthermore, the results from the urban sandy soils with different infiltration rate at saturation, together with a high sensitivity to the degree of sensitivity for maximum infiltration rate under dry conditions and minimum infiltration rate under wet conditions, indicate that field measurements of infiltration rate should be carried out at saturation for these soils.

Key words | hydrological modelling, initial soil moisture, permeable surfaces, STORM, SWMM, urban soils

Frida E. Å. Parnas
Multiconsult Consulting,
Nesttunbrekka 99, 5221 Nesttun,
Norway

Elhadi M. H. Abdalla
Tone M. Muthanna (corresponding author)
Department of Civil and Environmental Engineering,
The Norwegian University of Science and Technology (NTNU),
7491 Trondheim,
Norway
E-mail: *tone.muthanna@ntnu.no*

HIGHLIGHTS

- This research examines three commonly used infiltration models, Horton, Green-Ampt, and Holtan, in two urban stormwater modelling systems, SWMM and STORM.
- This research contributed new information about the sensitivity of the infiltration models applied to urban soils.
- The results provide enhanced understanding of the parameter sensitivity and selection for urban pervious surfaces.

doi: 10.2166/nh.2021.048

INTRODUCTION

In urban areas, it is commonly known that impervious areas contribute to increased runoff, among others (Bøyum *et al.* 1997; Redfern *et al.* 2016). In recent years, there is an increasing focus on preserving existing green areas and implementing new green areas to alleviate the runoff generated from impervious areas (Law et al. 2009; Jiang et al. 2018). 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 (Becker 2016; Redfern et al. 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 a significant amount of runoff from some of the urban green surfaces. Davidsen et al. (2018) used 30 years of historical rainfall events to investigate the runoff generation for compacted sandy and clayey soils. Furthermore, they simulated runoff from those pervious soils using a runoff model with the Horton method and a modified Horton's infiltration equation (Horton 1941). Only runoff from overland flow was considered. The Horton method describes how infiltration capacity declines as the precipitation event advances and is based on generating runoff when rainfall intensity exceeds the infiltration capacity. In addition, the modified Horton's equation describes the recovery of infiltration capacity during dry periods. Both versions are only valid when precipitation intensity exceeds the infiltration capacity. They found the following. (i) Surface runoff occurred for events with less than 1-year return period for clayey soils, and from 10-year return period for sandy soils. That is because the relative infiltration capacity of clayey soil typically are less than 50% at the onset of an event, as the drying period is much slower. (ii) Variation of runoff values is associated with variation of initial conditions (infiltration capacity at the start of the vent), soil type and event return period. (iii) Both soil types reduced the simulated runoff peaks and volumes compared with impervious surfaces. Nevertheless, the reduction is more significant in sandy soils than clayey and is dependent on the rainfall return period. They concluded that pervious areas would have a significant contribution to runoff during precipitation events of more than 5-year return period, basing the return period on the 1-h maximum intensity, depending on both initial infiltration capacity and the soil type.

In general terms, infiltration occurs when water enters the soil from precipitation i and/or ponded water d (wet conditions). In contrast, the recovery process occurs in dry conditions (Figure 1(a)). Infiltration equations aim to determine actual infiltration f (Figure 1(b)) following different approaches ranging from fully physically based, such as the Richard equation, to empirical- and data-driven methods. 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 and Ampt method is also a simplification of the Richards equation. The main difference from the Horton method is that it simplifies the physics from the Richards equation to derive an equation with an exact analytical solution (Chow et al. 1988).

Soils in urban areas differ in characteristics. The most common factors include: (i) degree of compaction during construction; (ii) amount of organic matter; (iii) contamination by construction debris (Pitt et al. 1999, 2008; Morel

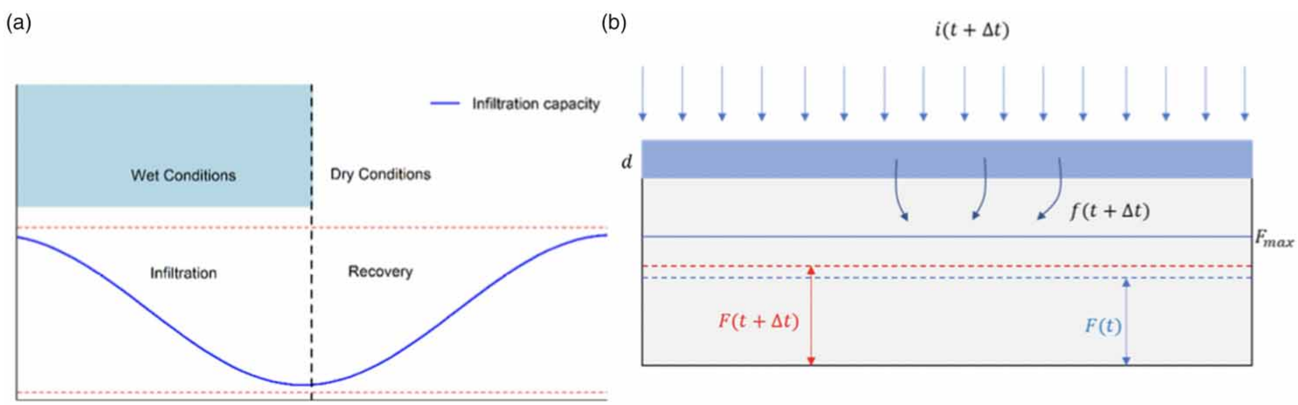

Figure 1 | (a) Schematic of the process of infiltration into the soil and the subsequent recovery process. (b) Schematic of the infiltration function which aims to describe the actual infiltration.

et al. 2005; Gregory et al. 2006; Wang et al. 2017). 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 could lead to 70–99% reduction in infiltration rates. The initial moisture condition in the soil has additional effects on the soil response to a rainfall event (Pitt et al. 1999; Redfern et al. 2016; Davidsen et al. 2018). Davidsen et al. (2018) showed that the infiltration capacity before an event can be significantly reduced, depending on the initial conditions in the urban soil, resulting in more surface runoff.

In this study, the Stormwater Management Model (SWMM) with the Horton and the Green-Ampt infiltration methods options, maintained by the United States Environmental Protection Agency (EPA); and the hydrological rainfall-runoff model STORM (Sieker 2014) with the 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 methods?
2. What are the most important parameters of 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?

THEORETICAL BACKGROUND

Infiltration algorithms

The Horton approach introduced by the Horton method (1941) is divided into two parts. By the following equation, it calculates the infiltration capacity into the soil for the precipitation events:

$$f_p = f_{\min} + (f_{\max} - f_{\min})e^{-k_d t} \quad (1)$$

where t is the time since the beginning of the storm in seconds, f_p is the infiltration capacity into the soil in m/s, $f_{\min}$ is the minimum infiltration rate in cm/s as t goes to ∞, $f_{\max}$ is the initial infiltration rate in cm/h, and k_d is the decay coefficient of the infiltration during precipitation in one over seconds.

Secondly, the Horton equation calculates the recovery during dry periods by the following equation:

$$f_p = f_{\max} - (f_{\max} - f_{\min})e^{-k_r(t-t_w)} \quad (2)$$

where k_r is the decay coefficient for recovery in seconds and t_w is the hypothetical projected time at which $f_p = f_{\max}$ on the recovery curve in seconds. This makes the recovery a function of available moisture and time, without considering the influence of evapotranspiration (ET).

The Green-Ampt infiltration method is based on a saturated upper layer, called the wetted zone, where the water is percolated to an un-wetted zone with an initial soil moisture content, θ_i. This makes the model only valid for saturated conditions. Darcy's law gives the infiltration velocity, f_p, through the saturated wetted zone, as shown in the following equations:

$$f_p = K_{\text{sat}}\left(\frac{\psi_s\,\theta_d}{F} + 1\right) \quad (3)$$

$$F = K_{\text{sat}} + \psi_s\theta_d \ln\left(1 + \frac{F}{\psi_s\,\theta_d}\right) \quad (4)$$

where K_{sat} is the saturated hydraulic conductivity and ψ_s is the suction head, which is caused by the capillary attraction in the soil voids. The suction head is larger for fine-grained clayey soils than the coarser-grained sandy soils. The θ_d is the moisture deficit, 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 the infiltration rate is equal to the rainfall intensity (Rossman & Huber 2016).

The recovery in the Green-Ampt model is calculated based on three recovery parameters: thickness of the upper crust, L_w, the recovery constant, k_r, and T_r, which is the time needed for a complete recovery.

$$L_w = 4\sqrt{K_s} \tag{5}$$

$$\theta_{du} \leftarrow \theta_{du} - \frac{f\Delta t}{L_w} \tag{6}$$

$$\theta_{du} \leftarrow \theta_{du} + k_r\theta_{d\,max}\Delta t \tag{7}$$

where K_s is saturated hydraulic conductivity (cm/h), θ_{du} is the moisture deficit in the upper soil crust, recall that θ_{du} is the difference between saturated moisture content, θ_s, and the initial moisture, θ_I, k_r is the recovery constant (h^{-1}), and f is the infiltration rate (cm/h).

Unlike Green-Ampt, the Horton equation was originally introduced as an empirical formula (Horton 1941) to estimate infiltration. However, the Horton equation can be derived from Richard equation by using a proper set of assumptions (Chow *et al.* 1988). In this assumption, the f_{min} parameter in the Horton equation can be assumed to equal the saturated hydraulic conductivity k_s in the Green-Ampt infiltration model. Nevertheless, there is a little guidance in estimating f_{max} and k_d values for the Horton equation, which might lead to miscalculation. Hsu *et al.* (2002) compared a numerical solution of Richards equation with the Holton equation. They found f_{min} to be well approximated from hydraulic conductivity, but the other parameters (f_{max}, k_d, k_r) were very difficult to estimate from physical properties.

The Holtan method (Holtan 1961) is based on the desire to estimate infiltration based on the physical properties characterizing soil water storage in the Horton equation (Holtan & Lopez 1971). This resulted in a method that linked the infiltration rate with the soil properties and fitted the equation based on field measurements. By making this physical connection, the Holtan method further made the recovery a function of the evapotranspiration (ET) coupled with available water in the soil through introducing field capacity, FP, when no more water can be stored in the soil without runoff occurring, and, WP, wilting point, which is the point at which plants can no longer draw water out from the soil. The infiltration rate, f_p, after modifications by Holtan & Lopez (1971) is given by the following equation:

$$f_p = \mathrm{GI}\, a((\theta_s - \theta_i)d)^{1.4} + f_c \tag{8}$$

where GI is the growth index of the crop in percent of maturity, a is an index of surface connected porosity, which is a function of surface conditions and density of plant roots measured in length/time·length$^{1.4}$, f_c is the minimum infiltration rate, θ_s is the saturated water content of the soil, θ_i is the simulated volumetric water content of the soil, and d is the depth of the surface layer.

Computational schemes

The general algorithm applied by SWMM and STORM to solve the three selected equations is presented in Figure 2. Differences in estimating infiltration and recovery rates between the three equations are discussed in the following sections.

In the Horton equation, the potential infiltration f_p decreases as a function of time only regardless of rainfall intensity, which might cause an underestimation of f_p values for light rainfall events. To overcome this issue, SWMM updates the time on the Horton curve t_p each time-step based on the cumulative infiltration value F that is

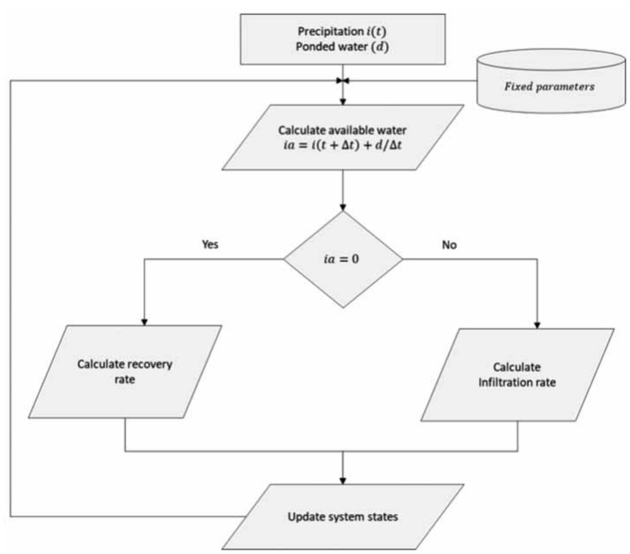

Figure 2 | A general algorithm applied to solve infiltration equations, where *ia* is the available water, and *i* is the precipitation.

determined from actual infiltration values (at the beginning of the event, $t_p = 0$). The integral form of the Horton equation is applied to determine the cumulative infiltration as follows:

$$F(t_p) = \int_0^{t_p} f_p dt = f_{\min} t_p + \frac{f_{\max} - f_{\min}}{k_d} \left(1 - e^{-k_d t_p}\right) \quad (9)$$

The computational scheme applied by SWMM for the Horton method is shown in Figure 3.

For the Green-Ampt, SWMM applies an empirical approach for the recovery calculation based on the moisture deficit of the uppermost layer. Three recovery parameters L_{u}, k_{rc}, and T_{r} represent the thickness of the uppermost layer, the recovery constant, and the time needed for a full recovery, respectively. They are all determined from the saturated soil conductivity (see Rossman & Huber (2016) for more details). The computational scheme applied by SWMM for the Horton equation is shown in Figure 4. The recovery calculation for the Green-Ampt and the Horton in SWMM is not based on evapotranspiration. STORM, on the other hand, applies a recovery module based on evapotranspiration values as shown in Figure 5.

In general, the Horton and the Green-Ampt methods show good results in non-urban soils (Esteves *et al.* 2000; Haghighi *et al.* 2010; Bauwe *et al.* 2016). However, previous studies have shown poor results modelling urban soils (Pitt *et al.* 1999; Wang *et al.* 2017). Wang *et al.* (2017) highlight that infiltration methods can have distinctive variation in their performance with large uncertainties modelling urban soils. This indicates that a better understanding of how the transformations that occur in urban soils affect the input parameters of the soils with respect to original classification.

Sensitivity analysis

Sensitivity analysis is used to achieve an awareness of the models' uncertainties, optimize their functions, and identify the key parameters for which the model output is most sensitive (Loosvelt *et al.* 2013; Song *et al.* 2015). Given the wide range of input parameter values given in the literature

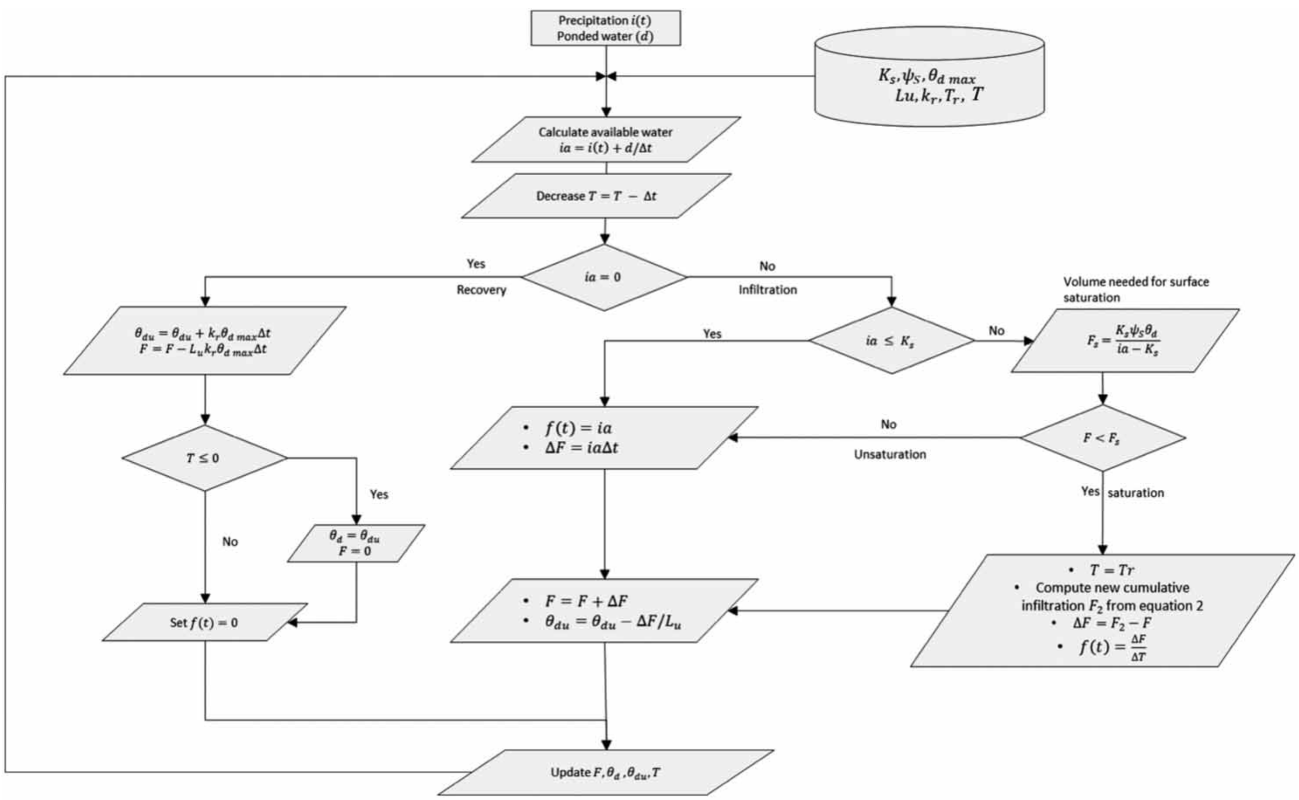

Figure 3 | The computational scheme applied by SWMM for the Horton method.

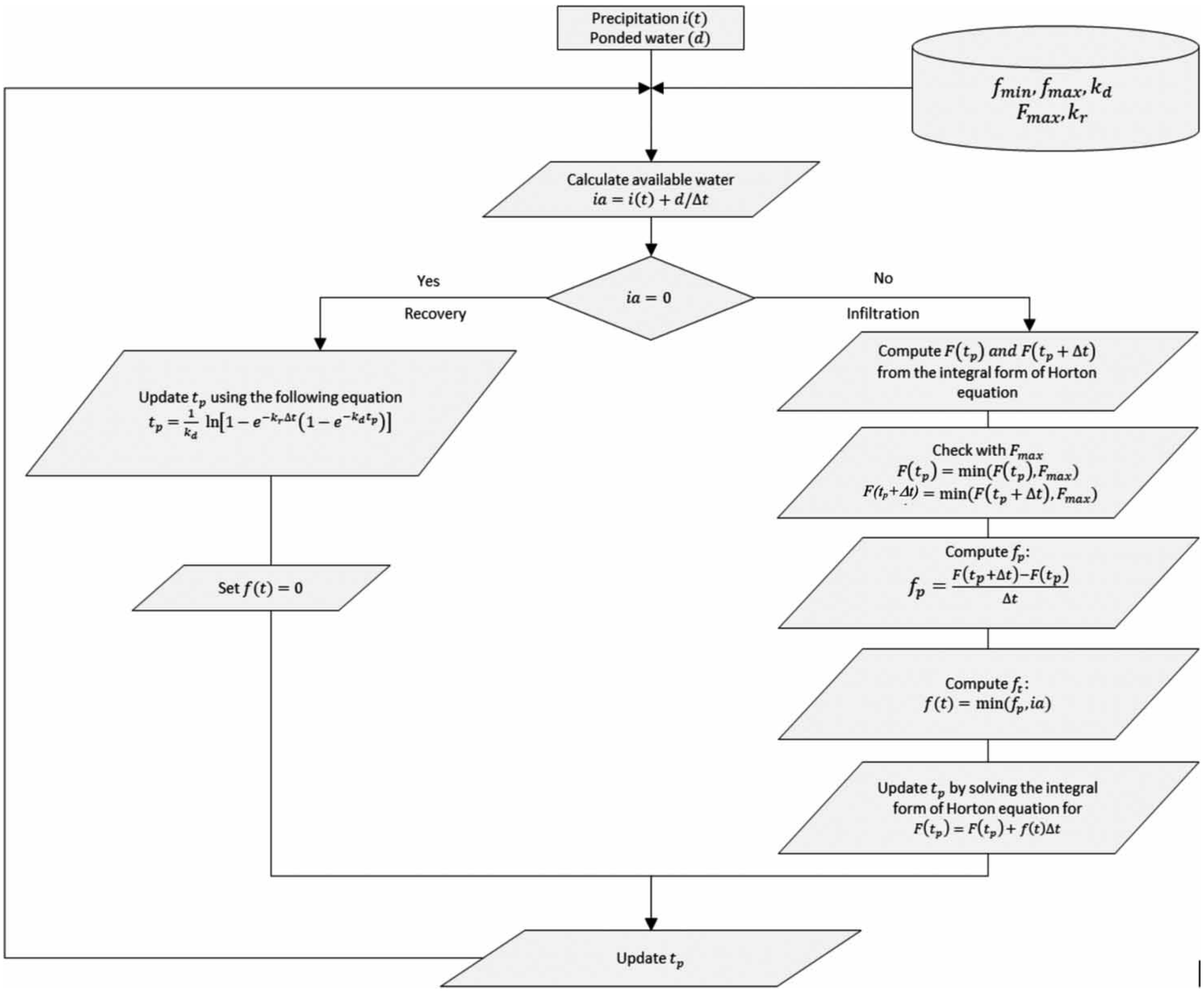

Figure 4 | The computational scheme applied by SWMM for the Green-Ampt method.

(Pitt *et al.* 1999), it is important to know which parameters are the most sensitive. For parameters where field measurements are possible, the sensitivity was investigated by choosing a value that differed from the true field value of the parameter(s) and investigating if it resulted in a significant change in output, thereby indicating that the parameter would be 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 the Green-Ampt infiltration method is sensitive to saturated hydraulic conductivity (Bauwe *et al.* 2016) and the 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 their uncertainties modelling urban permeable areas is needed (Law *et al.* 2009; Redfern *et al.* 2016).

STUDY AREA AND DATA

Three datasets with observed infiltration measurements, from previous studies for urban sandy soils from three different cities in Norway: Oslo, Trondheim, and Sandnes, were

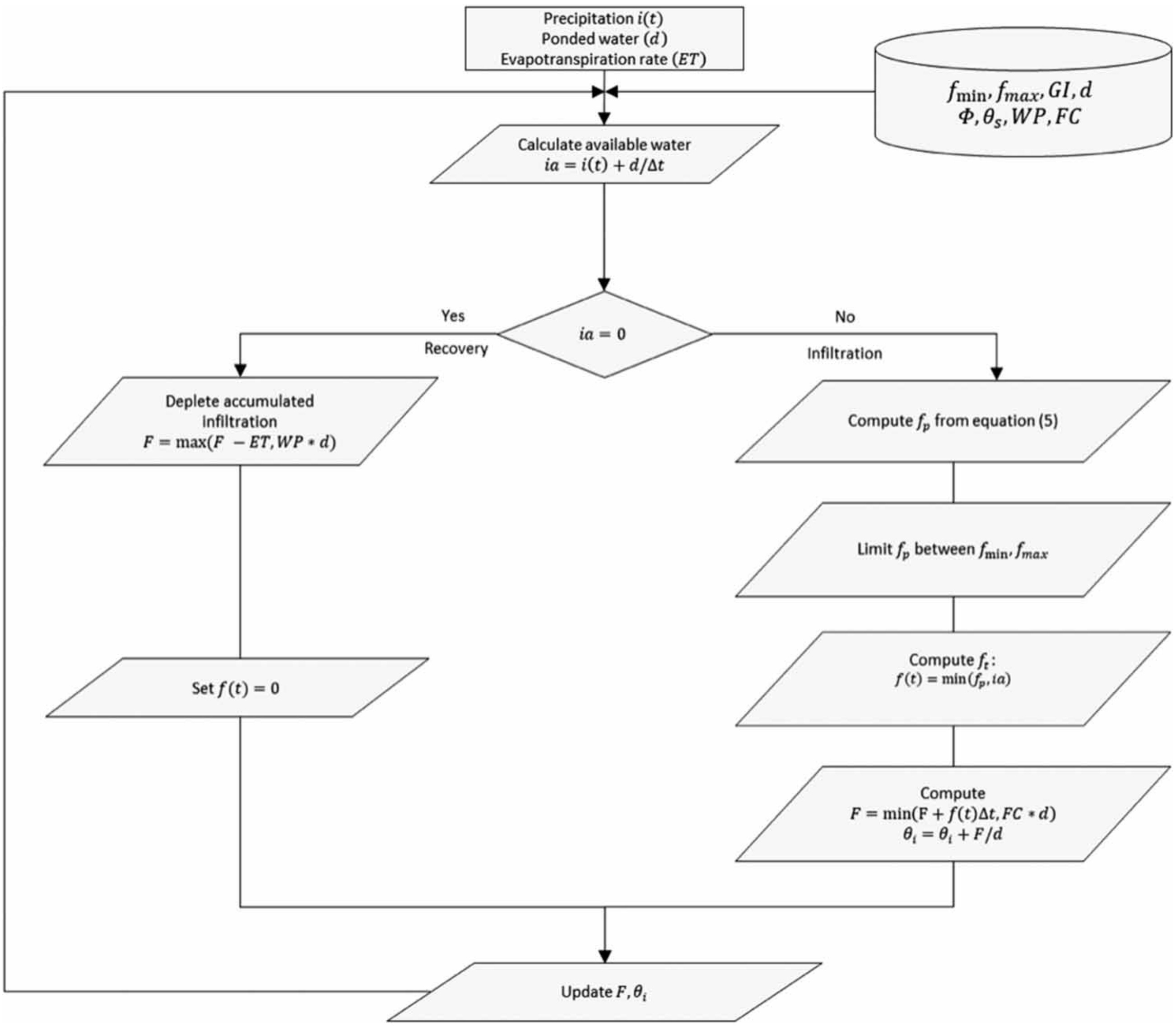

Figure 5 | The computational scheme applied by STORM for the Holtan equation (based on authors interpretation from the software's required inputs and results, but not clearly stated in the software manual).

used to evaluate urban soils (Bandermann *et al.* 2013; Becker 2016). Table 1 shows data from the field measurements and previous studies of these areas.

A design storm with 28.52 mm precipitation over a 120 min duration, which equals a 5-year return period at Blindern in Oslo, constructed by the symmetric hyetograph

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

Parameters		Unit	Oslo	Trondheim	Sandnes
Saturated hydraulic conductivity	K_{sat}	cm/h	10.464	3.19	1.41
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)	

method (Bøyum *et al.* 1997) from an IDF-curve in the period of 1968–2017 obtained by Norwegian Centre for Climate Services (NCCS, 2018), was used for Oslo, Trondheim, and Sandnes.

METHODS

The Green-Ampt and Horton infiltration equations were evaluated in SWMM, and the Holtan infiltration method was evaluated in STORM (Sieker 2014). The study was divided into three parts: (i) evaluating the three selected infiltration models for urban sandy soils; (ii) sensitivity analysis of a selected set of model parameters; and (iii) evaluating the influence of different initial conditions. Part (i) used all three locations and the synthetic storm event. Part (ii) and (iii) used the Sandnes location with the synthetic storm event.

In order to evaluate the different infiltration methods, a simplified watershed with a 100% pervious area of 100 m^2, and a depression storage, *ds*, 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, excluding winter (Hanssen-Bauer *et al.* 2009). From a model conceptual point of view, it is important to notice that there is a difference in the model setup in terms of how the models route the runoff in SWMM and STORM. This makes direct comparisons not of runoff distribution, not feasible for the two models.

For part (i), single-event simulations were conducted to evaluate the infiltration methods' response to different urban sandy soils. First, the simulations were done with initial soil moisture measured in field (wet conditions), followed by an initial soil moisture content of 70% of field capacity (dry conditions). A summary of the input values is given in Table 2.

For part (ii), a sensitivity analysis for single-event simulations was performed for both wet and dry conditions. An approach where the initial parameter values were changed within ±50%, while the other parameters were unchanged was used, as described in Rosa *et al.* (2015). The sensitivity to changes in the peak runoff, total runoff volume, peak delay, time to start of runoff, and runoff duration were calculated. The sensitivity of the change of parameters was compared as follows:

$$\text{Sensitivity} = \left(\frac{\partial R}{\partial P}\right)\left(\frac{P}{R}\right) \quad (10)$$

where ∂R is the change in output from the initial state and after changed parameter value, ∂P is the change in parameter, R is the original model output, and P is the original parameter value.

For part (iii), to compare the methods' ability to account for different initial conditions in the soil, long-term simulations were performed with an initial rainfall, pre-rainfall, and evaluated rainfall. 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. The return period and duration of the pre-rainfall was changed, as well as the ADWP between the pre-rainfall and evaluated rainfall (Figure 6).

The storm events used as pre-rainfall were obtained by the symmetric hyetograph method (Bøyum *et al.* 1997) from the IDF-curve of Blindern in Oslo in the period of 1968–2017 (NCCS 2018). The precipitation values under 1 mm over 5 min were changed to 1 mm, in order to obtain continuous 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 a smaller time step than 5 min were adjusted to 5 min in STORM, which is the minimum time step possible in the model. The simulations were conducted with evaporation equal to 1 and 7 mm/day. The drying time in the Horton was set to 4.20 days based on the embedded formula used in the Green-Ampt, where the drying time is based on the K_{sat}-value (Rossman & Huber 2016). The maximum infiltration rate was set to two times the minimum infiltration rate. For the Holtan method, the initial soil moisture was set to 70% of field capacity. For the Green-Ampt, the initial deficit was set equal to the porosity, to make the method consider the whole spectre of available storage for water.

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[a]	ψ_s	mm/h	51.68	76.31	99.84
	Initial deficit, wet[b]	θ	–	0.080	0.040	0.036
	Initial deficit, dry[b]			0.260	0.258	0.220
Horton	Minimum infiltration rate	f_{min}	mm/h	104.64*	31.88*	14.05*
	Maximum infiltration rate, wet[c]	f_{max}	mm/h	130.99	35.90	15.82
	Maximum infiltration rate, dry[c]			190.02	57.75	25.00
	Decay coefficient[d]	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[e]	f_{max}	mm/h	209.28	63.76	28.10
	Wilting point[f]	WP	–	0.050	0.050	0.050
	Field capacity	FC	–	0.115[g]	0.117[g]	0.117[h]
	Porosity	ϕ	–	0.340*	0.340*	0.302[i]
	Initial soil moisture, wet	θ_i	–	0.260*	0.300*	0.266[j]
	Initial soil moisture, dry			0.081	0.082	0.082

*See Table 1.
[a]Based on the relationship between K_{sat} and ψ_s described in the SWMM technical manual (Rossman & Huber 2016).
[b]The difference between porosity and initial soil moisture content.
[c]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 h, based on Equation (1).
[d]From recommendation by SWMM technical manual (Rossman & Huber 2016).
[e]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).
[f]Based on values from Wang *et al.* (2017).
[g]Calculated based on measured values and method described by Becker (2016).
[h]Assumed the same as for Trondheim.
[i]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.
[j]Initial soil moisture percentage of porosity is assumed the same as in Trondheim, due to the high amount of rainy days in both locations (NCCS 2018).

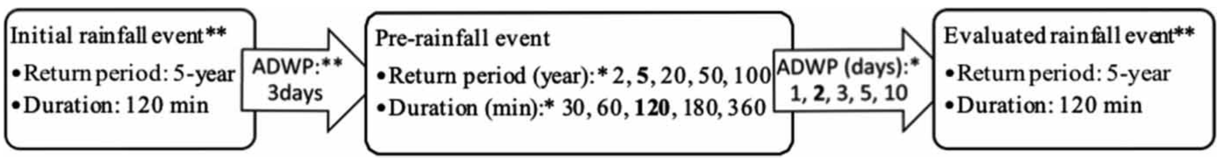

Figure 6 | Schematic representation of the long-term simulations. *Return period, duration, and ADWP are changed one at a time to evaluate the effect on the evaluated rainfall event. Highlighted values correspond to base values that are used when other rainfall characteristics are changed. **Constant.

RESULTS AND DISCUSSION

Urban soils analysis

For the single-event simulations, the event did not generate surface runoff in Oslo as the rainfall intensity never reaches the saturated infiltration rate. It generated more surface runoff for Sandnes than for Trondheim, which was as expected, due to the soil characteristics shown in Table 2. There was a difference in peak runoff, runoff volume, and duration of runoff between the different urban sandy soils (Table 3), which confirms the difficulty of classifying an urban soil.

The three methods generate more similar results for wet conditions, compared with the dry conditions. The methods are more similar closer to saturation, which is expected as 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 differently in the process from a

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 (m^3)	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 the Holtan equation was simulated with 5 min time step and is not routed to an outlet as in the Green-Ampt (G-A) and Horton.

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 results.

For the dry condition in Sandnes, the peak runoff and runoff volume using the Green-Ampt were only 30 and 11%, respectively, of the peak runoff and runoff volume using the Horton. The soil capacity in the Horton is filled up during the first lower intensities, and the highest observed infiltration rate reached during dry conditions was 25 mm/h (the complete results from the Horton infiltration calculation is included in the Supplementary Material). The Green-Ampt is based on the available pores for water storage without any limitation for maximum infiltration capacity (f_{max}), resulting in the highest infiltration rate at almost three times as high as in the Horton equation. The method will not generate any surface runoff if there is water storage available in the soil. This principal difference in how the Green-Ampt and the Horton equations generate surface runoff for a dry soil should be evaluated when choosing infiltration method in SWMM. The choice of the equation was shown to be important in order to obtain the most realistic runoff behaviour for a specific soil. The Horton equation generated similar results for dry and wet conditions at Sandnes. The reason for this is that the 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 a larger difference in runoff characteristics between wet and dry conditions can be seen for Trondheim. It can be seen that, as the maximum infiltration rate gets closer to the minimum infiltration rate, the difference between the runoff characteristics between a wet and dry condition will decrease for Horton.

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 (WP) and field capacity (FP), the infiltration decreases continuously from a maximum infiltration rate (f_{max}). Reaching soil porosity (ϕ), the infiltration rate is set to a minimum (f_{min}). Exfiltration starts at a slow rate when the soil moisture content is 70% of field capacity, before it reaches the minimum infiltration rate when the soil moisture content reaches the soil porosity. In addition to the maximum infiltration rate, the Holtan method also considers available soil storage at a specific time and, and thereby allows for more water to infiltrate compared with the Horton method. The Holtan's method's ability to account for both maximum infiltration rate, and available storage (FC-WP), makes the method more realistic.

Sensitivity analysis

In the Green-Ampt, the governing parameters are saturated hydraulic conductivity (K_{sat}), suction head (Ψ), and initial deficit (θ). For both wet and dry conditions, saturated hydraulic conductivity is the most sensitive parameter. A 50% reduction of this parameter leads to a more than 50% decrease in the runoff volume for wet conditions. The literature shows 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 the chosen value for this parameter. All the parameters in the Green-Ampt are sensitive for dry conditions. For wet conditions (Figure 7), the most sensitive parameter was found to be saturated hydraulic conductivity (K_{sat}), followed by increasing initial deficit (θ), while there were no changes in runoff characteristics when changing the suction head (Ψ). Assuming a worst-case scenario for design purposes, i.e. saturated condition, the above indicates that saturated hydraulic conductivity is the essential parameter to be considered. For dry conditions, on the other hand, all parameters should be considered.

The minimum infiltration rate for wet conditions is the most sensitive parameter in the Horton method. For dry conditions, the method is also most sensitive to minimum infiltration rate, followed by maximum infiltration rate and the decay coefficient. For dry conditions, the sensitivity of the 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 in Sandnes using the Horton method, compared with the other two methods. The Holtan method, on the other hand, showed 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 the Horton method for dry conditions, the peak runoff only decreased by 1.3%. The corresponding value for the Holtan method was 5.1% change in peak runoff. The Holtan method's ability to continuously calculating the soil moisture content in the soil leads to a higher sensitivity in the parameters: maximum infiltration rate (f_{max}), initial soil moisture content (θ), and porosity (ϕ), especially for dry soil conditions. Measurements of compacted sandy soils showed that the 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 the Holtan method. Whereas for the Horton method, the minimum infiltration rate is more important for both conditions, while also including maximum infiltration rate for dry conditions.

In general, the sensitivity analysis demonstrated the importance of an accurate representation of the infiltration rate. The infiltration rate is the controlling process in the model by which runoff is generated. As the three datasets from urban sandy soils in Norway used here show, the runoff characteristics vary quite extensively. The use of standard values or values from compacted soils from another field can lead to a wrong estimation due to the high sensitivity of the parameter. 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 surface runoff, leading to an under-design of stormwater measures.

A full-scale infiltration and runoff study should be carried out in order to compare observed and modelled data. The comparisons between the three methods need to be compared with observed data before a final conclusion on suitability for different conditions can be assessed. It is not a simple field setup as both runoff and infiltration need to be fully monitored, and preferable on an urban pervious area. The scale will also be important, as minimizing natural conditions will be important.

Initial moisture content

Long-term simulations for the soil in Sandnes were conducted to evaluate the three methods' ability to account for initial soil moisture content in the soil before a precipitation event. An essential part of this is the way that the methods are modelling the regeneration of soil moisture from a saturated soil to a dry soil.

The runoff characteristics of the evaluated rainfall were 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 was higher than the minimum infiltration rate for the soil in Sandnes. This indicates that the soil reaches a saturated

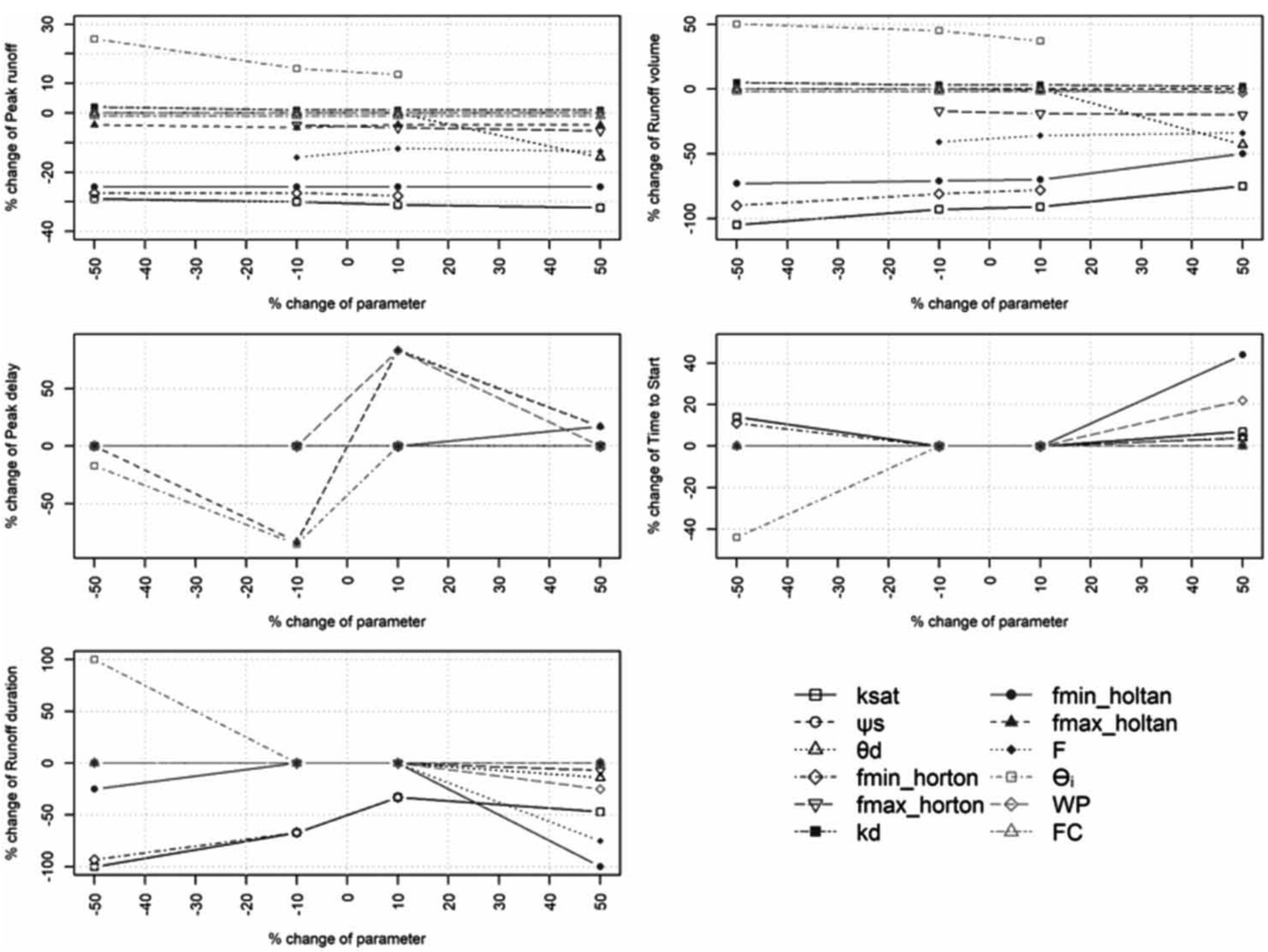

Figure 7 | Sensitivity of parameters where the initial parameter values are changed from −50 to +50% for wet conditions. K_{sat}, saturated hydraulic conductivity; ψ_s, suction head; θ_d, initial deficit; f_{min}, minimum infiltration rate; f_{max}, maximum infiltration rate; k_d, decay coefficient; ϕ, porosity; θ_i, initial soil moisture; WP, Wilting point; FC, field capacity. It is important to note that some of the results of the sensitivity analysis is not physically possible. Initial soil moisture content cannot be higher than porosity. Minimum infiltration rate cannot be higher than maximum infiltration rate.

condition during pre-rainfall; hence, no difference in soil conditions at the evaluated rainfall event was expected.

The Green-Ampt is highly affected by changes in ADWP after pre-rainfall between 1 and 5 days. The Horton method shows a smaller change in runoff characteristics by changing ADWP between 1 and 3 days. This indicates that the Green-Ampt method reaches a dry condition after 5 days, whereas the Horton method reaches a dry condition after 3 days. This can be an explanation for the differences in the methods' reaction to changes in the duration of pre-rainfall. The Green-Ampt method is more affected by changes in the pre-rainfall's duration than the Horton method. The slope of the graph at ADWP equal to 2 days in the Green-Ampt method (Figure 8, case 2.1B) is steeper than that for the Horton method (Figure 8, case 2.2B). This, in turn, indicates that a longer duration has a greater effect on the surface runoff for the Green-Ampt method, due to that 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 the Green-Ampt method and the Horton method, as seen in

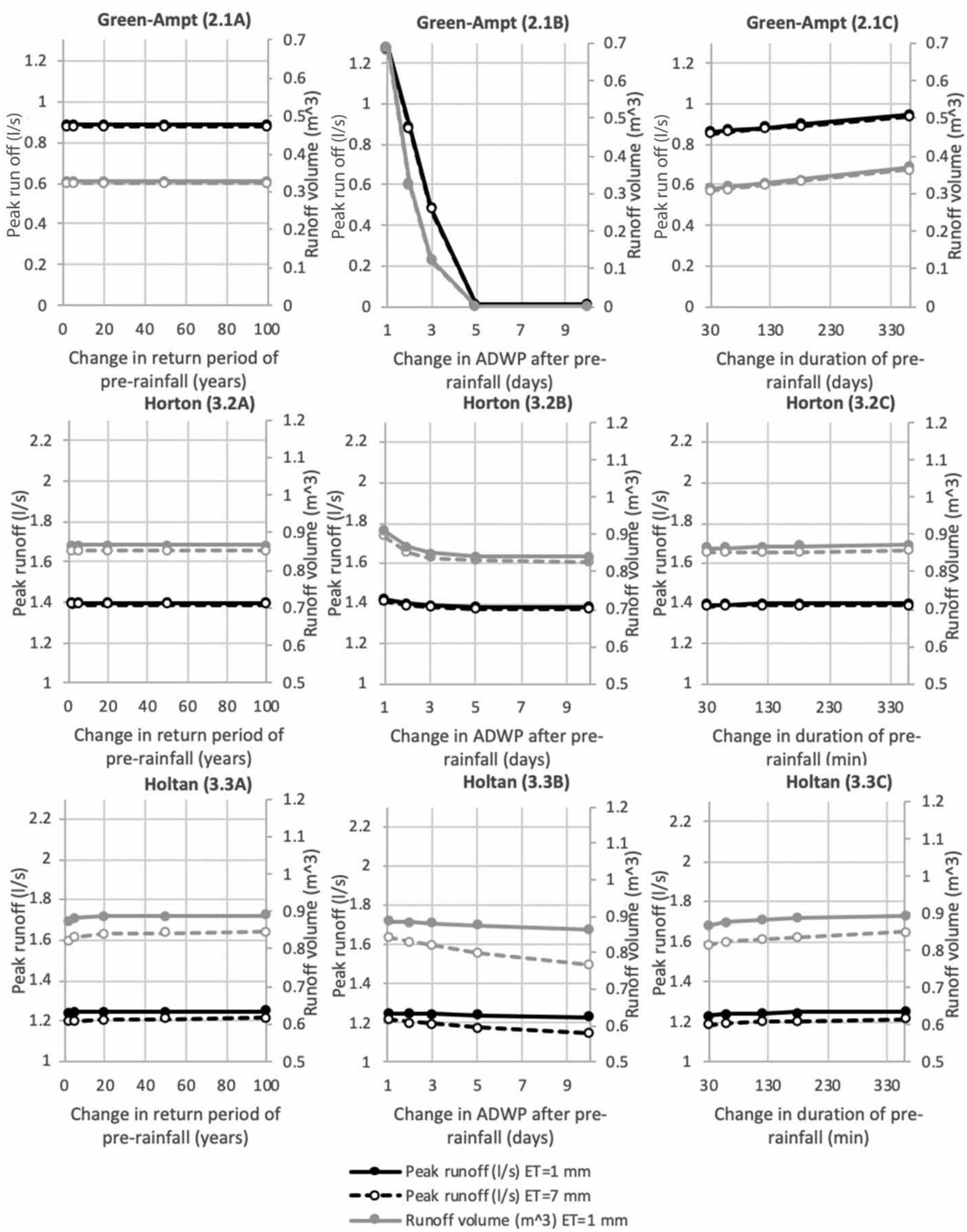

Figure 8 | Green-Ampt (1), Horton (2), and Holtan (3) infiltration method response to changes in return period of pre-rainfall (A), ADWP after pre-rainfall (B), and duration of pre-rainfall (C).

Figure 8. A study by Seneviratne *et al.* (2010) showed the complexity of factors contributing to changes in soil moisture content, where ET has a 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 during the summer months and an underestimation of runoff during the winter months. This indicates that long-term simulations of catchments with significant permeable areas in SWMM can be unsuitable where the ET-value is low, due to the fast recovery time from saturated to dry condition.

The Holtan method shows a large difference when changing the ET-value (Figure 8, case 3.3A, 3.3B, 3.3C). The main source of soil water loss in STORM is exfiltration and ET. This exfiltration is set to start 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 the duration of pre-rainfall was approximately constant (Figure 8, case 3.3A and 3.3C) as it was the same number of ADWP before the evaluated rainfall for both return periods. As the number of ADWP after pre-rainfall increased, the difference between the output values when changing ET-value increased (Figure 8, case 3.3B). This makes the Holtan method 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 is in response to changes in ADWP after the pre-rainfall (Figure 8, case 3.1B, 3.2B, 3.3B). For the Green-Ampt method, 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).

The Horton method gives the option of a user-specified value for the regeneration of infiltration capacity. The value for this shown in Figure 8 is based on the embedded formula in SWMM used for the Green-Ampt method. The Horton method moved faster towards dry condition than the Green-Ampt, due to the models' procedure of calculating the recovery process as described in 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 the drying time was more sensitive if the maximum infiltration rate was larger. With a 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 the maximum infiltration rate. However, the regeneration time to a dry state is relatively fast, which suggests that the Horton is better suited for single-event simulation or if it is known that the soil changes rapidly from saturated to dry condition, as for example would be expected from very sandy soil.

CONCLUSIONS

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

There are different parameters that account for the initial soil moisture in different infiltration methods. The Green-Ampt infiltration method takes the available storage for water into account, while for the Horton method, a user-specified maximum infiltration rate is needed. The Holtan method accounts for both these parameters, giving the method more confidence, but it also requires more input data than the other two methods. If dry initial conditions are assumed, the selection of a 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. The Green-Ampt method and the Horton method lack the option to account for evapotranspiration in the regeneration of soil moisture, which makes both these methods 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. The 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. The additional soil infiltration parameters in the methods are more important for dry soil conditions. The Green-Ampt method is most sensitive to saturated hydraulic conductivity, followed by the initial deficit, and suction head for dry condition. The Horton method is most sensitive to minimum infiltration rate, followed by maximum infiltration rate. The Holtan method is most sensitive to maximum infiltration rate, followed by the porosity, and the initial soil moisture content for dry condition. This is also the most demanding model with respect to input parameters.

To obtain accurate results for urban compacted sandy soils with the simplified infiltration methods used in this study, field measurement of infiltration rates are essential. This study highlights two reasons for this. (i) There is a large variance in the field measurements of the different compacted urban sandy soils leading to different runoff characteristics. (ii) The methods show a high sensitivity to saturated infiltration rate, implying that a small change in this parameter would lead to a large change in runoff characteristics. Urban soils have additional parameters that can affect the infiltration procedure, which these methods are not accounting for. Hence, field measurements are important. Preferably, a full-scale runoff and infiltration study. Future studies should focus on a classification system of urban soils, in order to incorporate the complexity of urban soils' characteristics into the infiltration model input parameter sets.

ACKNOWLEDGEMENTS

This research was funded by Klima 2050 through the Norwegian Research Council SFI grant program (grant number 237859/030), and performed in collaboration with Professor Heiko Sieker and Stephan Bandermann at Technischen Universität Berlin (TU Berlin)/ Ingenieurgesellschaft Prof. Dr Sieker mbH.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Bandermann, S., Potrawiak, J. & Sommer, H. 2013 *Feasibility Study - Flood Mitigation by On-Site Stormwater Management (SUDS) - Preplanning of SUDS in Sandnes City*. Report for the Municipality of Sandnes, Norway.

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**, 311–321. doi:10.1016/j.jhydrol.2016.03.054.

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)*. Thesis, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Becker, M. A. 2016 *Assessment of Downspout Disconnection by Modeling Infiltration Potential in Urban Areas*. Thesis, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

Bøyum, Å., Eidsmo, T., Undholm, O., Noreide, T., Semb, T., Skretteberg, R. & Markhus, E. 1997 *Anvendt Urbanhydrologi (Applied Urban Hydrology)*. Report by the Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway.

Chow, V., Maidment, D. & Mays, L. 1988 *Applied Hydrology*. McGraw-Hill Book Company, New York.

Davidsen, S., Löwe, R., Ravn, N. H., Jensen, L. N. & Arnbjerg-Nielsen, K. 2018 Initial conditions of urban permeable surfaces in rainfall-runoff models using Horton's infiltration. *Water Science and Technology* **77** (3), 662–669. doi:10.2166/wst.2017.580.

Esteves, M., Faucher, X., Galle, S. & Vauclin, M. 2000 Overland flow and infiltration modelling for small plots during unsteady rain: numerical results versus observed values. *Journal of Hydrology* **228** (3–4), 265–282. doi:10.1016/S0022-1694(00)00155-4.

Gregory, J., Dukes, M., Jones, P. & Miller, G. 2006 Effect of urban soil compaction on infiltration rate. *Journal of Soil and Water Conservation* **61** (3), 117–124.

Haghighi, F., Gorji, M., Shorafa, M., Sarmadian, F. & Mohammadi, M. H. 2010 Evaluation of some infiltration models and hydraulic parameters. *Spanish Journal of Agricultural Research* **8** (1), 210–217. doi:10.5424/sjar/2010081-1160.

Hanssen-Bauer, I., Drange, H., Førland, E. J., Roald, L. A., Børsheim, K. Y., Hisdal, H., Lawrence, D., Nesje, A., Sandven, S., Sorteberg, A., Sundby, S., Vasskog, K. & Ådlandsvik, B. 2009 *Klima I Norge 2100 Bakgrunnsmateriale* til NOU Klimatilplassing (Climate in Norway 2100 Background Material for NOU Climate Adaptation)*. Report by the Norwegian Centre for Climate Services (NCCS), Oslo, Norway.

Holtan, H. N. 1961 *A* Concept *for* Infiltration Estimates *in* Watershed Engineering. USDA-ARS Volume Nr 41–51, Washington, DC, USA.

Holtan, H. N. & Lopez, N. C. 1971 *USDAHL-70 Model of Watershed Hydrology*. USDA, Washington, DC, USA.

Horton, R. E. 1941 An approach toward a physical interpretation of infiltration-capacity. *Soil Science Society of America Journal* **5**, 399. doi:10.2136/sssaj1941.036159950005000C0075x.

Hsu, S. M., Ni, C. F. & Hung, P. F. 2002 Assessment of three infiltration formulas based on model fitting on Richards equation. *Journal of Hydrologic Engineering* **7** (5), 373–379. https://doi.org/10.1061/(ASCE)1084-0699(2002)7:5(373).

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**, 132–143. doi: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), 2550–2563. doi:10.1080/00103624.2012.711877.

Law, N. L., Cappiella, K. & Novotney, M. E. 2009 The need for improved previous land cover characterization in urban watersheds. *Journal of Hydrologic Engineering* **14** (4), 305–308. doi: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**, 356–365. doi:10.1016/j.jhydrol.2016.01.060.

Liong, B. S. Y., Chan, W. T. & Lum, L. H. 1991 Knowledge-Based system for SWMM runoff component calibration. *Journal of Water Resources Planning and Management* **117** (5), 507–524. doi:10.1061/(ASCE)0733-9496(1991)117:5(507).

Loosvelt, L., Vernieuwe, H., Pauwels, V. R. N., De Baets, B. & Verhoest, N. E. C. 2013 Local sensitivity analysis for compositional data with application to soil texture in hydrologic modelling. *Hydrology and Earth System Sciences* **17**, 461–478. doi10.5194/hess-17-461-2013.

Morel, J. L., Schwartz, C., Florentin, L. & de Kimpe, C. 2005 Urban soils. In *Encyclopedia of Soils in the Environment*, pp. 202–208. doi:10.1016/B0-12-348530-4/00305-2.

NCCS 2018 *Online IDF-curves and climate data*. Norwegian Centre for Climate Services (NCCS). Available from: https://klimaservicesenter.no/ (accessed 04 April 2018).

Pitt, R., Lantrip, J., Harrison, R., Henry, C. L., Xue, D. & O'Conner, T. P. 1999 *Infiltration Through Disturbed Urban Soils and Compost: Amended Soil Effects on Runoff Quality and Quantity*. US EPA, Cincinnati, OH, USA.

Pitt, R., Chen, S.-E., Clark, S. E., Swenson, J. & Ong, C. K. 2008 Compaction's impacts on urban storm-water infiltration. *Journal of Irrigation and Drainage Engineering – ASCE* **134**, 652–658. doi:10.1061/(ASCE)0733-9437(2008)134:5(652).

Redfern, T. W., Macdonald, N., Kjeldsen, T. R., Miller, J. D. & Reynard, N. 2016 Current understanding of hydrological processes on common urban surfaces. *Progress in Physical Geography* **40** (5), 699–713. 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), 746–757. doi:10.1111/jawr.12272.

Rossman, L. A. & Huber, W. C. 2016 *Storm Water Management Model (SWMM) Reference Manual*. US EPA, Cincinnati, OH, USA.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B. & Teuling, A. J. 2010 Investigating soil moisture-climate interactions in a changing climate: a review. *Earth-Science Reviews* **99** (3–4), 125–161. doi:10.1016/j.earscirev.2010.02.004.

Sieker 2014 STORM XXL (https://www.sieker.de/en/software) and manual. https://www.sieker.de/en.

Song, X., Zhang, J., Zhan, C., Xuan, Y., Ye, M. & Xu, C. 2015 Global sensitivity analysis in hydrological modeling: review of concepts, methods, theoretical framework, and applications. *Journal of Hydrology* **523**, 739–757. doi10.1016/j.jhydrol.2015.02.013.

Wang, X., Sample, D. J., Pedram, S. & Zhao, X. 2017 Performance of two prevalent infiltration models for disturbed urban soils. *Hydrology Research* **48** (6), 1520–1536. doi:10.2166/nh.2017.217.

First received 4 April 2019; accepted in revised form 28 September 2020. Available online 4 January 2021