White Paper:
The Rainfall-Runoff Model in the Flash Flood Map in SCALGO Live Denmark

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Contents

1. Introduction

In the default mode of the Flash Flood Map in SCALGO Live, every drop of rainfall, which hits the surface of the earth, is moved downstream in accordance with the terrain model, filling up depressions on the way. In hydrological terms, this means that 100% of the rainfall is converted to runoff. However, this is seldom the case in reality. Rainfall that hits the surface of the earth will be subject to several processes before runoff occurs, processes often referred to as hydrological losses. These include:

- Surface wetting: the first drops of water to hit a dry surface will form a thin coating of water on the surface before any water can move further. These are usually relatively small amounts.
- Canopy storage: if rain is falling on dense vegetation, there can be a lot of leaf surface that needs to get wet before any water falls through the vegetation to the surface beneath. Hence, the amount of water that is trapped as surface wetting can become significant and is referred to as canopy storage or rainfall interception.
- Infiltration: Many surfaces, especially soils, but also e.g., certain kinds of paving, have some degree of permeability, allowing water to penetrate the material and fill up pore spaces otherwise filled with air. The amount of water that will infiltrate before runoff starts occurring is highly variable, depending on many parameters, including:
    - The degree to which water was filling the available pores at the beginning of the rain event, often referred to as the antecedent moisture condition,
    - The hydraulic conductivity of the material, which often shows large variability in time and space,
    - The intensity of the rainfall, and whether it surpasses the hydraulic conductivity of the material.
- Depression storage: all surfaces are uneven to some degree and include minor depressions where water will get caught before running further off the surface, think of e.g., the many small holes on the surface of rough asphalt. Some surfaces also include larger depressions, clearly visible during rain events as puddles. There are also major depressions, which usually only become visible during extreme rain events.
- Drainage systems: in most built environments, there is some type of drainage system installed to convey rainwater away from buildings, pavements, roads, etc. When these systems are above ground, and detectable in the digital elevation model, they will be included as part of the flow pattern in the Flash Flood Map. Mostly, these systems are below ground, hence not detectable in the digital elevation model and not included in the Flash Flood Map. Drainage systems have a limited flow capacity. This means that when the rainfall intensity, and resulting inflow rate to the drainage system, surpass the flow capacity of the system, there will be some points of inflow where water temporarily cannot enter the system and will flow on the surface instead. Furthermore, the water level in some parts of the drainage system may rise beyond the surface level, causing water to flow out of the system in these parts (through inflow points or otherwise covered manholes) and onto the surface, a process known as surcharge. The amounts, and locations, of water surcharging or not being able to enter the drainage system, are highly variable, depending on many parameters, including:
    - The designed capacity of the drainage system,

  - The state of the drainage system,
  - The intensity and spatial distribution of the rain event.
- Evaporation and evapotranspiration: these processes are often significant when considering the hydrological cycle over long periods of time. However, during the short time span of intensive rain events, they are generally insignificant and will therefore not be considered further in this context.
- Snow build-up and melt: in this context we only consider precipitation that falls as fluid water and not in any other state.

As is evident from the above, the processes and parameters that determine how much rainfall is converted to runoff are plentiful, complex, and transient. Accordingly, many mathematical models that predict runoff, known as Rainfall-Runoff Models, are quite complex and require many user inputs. Yet, for engineering purposes, simplified Rainfall-Runoff Models have been developed too. For application in the Flash Flood Model in SCALGO Live we need a simple and robust Rainfall-Runoff Model, which can make useful predictions about runoff, in the context of flood screening and design of surface-based measures for stormwater management, taking as many significant parameters into account as possible, while requiring as few inputs from the user as possible.

2. Overall methodology

The Rainfall-Runoff Model in the Flash Flood Map calculates the expected runoff given any depth of rainfall on a model cell level. The model cell size depends on the cell size of the Digital Terrain Model of the country (between 0.16 – 25 m^2).

For each model cell, we first look at its land cover. Our land cover maps are produced using machine learning based on orthophotos and some auxiliary data. The full range of land cover classes varies from country to country, but typically includes the classes shown in Table 1.

Table 1: Typical land cover classes in SCALGO Live's own Machine Learning-based maps. For futher details please see the documentation page for country specific data for your country.

Land cover groups	Land cover classes	Runoff estimation method
Water	Inland permanent water	100% of rainfall
Natural	Bare land	Rainfall minus infiltration
	Shallow vegetation	
	Dense vegetation	
	Fields	
	Bare rock	
Artificial	Buildings	Rainfall minus drainage system capacity
	Paved roads	
	Other paved	
	Unpaved roads	Rainfall minus infiltration

For rainfall falling directly on water surfaces, we assume that 100% of the rainfall is converted to water that either accumulates on top of the existing water or flows downstream.

For natural land cover classes, we assume that the main hydrological loss is infiltration, hence the runoff is calculated as rainfall minus infiltration. The infiltration is assessed based on available knowledge regarding the soil type and the soil condition, where the latter is assessed based on the land cover class. For more details, see the section on runoff from natural surfaces below.

For artificial land cover classes, we assess the likelihood of the presence of an underground drainage system. For surfaces we assume are connected to an underground drainage system, runoff is calculated as rainfall minus expected capacity of the drainage system. For artificial surfaces we assume not connected to a drainage system, 100% of the rainfall is turned into runoff. For more details, see the section on runoff from artificial surfaces below.

For natural land cover classes, we use curve numbers to describe the runoff properties of the surfaces and to calculate the exact runoff for any given rainfall depth. Note that the curve numbers we use differ from the curve numbers that the same types of surfaces would be assigned using the original version of the curve number method. Please carefully read the section on the curve number method below if you wish to use your own curve numbers in a workspace.

2.1 The curve number method (CN)

One very well-known and broadly applied rainfall-runoff model is the Runoff Curve Number Method by the US Soil Conservation Service (now Natural Resources Conservation Service), often referred to as the CN method (USDA-SCS, 1986). The method provides a simple, empirically based relationship between rainfall and runoff using only two parameters: a curve number (CN) and a proportionality factor (λ). The governing equation is:

$$R = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Where:

$R = Runoff\ [mm]$

$P = Precipitation\ [mm]$

$I_a = Initial\ loss\ [mm]$

$S = Potential\ maximum\ retention\ after\ runoff\ begins\ [mm]$

The initial loss can be approximated as a fraction of the potential maximum retention after runoff begins:

$$I_a = \lambda * S$$

Where λ, the proportionality factor, is advised to be set to 0.2. However, many later studies propose different values.

The potential maximum retention after runoff begins, S, is related to the curve number, CN, via:

$$S = \frac{25400}{CN} - 254$$

The curve number is normally determined via lookup tables based on knowledge of the hydrologic soil group, land cover type, hydrologic condition of the soil, and the type of treatment the soil receives (the latter only applicable for agricultural soils).

The simplicity and popularity of the CN method make it a good candidate for the Flash Flood Map in SCALGO Live. However, there are some mismatches between the applications the CN method was developed for, and the way the Flash Flood Model in SCALGO Live operates. The CN method is intended for predicting total runoff into streams (or other water bodies) from catchments (or watersheds) of sizes in the order of magnitude of hectares (or acres). In SCALGO Live we would like to predict local surface runoff from each cell in the terrain model, which corresponds to catchment sizes of ca. 0.16 – 25 m^2. Some hydrological losses act differently across these scales, e.g., depression storage. On a catchment scale there may be quite large quantities of water held back in surface depressions, which are therefore implicitly included in the loss terms of the CN method (the initial loss and the potential maximum retention). On the pixel scale, the depression storage is significantly smaller, approaching what would normally be considered “wetting loss”, whereas larger surface depressions (>1 m^3) are explicitly managed in SCALGO’s Flash Flood Map. Furthermore, as the original CN method is designed to estimate increases in flow in streams, it does not take into account only true surface runoff but also subsurface flows such as near-surface saturated flow in natural media and flow through drainage systems (that normally empty into the nearest stream). In the Flash Flood Map, we are only interested in “true” surface flows.

Therefore, we have developed other methods for predicting surface runoff, as explained below. The outputs from these methods can be approximated using curve numbers, which understates that they capture similar hydrological processes. Furthermore, the curve numbers we find for different land cover classes are generally well correlated with the curve numbers assigned to the same land cover classes in the original CN method. Since curve numbers provide a simple and transparent way of characterizing runoff properties, and since we use curve numbers slightly differently than in the original CN method, we chose to use curve numbers but name them CN-p to underline the difference.

2.2 The Chicago Design Storm (CDS)

A design storm is a synthetic rain event created to design adequate solutions, based on statistical analysis of historical rainfall records. The Chicago Design Storm (CDS) is one the most used methods for creating design storms for urban applications. The CDS model for generating precipitation rates can be described as follows:

$$i_t = \frac{a}{(t+b)^n}$$

$i_t = Rainfall\ intensity\ [mm \cdot hr^{-1}]$

$t = Event\ duration\ [hr]$

$a, b, n = Parameters\ that\ represent\ local\ conditions\ and\ the\ chosen\ return\ period$

To assign the local parameters we consult publicly available rainfall data in each country. Depending on the size of the country and the availability of regional rainfall statistics we produce one or more CDS series for each country. We assume a standard event duration of 4 hours and generate a series of design storms with varying return periods, ranging from 0.5 to 500 years.

2.2.1 Denmark

For creating design storms in Denmark, we used the Excel Sheet Regionalregnrække (Gregersen et al., 2014) set to Odense.

Table 2 Overview of CDS-rains used for Denmark.

	Denmark	
Return period [yr]	Depth [mm]	Max 1-min intensity [mm]
2	23	1.75
5	30	2.17
10	35	2.52
20	41	2.89
50	51	3.41
100	59	3.85
200	68	4.31
500	82	4.96

3. Natural surfaces: runoff as infiltration excess

For most natural surfaces, and especially for natural soils covered with natural vegetation, infiltration will be the most significant hydrological loss during single rain events of significant volume. In other words, the mass balance equation over a single pixel can be approximated with the following equation:

$$R = \int_{t_0}^{t} i_t - f_t$$

$$i_t = Rainfall\ rate\ at\ time\ t\ [mm \cdot hr^{-1}]$$

$$f_t = Infiltration\ rate\ at\ time\ t\ [mm \cdot hr^{-1}]$$

As both the rainfall rate and infiltration rate vary over the time course of a single rain event, we need a model for each. For rainfall rates we use the Chicago Design Storm, as described above. For infiltration rates we use Horton’s equation, as described below.

3.1 The Horton infiltration equation

In choosing between the many models of infiltration available, Horton's equation is relevant in the context of the Flash Flood Map because it considers how the infiltration rate of the soil changes with increased saturation over the course of a single rain event.

$$f_t = f_c + (f_0 - f_c) \cdot e^{-kt}$$

$f_t = Infiltration\ rate\ at\ time\ t\ [mm \cdot hr^{-1}]$

$f_c = Constant/equilibrium\ infiltration\ rate\ [mm \cdot hr^{-1}]$

$f_0 = Initial/maximum\ infiltration\ rate\ [mm \cdot hr^{-1}]$

$k = Decay\ constant\ [-]$

As can be seen from the equation above, the model requires knowledge of a soil's infiltration rate both in its saturated state (f_c) and in an initial state (f_0, at the beginning of the rain event), and a decay constant (k) which describes how fast the infiltration rate decreases from the initial state to the saturated state. The infiltration rate at saturation is also known as the soil's hydraulic conductivity (K), a parameter which can be relatively easily measured (using, e.g., a double ring infiltrometer), or its order of magnitude can be assessed based on soil properties. The two additional parameters (f_0 and k) are less commonly known and more complicated to measure, but they can be estimated based on K and soil properties.

3.2 Soil properties

The hydraulic conductivity of a topsoil is influenced by many parameters, including:

- The composition of the soil: generally, the hydraulic conductivity increases with particle size and with organic matter content.
- The degree of compaction of the soil: as compaction increases the hydraulic conductivity decreases.
- The degree to which the soil is covered with vegetation: perennial and dense vegetation has larger root systems and is associated with more biological activity in the soil, which increases the hydraulic conductivity.

The latter two, the degree of soil compaction and the degree of vegetation cover, are generally correlated. In urban areas, soils covered with little or shallow vegetation, such as bare land or lawns, are often soils that experience traffic on them and hence get compacted, and vice versa – soils that experience compaction due to frequent traffic develop less vegetation cover. In rural areas, soils in agricultural fields have shallow vegetation density and often partly bare land for some part of the year, and experience regular compaction from machinery. Soils covered with dense vegetation, on the other end, such as hedges and forests, experience much less compaction from traffic and machinery, and the well-developed roots of dense vegetation improve the hydraulic conductivity of the soil, as does the activity of different insects and animals that are more likely found in zones with dense vegetation.

Therefore, and since there is generally no national mapping on the degree of compaction of soils, we approximate the degree of compaction through the degree of vegetation cover (implied by the land cover class).

For the composition of the soil, we depend on publicly available maps. In some countries, we have maps of the top layer of the soil, which is ideal for our purpose since the properties of this layer are the most important for the immediate infiltration from the surface of the soil to the subsurface. In other countries, we have geological maps of the sediment and rock types found 1 – 1.5 m below the surface. This is less ideal for our purpose since the geological type is not always a good descriptor of the composition of the soil (e.g., glacial tills may include a large variety of particle sizes), and since the properties of the topsoil may be very different from the properties of the geological substrate (e.g., varying types of soil, from sandy to clayey, may be found on top of rocks).

Note that no matter how detailed the soil maps in a country may be, the actual soil composition at any given point may differ considerably from that indicated by the maps, as natural processes as well as human interventions produce large heterogeneities in soils.

3.2.1 Denmark

For soil types in Denmark, we used a map from the Institute of Agroecology at Aarhus University with a resolution of 30.4 meters, covering all of Denmark (Adhikari et al., 2013). The map was created using equal-area quadratic splines predicting the vertical distribution of soil texture. The map is based on data from 1958 soil profiles, dug to the depth of 170-180 cm. Soil samples were analyzed in a lab to find the textural components at different depths in the profile. Texture combinations are categorized into 11 soil types known as JB-1 to JB-11. As we are interested in the infiltration rate of the topsoil, we use the top layer soil map, representing the upper 30 cm (see Figure 1).

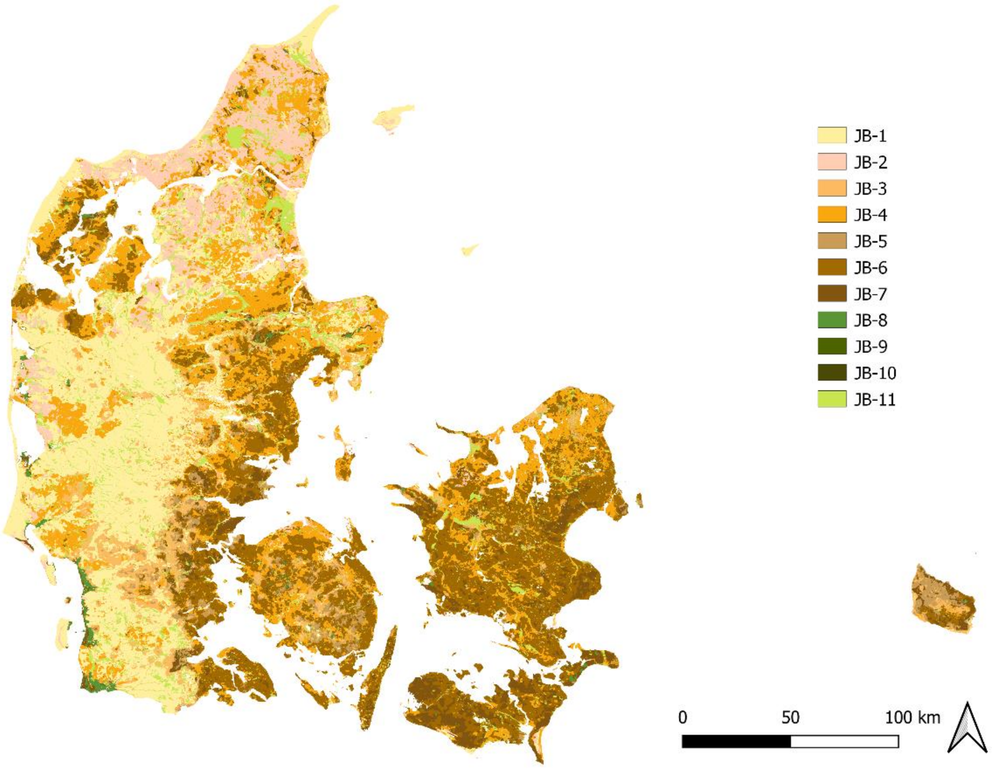

Figure 1 *Map of top layer soil type distribution in Denmark (from Institute of Agroecology at Aarhus University). See table 2 for soil type names.*

For the compaction degrees in Denmark, we use the following classification:

Land cover classes	**Compaction degree**
Bare land	High
Shallow vegetation	High
Dense vegetation	Low
Fields	High
Unpaved roads	High

3.3 Horton parameters

The parameters necessary for calculating infiltration using Horton's equation were estimated for the different types of soils for both a high and a low compaction level, using multiple sources (Dukes et al., 2006; Dyhr & Lindbæk, 2021; Kotlar et al., 2020; Parnas et al., 2021; Rossman & Simon, 2022).

3.2.1 Denmark

Table 2 below summarizes the parameters values we used for the soil types in Denmark.

Table 2 *Parameters for simulating infiltration with Horton's equation for the soil types in Denmark.*

JB-nr	JB-name (Danish)	JB-name (English)	High compaction			Low compaction		
			f_c	f_0	k	f_c	f_0	k

			[mm/hr]	[mm/hr]	[-]	[mm/hr]	[mm/hr]	[-]
1	Grovsandet jord	Coarse sandy soil	30	120	5	1000	4000	5
2	Finsandet jord	Fine sandy soil	25	100	5	500	2000	5
3	Grov lerblandet sandjord	Coarse sandy soil with clay	21	85	5	85	150	5
4	Fin lerblandet sandjord	Fine sandy soil with clay	20	80	5	50	130	5
5	Grov sandblandet lerjord	Coarse clayey soil with sand	12	50	5	30	120	5
6	Fin sandblandet lerjord	Fine clayey soil with sand	9	47	6	25	100	4
7	Lerjord	Clayey soil	5	20	5	20	50	5
8	Svær lerjord	Heavy clayey soil	0.5	2	5	2	20	5
9	Meget svær lerjord	Very heavy clayey soil	0.01	0.1	5	0	1	5
10	Siltjord	Silty soil	20	80	5	50	130	5
11	Humus	Soil with high fraction of hummus	21	85	5	85	150	5

3.4 Infiltration simulations' results

We simulated runoff as the rainfall rate that exceeds the infiltration rate, using Horton's equation and the Chicago Design Storms as described above, from a catchment sized 1 x 1 m, using SWMM, for all soil types and compaction degrees described above. This results in multiple pairs of accumulated rainfall and runoff volumes for each soil type and compaction degree. Plotting these value pairs shows a pattern of slowly rising curves, which can be well matched using CN curves, see a selection of soil types with high compaction in Figure 2 and a selection of soil types with low compaction in Figure 3 below.

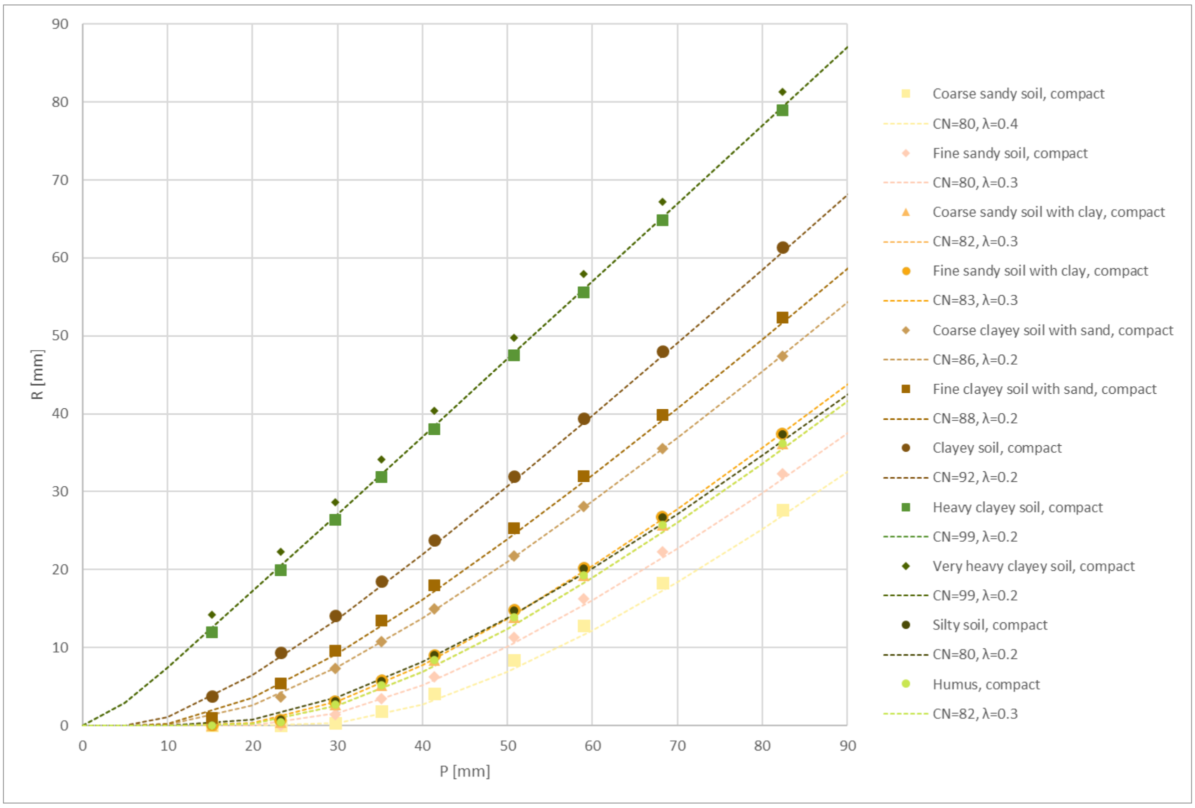

Figure 2 *Results from simulating runoff from natural surfaces with different JB soil types, all with high compaction, and CDS rains with varying return periods. The point results are matched with curves of varying curve numbers (CN) and proportionality factors (λ). Note the overlap in datapoints and CN-curve between coarse sandy soil with clay (JB-3) and humus (JB-11) as well as the overlap between fine sandy soil with clay (JB-4) and silty soil (JB-10).*

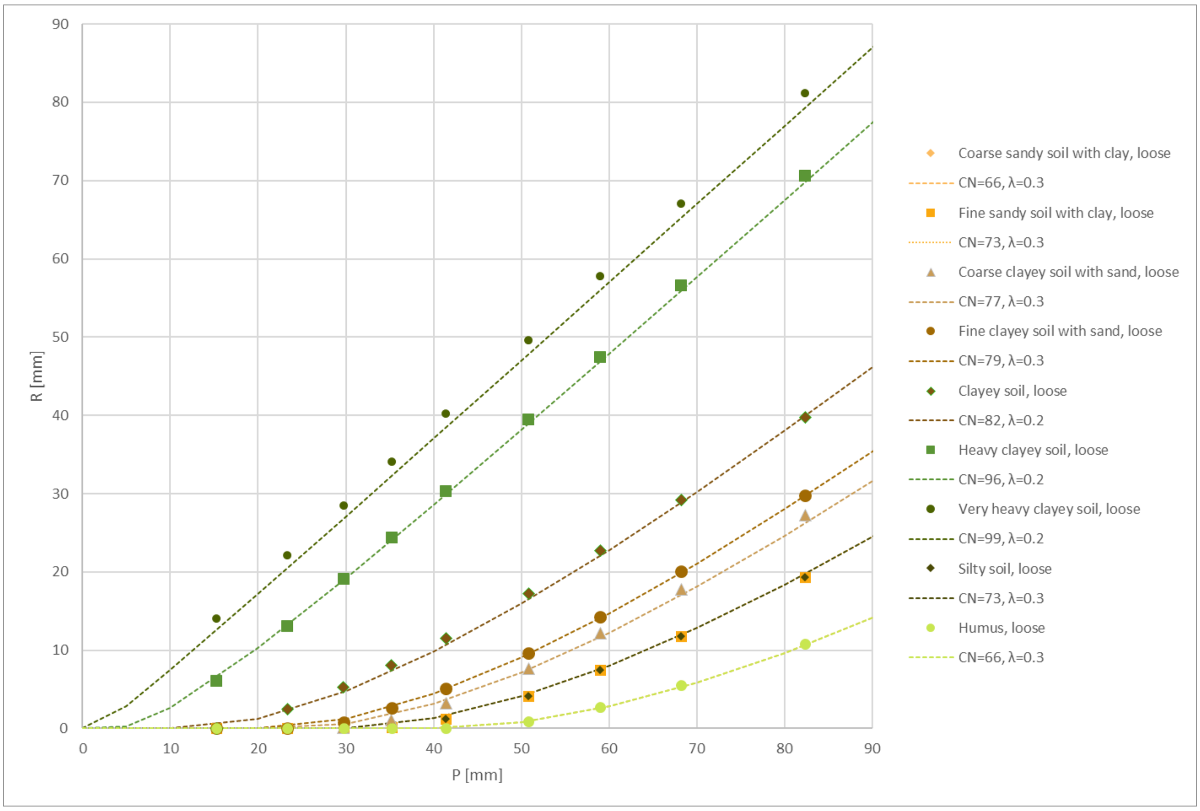

Figure 3 *Results from simulating runoff from natural surfaces with different JB soil types, all with low compaction degree, and CDS rains with varying return periods. The point results are matched with CN curves of varying curve*

numbers (CN) and proportionality factors (λ). A few soils are not included as the simulated runoff was 0 for all included rain events. Note the overlap in datapoints and CN-curve between coarse sandy soil with clay (JB-3) and humus (JB-11) as well as the overlap between fine sandy soil with clay (JB-4) and silty soil (JB-10).

3.5 Final curve numbers and comparison with other methods

Table 4 below summarizes the curve numbers found based on the method described above, together with curve numbers that would be assigned to the same soils based on the original CN method as described in TR-55 (USDA-SCS, 1986). The values for compacted soil are also compared to values for agricultural fields for the most common crop types in Denmark (barley, wheat, corn, rapeseed).

Table 4 *Curve numbers for the 11 soil types and two compaction degrees according to the original CN method, and the curve numbers found to match our simulation results (labelled CN-p). *According to TR-55 the actual curve number is less than 30, but 30 should be used for runoff computations; in practice curve number 30 results in no runoff for the magnitudes of rainfall we cover here.*

JB-nr	JB-name (English)	High compaction			Low compaction	
		Urban open spaces	Agricultural fields		Wooded areas	
		CN original (λ)	CN original (λ)	**CN-p (λ)**	CN original (λ)	**CN-p (λ)**
1	Coarse sandy soil	68 (0.2)	67 (0.2)	**80 (0.4)**	30 (0.2)*	**30 (0.2)**
2	Fine sandy soil	68 (0.2)	67 (0.2)	**80 (0.3)**	30 (0.2)	**30 (0.2)**
3	Coarse sandy soil with clay	79 (0.2)	77 (0.2)	**82 (0.3)**	55 (0.2)	**66 (0.3)**
4	Fine sandy soil with clay	79 (0.2)	77 (0.2)	**83 (0.3)**	55 (0.2)	**73 (0.3)**
5	Coarse clayey soil with sand	86 (0.2)	85 (0.2)	**86 (0.2)**	70 (0.2)	**77 (0.3)**
6	Fine clayey soil with sand	86 (0.2)	85 (0.2)	**88 (0.2)**	70 (0.2)	**79 (0.3)**
7	Clayey soil	86 (0.2)	85 (0.2)	**92 (0.2)**	70 (0.2)	**82 (0.2)**
8	Heavy clayey soil	89 (0.2)	89 (0.2)	**99 (0.2)**	77 (0.2)	**96 (0.3)**
9	Very heavy clayey soil	89 (0.2)	89 (0.2)	**100 (0.2)**	77 (0.2)	**99 (0.2)**
10	Silty soil	79 (0.2)	77 (0.2)	**80 (0.2)**	55 (0.2)	**73 (0.3)**
11	Soil with high fraction of hummus	79 (0.2)	77 (0.2)	**82 (0.3)**	55 (0.2)	**66 (0.3)**

As can be seen, the curve numbers that describe our infiltration simulation results (the CN-p values) are generally higher than the curve numbers that would be applied to the same soil types using the original CN method. This is as expected, due to the difference in catchment sizes. In the ultra-small scale that we use in the Flash Flood Map (model cells of 0.16 –25 m^2) there are only very small depressions, whereas in the larger catchments that the original CN method was developed for there can be much larger depressions. In the Flash Flood Map in SCALGO Live we account for these large depressions explicitly, i.e., we route runoff on the detailed surface of the earth and store it in depressions where applicable. Therefore, to predict the same magnitude of runoff at the larger catchment scale, each cell in the Flash Flood Model must generate more runoff than if it had been assigned its fair share of the catchment runoff in the original CN method.

Unfortunately, there are very few studies worldwide that measure direct surface runoff from natural surfaces. In the following, we compare the runoff predicted by the CN-p with the few relevant studies we have found (please tip us know if you know more!).

Figure 4 below shows results from a study that simulated runoff as infiltration excess using Horton's equation (Davidsen et al., 2018), much like our own simulations, except that they used the historical rainfall record for Copenhagen rather than CDS rains, including simulating how the infiltration capacity of the soil recovered between rain events. The soil parameters they used in Horton's equation were derived from point infiltration measurements at a site with clayey soil covered with grass and exposed to considerable pedestrian traffic (Charlottenlund Fort). According to the soil type map of Denmark, the soil at this site is JB-6.

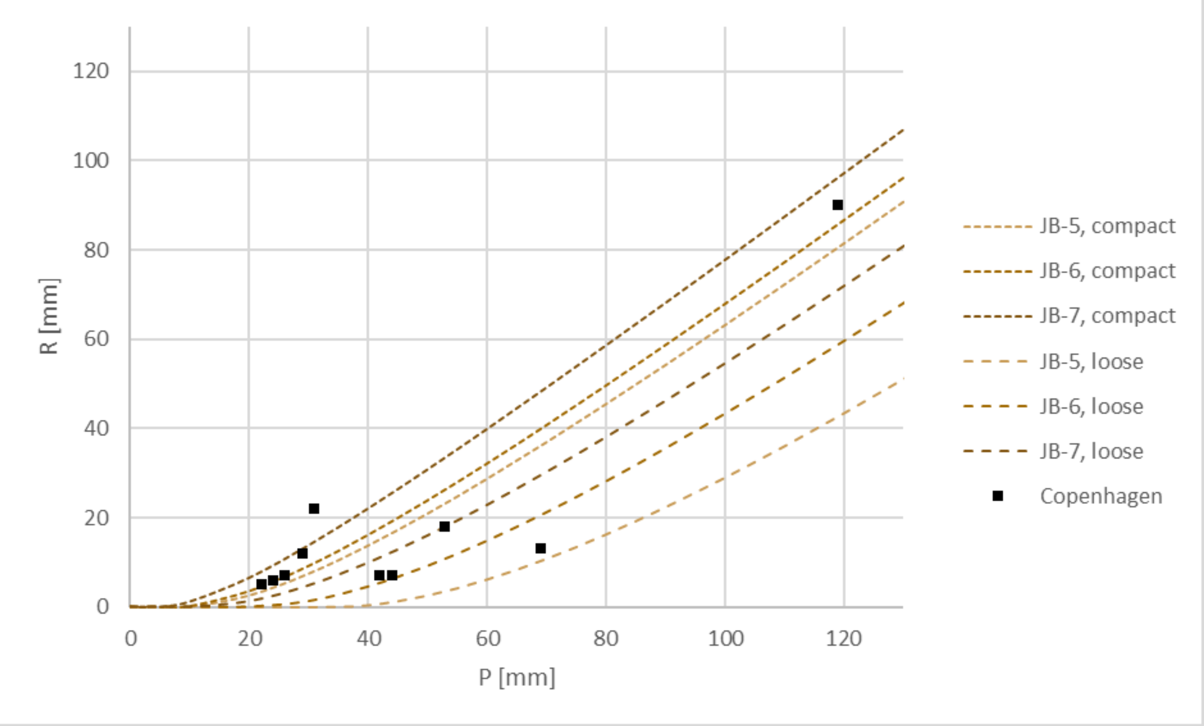

Figure 4 *Results from runoff simulations with historical rain events from a clayey soil with shallow vegetation in Copenhagen (Davidsen et al., 2018) together with relevant CN-p curves.*

The figure shows a substantial spread for the ratio between rainfall and runoff among the rain events from the Copenhagen study, as expected given that they are historical events with individual characteristics that do not conform to the idealized form of a design storm. Nonetheless, three of the events fall almost precisely on the curve that describes the expect runoff from this site (the curve for a compacted JB-6 soil type, CN-p=88); four events fall slightly below this curve and closer to the loose forms of JB-5, JB-6 and JB-7 soil types; three events fall above the expected curve, one of them standing out as an unusually intense event (31 mm of rain with a maximum 1-minute intensity of 3.4 mm), and one of them representing the infamous extreme event of the 2nd of July 2011 (with a cumulated rainfall depth of almost 120 mm). All in all, considering the natural variability of the intensity of these rainfall events and of the antecedent moisture conditions, the simulated runoff in this study shows a good agreement with the runoff predicted by the CN-p curve.

Figure 5 below shows results from in situ measurements of runoff from a public park in Lystrup, Denmark (Nielsen et al., 2019) and a follow up study using the same field measurement techniques at a similar site in Viby (Kjærgaard & Bjørn, 2021). According to the soil type map of Denmark, the soil type at both sites is JB-6; both sites were covered with short grass and hence classified shallow vegetation, which translates to a high compaction degree. However, the site at Viby is described to experience considerably more traffic than the site in Lystrup, including patches with bare land (grass cover worn down).

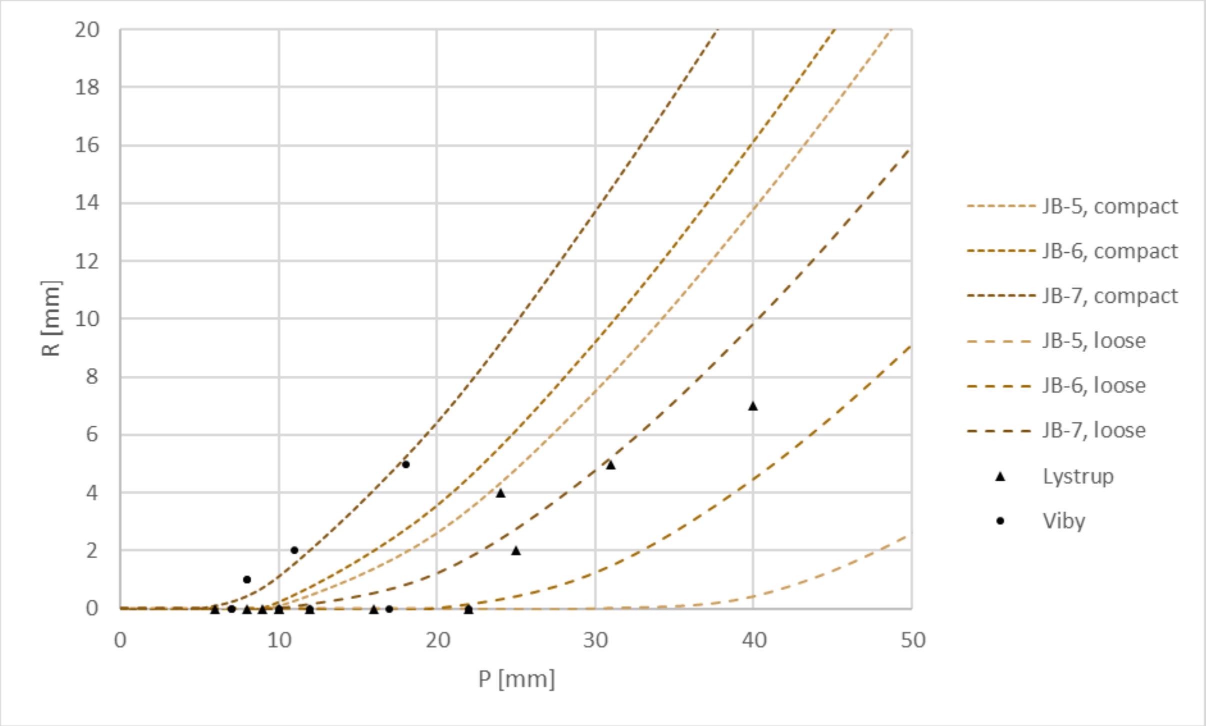

Figure 5 *Results from in-situ measurements of runoff from clayey soils with shallow vegetation in Lystrup and Viby, Denmark, together with CN-p curve for the soil type and compaction degree of the sites (JB-6 compact) and CN-p curves for similar soils.*

The measured runoff at Lystrup generally falls below the JB-6 compact curve and closer to the JB-7 loose curve. Three events in Viby fall close to the JB-7 compact curve, the other events at Viby show no runoff at all. The difference in matching CN-p curves between Lystrup and Viby seems to correspond to the difference in traffic intensity between the sites, emphasizing that the default CN-p curves based on soil type and land cover alone cannot fully predict the local conditions due to variations in, e.g., traffic intensity, yet they give very reasonable approximations.

3.5.1 Denmark

Based on the results and discussions presented above, the final CN-p curve numbers and the minimum infiltration values (f_c), equivalent to the saturated hydraulic conductivity (K), used in the process of determining the CN-p values, for natural surfaces in SCALGO Live Denmark, are presented below in Table 3.

Table 3 Overview of the soil types and their corresponding CN-curves and f_c values used for simulations.

Soil type			Compacted soil		Loose soil	
JB-nr	JB-name (Danish)	JB-name (English)	f_c / K [mm/hr]	CN-p (λ)	f_c / K [mm/hr]	CN-p (λ)
1	Grovsandet jord	Coarse sandy soil	30	80 (0.4)	1000	30 (0.2)
2	Finsandet jord	Fine sandy soil	25	80 (0.3)	500	30 (0.2)
3	Grov lerblandet sandjord	Coarse sandy soil with clay	21	82 (0.3)	85	66 (0.3)
4	Fin lerblandet sandjord	Fine sandy soil with clay	20	83 (0.3)	50	73 (0.3)
5	Grov sandblandet lerjord	Coarse clayey soil with sand	12	86 (0.2)	30	77 (0.3)
6	Fin sandblandet lerjord	Fine clayey soil with sand	9	88 (0.2)	25	79 (0.3)
7	Lerjord	Clayey soil	5	92 (0.2)	20	82 (0.2)
8	Svær lerjord	Heavy clayey soil	0.5	99 (0.2)	2	96 (0.3)
9	Meget svær lerjord	Very heavy clayey soil	0.01	100 (0.2)	0	99 (0.2)
10	Siltjord	Silty soil	20	80 (0.2)	50	73 (0.3)
11	Humus	Soil with high fraction of humus	21	82 (0.3)	85	66 (0.3)

3.6 Limitations and recommendations

The CN-p curve numbers entail a substantial improvement in the prediction of runoff volumes in the Flash Flood Map in SCALGO Live, for typical summertime short-duration high-intensity storms, compared with the “glass plate” model that turns 100% of the rainfall into runoff. Meanwhile, in the sake of making a very simple, robust, and user-friendly model, some simplifications were necessary, and the predicted runoff volumes should be considered rough approximations. Users are encouraged to consider how well the sites and the situations they are analyzing correspond to the assumptions we made, and where differences arise, consider how to interpret the results, or adjust the CN-p values (possible in Workspaces).

The biggest limitation of the method is that water can only infiltrate in the cell that the rain falls on. For natural surfaces, rainfall often infiltrates directly where it lands, but when runoff is generated, it may flow over to an artificial area and flow into a drainage system inlet there. Since this process cannot be represented with the current model, simulated runoff from natural surfaces will inevitably generate some ponds (flooded areas) that would not be expected in reality. For example, given a rain of 15 mm over an urban area with compacted clayey soil, some of the runoff generated from the natural areas in the model will generate ponds on downstream artificial areas (where in reality, such flows would continue into the drainage system, given that these most likely still have available capacity at this rainfall depth).

We chose to simulate rainfall-runoff using Horton's equation and CDS events. This was mainly done to align the rainfall-runoff processes on natural surfaces with industry standards regarding critical rainfall events for urban drainage systems, given that the typical use of the Flash Flood Map is for assessing flooding in cities. However, CDS events do not necessarily represent worst-case rain events in terms of generating runoff from natural surfaces. Soils, both urban and rural, may generate more runoff when exposed to long-duration low-intensity rain events (typical in winter), where the soil gets fully saturated, than under high-intensity short-duration events (typical in summer). Furthermore, runoff due to saturation is not well represented by Horton's equation. In case the user is interested in assessing runoff volumes given long-duration rain events or given saturated soil at the onset of a rain event, the user is advised to specify alternative CN-p values (possible in Workspaces).

The soil parameter sets that we used in our simulations do not explicitly represent a specific degree of moisture in the soil at the beginning of the rain event. The parameter values are based on a mix of sources expected to represent an average moisture condition. They might be slightly to the conservative side, as is indicated by how the JB-6 compact curve matches the extreme event of July 2011, which fell on a relatively moist soil.

Remember that soils are extremely heterogenous, and one clayey soil may exhibit substantially different infiltration rates than another clayey soil. Again, if precision is important, the user is advised to perform in-situ measurements of the infiltration capacity of the soil at their site and apply updated CN-p values if necessary (possible in Workspaces).

Remember also that our approach only considers the infiltration through the topsoil. The user is advised to investigate if there is high probability of significantly lower infiltration capacity in underlying soil layers, and/or there is high probability of a secondary groundwater table close to the surface, in which cases the runoff rates may be higher than indicated by the default curves.

3.6.1 Denmark

The validity of basing the results on using Odense as location for generation of CDS rain events and a safety factor of 1.0 was tested by comparing with two other locations (Esbjerg and Copenhagen) and one additional safety factor (1.3). As shown in Figure 6, the results of simulations with other locations and other safety factor largely fall on the same curve. This confirms that these choices are not important for the choice of CN-p curves – the user will get an equally relevant result for any choice of accumulated rainfall depth as long as they assume the rain to fall with an intensity-duration relation as in a CDS.

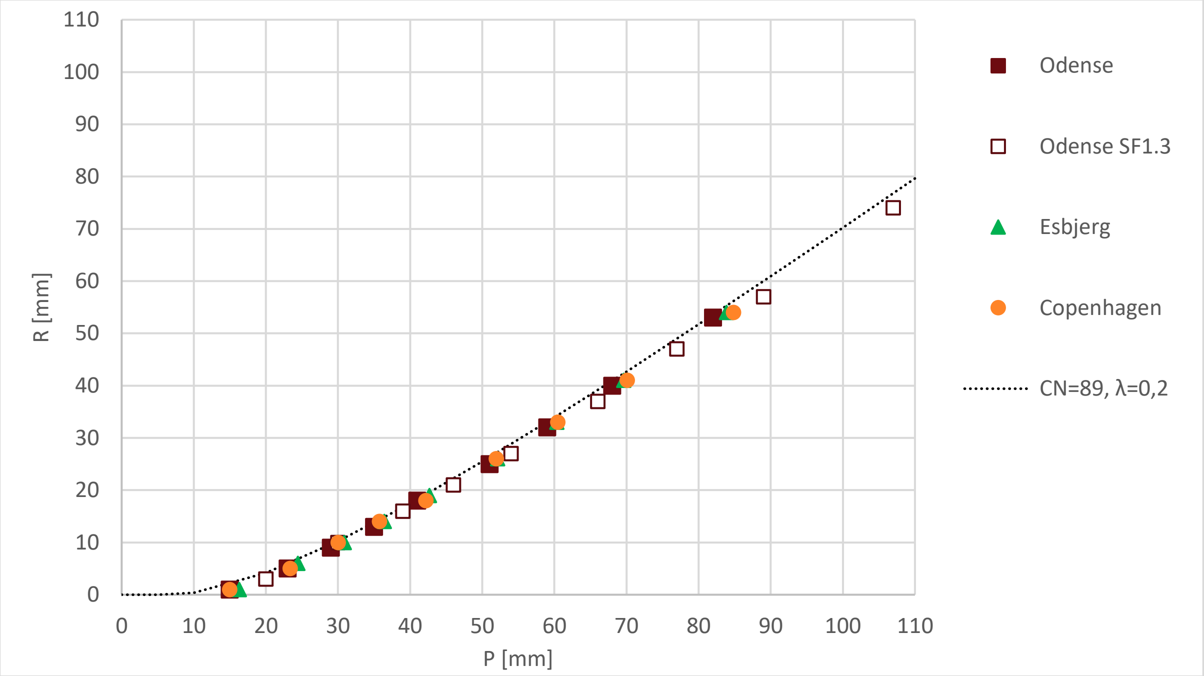

Figure 6 *Results from runoff simulations with different CDS rains (all with a duration of 4 hours).*

4. Artificial surfaces: runoff as surcharge from drainage systems

Practically all artificial surfaces in Europe are connected to some sort of drainage system which transports water away from built areas. In urban areas the drainage systems are mainly piped underground systems, designed to manage rain events with a given return period, often in the range of 2-10 years. This means that, seen from the perspective of flows on terrain, for "technical domain" rain events (rains with a return period smaller than 2-10 years), it can be assumed that most rainfall will runoff the immediate surface that it lands on and only flow on the surface for very short distances before it meets an inlet point and "disappears" from the surface and into the underground drainage system (coming out to the surface again at the intended outlet from the drainage system, usually a natural water body if the drainage system is separate, or a wastewater treatment plant if the system is combined).

When a rain event surpasses the designed capacity of the drainage system, some of the runoff will not be able to enter the drainage system at intended inlet points, due to congestion; furthermore, other points in the system may experience elevated water levels that press water out of the system and on to the terrain (a process called sewer surcharge). This water may accumulate or flow on the terrain for some time as if there was no drainage system, until it hits an entry point that is not congested, or until the capacity of the drainage system is regained. Seen from the perspective of the FFM in SCALGO Live, the water that flows on the surface in such situations can be considered the "de-facto runoff" that needs to be simulated as flow on the terrain.

How much "de-facto runoff" (surcharge) is generated depends on the actual capacity of the drainage system and on characteristics of the rain event. Thanks to the generous help of multiple collaboration partners, we have been able to assemble results from hydrodynamic simulations of existing drainage systems from multiple sites across Denmark and Sweden. The simulations were performed using models built in different software packages, by different people, in different utility companies and engineering consultancy agencies, for different purposes. With each model, the partners performed a series of simulations applying CDS rainfall events of 4 hours duration with return periods of 2-500 years, retrieving the accumulated volume of water that surcharged from each simulation, and dividing that volume by the total artificial area connected to the system in the model (to yield an average depth of surcharged water across the artificial area). This yields approx. 8 pairs of rainfall and “de facto runoff” from each drainage system, which are plotted in Figure 1 below, together with the CN curves that fit the simulation results of the worst and the best performing drainage systems in the sample, and the CN curve that represents the median of the systems’ CN-curves.

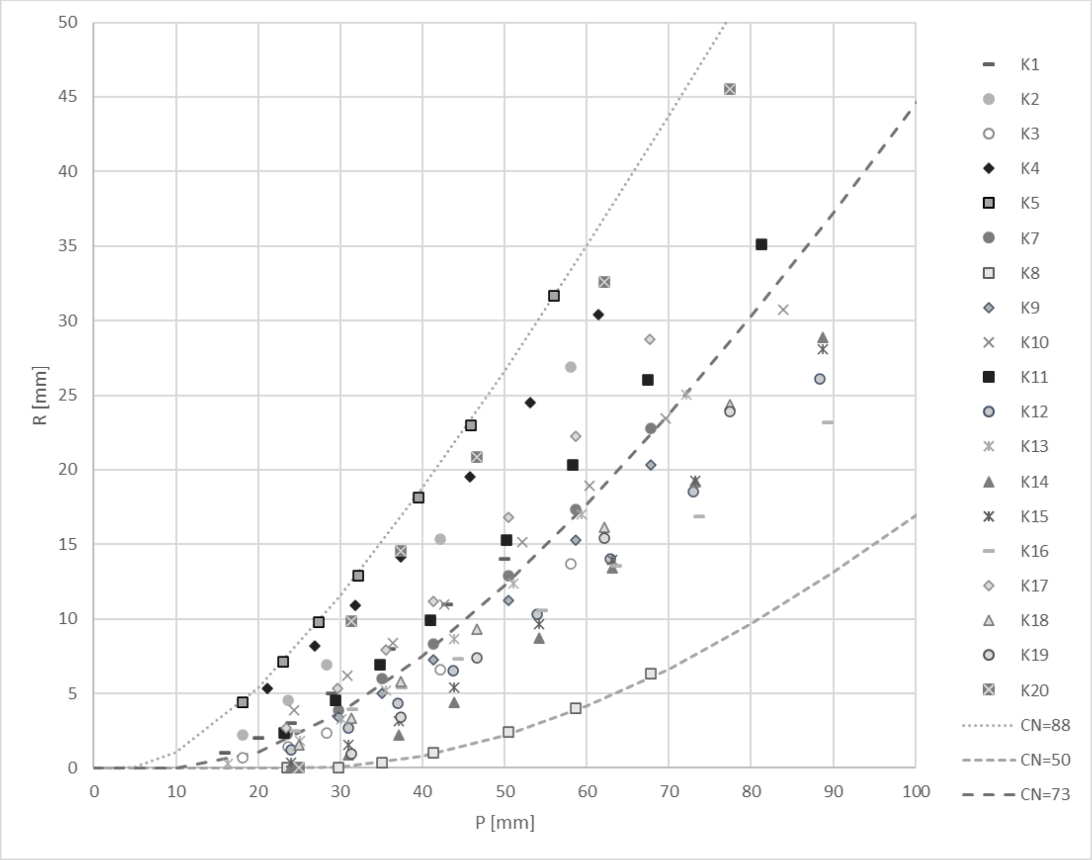

Figure 1 Results of simulations of surcharge from urban sewer systems given local CDS-events, presented in mm (cumulated volume of surcharge during each event divided with the sum of artificial area connected to the sewer system). The three CN-p curves reflect the curves that match the best performing system (50), the worst performing system (73) and the median of the sample (73). Data kindly provided by SCALGO Live users in Denmark and Sweden.

As can be seen, the curves fit the data points quite well, indicating that the CN function is suited to describe the relation between rainfall and surcharge / “de facto runoff” from drainage system served areas.

As can also be seen, there is a significant spread in performance between the drainage systems included. Analysis of the sample showed no clear correlation between the curve numbers that fit the results and the type of the system (separate or combined). The median curve number was 73 with a λ of 0.1, and this curve is hence applied to predict runoff from artificial surfaces in zones that are expected to be connected to drainage systems.

The median CN-p (73) is significantly lower than the value suggested for impervious surfaces in TR-55 (the technical reference for the CN-method), namely 98. The explanation for this lies in the different perspectives used here and in TR-55: the original CN method was designed for predicting runoff into streams (or other water bodies), including the water that is deliberately discharged into the stream from the drainage system. In the FFM we aim to predict only the “runoff” that “accidentally” exits the drainage system onto terrain through surcharge. The amount of water that escapes the drainage system in this way will normally be smaller than the water that ends in the local stream (or other water body that receives discharge from a drainage system), and hence it is appropriate that the CN-number used in the FFM for sewer connected surfaces is significantly lower than in the original CN method.

Note that most of the drainage systems in the sample start producing surcharge at rainfall depths below 30-35 mm, which roughly corresponds to a 5-10-year event in Denmark and hence represents the required performance of sewer systems in Denmark. This is as expected, given that most urban areas have seen substantial growth and densification since their drainage systems were designed and established, which has reduced their actual performance relative to the original performance. Note also that once the capacity of a system is exceeded, the surcharge does not correspond to 100% of the surplus rain but shows a less steep increase. This is also as expected, given that drainage systems continue to transport water also when saturated. The figure below shows the simulation results together with the common assumption of zero surcharge for rainfall depths below the required performance, and 100% runoff for the rainfall that exceeds the required performance, demonstrating that this assumption does not fit the sewer simulations very well.

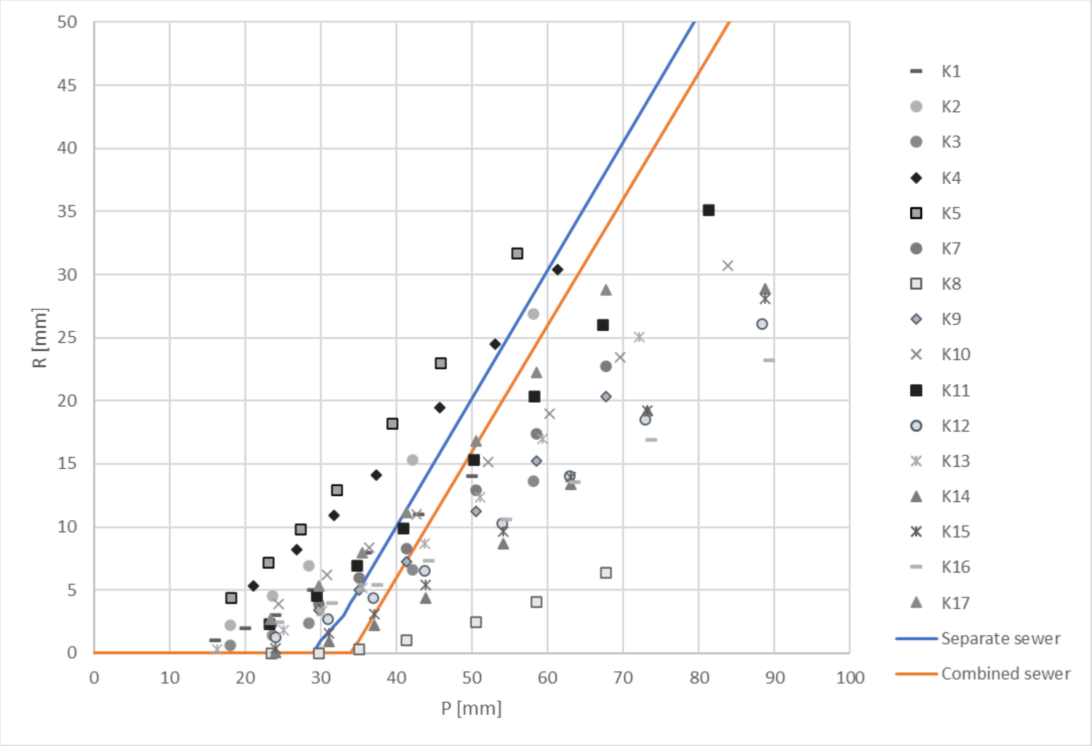

Figure 2 The same results as in the previous figure, here plotted with lines indicating the general performance assumption for Danish drainage systems (initial loss of 29/34 mm and runoff coefficient = 1).

For artificial surfaces that are not connected to a drainage system, we assume that 100% of the rainfall turns into runoff.

For unpaved roads, we assume that these are not connected to a drainage system, and that the (natural) paving material used to construct them is highly compacted, with infiltration capacities corresponding to a compacted coarse clay, which has a CN-p value of 85 (0.2). Hence, if the unpaved road is on top of a soil type with a lower CN-p value, the CN-p value assigned is 85 (0.2), while if the soil beneath the unpaved road has a higher CN-p value (e.g. if it is fine clay), the CN-p value of the native soil type is applied.

4.0.1 Denmark

In Denmark we use the layer “Kloakoplande – Vedtaget” from plandata.dk to distinguish between artificial surfaces connected to a drainage system and artificial surfaces not connected to a drainage system. All artificial surfaces that fall within a polygon in this layer are treated as connected to a drainage system, no matter what class the polygon is given in this layer. This means not only that separate and combined sewer systems are treated equally, but also that systems that are classified as, e.g., “only household sewers” or “other”, are treated equally. The rational is that these areas may not be served by a traditional combined or separate sewer system, yet in most cases have some kind of functioning drainage system in place, e.g., a system based on local infiltration.

4.1 Advantages and limitations

The “de facto runoff” from drainage systems, estimated using drainage system models, is in the FFM equally distributed among all artificial model cells. In reality, drainage systems have weak points where the capacity is more often surpassed, and surcharge more often occurs. Currently we do not have any algorithm which can predict these weak points, but this may become feasible in the future. Meanwhile, if the user has made simulations with a hydraulic model of the drainage system in their area of interest, it is possible to extract the points of surcharge and the volume at each point from the results and apply this as runoff in SCALGO Live (in a Workspace, with a little workaround).

As seen, the spread in performance among the drainage systems sampled was rather large. If the user has knowledge about the capacity of the drainage system in their area of interest, e.g., based on knowledge of when the system was designed and how the city has evolved since, the user is encouraged to adjust the curve number for the artificial areas in their area of interest (in a Workspace).

For artificial surfaces not connected to a drainage system, converting all rainfall to runoff may result in puddles forming in nearby (downstream) depressions already at very small rainfall depths, also when the downstream depression has a natural surface, since runoff in our model cannot infiltrate once it has left the model cell where it was generated. In reality, this water will often likely infiltrate in those natural areas (at low rainfall depths immediately, at higher rainfall depths over longer time). Thus, the user should consider blue spots around rural properties and roads with care, for smaller rain depths they are most probably non-existent in reality, and for larger rain depths they are probably overestimated in size and depth in the model compared to reality.

In some cases, drainage systems are constructed on the surface, using trenches and ditches to direct water from artificial surfaces to rain gardens or detention basins or other nature-based solutions for stormwater management. In such cases we advise to let all rainfall on artificial surfaces become runoff in order to simulate most correctly how this water flows around in the system. The user may also choose to apply rainfall-runoff functions that represent the small hydrological losses expected on different types of artificial surfaces. E.g., rough surfaces such as asphalt may be assigned an initial loss of a few millimetres representing wetting of the surface, and semi-permeable surface types such as paving stones may be assigned a runoff coefficient of 0.8 or lower representing some infiltration loss through the gaps between the paving stones. Note that when creating a workspace in an existing urban zone to experiment with nature-based solutions for stormwater management, the user may need to change the predefined curve numbers for the artificial surfaces to indicate if they will be disconnected from the sewer system (otherwise the runoff from these surfaces will be underestimated).

5. Revision history

Version	Release date	Main changes
1.1	15/3-2023	The land cover map was considerably improved, with multiple new land cover classes.
1.2	19/10-2023	1. All artificial surfaces, except unpaved roads, that are expected to be connected to any kind of stormwater management system, are assigned a CN-p value of 73 (λ=0.1). 2. Unpaved roads are assigned CN-p values that reflect their unique properties. 3. CN-p values for natural surfaces have been updated for some soil types.

5.1 Changes between version 1.1 and version 1.0

The updated version of the land cover map for Denmark was used for a new calculation of the rainfall-runoff in the flash flood map. No changes were made with respect to CN-p values. A description of the new land cover map can be found here: https://scalgo.com/en-US/blog/nyt-arealdaekkekort-i-danmark-2023 .

5.2 Changes between version 1.2 and version 1.1

Several changes have been made to CN-p values. None of them are expected to generate significant changes in runoff values, but minor changes are expected.

For artificial surfaces, not including unpaved roads, a distinction is still made based on the sewer system map from plandata.dk. However, all the plandata.dk categories are now expected to behave as if they have a stormwater management system, see Table 4 below. Furthermore, all stormwater management systems are treated equally and assigned a CN-p value of 73 (with λ set to 0.1), replacing the distinction previously made between combined and separate sewer systems; see Section 4 for explanation on how this new CN-p was found.

Table 4 Interpretation of classes in the sewer system map from plandata.dk in SCALGO Live versions 1.1 and 1.2

Class in plandata.dk (type1201a)	In v1.1 assigned the rainfall-runoff function of:	In v1.2 assigned the rainfall-runoff function of:
fælles (1)	Combined	Sewered
separat (2)	Separate	Sewered
kun spildevand (3)	No sewers	Sewered
kun overfladevand (4)	Separate	Sewered
ingen kloak (5)	No sewers	Sewered
andet (6)	No sewers	Sewered
(No polygon)	No sewers	No sewers

Unpaved roads, in version 1.1, were assigned a CN-p reflecting a high compaction state of the soil type indicated by the soil type map. This has been slightly revised to take into account that the material used for paving so-called unpaved roads most often has rather low infiltration capacity, which we assumed corresponds to the infiltration capacity of JB5 (CN-p 86, λ 0.2). Hence, if the native soil has a higher infiltration capacity, e.g., if it is a sandy soil (80, λ 0.3), the CN-p of the road is set up to CN-p 86, λ 0.2, while if the native soil has a lower infiltration capacity, e.g., it is a heavy clay (99, λ 0.2), the CN-p of the road retains the CN-p value of heavy clay.

For natural surfaces, we have updated the CN-p values of some soil types based on improved knowledge. Furthermore, all soil types that formerly had their runoff set to zero, have been changed to CN-p 30 (to better align with the original CN method). See Table 5 below for details.

Table 5 Soil types which have received new CN-p values compared to version 1.1 are highlighted with bold.

Soil type		High compaction		Low compaction	
JB nr	JB name	CN-p in version 1.1 (λ)	CN-p (λ)	CN-p in version 1.1 (λ)	CN-p (λ)
1	Coarse sandy soil	80 (0.4)	80 (0.4)	0 (0)	**30 (0.2)**

2	Fine sandy soil	80 (0.3)	80 (0.3)	0 (0)	**30 (0.2)**
3	Coarse sandy soil with clay	82 (0.3)	82 (0.3)	0 (0)	**66 (0.3)**
4	Fine sandy soil with clay	83 (0.3)	83 (0.3)	0 (0)	**73 (0.3)**
5	Coarse clayey soil with sand	86 (0.2)	86 (0.2)	75 (0.4)	**77 (0.3)**
6	Fine clayey soil with sand	88 (0.2)	88 (0.2)	79 (0.3)	79 (0.3)
7	Clayey soil	92 (0.2)	92 (0.2)	82 (0.2)	82 (0.2)
8	Heavy clayey soil	99 (0.2)	99 (0.2)	96 (0.3)	96 (0.3)
9	Very heavy clayey soil	99 (0.2)	100 (0.2)	99 (0.2)	99 (0.2)
10	Silty soil	80 (0.2)	80 (0.2)	69 (0.4)	**73 (0.3)**
11	Soil with high fraction of hummus	78 (0.2)	**82 (0.3)**	0 (0)	**66 (0.3)**

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