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Storm Water Management Model Sensitivity to infiltration methods and soils impermeability: The Case of Tangier Experimental Basin, Morocco

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- ✓ IDF
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Abstract

The Storm Water Management Model (SWMM) uses many parameters and functions that require selecting those that significantly affect the generated peak flows of the design of storm water sewerage in urban areas. In this paper, we are interested in the infiltration loss function through the study of SWMM sensitivity to different infiltration method integrated into this model, namely Horton, SCS and Green-Ampt methods. The case study concerns the Tangier experimental basin soil type located in Morocco. For sandy and clayey soils, the Horton and Green-Ampt have given the same infiltrated volumes and peak flows. However, for a clayey structure, the SCS gives maximum deviations of infiltrated volumes of 125% compared to the Horton and Green-Ampt. This variation causes maximum deviation of peak flows not exceeding -10%. Simulation results also showed a discrepancy in the Green-Ampt method which increased volumes infiltrated cause increased peak flows. SWMM model sensitivity studies for loamy soil showed that the maximum deviations of infiltrated volumes are of 7% for the SCS and 12% for the Green-Ampt compared to the Horton method. These deviations generate a variation of peak flows respectively of -7% and 2%. Consequently, we have retained the Horton method. The SCS method can be used by modifying the CN parameter for clayey soil at 91 instead of 83.

1. Introduction

This article is part of a research project of national requirements on evaluating existing methods of calculating peak flows of the design of storm water sewerage in urban areas used by various sewerage sector stakeholders in Morocco (local engineering firms and concession of sanitation networks). These stakeholders primarily use empirical methods (e.g., the Caquot method) for the determination of peak flows of storm water. While, the Caquot method is simple to use, it has some limitations. The method is applicable only for small areas (< 200 ha) and high runoff coefficients (> 20%) [1]. Using this method in areas with features outside her limits would lead to either over estimation of the peak flows and thereby increase size of rainwater conduits, which will lead to additional investment costs.
Therefore, there is an increasing need to evaluate reliability of existing methods currently used by various sewerage sector stakeholders to effectively predict peak storm flows in urban areas in Morocco. To achieve this, we proposed to use the Storm Water Management Model Version 5.0.022 [2] for analyzing complex and interdependent hydrologic parameters (e.g., infiltration, depression storage, terrain roughness, etc…). However, this model requires an important number of parameters and variables. The SWMM model parameters were subject to a detailed sensitivity analysis [3] which is meant to select those that significantly affect the peak flow for the design of storm water sewerage. Considering the SWMM model variables, we quote rainfall data and infiltration loss function. For the first variable, we have treated the different forms of design storm [4] in

common use in rainfall-runoff modeling. Concerning the second variable, it has been the subject of this article, which consists of the evaluation of infiltrated volumes and peak flows generated by the SWMM model, in relation to the choice of infiltration sub models and to the variation of soil impermeability .

In urban areas, the Soil impermeability variation is affected by the effect of urbanization. It has profound impacts on the runoff characteristics of the land and, consequently, on the aquatic environments of the urban streams to which the runoff drains [5, 6, 7, 8]. The Infiltration affects the runoff generation process and is dramatically influenced by the soil hydraulic properties and soil porous texture [9]. Most physically based hydrologic models have described the relationships between rainfall, runoff, and infiltration processes implicitly or explicitly [10]. Other studies have also discussed the method of calculating infiltration through the pavement layers of permeable pavement systems using the low-impact development module [11]. They have discovered that it is inadequate when the depth of the pavement layer is less than 120 mm and the computational time steps are longer than 30 min.

Each infiltration sub model requires the determination of a limited number of parameters the values of which are offered by soil type at the level of the SWMM model. The surveyed infiltration sub models include those of Horton, Green-Ampt and SCS.

Tholin and Keifer [12] suggested values for a lawn loam for the three model parameters of Horton parameters. Desbordes [13] has proposed a range of infiltration which varies from 3 to 20 mm / h. There are also tables allowing the estimation of the parameters of the Horton formula for different soil types [14]. The US Soil Conservation Service (SCS) [15] has proposed tables showing four classes of soil (A, B, C and D) according to their impermeability degree. The Green-Ampt (G-A) infiltration model is one such model based on the soil porous media characteristics [16].

2. Materials and Methods

2.1. Methodology

The present study has been carried out using an approach that involves the evaluation of all the infiltration sub models included in the SWMM model. These concern the methods of Horton, Green-Ampt and SCS. Each sub infiltration model requires a number of parameters to define the adopted values of which are those proposed by the SWMM model. In the first stage, we have done the evaluation of these infiltration methods through a comparison of infiltrated volumes and peak flows generated for the type of Tangiers experimental basin loamy soil. In the second stage, we have extended our assessment of the impact of the choice of sub infiltration models on the soil extreme types, namely sandy and clayey soil types.

The compared volumes and peak flows results have always been referred to those of the Horton method. Subsequently, we have studied the relationship of the variation of the infiltrated volumes and the generated flows in function to the degree of soil impermeability for all the infiltration sub models. To explain the difference of the calculated infiltrated volumes in relation to the Horton method, we have used the HEC-HMS model [17], which is of the same family as the SWMM model.

Concerning the infiltration sub-models which generate large deviations of infiltrated volumes from the Horton model, we have adjusted their parameters so as to minimize these differences. The infiltration sub models used are shown in the table 1, below [18]. The infiltration parameters proposed by the SWMM model of the different infiltration functions for three soil types (sandy, Loamy and clayey) have been presented in the table 2 below.

2.2. Study Area

Selection of the study area was determined by the existence of Tangier's experimental basin located in Northern Morocco. In 1990, this basin was equipped with Direction de la Région hydraulique du Loukous in collaboration with Régie Autonome de distribution d'eau et d'électricité de Tanger (RAID) [19]. However, data collection and follow up in this experimental basin, was suspended in 1993.

2.3. Determination of the characteristics of the experimental basin

The map treatment was carried out under ArcView, which includes the digitization of contours and altimetry points, the boundary of the experimental basin and the materialization of the main collector of the basin case of study. This treatment was elaborated based on the plans of restitution of the city of Tangiers at 1/2000 and aerial photographs dating from the year 1990 that covered the site of the basin. The calculated characteristics of the experimental basin are shown in table 3.

Table 1. Characteristics of Infiltration models used.

Infiltration model	Formulas	Parameters
Horton [18]	$\frac{dI(t)}{dt} = F(t) = Fc + (F0 - Fc) * e^{-\alpha t}$ $I(t) = \int_0^t F(u) * du = Fc * t + \frac{(F0 - Fc) * (1 - e^{-\alpha t})}{\alpha}$	I(t) is the cumulative infiltration (mm) F(t) is the Infiltration rate at time t (mm/h) Fc is ultimate infiltration rate (mm/h) F0 is initial infiltration rate (mm/h) α is the decay constant (h^{-1})
Green-Ampt [18]	$\frac{dI(t)}{dt} = F(t) = K_S * \left(\frac{(h_0 - h_f) * (\theta_f - \theta_0)}{I(t)} + 1\right)$ Where $h_f < 0$ $I(t) = \int_0^t F(u -) * du = Fc * t + \frac{(F0 - Fc) * (1 - e^{-\alpha t})}{\alpha}$	I(t) is the cumulative infiltration (mm) F(t) is the Infiltration rate at time t (mm/h) h_f is the hydraulic head at the wetting front (mm) (h_f <0) h_0 is the hydraulic head at the surface (mm) θ_0 is initial moisture content before infiltration began θ_f is saturated moisture content (%) K_s : saturated hydraulic conductivity (mm/h)
SCS [18]	$Q = \frac{(P - I_a)^2}{(P - I_a + S)}$ $I_a = 0.2 * S\ ;\ CN = \frac{25400}{S + 254}$ $I(t) = \frac{S * (P(t) - I_a)}{P(t) - I_a + S}$ $F(t) = \frac{dI(t)}{dt} = \frac{S^2}{(P - I_a + S)^2} * \frac{dP}{dt}$	I_a is initial abstraction (mm) P is Rainfall (mm) Q is Runoff (mm) S is the potential maximum retention (mm) CN is curve number I(t) is the cumulative infiltration (mm) F(t) is the Infiltration rate at time t (mm/h)

Table 2. Selected parameters of the different infiltration sub-models [2]

	Sandy	**Loamy**	**Clayey**
Horton			
f0 (mm/h)	127	76.2	25.4
fc(mm/h)	120.396	3.302	0.254
K (h^{-1})	4.5	4.5	4.5
Green-Ampt			
K_s (mm/h)	120.396	3.302	0.254
$(h_0 - h_f)$ (mm)	49.02	88.9	320.04
$(\theta_f - \theta_0)$	0.375	0.231	0.097
SCS			
CN	45	77	83
K_s (mm/h)	120.396	3.302	0.254

Table 3. Summary of Tangier experimental basin's characteristics

Parameters	**Value**
Area (ha)	226
Length (m)	2660
Weighted average slope (%)	1.23
Area of the zone in progress urbanization (ha)	69
Area of urbanized zone (ha)	157
Gravelius Compactness coefficient	1.28
Length of the equivalent rectangle (km)	2.5
Width of the equivalent rectangle (km)	0.9
Impermeability Coefficient (%)	37

2.4. Data analysis

Rainfall and runoff data for the experimental basin of Tangiers were reported by Rakik and Ejjelouli [19]. The reports cover eight rainfall-runoff events recorded. The storms selected are those with a total rainfall amount greater than 4 mm, which is generally considered as sufficient to cause runoff in the sewerage system.

This threshold of 4 mm was determined on the basis of hydrographs generated from rainfall events observed in the Tangiers experimental basin, which losses all the rainfall greater than 4 mm [19]. The analysis of the observed events of the experimental basin allowed us to determine the following:

- Rainfall duration : 65 min to 135 min
- Time of concentration; Tc: 60 min
- Runoff coefficient: CR: 0.22
- return period T <2 years.

The observed rainfall data has been used to determine the structure of the average storm for different return periods. These return periods were used for the design of storm water sewerage in Morocco [3], and includes:

- storm water sewerage in urban areas (2 years for tertiary collectors, 5 years for secondary collectors, and 10 years for primary collectors)
- storm water collection network in extra-urban areas and road works (20, 50, and 100 years).

For return period more than 2 years, we have used the IDF curves from the city of Tangiers for the period 1940-2001 [4]. IDF (Intensity-Duration –Frequency) rainfall curves allowed us to have the Montana coefficients for different return periods presented in the table 4 below:

Table 4. Montana coefficients for different return periods of the Tangiers city

T(ans)	a(T)	b(T)
5	285.18	0.526
10	316.74	0.5
20	350.64	0.484
50	396.84	0.471
100	432.42	0.464

The intensity of rainfall with Return period T and duration d can be described using a Montana formula [20]:

$$i(T,d) = a(T) * d^{-b(T)}$$

i(T,d) = intensity of rainfall (mm/h)
d = duration of rainfall (hours)
a(T) and b(T) = Montana coefficients with Return period T .

3. Results and Discussion

3.1. SWMM model Sensitivity to different infiltration methods for the experimental Basin soil Type

This step aims at comparing on one hand, the results of the infiltrated volumes determined by the different infiltration sub-models for the loamy soil of the Tangiers experimental basin, on the other hand, the generated flows by these infiltration sub models. This comparison was made with reference to the results obtained by the Horton method. A comparison of the infiltrated volumes from the different infiltration sub-models is shown in the following figure (Fig.1).

According to the figure 1 below, it is found that:

- The studied infiltration sub models give different infiltration volumes with relative deviations, compared to the results obtained by the Horton method, which increase along with the increase of the return period.
- The Green and Ampt infiltration model generates larger gaps than the SCS model. In fact, for a centennial return period, we have discovered an infiltrated volume deviation of 12% using the Green-Ampt sub-model and of 7% using the SCS method compared to the Horton method.

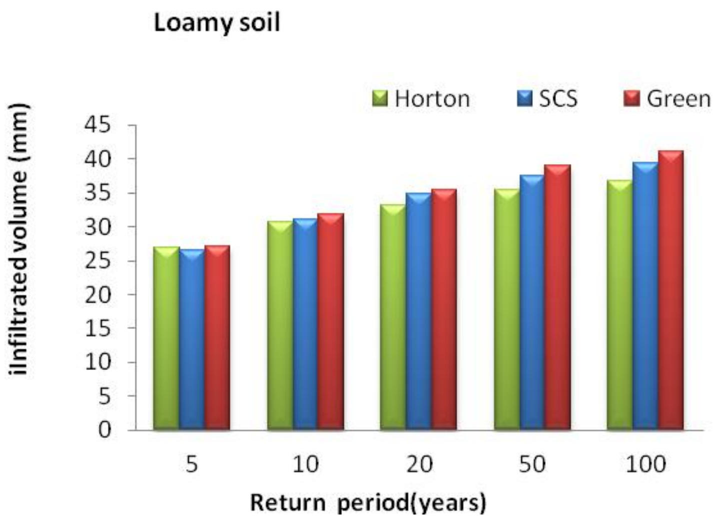

Figure 1.Comparison of volumes infiltrated calculated by different infiltration sub models -case for Loamy soil.

The simulation results obtained by the SWMM model based on different infiltration sub models used are shown in the following figure (Fig.2):

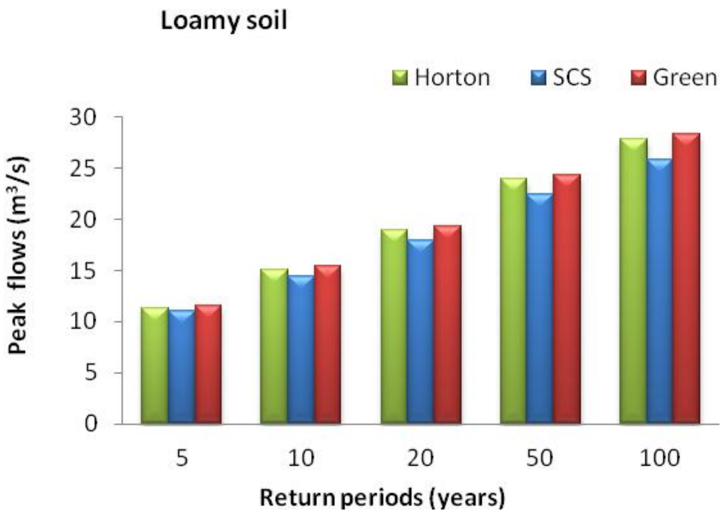

Figure 2. Comparison of the peak flows generated by different infiltration sub models for Loamy soil.

As shown by the Figure 2 above, the variation of the infiltrated volume generates the differences of the flow:

- almost uniform around 2% using the Green-Ampt method.
- evolve decreasingly in proportion to the increase of the infiltrated volumes with using the SCS method. They reach -7% for a hundred-year return period.

Moreover, it is found that, despite the infiltrated volumes calculated from the Green-Ampt method are higher than those of the SCS model, the generated flows obtained from the use of the Green-Ampt method are larger than the resulting peak flows obtained from the SCS method. It has to be noted here that the increase of infiltrated volumes should undergo the resulting flows in the descending direction and not in the ascending one.

Following this difference of the infiltrated volumes for the same soil type and the discrepancy between the evolution of infiltrated volumes and the generated peak flows, we have extended our study to the impact of the choice of infiltration sub-models on the infiltrated volumes and the peak flows relative to the extreme soil types (clayey and sandy).

3.2. SWMM model Sensitivity to different infiltration methods for clayey and sandy soils

We have adopted a comparison between the different assessment methods of the infiltrated volumes for the case of clayey and sandy soils with constant reference to the Horton model. The simulation results of the SWMM model based on the different infiltration sub-models are presented in the following figures (Figs.3 and 4).
The Green-Ampt model generates infiltrated volumes similar to those of Horton (Relative deviation = 0%) for clayey (Fig.3) and sandy (Fig.4) soil structures. As for the SCS model, the differences of the infiltrated volumes are minor and vary between -2% and -4%, depending on the increase of the return period for the sandy soil (Fig. 4). However, for the clayey structure, there has been a significant difference in volumes from 80% to 125% depending on the evolution of the return period (Fig.3).

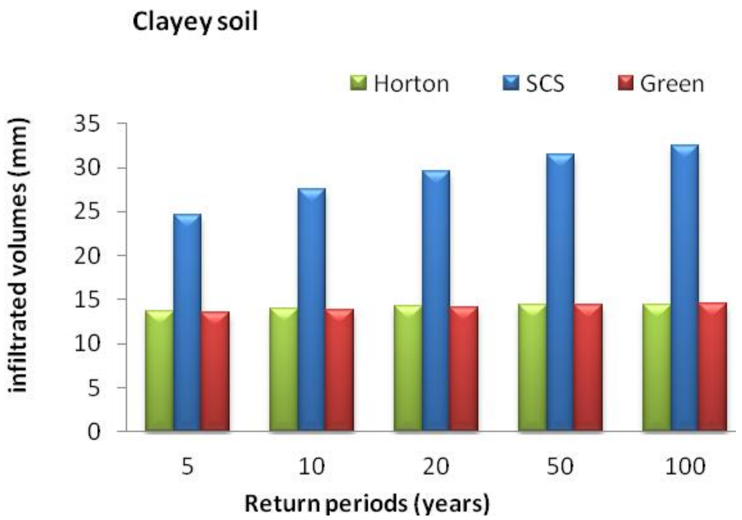

Figure 3. Comparison of volumes infiltrated calculated by different infiltration sub models - case for clayey soil.

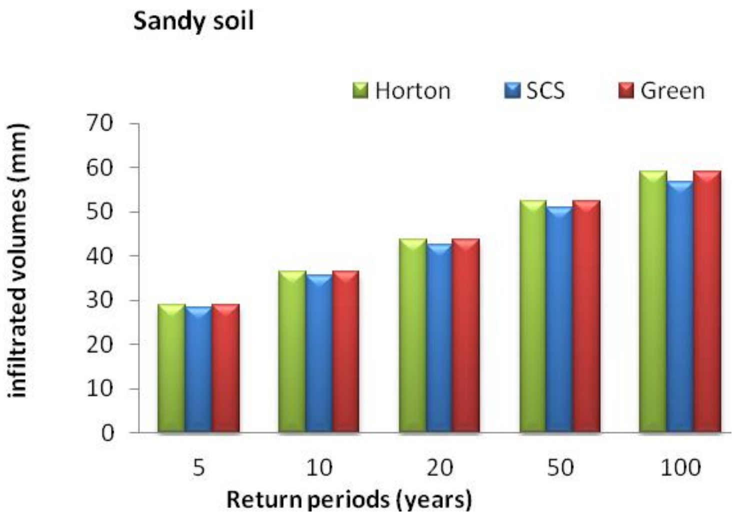

Figure 4. Comparison of volumes infiltrated calculated by different infiltration sub models - case for sandy soil.

Accounting for the effect of the choice of infiltration models on the resultant peak flows for both the extreme types of clayey and sandy soils, we have recorded relative deviations of peak flows:

- They not exceed -10% for the clayey soil (Fig.5) and are negligible for the sandy structure (Fig.6) for Green-Ampt method.
- They are negligible for the SCS method (Figs. 5 and 6).

The obtained remark concerning the variation between the increasing infiltrated volumes and the increase of the generated peak flows, has led us to study the relationship of the infiltration variations and the generated peak flows obtained by the SWMM model.

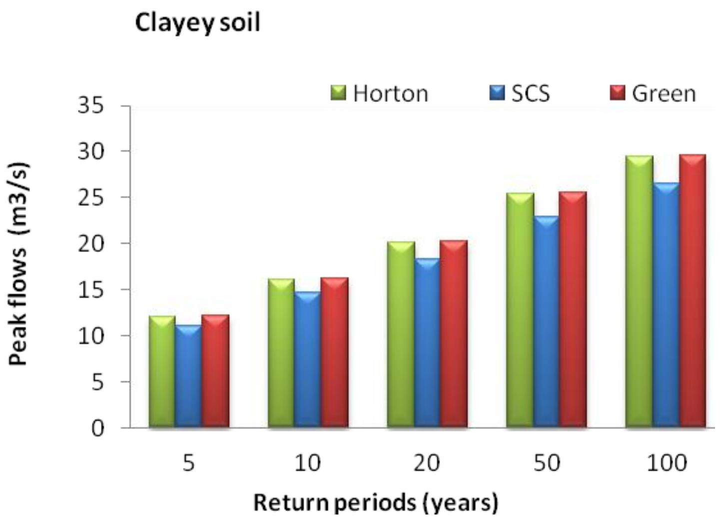

Figure 5. Comparison of the peak flows generated by different infiltration sub models for clayey soil.

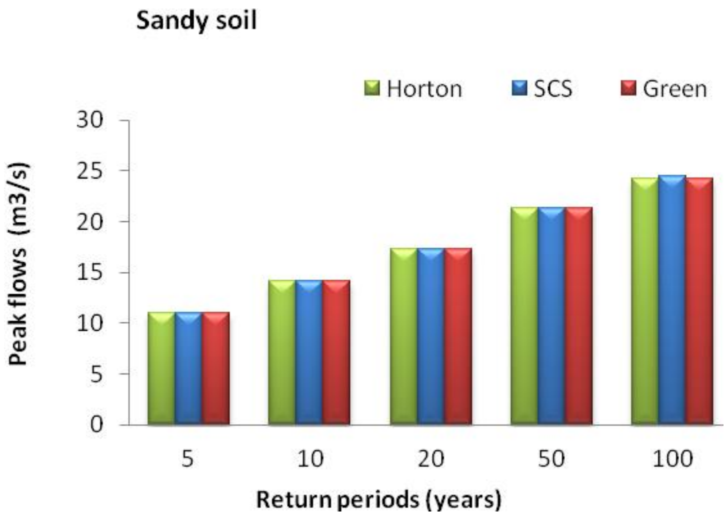

Figure 6. Comparison of the peak flows generated by different infiltration sub models for sandy soil.

3.3. Study of the relationship of the infiltrated variation and the generated peak flows according to the soil impermeability

We have adopted an approach which consists of fixing a basis of comparison relative to a type of impermeable soil and of varying the soil type to a permeable structure. Simulation results have been presented in the figure 7 below for Horton, Green-Ampt and SCS models.

According to the figure 7, we have found at the level of Horton (Fig.7A) and Green - Ampt models (Fig.7B), the existence of two trends of peak flows variation relative to the variation of the infiltrated volumes one of which is relative to the loamy soil and the other concerns the sandy soil. We have also noted that, for the same variation range of infiltrated volumes, we have obtained different peak flows variations. In fact:

- For the Horton model (Fig.7A), the infiltration variation between 100% and 160%, has given peak flows relative deviations of -6% and -5% for the first trend and of -9% and-12% for the second trend.
- For the Green-Ampt model (Fig.7B), the infiltration variation between 100% and 180% has given peak flows relative deviations of -5% and -4% for the first trend and of -10% and -14% for the second trend.

Also, for the first trend (Loamy soil), we have noted a slight peak flows increase despite the increased infiltrated volumes. However, for the second trend (sandy soil), the peak flows decrease with the increasing infiltrated volumes.

For the SCS model (Fig.7C), the variation of the peak flows is proportional to the variation of the infiltrated volumes regardless of soil type. Consequently, the increase of infiltrated volumes causes the reduction of the resulting peak flows. In addition, for all of infiltration models, the change of soil type from the impermeable to permeable type influences the infiltrated volumes. This differences increase with the increase of the return period.

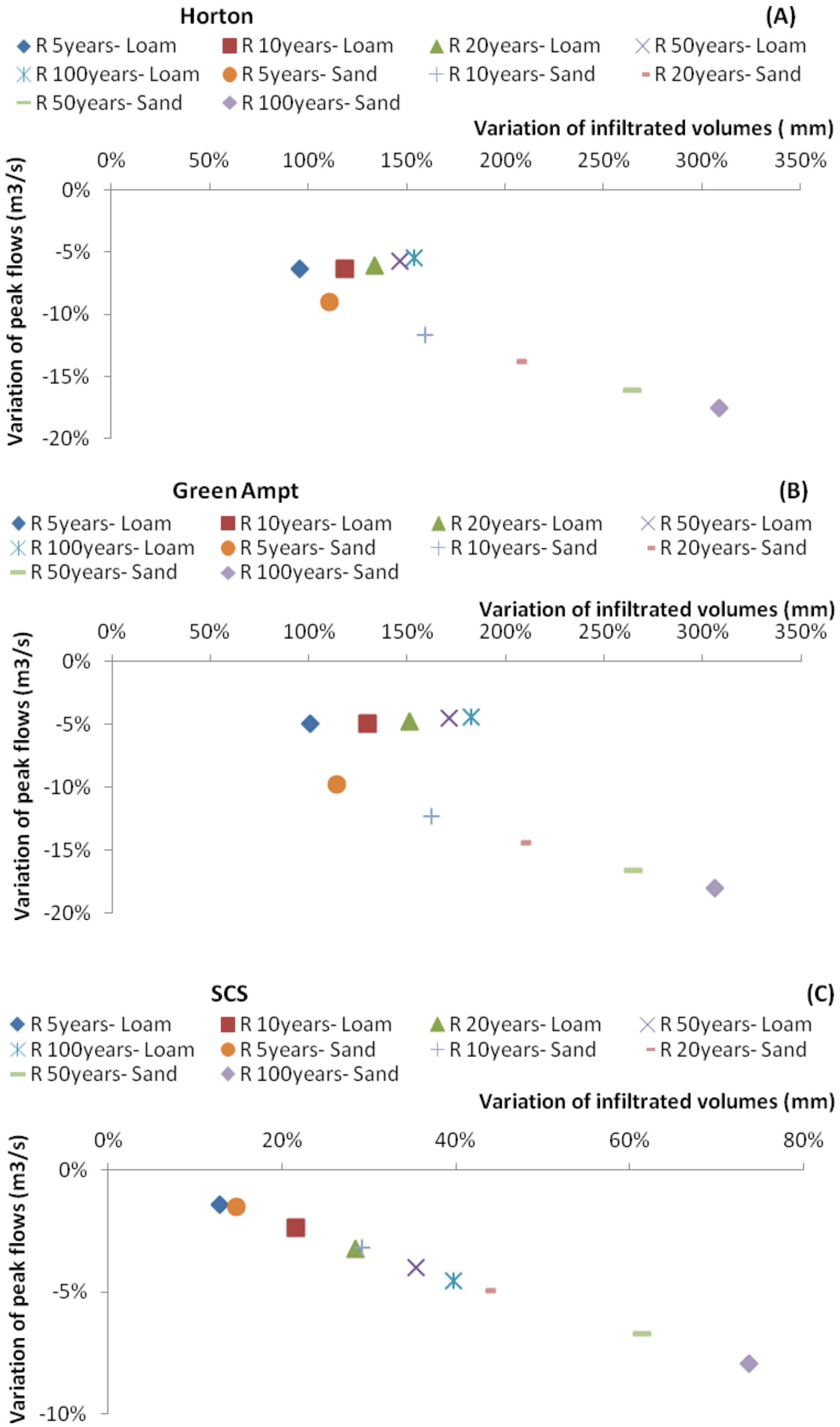

Figure 7. Variation of peak flows as a function of the variation of infiltrated volumes for Horton (A), Green-Ampt (B) and SCS (C) sub-models.

These differences are significant using the Horton and Green-Ampt models, which can reach, for a hundred-year return period:

- 154% for a change of the soil type from clayey to loamy, and 309% for a change from clayey to sandy in the Horton model (Fig.7A).
- 183% for a change of the soil type from clayey to loamy, and 306% for a change from clayey to sandy in the Green-Ampt model (Fig.7B).

For these two infiltration models, these extreme variations of the infiltrated volumes generate peak flows decrease of 4% and 5% for a change of the clayey soil type to the loamy one and of 18% for a change of the clay soil type to the sandy one (Figs.7A and 7B).

As for the SCS model and for the same centennial return period, the infiltrated volumes relative deviations following the change of soil type remain less important compared to those of Horton and Green-Ampt models. The difference is of 40% for a variation of the clayey soil type to the loamy one, and of 74% for a change of the clayey soil type to the sandy one (Fig.7C). This change causes a decrease of the peak flows of 5% and 8% subsequently (Fig.7C).

From the results of the SWMM model sensitivity study to the choice of infiltration sub models, we discovered that the SCS method, for a clayey soil, generates the infiltrated volumes that have given a difference of 75% and 120% relative to the infiltration volumes determined by the Horton and Green-Ampt methods (Fig.3).

This difference of calculated infiltrated volumes by the SWMM model requires verification using another model of the family of SWMM. This concerns the HEC-HMS rainfall-runoff model, which also involves the Green - Ampt and SCS infiltration methods. The simulation results by the HEC-HMS model for a 100 years return period are presented in the figure 8 below.

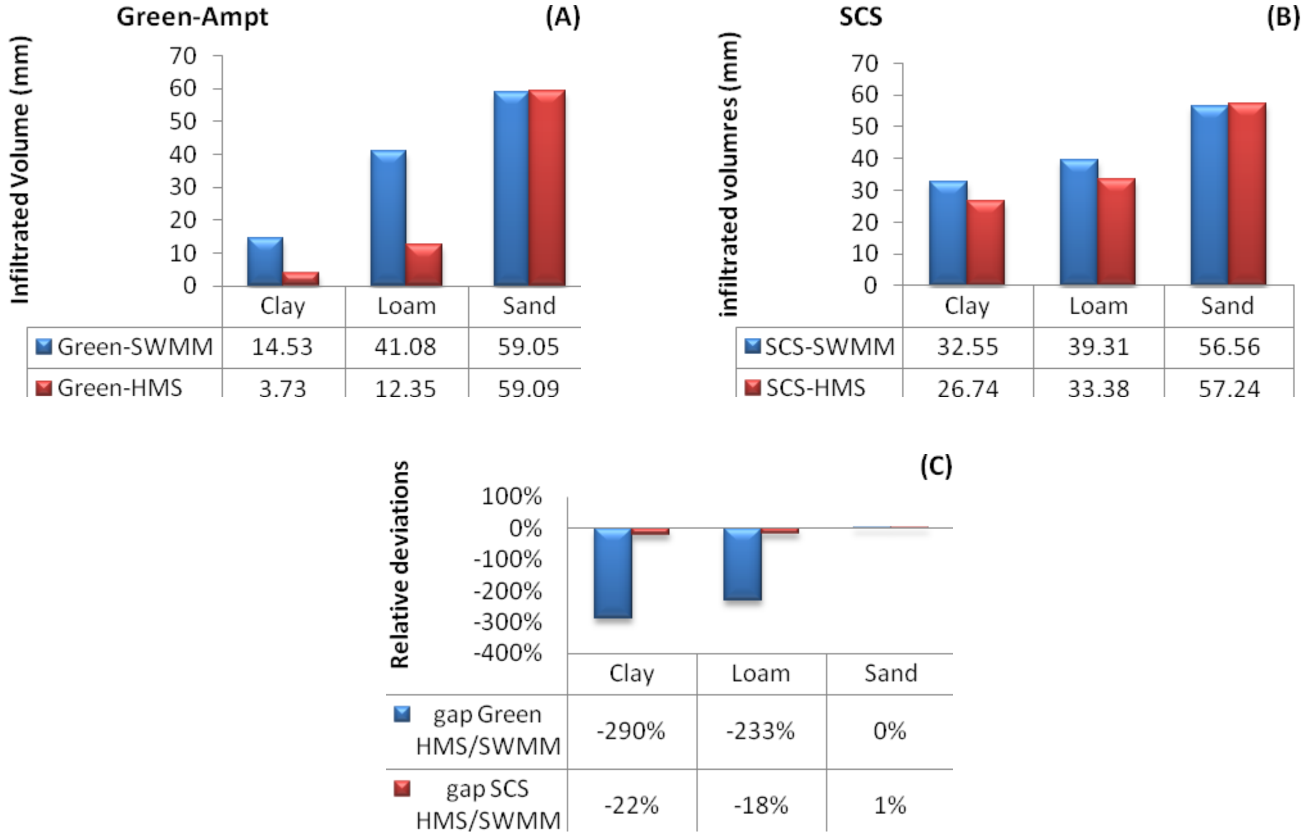

Figure 8. Comparison of infiltrated volumes of Green-Ampt method (A) and of SCS method (B) calculated by SWMM and HEC HMS models, and the relative deviations of infiltrated volumes of HEC-HMS model in relation to SWMM model (C).

The Comparison of infiltrated volumes, for a return period of 100 years, calculated by the -SWMM and the HEC-HMS models shows that (Fig. 8):

- The infiltrated volumes determined by the HEC-HMS model are strictly lower than the SWMM model for clayey and loamy structures the relative deviations of which are respectively of -290% for clayey soil and of -233% for loamy one.
- For the SCS method, the relative deviations of infiltrated volume in relation to the SWMM model are less important, reaching -20% for clayey and loamy soils.

For the sandy soil type, the infiltrated volumes are nearly equal regardless of the infiltration method and rainfall runoff model used.

Thus, we suggest the resort to the Horton method for the simulation of the rainfall-runoff SWMM model. The SCS method can be used by modifying the CN parameter for clayey soil at 91 instead of 83. The results of the SWMM model simulation for CN equivalent to 91 for clayey soil are shown below (Figs.9 and 10). The infiltrated volumes from the SCS method present relative deviations, compared to the Horton method, which vary between 10% and 15% (Fig.9), given result to small variation peak flows of the order of -5%. (Fig. 9).

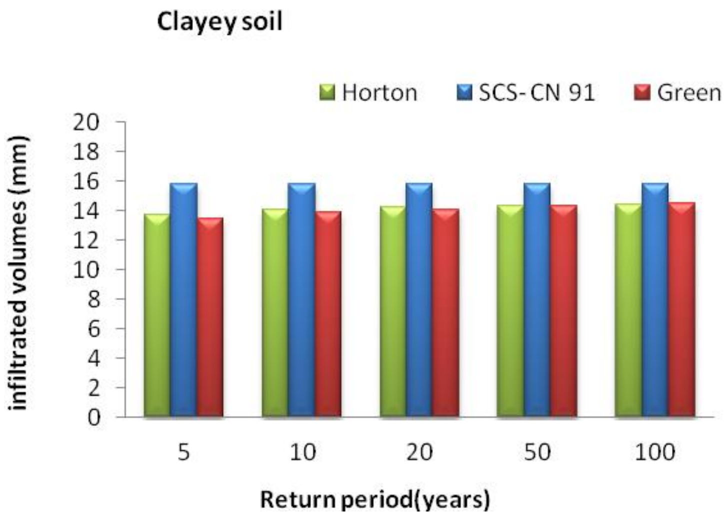

Figure 9. Comparison of volumes infiltrated calculated by different infiltration sub models after modifying the CN parameter for SCS method at 91 instead of 83 - case for clayey soil.

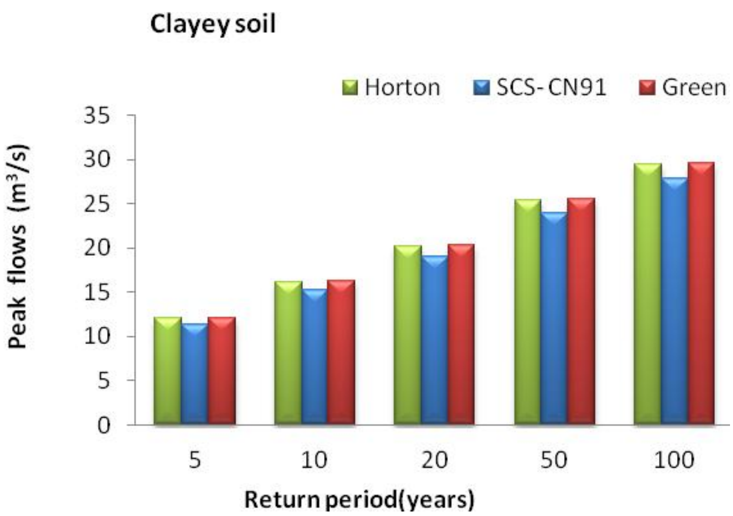

Figure 10. Comparison of the peak flows generated by different infiltration sub models after modifying the CN parameter for SCS method at 91 instead of 83 for clayey.

The coefficient used for the CN 91 has affected the curve of peak flows variation generated by the SWMM model in relation to the infiltration variation. From the figure 11 below, we have observed that the SCS model continues to meet the trend of declining peak flows relative to the increase of infiltrated volumes.

The variation of infiltrated volumes between a clayey soil and a loamy one increases along with the increase of the return period (importance of rainfall intensity). These differences may reach 190% for a hundred-year return period for a change of the soil type from the clayey to the Loamy, and 260% for a change from the clayey soil to the sandy one. These two extremes of infiltrated volumes generate peak flows deviations of -9% and -12% successively.

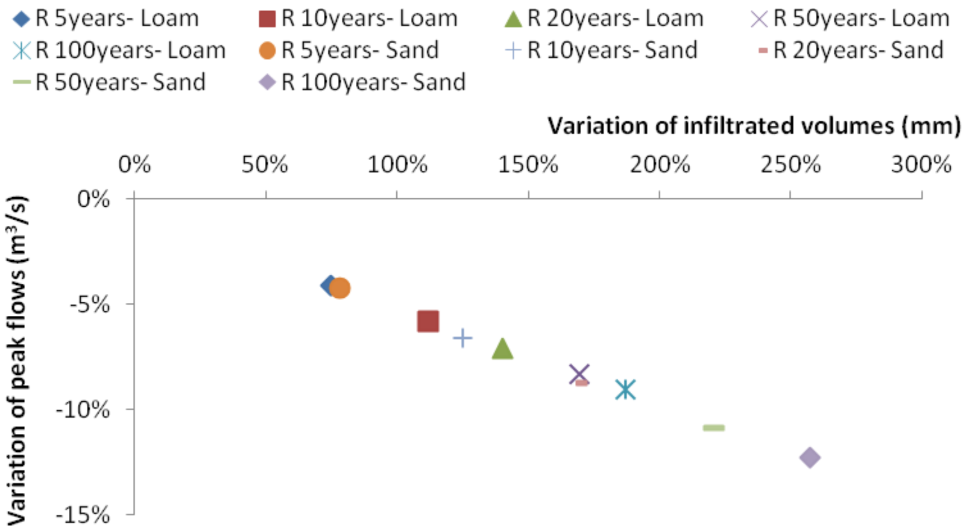

Figure 11. Variation of peak flows as a function of the variation of infiltrated volumes for SCS sub-model after modifying the CN parameter at 91 instead of 83 for clayey soil.

Conclusion

In this work, the sub infiltration models used are those integrated into the SWMM model, namely Horton, SCS and Green-Ampt models. The simulation results for SWMM model sensitivity study in relation to the choice of infiltration models for the Tangiers experimental basin soil type (loamy soil) give infiltrated volumes with maximum deviations, compared to the results obtained by the Horton method are of about 7% for the SCS method and 12% for the Green-Ampt method. These deviations of infiltrated volumes generate a variation of peak flows relative to the Horton method of -7% for the SCS method and of 2% for the Green-Ampt method. Although the calculated infiltrated volumes based on the Green Ampt method for the different return periods are higher than the SCS model, the generated flows are still larger than the resulting peak flows relative to the SCS method. It has to be noted that the extra infiltrated volumes should lead to the resulting flow downwards.

An extension of the SWMM model sensitivity study relative to the extreme soil types has shown that the Horton and Green-Ampt models have given infiltrated volumes and peak flows similar for both clayey and sandy soil types. The relative deviations of infiltrated volumes calculated by SCS method are minor compared to the other models for the sandy soil. They vary between -2% and -4% depending on the increase of the return period. However, for the clayey structure, there are significant deviations of infiltrated volumes from 80% to 125% depending on the evolution of the return period. This variation of infiltration causes maximum deviation peak flows not exceeding -10%. The difference of calculated infiltrated volumes by the SWMM model required verification using HEC-HMS rainfall-runoff model.

Consequently, we have retained the Horton method for the rainfall-runoff simulation of the SWMM model. The SCS method can be used by modifying the CN parameter for clayey soil at 91 instead of 83. Thus, The infiltrated volumes variation between a clayey soil and a loamy one increases along with the increase of the return period (importance of rainfall intensity). These differences may reach 190% for a hundred-year return period for a change of the soil type from the clayey to the Loamy, and 260% for a change from the clayey soil to the sandy one. These two extremes of infiltrated volumes generate peak flows deviations of -9% and -12% successively.

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