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Article

A Comparative Study of Infiltration Methods Based on the SWMM Model: Application of Horton and Green-Ampt Models in Drainage System Design in Northeast China

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Abstract: This study conducts a comparative analysis of infiltration methods in a region of Northeast China using the SWMM model, aiming to assess the impact of different infiltration models on drainage system design. We selected the Horton infiltration method and the Green-Ampt infiltration method, derived from soil properties, to simulate rainfall-runoff processes in various areas. The results show that while the Horton method is suitable for infiltration simulations under conventional conditions, the Green-Ampt method provides more accurate results in regions with significant soil variability, offering a better reflection of actual drainage performance. The study recommends that, for drainage system design, the choice of infiltration method should be based on local soil characteristics to ensure system efficiency and reliability.

Keywords: SWMM; green-ampt; horton method; peat soil

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1. Introduction

Soil infiltration plays a crucial role in urban drainage and flood management as it directly influences the runoff generated during rainfall events [1]. The infiltration process determines how much water the soil absorbs, thereby reducing surface runoff and alleviating pressure on drainage systems. Effective infiltration can significantly reduce the risk of urban flooding, especially during intense rainfall events. The effectiveness of different infiltration models may vary due to regional soil characteristics, making accurate simulation essential for designing efficient drainage systems.

SWMM is widely used to simulate the rainfall-runoff process and integrates several infiltration models to represent soil water movement [2]. Among these models, the Horton infiltration model is often applied due to its simplicity and applicability to general scenarios [3]. This model assumes that the infiltration rate declines exponentially over time. However, the Green-Ampt infiltration model [4] is more suitable when considering local soil characteristics. This model accounts for the initial infiltration rate and the soil's moisture retention capacity, providing a more accurate representation of infiltration for areas with specific soil types. Some studies now use the Green-Ampt model to explore the impact of different soil types on sponge city infrastructure [5]. Other research has examined the differences between concentrated infiltration and traditional infiltration, reviewing the progress and shortcomings of studies on the effects of concentrated infiltration on soil pollution, groundwater volume, and water quality. However, there is still a lack of comparative studies on the specific differences between the Horton and Green-Ampt infiltration models. In this study, we use both the Horton and Green-Ampt models to simulate the runoff process in Northeast China and compare the results to explore the differences between the two models.

2. SWMM Parameter Settings

2.1. Horton Model Parameter Settings

The Horton infiltration model is widely used for its simplicity, assuming that the infiltration rate decreases exponentially over time, with the initial maximum rate gradually declining to a stable minimum rate. This model is particularly effective for simulating infiltration in homogeneous soils under typical environmental conditions, such as urban areas. For the purpose of this study, the parameters of the Horton model were selected based on previous research by He et al. [6], as shown in Table 1. These parameter values have been validated to represent typical conditions in Northeast China, where soils are often peat-rich, and the infiltration rate can vary significantly depending on local conditions. The selection of these parameters is critical for ensuring that the model can effectively simulate runoff and accurately assess the impact of infiltration on drainage system design.

Table 1. Horton Model Parameter Selection Values.

ID	Description	Value
Max. Infil. Rate	Maximum infiltration rate (mm h^{-1})	112
Mix. Infil. Rate	Minimum infiltration rate (mm h^{-1})	2.6
Decay Constant	Decay Constant	0.25

By incorporating these parameters into the SWMM model, we can simulate the runoff behavior of various subcatchments in the study area. The results of these simulations are crucial for understanding the impact of different infiltration processes on urban drainage, especially when evaluating stormwater management systems that need to adapt to varying rainfall intensities and durations.

2.2. Green-Ampt Model Parameter Settings

The Green-Ampt model offers a more physically-based approach to infiltration, taking into account factors such as the soil's initial moisture content and its retention capacity. The model considers variations in soil texture, hydraulic conductivity, and capillary pressure. In this study, we used undisturbed soil samples collected from the study area for the analysis.

The first step in setting up the Green-Ampt model was determining the field capacity of the soil, which was done using the ring knife method, following ASTM-D3080 standards. This method provides an accurate measure of the soil's ability to retain water, essential for understanding the dynamics of water movement through the soil. Additionally, the matric suction curve, derived from the filter paper method (ASTM-D5298), was used to determine the suction head, which reflects the soil's capacity to draw water into the unsaturated zone. The matric suction curve, shown in Figure 1, is a critical component in understanding how water infiltrates the soil under different conditions.

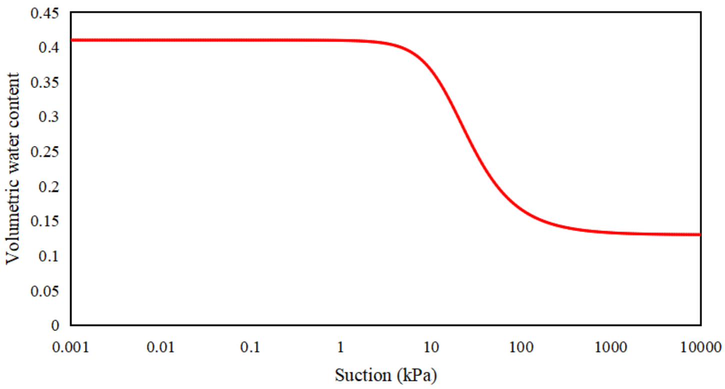

Figure 1. matric suction curve.

The saturated hydraulic conductivity, which measures how easily water can move through the soil when fully saturated, was determined through the constant head permeability test (ASTM-D2434). The results revealed in Table 2, which are consistent with typical soil characteristics found in the region, particularly the peat-rich soils. These values are crucial for accurately simulating the infiltration process in the Green-Ampt model, as they reflect both the capillary forces acting within the soil and the ease with which water can pass through the soil matrix.

Table 2. Green-Ampt Model Parameter Selection Values.

ID	Description	Value
Suction Head	Soil capillary suction head (mm)	325
Conductivity	Soil saturated hydraulic conductivity (mm h^{-1})	14.4

By incorporating these parameters into the SWMM model, we can simulate more realistic infiltration processes, particularly in areas with diverse soil types. The Green-Ampt model's consideration of soil properties allows for more accurate runoff predictions, making it a valuable tool for urban drainage system design, especially when local soil conditions play a significant role in runoff dynamics.

The parameters of the Green-Ampt Model in the SWMM model mainly include suction head and saturated hydraulic conductivity. In this study, undisturbed soil samples were collected from the research area. First, the field capacity was determined using the ring knife method (ASTM-D3080). Then, the matric suction curve was derived using the filter paper method (ASTM-D5298) and the van Genuchten equation, as shown in Figure 1, to determine the matric suction corresponding to the field capacity, i.e., the suction head. Finally, the saturated hydraulic conductivity was obtained through the constant head permeability test (ASTM-D2434). The results are presented in Table 2.

3. Application to an Urban Drainage Modeling Case Study

This study was conducted in a region located in the northeastern part of China, through which a river flows. The stormwater drainage system in the area ultimately discharges into the river, and since the floodwater level is lower than the elevation of the outfall, reverse flow from the outfall is not a concern. The study area spans 135.39 hectares, with the soil predominantly consisting of peat. The drainage system is designed for a return period of 2-3 years. The catchment area was initially delineated into subcatchments by analyzing the stormwater drainage network and the locations of drainage wells to classify the main roads. A more detailed classification of the subcatchments was then carried out using land-use maps and digital elevation models, minimizing simulation errors and ensuring the modeled rainfall-runoff processes closely matched the actual ones. As shown in Figure 2, the final delineation consisted of 76 subcatchments, 79 inspection wells, 79 drainage pipe segments, and 13 discharge outlets, with each black dot representing a subcatchment center. The study area was divided into thirteen subsystems based on the layout of drainage pipelines and outlets, with each black triangle symbolizing a drainage outlet. Hydrological and hydraulic parameters for the subcatchments were selected according to the research of He et al [6] in Changchun.

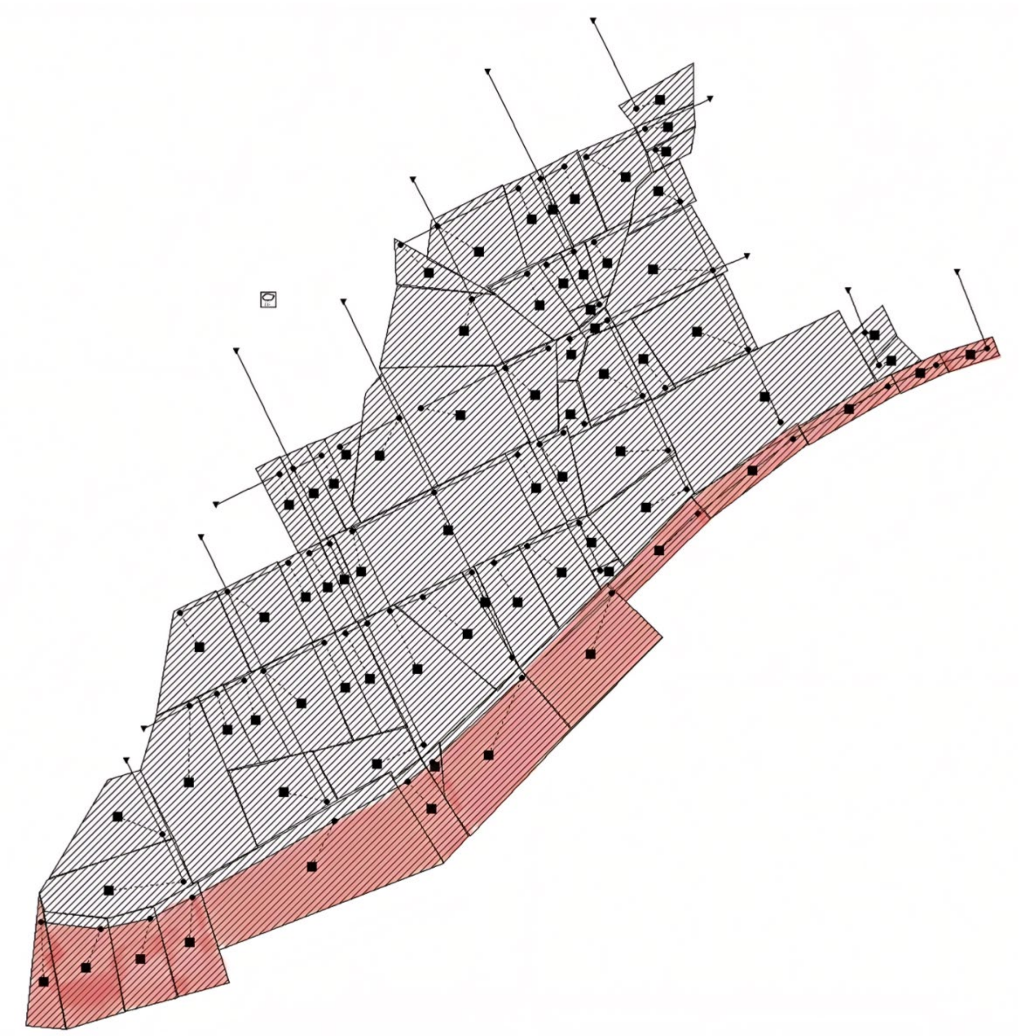

Figure 2. SWMM model of the study area.

The model was run for the different infiltration models mentioned earlier, simulating a rainfall event with a return period of 0.25/2/5 years, a peak rainfall coefficient of 0.4, and a rainfall duration of 120 minutes. A representative sub-drainage system was selected (The red zone), and for each scenario, the outlet flow hydrographs were obtained using the PCSWMM model, as shown in Figure 3 to Figure 5. Table 3 summarizes the principal hydrological characteristics of these hydrographs, including peak flow rate (QP), time to outlet inflow curve peak (tQP), and total runoff volume (R).

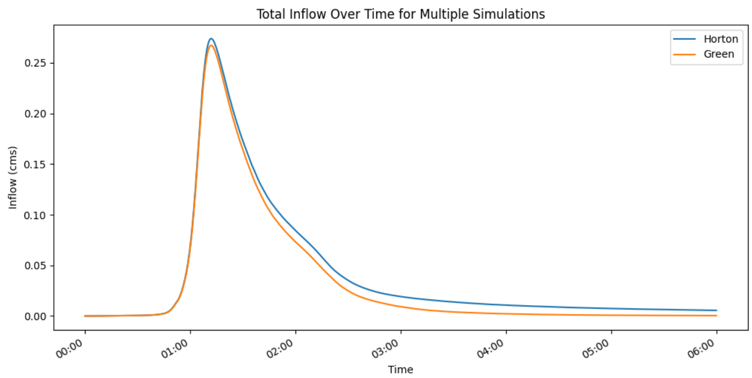

Figure 3. Total inflow over time for multiple simulations for different scenarios(0.25a).

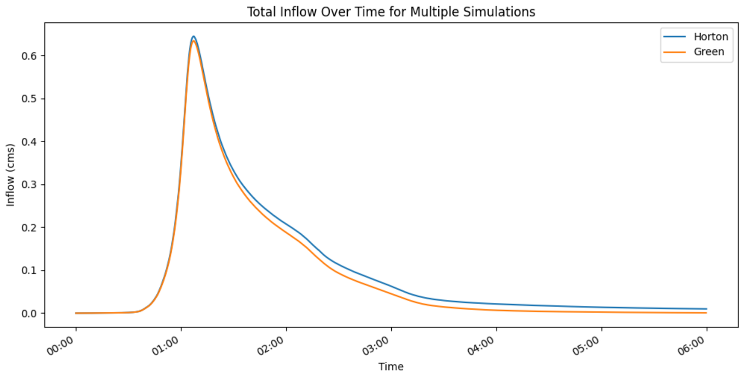

Figure 4. Total inflow over time for multiple simulations for different scenarios(2a).

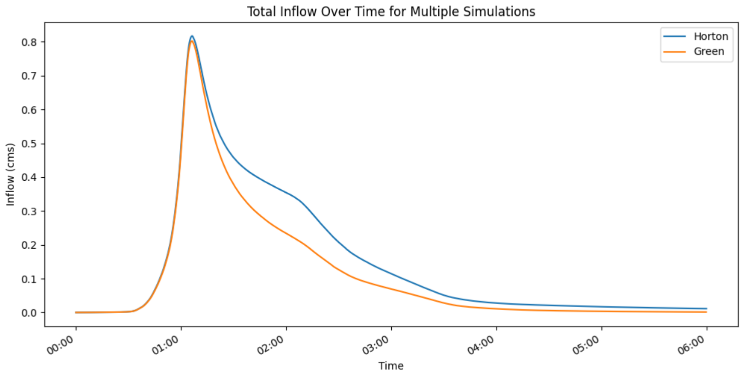

Figure 5. Total inflow over time for multiple simulations for different scenarios(5a).

Table 3. Hydrological characteristics in different scenarios.

Period (years)	Model	QP (cms)	tQP (hours)	R (cms)
0.25	Horton Model	0.274	1.137	62.98
0.25	Green-Ampt Model	0.267	1.129	52.56
2	Horton Model	0.645	1.181	202.01
2	Green-Ampt Model	0.634	1.176	177.95
5	Horton Model	0.817	1.199	339.43
5	Green-Ampt Model	0.803	1.220	244.38

Initially, the Horton model produced a peak flow (QP) that was 2.6% higher than that of the Green-Ampt model, with a slight delay in the peak time (tQP). Moreover, the Horton model resulted in a total inflow that was 19.8% higher than that produced by the Green-Ampt model. This suggests that, under similar design conditions, the Horton model may overestimate runoff volumes and flood risks, which is particularly concerning in flood-prone urban areas where managing peak flows and runoff volumes is critical.

Furthermore, the analysis of multiple simulations conducted for different return periods (0.25 years, 2 years, and 5 years) revealed some important trends. As the return period increased, the ratio of total runoff generated by the Horton model relative to the Green-Ampt model also increased. Specifically, the difference in total inflow between the two models became more pronounced with longer return periods, which indicates that the Horton model, with its simpler exponential decay assumption, tends to increasingly overestimate runoff as storm intensity and duration increase. This pattern is particularly evident when comparing the inflow hydrographs for the 0.25-year, 2-year, and 5-year return periods.

In Figures 3 to Figures 5, which show the total inflow over time for the different return periods, the inflow curve for the Horton model demonstrates a noticeable shift, especially when compared to the Green-Ampt model. The curve for the Horton model shows a more pronounced peak and a larger total runoff volume, which suggests that the soil has reached a certain saturation point earlier, affecting the infiltration dynamics. This difference in the infiltration behavior is attributed to the distinct parameterization of the Horton model, where the infiltration rate declines exponentially over time, not accounting for soil moisture retention as accurately as the Green-Ampt model. This saturation effect becomes more significant as storm duration and intensity increase, further emphasizing the importance of considering regional soil characteristics in selecting the appropriate infiltration model.

This discrepancy between the two models reinforces the significance of local soil conditions in drainage system design. The Green-Ampt model, by incorporating factors such as soil moisture retention and initial infiltration rate, offers a more accurate reflection of runoff dynamics, especially in areas with high soil variability. As the simulations show, the Green-Ampt model provides a more reliable and precise estimate of runoff behavior, particularly in regions where soil texture and hydraulic conductivity exhibit significant variation. This makes the Green-Ampt model a better choice for urban drainage design in areas with diverse and heterogeneous soil types.

4. Conclusions

This study presents a comprehensive comparative analysis of the Horton and Green-Ampt infiltration models using the SWMM model to evaluate their performance in drainage system design within the Northeast China region. By simulating runoff under the same rainfall conditions and considering the local soil characteristics, we focused on three key hydrological parameters: peak flow (QP), peak time (tQP), and total runoff volume (R). The results highlight distinct behaviors between the two models, with significant implications for urban drainage system design.

Given the results, it is evident that the Green-Ampt model should be prioritized in regions where soil characteristics play a crucial role in infiltration. It provides a more accurate and reliable reflection of the infiltration process, leading to a more efficient and cost-effective drainage system design. In contrast, the Horton model, although effective for general scenarios with homogeneous soils, may lead to overestimations of runoff in areas with more complex soil conditions, leading to inefficient flood management and urban drainage strategies.

The findings of this study underscore the importance of selecting the appropriate infiltration model based on local soil conditions to ensure effective flood management and optimal drainage system design. In the context of future climate change scenarios, where rainfall intensity and duration are expected to increase, accurately modeling the infiltration process will be even more critical to mitigate urban flooding risks.

Future research should focus on calibrating both models using field data, particularly in regions with varied and complex soil types, to further improve the accuracy of runoff simulations. Additionally, conducting sensitivity analyses on key model parameters will help better understand the limitations of each model and refine the simulation results. This will provide more robust data for urban drainage planning and enhance the resilience of cities to extreme weather events.

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