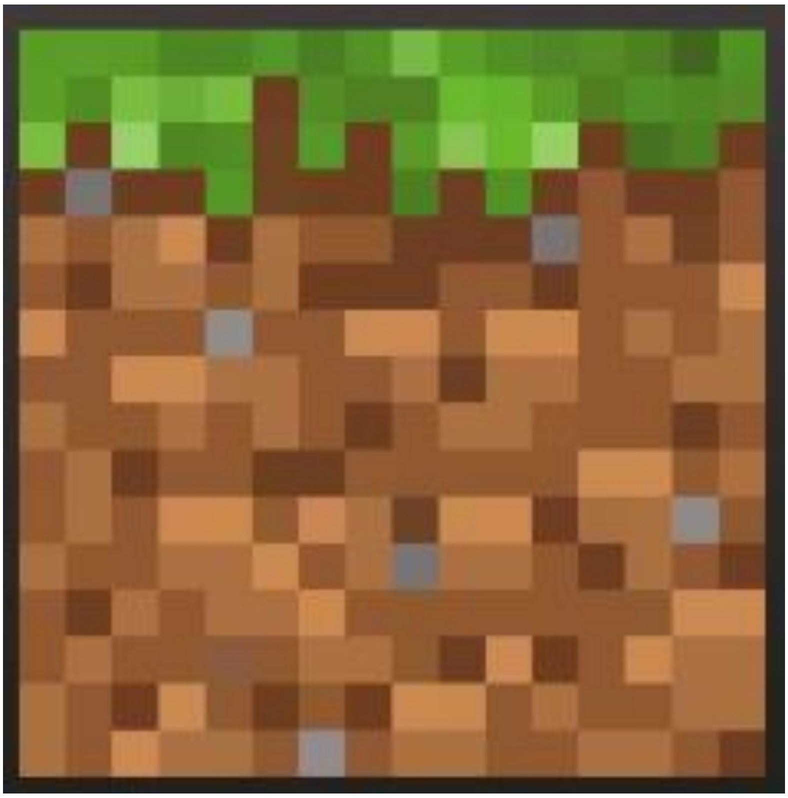
"From Watersheds to Cities: Applying the SCS-CN Method for Urban Infiltration"

ENV-270 : COMPUTATIONAL METHODS AND TOOLS

PROJECT ASSIGNMENT



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1. Deviation from our Initial Project Proposal

Our initial project aimed to create a model that could estimate the infiltration rate based on soil density, offering valuable insights for aquifer management and preventing over-exploitation. The idea was to take advantage of the many affordable techniques available for measuring soil density. The project proposed simulating homogeneous soil permeability, which would serve to calculate the water infiltration rate.

However, during the project's development, it became clear that the initial scope was overly simplistic. While we considered adding complexity by introducing additional parameters, this approach seemed to detract from the primary purpose of the project, which was meant to rely on minimal information and remain low-cost.

As a result, we decided to pivot toward a different project, one that retains a similar thematic focus but adopts a new methodology. In this revised project, we model water infiltration based on its soil covering and structural arrangement.

2. Introduction to the Problem

Water management in urban areas is a growing challenge due to increasing population density, urbanization, and climate change. Cities face issues such as flooding, water shortages, and pollution, which are exacerbated by impermeable surfaces and inefficient drainage systems. Developing sustainable solutions for managing water infiltration is critical to mitigating these problems and ensuring long-term resilience in urban environments.

Our project focuses on modeling water infiltration into soil to better understand how the composition and distribution of various soil types affect precipitation water in urban settings. Cities are often characterized by a mix of soil types in varying proportions, and this diversity influences how water infiltrates and interacts with the ground. By simulating these dynamics, we aim to explore the impact of soil arrangements on infiltration.

This approach aligns with the concept of sponge cities, which seek to address urban challenges such as flooding and water scarcity. By integrating green infrastructure like parks, gardens, wetlands, and permeable pavements, sponge cities create natural systems that capture, store, and absorb excess stormwater.[1]

Our project aims to examine how soil covering types and arrangements affect water infiltration processes, providing practical insights for urban planning to help develop cities that effectively balance environmental sustainability with urban needs.

3. Approach used

Introduced in 1954 and refined over decades, the **Soil Conservation Service-Curve Number (SCS-CN) Method**, developed by the U.S. Department of Agriculture Soil Conservation

Service (now the Natural Resources Conservation Service)[2], provides a simple yet effective way to model rainfall-runoff relationships.

The **SCS-CN method** models the partitioning of total rainfall (P) during a rainfall event into three components:

1.Initial Abstraction (Ia): Rainfall intercepted by vegetation, initial soil saturation, and surface retention. Runoff and infiltration does not occur until the soil's infiltration capacity is exceeded.
2.Runoff (Ro): Rainfall that flows over the surface when the soil's infiltration capacity is reached.
3.Infiltrated Precipitation (I): Rainfall that infiltrates into the soil, contributing to subsurface flow.

These components are governed by the **maximum retention capacity (S)**, which defines the soil's ability to retain water after initial abstraction.

The relationship between these variables is expressed through the **Runoff Equation**:

$$Ro = \frac{(P - I_a)^2}{P - I_a + S}, \quad \text{for } P > I_a$$

Empirical studies have shown that initial abstraction is proportional to the maximum retention capacity:

$$I_a = \text{coeff\_of\_initial\_abstraction} \times S = 0.05 \times S$$

Historically, the initial abstraction in the SCS Curve Number method has been approximated as 20% of the potential maximum retention. However, recent studies [3] suggest that a lower ratio may provide more accurate runoff estimations in urbanized regions.

Form these tools, the infiltrated precipitation can then be calculated applying a mass balance:

$$I = P - Ro - I_a \quad \text{for } P > 0.05S$$

The maximum retention capacity is determined by the **Curve Number (CN)**, a dimensionless parameter (between 0 and 100) that depends on land use, soil type, and antecedent moisture conditions. Higher CN values indicate less infiltration (e.g., impermeable surfaces), while lower values reflect greater infiltration (e.g., sandy soils). The relationship is:

$$S = \frac{25400}{CN} - 254 \quad (\text{in mm})$$

Traditionally, this method has been employed for watershed management. However, in this project, we apply the SCS-CN method to urban water management, which is the originality of our approach. Urban areas present a greater variety and marked differences in soil types compared to rural watersheds. Therefore, it is pertinent to study the interactions between different soil types in an urban context.

To apply these formulae to urban uses we selected 3 typical CN values from literature, referring to concrete, gravel and green space.[4]

Land type	CN value
Concrete	98
Gravel	85
Green space	69

This project aims to answer two mains questions using the SCS-CN method: *How does the composition of our soil types affect infiltration? And how does the disposition of those soil types have an effect on infiltration?*

3.1 How does the different composition of soil types affect infiltration of water in soils?

To answer this question based on the tools provided by the SCS-CN method, we considered a composite CN calculated by weighting the individual CNs based on the proportion of each land type (Ai):

$$CN_{\text{composite}} = \frac{\sum (A_i \times CN_i)}{\sum A_i}$$

The obtained CN is then used to get the infiltration and runoff rate of water from a rainfall event.
To apply the formulas realistically, cumulative rainfall is considered, allowing the initial abstraction to be reached over the rain period, enabling runoff and soil infiltration.
Two scenarios with different proportions of land types are used to evaluate the model, (refer to Fig.4 and Fig. 5 in section 4.1).

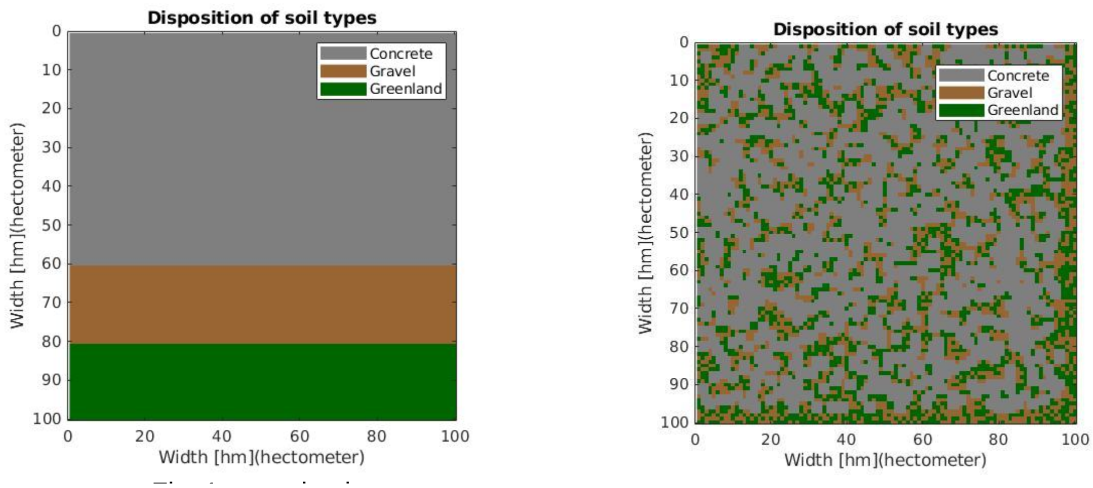
3.2 How does disposition of the soil types affect the infiltration?

It seems quite clear that soil with more greenery shows a better ability to infiltrate water, but what about land with the same proportion of soil types but arranged differently?

3.2.1 Generating different dispositions of land type.

First, it was necessary to generate different land arrangements from the same proportion of land types. Opposing cases were considered: a **non-mixed model** (heterogeneous) was constructed with large, contiguous blocks of the same land type (Fig.1). The **mixed model** (homogeneous) was designed to emulate 'sponge cities,' incorporating green areas to encircle permeable soils (Fig. 2).

Each land was modeled using a 2D grid (100x100 cells), where each cell represented a specific land type. The size of the grid can be changed to fit a desired land, with units set in **hectometers (hm)** to approximate the scale of a typical urban area. Each cell was assigned

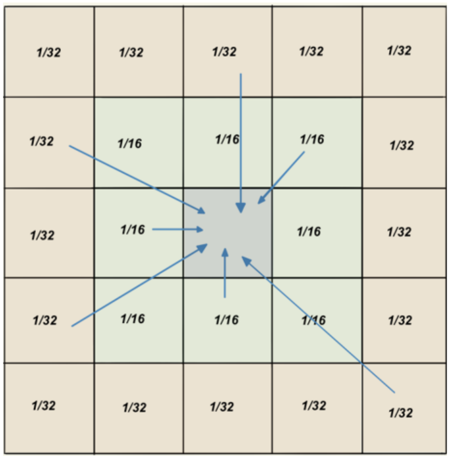


the following parameters:

- ❖ CN value
- ❖ Runoff
- ❖ Received water: Additional water received from neighboring cells' runoff.

3.2.2 Application of the SCS-CN Method

To account for the effect of arrangement, the runoff calculation from the SCS-CN method was utilized. Indeed, since infiltration is obtained through a mass balance, an additional incoming water was considered in addition to precipitation: the runoff from surrounding areas.



For more details, each cell first calculated its runoff using the SCS-CN method, based on the cumulative precipitation and soil properties.
Runoff generated from one cell is not considered to remain confined at this cell; instead, it flowed into adjacent cells, distributing its produced runoff to the 24 surrounding cells. Direct neighbors receive a larger portion of runoff, with each neighbor receiving 1\16 of the total runoff. Additionally, second-order neighbors—those located two cells away—receive half of it, each receiving 1\32 of the runoff. This redistribution was chosen to ensure a gradual spread of water across the grid (see Fig. 3).

Then, for each cell, the water received from the runoff of neighboring cells is calculated according to the explained distribution.

Finally, runoff is recalculated for each cell based on a new mass balance.

- ➔ Effective Precipitation=Rainfall+Received Water
- ➔ Infiltration=Rainfall+Received Water−Runoff

This process was repeated iteratively over the whole rainfall event.

The total amount of infiltration of water over the land at each hour can be calculated from this modeling (refer to Fig. 6 in section 4.2).

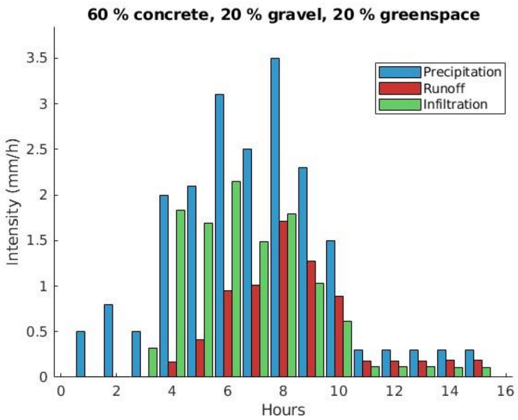
3.3 Discussion of the models

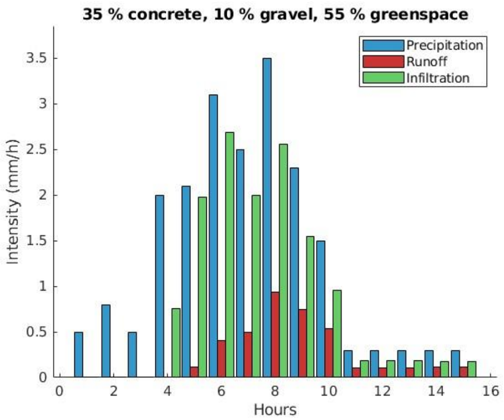
To assess the significance of land arrangement compared to land proportion, and to evaluate the effectiveness of arrangement versus proportion, calculations were performed using only concrete and greenspace land types. Infiltrated water for both mixed and non-mixed configurations were calculated by varying the proportions of concrete and greenspace. We also calculated the infiltrated water using the model that does not account for spatial arrangement, using the same land proportions (refer to Fig. 7 in section 4.3).

These comparisons can serve as a tool to determine the equivalent proportion of land types for a specific amount of water infiltrated in both mixed and non-mixed land.

4. Results

4.1 Results of different composition of soil types.





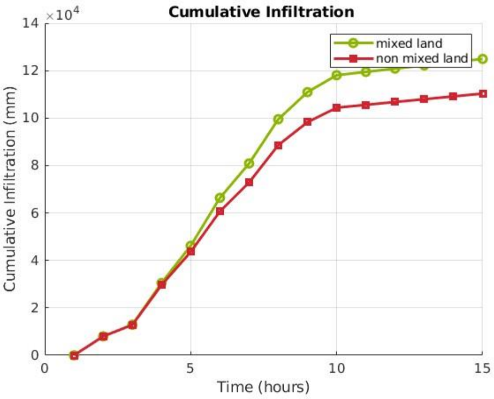
The plots provide a detailed visualization of how precipitation, runoff, and infiltration vary with different soil type compositions. For the simulations, specific percentages of concrete, gravel, and greenspace were chosen to represent two scenarios. In **Scenario 1**, the land distribution consisted of 60% concrete, 20% gravel, and 20% greenspace, while in **Scenario 2**, the distribution was adjusted to 35% concrete, 10% gravel, and 55% greenspace. These percentages were chosen to explore the effects of different proportions of impermeable and permeable surfaces on water infiltration and runoff.

The graphs demonstrate that runoff begins only after the cumulative precipitation exceeds the **Initial Abstraction**. This behavior aligns with the theoretical basis of the SCS-CN method.

Comparing the two scenarios reveals clear trends:

- **Scenario 1 (Fig. 4)**: The higher percentage of concrete, an impermeable surface, resulted in significant runoff and minimal infiltration. This outcome underscores the challenges posed by heavily urbanized areas with limited green infrastructure.
- **Scenario 2 (Fig. 5)**: With a larger proportion of greenspace, infiltration increased, while runoff decreased significantly. This highlights the benefits of integrating more permeable surfaces into urban planning to enhance water absorption and reduce surface water accumulation.

4.2 Results of different disposition of land



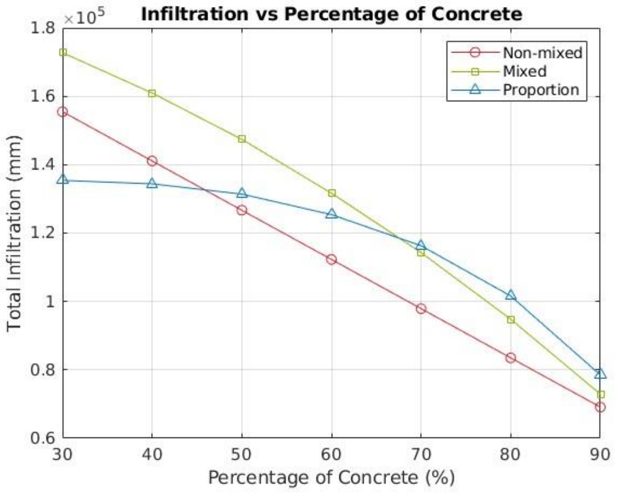
Using the same soil-cover proportions as Scenario 1, the impact of land arrangement on cumulative infiltration was analyzed. The graph compares two configurations: **mixed land** and **non-mixed land**.

The **mixed land configuration** consistently achieves higher cumulative infiltration over time compared to the non-mixed arrangement.

During the first few hours, the cumulative infiltration is similar for both configurations, as the initial abstraction dominates water behavior. However, as runoff and infiltration processes intensify, the mixed land setup begins to outperform the non-mixed configuration. Because the homogeneous distribution of permeable and impermeable surfaces reduces localized pooling and allows water to infiltrate more uniformly.

4.3 Comparisons of the models

The graph illustrates the relationship between total infiltration (over the whole land and rainfall event) and the percentage of concrete for all models (non-mixed configuration, mixed configuration and only proportion model). The remaining percentage of land type is greenspace.



As expected, the general trend is that infiltration decreases as the percentage of concrete increases and the mixed configuration consistently outperforms the non-mixed configuration, across all concrete percentages.

At 70% concrete, the mixed configuration achieves a total infiltration of approximately 1.15 × 10^5 mm, which is comparable to the non-mixed configuration at a little below 60% concrete, highlighting the efficiency of mixed layouts. Even at 80% concrete, the mixed layout retains significantly higher infiltration than the non-mixed layout, showcasing its resilience in high-concrete environments.

The proportion-based model (blue curve) provides a simplified perspective by ignoring spatial arrangement, which is the usual SCS-CN method. For lower concrete percentages (30%-45%), the proportion-based model underestimates infiltration compared to the disposition-based model, as it does not account for the efficiency of distributed greenspaces. At higher concrete percentages (68%-90%), it slightly overestimates infiltration, as it cannot capture the inefficiencies caused by large impermeable blocks.

These findings highlight the limitations of the classic SCS-CN model when considering spatial arrangement. While the proportion-based model offers a useful baseline, it lacks the precision needed for detailed planning.

5. Conclusion and outlook

This project provided new insights into the interplay between land-cover composition, spatial arrangement, and water infiltration in urban settings. Beyond confirming the expected effects of impermeable surfaces on runoff, the study revealed that land arrangement can significantly offset the negative impacts of high concrete proportions. For instance, mixed configurations not only promote more uniform infiltration but also allow higher proportions of impermeable surfaces to maintain comparable infiltration rates, which has practical implications for densely built environments.These findings align with the principles of sponge city design, emphasizing the importance of integrating green infrastructure and permeable surfaces to mitigate flooding risks, and improve groundwater recharge.

Looking ahead, this methodology of introducing configuration could be applied to identify optimal combination and disposition of soil covering types. it could also be applied to fit a specific urban area.. Future developments could include evaluating the potential for groundwater recharge in areas with underlying aquifers, assessing the role of vegetation types and root systems in enhancing infiltration, and studying how soil compaction affects water movement. Additionally, integrating the impact of seasonal variations, such as frozen soils or drought conditions, could refine the model further. These extensions would help address broader water management challenges and offer actionable insights for designing sustainable urban landscapes.

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