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

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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.*

Land cover groups	Land cover classes	Runoff estimation method
Water	Inland permanent water	100% of rainfall
Natural	Bare soil	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 artificial surfaces which we assume are connected to an underground drainage system, runoff is calculated as rainfall minus expected capacity of the drainage system. For artificial surfaces which we assume are 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.

We use curve numbers to describe the runoff properties of the surfaces and to calculate the 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 change the curve numbers in a workspace.

2.1 The curve number method (CN) and our adaptation (CN-p)

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". 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 (which normally empty into the nearest stream or other water body). 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. The curve numbers we find for different land cover classes are generally correlated with the curve numbers assigned to the same land cover classes in the original CN method (e.g. clayey soils have higher curve numbers than sandy soils both in our simulations and in the original CN method). Since curve numbers provide a simple and transparent way of characterising runoff properties, yet since we use curve numbers slightly differently than in the original CN method, we name our curve numbers CN-p (p for pixel) to underline the difference.

2.2 The Chicago Design Storm (CDS)

A design storm is a synthetic rain event created to design adequate engineering 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 Sweden

CDS events for Sweden were created using a national IDF-table based on Dahlström (2010), which was featured in the Svenskt Vatten report P110 (2016) and has return periods ranging from 6 months to 100 years.

***Table 2**: Overview of CDS-rains used for Sweden.*

	Sweden	
Return period [yr]	Depth [mm]	Max 1-min intensity [mm]
0.5	15.6	0.7
1	18.9	0.9
2	23.1	1.1
5	30.3	1.5
10	37.3	1.9
20	46.3	2.4
30	51.7	2.7
50	61.7	3.2
100	77.0	4.0

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 increase 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 soil 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 soil 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 in a 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 Sweden

Soil maps from the Swedish Geological Survey (SGU) are used as main source of information. The soil map in SCALGO Live is a combination of regional SGU maps of different resolutions, all of which map the soil at a depth of 0,5 m under the surface. A map of topsoil types is available from the Swedish Board of agriculture, but this map only covers a little fraction of the Swedish territory. The SGU maps contain many different soil types, named after the depositional environment of the deposit, which may indicate the soil's infiltration properties, but not always. To see if we could better infer the infiltration capacity of different SGU soil types from the topsoil map, we compared the two maps over two different areas. This confirmed some of the assumptions we had made (e.g., Isälvssediment is mostly sand) but there were also large variations (e.g., on top of SGU Urberg we found both sandy loam, loam, silty loam, clay loam, silty clay, and clay) and some inconsistencies (e.g., SGU Postglacial sand could be covered by both sandy loam and clay loam).

The following Table 3 shows the simplified soil types we defined for Sweden and how original SGU soil types are reclassified into them.

Table 3 Soil type names in Swedish and English and their corresponding SGU deposit type.

Soil type (Swedish)	Soil type (English)	SGU name
Sten/block	Rocks/blocks	Slamströmssediment, ler--block
		Älvsediment, sten--block
		Sten--block
		Blockmark
		Isälvssediment, sten--block
		Morän, sten--block
		Rösberg
		Talus
		Klapper
Grus	Gravel	Älvsediment, grus
		Svämsediment, grus
		Sand--grus

		Svallsediment, grus
		Isälvssediment, grus
		Vittringsjord, sand--grus
		Grusig morän
		Skaljord
		Fyllning, rödfyr
		Postglacial sand--grus
Sand	Sand	Sand
		Sandig morän
		Isälvssediment, sand
		Postglacial sand
		Svämsediment, sand
		Älvsediment, sand
		Vittringsjord
		Isälvssediment
		Flygsand
		Älvsediment
		Flytjord eller skredjord
		Fyllning
		Morän eller vittringsjord
		Morän omväxlande med sorterade sediment
Finsand	Fine sand	Postglacial finsand
		Postglacial grovsilt--finsand
		Glacial grovsilt--finsand
		Sandig-siltig morän
		Älvsediment, grovsilt--finsand
		Svämsediment, grovsilt--finsand
Silt	Silt	Morän
		Postglacial silt
		Silt
		Glacial silt
		Svämsediment
Grovler	Coarse clay	Svämsediment, ler--silt
		Lerig morän
		Älvsediment, ler--silt
		Postglacial grovlera
		Postglacial lera
		Lera--silt
		Glacial grovlera
		Morängrovlera
		Vittringsjord, ler--silt
		Oklassat område
		Oklassat område, tidvis under vatten
		Lera--silt, tidvis under vatten
		Moränlera eller lerig morän
		Moränlera
Ler	Clay	Lera
		Glacial lera

		Kalktuff
Finler	Fine clay	Postglacial finlera
		Glacial finlera
		Moränfinlera
Gyttja/torv	Gyttja/peat	Gyttjalera (eller lergyttja)
		Gyttja
		Bleke och kalkgyttja
		Torv
		Mossetorv
		Kärrtorv
		Torv, tidvis under vatten
Berg	Bedrock	Berg
		Sedimentärt berg
		Fanerozoisk diabas
		Urberg
		Skålla av sedimentärt berg
		Skålla av sandsten
Glaciär	Glacier	Glaciär
Vatten	Water	Vatten

In some cases, we can see that our land cover map finds vegetation (shallow, dense or within a field) on top of areas that are classified as bedrock. Obviously, vegetation cannot grow directly on bedrock, so there must be some other soil on top of the bedrock in these areas. As we cannot know what this soil consists of, we assume this to be coarse clay, as a conservative estimate of the infiltration capabilities of a relatively thin layer of soil with a root network on top of bedrock. In the cases where bedrock is found with the land cover class bare rock, we assume bedrock to be present in the entire horizon. In cases where bedrock is covered by bare land in the land cover map, we assume that the sediment layer on top of the bedrock so thin (since it does not support any vegetation) that it has insignificant impact on the infiltration and hence we assign these pixels the same runoff function as for bare rock.

For the compaction degrees in Sweden, we use the classification in Table 4 below. When the land cover is bare rock, the area is considered as bedrock in the simulations (no matter what the SGU map says).

Table 4: *Land cover classes and the soil compaction degree they are assigned.*

Natural land cover class	Compaction degree
Bare soil	High
Shallow vegetation	High
Dense vegetation	Low
Fields	High
Bare rock	N/A (soil type set to bedrock)

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 degree, using multiple sources (Dukes et al., 2006; Dyhr & Lindbæk, 2021; Kotlar et al., 2020; Parnas et al., 2021; Rossman & Simon, 2022).

3.3.1 Sweden

20 pairs of infiltration parameters were chosen for the combination of ten soil types and two soil compaction degrees, see Table 5 below.

Table 5 Soil types and their corresponding Horton's parameters for the different natural land covers. A k-value of 5 was chosen for all soil types.

Soil type	High compaction			Low compaction		
	f_c	f_0	k	f_c	f_0	k
Rocks/blocks	500	1000	5	2000	5000	5
Gravel	500	1000	5	2000	5000	5
Sand	30	120	5	1000	4000	5
Fine sand	25	100	5	500	2000	5
Silt	20	80	5	50	130	5
Coarse clay	12	50	5	30	120	5
Clay	5	20	5	20	50	5
Fine clay	0.5	2	5	2	20	5
Gyttja/peat	21	85	5	85	150	5
Bedrock	0	0	5	0	0	5

3.4 Infiltration simulations' results and matching curve numbers

3.4.1 Sweden

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 each of the 10 soil types and two compaction degrees described above. This results in 9 pairs of accumulated rainfall and runoff volumes for each soil type and compaction degree. Plotting these value pairs shows a clear pattern of slowly rising curves, which can be well matched using CN-p curves, see Figure 1 below.

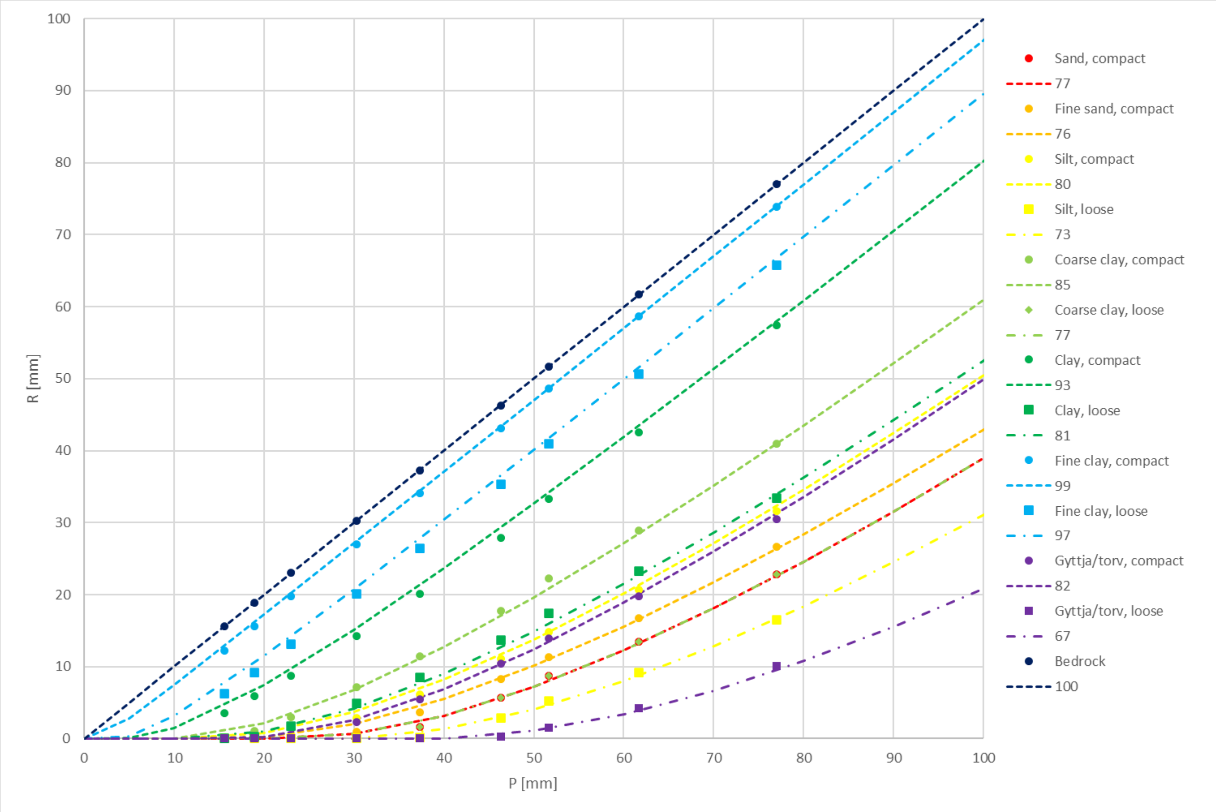

Figure 1 Results of runoff simulations for different soil types with fitted CN-p-curves. Note that results for fine sand are hidden below results for gyttja/peat, as these soil types have identical Horton parameters.

Table 6 below summarizes the CN-p 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). For using the lookup tables in TR-55, we considered high compaction of soils (used when land cover is shallow vegetation, field, or bare land) as poor hydrological condition in urban open spaces, and low compaction of soils (used when land cover is dense vegetation) to good hydrological condition in wooded areas.

*Table 6 Curve numbers for the 10 soil types and two compaction degrees according to the original CN method, and the curve numbers found to match the results obtained from our simulations (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.*

Soil type	Hydrologic soil group (TR-55)	High compaction		Low compaction	
		CN original (λ)	**CN-p (λ)**	CN original (λ)	**CN-p (λ)**
Rocks/blocks			**30 (0.2)**		**30 (0.2)**
Gravel			**30 (0.2)**		**30 (0.2)**
Sand	A	68 (0.2)	**77 (0.3)**	30 (0.2)*	**30 (0.2)**
Fine sand	A	68 (0.2)	**76 (0.2)**	30 (0.2)*	**30 (0.2)**
Silt	B	79 (0.2)	**80 (0.2)**	55 (0.2)	**73 (0.3)**
Coarse clay	B	79 (0.2)	**85 (0.2)**	55 (0.2)	**77 (0.3)**
Clay	C	86 (0.2)	**93 (0.2)**	70 (0.2)	**81 (0.2)**
Fine clay	D	89 (0.2)	**99 (0.2)**	77 (0.2)	**97 (0.4)**
Gyttja/peat	B	79 (0.2)	**82 (0.3)**	55 (0.2)	**67 (0.3)**

Bedrock			**100 (0.2)**		**100 (0.2)**

As can be seen from the table, 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.

3.5 Final CN-p curve numbers

3.3.1 Sweden

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 Sweden, are presented below in Table 7.

Table 7 Overview of the soil types and their corresponding CN-curves and f_c values used for simulations.

Soil type	High compaction		Low compaction	
	f_c / K [mm/hr]	CN-p (λ)	f_c / K [mm/hr]	CN-p (λ)
Rocks/blocks	500	30 (0.2)	2000	30 (0.2)
Gravel	500	30 (0.2)	2000	30 (0.2)
Sand	30	77 (0.3)	1000	30 (0.2)
Fine sand	25	76 (0.2)	500	30 (0.2)
Silt	20	80 (0.2)	50	73 (0.3)
Coarse clay	12	85 (0.2)	30	77 (0.3)
Clay	5	93 (0.2)	20	81 (0.2)
Fine clay	0.5	99 (0.2)	2	97 (0.4)
Gyttja/peat	21	82 (0.3)	85	67 (0.3)
Bedrock	0	100 (0.2)	0	100 (0.2)
Water	0	100 (0.2)	0	100 (0.2)
Glacier	0	100 (0.2)	0	100 (0.2)

SGU include water and glaciers as soil types in their maps, though these are not soil types but land cover classes, used by SGU where water or glaciers impede the investigation of underlying soil types. For pixels identified as water in our land cover map we apply 100% runoff. Our land cover map currently does not include glaciers or snow as a class. For pixels that have any land cover class and an underlying SGU soil class of water or glacier, we assume, in lack of other data sources, that the runoff is 100% (as it would be from a land cover class of water or glacier). Glaciers are very dynamic and have a varying extent, and the SGU-map may be outdated on the true position of them. The extent of water bodies is likewise not always correct, as the resolution in SGU's maps is rather coarse and the water levels in lakes and rivers change across the seasons, exposing soil with infiltration capabilities. However, we assess that the error introduced to the rainfall-runoff model by this lack in the soil map is negligible in most practical cases.

3.6 Comparison of CN-p runoff with other studies and sensitivity analyses

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 2 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, Denmark, rather than CDS rains, including simulation of 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.

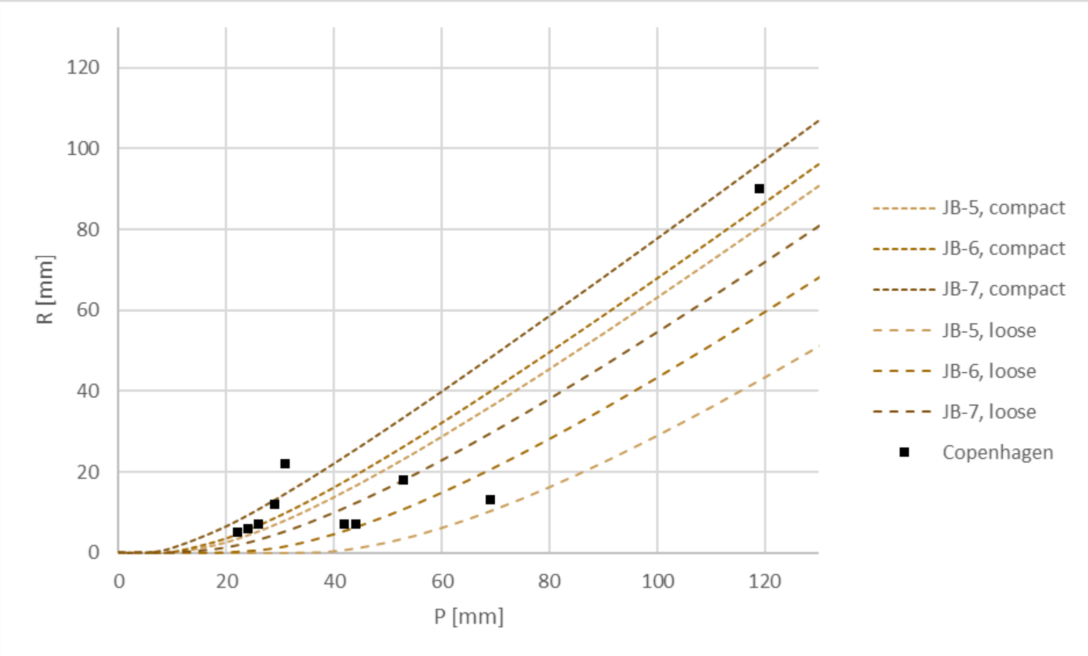

Figure 2 Results from runoff simulations with historical rain events from a clayey soil with shallow vegetation in Copenhagen (Davidsen et al., 2018) together with relevant CN-p curves.

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 3 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 soil (grass cover worn down).

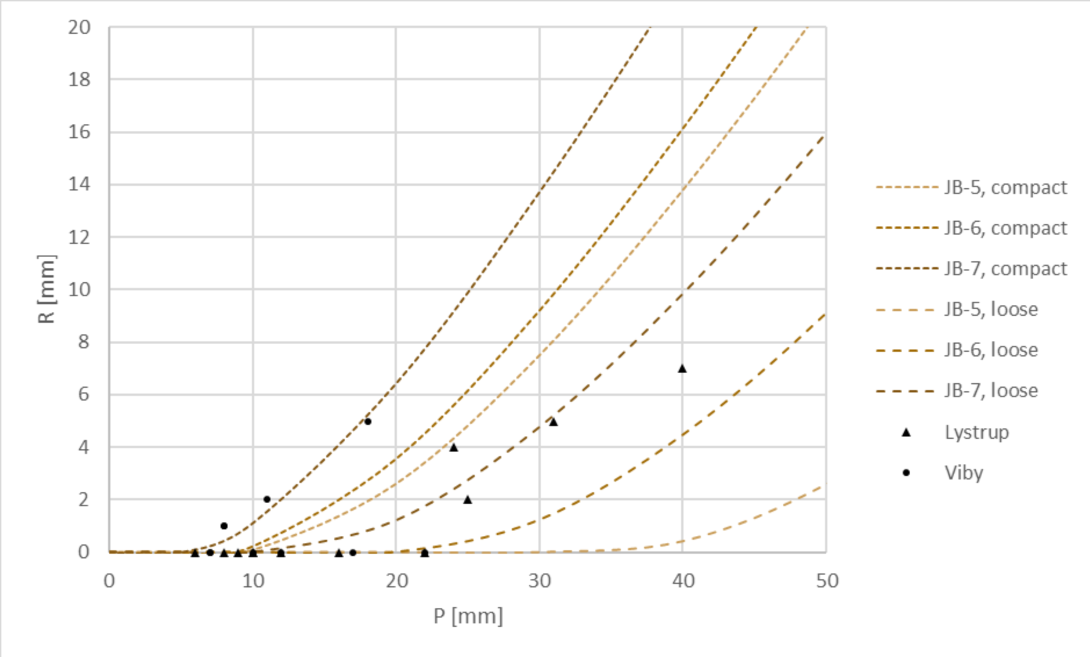

Figure 3 Results from in-situ measurements of runoff from clayey soils with shallow vegetation in Lystrup and Viby, Denmark, together with CN-p curve for the soil type and compaction degree of the sites (JB-6 compact) and CN-p curves for similar soils.

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.

3.6.1 Sweden

Sensitivity analyses were performed on the modelled CDS-rain for safety factors (figure 4), rain durations (figure 5), and rain block lengths (figure 6).

The CDS rain created for the simulations was based on a national IDF-curve in the P110 report from Svenskt Vatten. The rain was simulated with a safety factor of 1, and two additional safety factors (1.25 and 1.4). As seen in Figure 4, the results of the simulations with the different safety factors fall largely on the same curve as the safety factor affects only the amplitude of the rain event and not the shape. This confirms that these choices are not important for the choice of CN curves – the user will get an equally relevant result for any choice of accumulated rainfall depth (determined with or without safety factor).

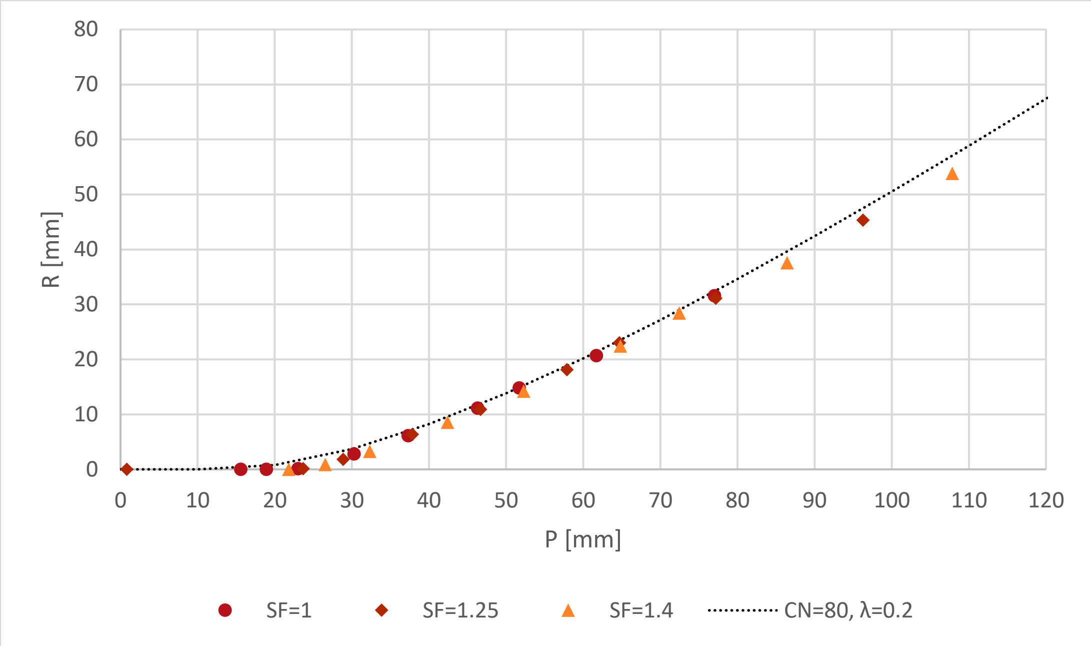

Figure 4 Results from runoff simulations with different safety factors (1, 1.25, and 1.4). Here simulated using the Horton parameters for compacted silt.

Changing the duration of the CDS-events affects the rainfall-runoff relation and matching CN-p curve numbers –longer durations yield lower CN-p, as can be seen in Figure 5 below. Simulating runoff for the 2-hour duration CDS-rain shows slightly higher runoff values than using 4-hour CDS-rain, with fitted CN-curves being 3 numbers higher than for the 2-hour CDS-rain. The 6-hour CDS-rain likewise results in slightly smaller runoff than the 4-hour CDS-rain, with CN-curves being 2-3 numbers lower. This is due to the longer “tails” of the 4 hour and 6-hour events, which is the periods of time with a low intensity, which increase the total precipitation amount but the total runoff (as runoff in the Horton’s equation is generated at high rainfall intensities). This shows that the duration of the CDS-rain has a small but consistent effect on the simulated runoff and resulting CN-p. The choice of 4-hours duration seems to be a reasonable compromise.

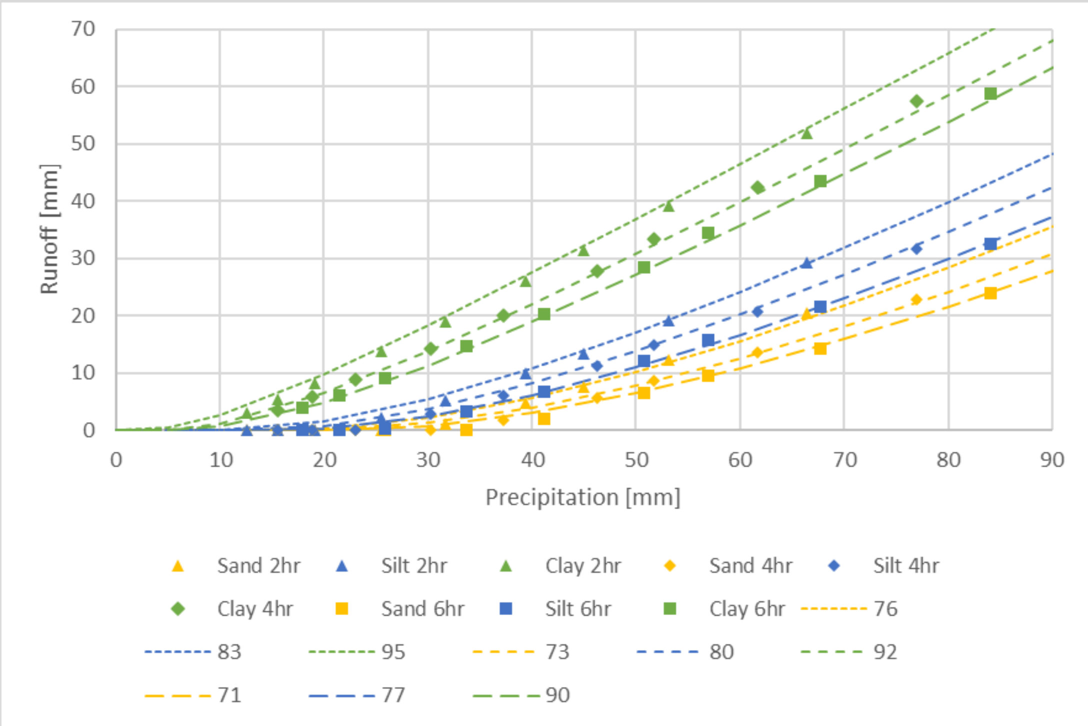

Figure 5 Results from sensitivity analysis of the CDS duration. Runoff simulations from rain durations of 2 hours, 4 hours, and 6 hours plotted along with fitted CN-curves. For each soil type there is a deviation in the CN-curve of +/- 3 as you change the CDS duration from 4 hours.

For the simulations in this paper, we have used a 5-minute block rain, which has a higher resolution and therefore a higher peak than a 10-minute block rain. However, choosing a different rain block length does not seem to affect results. As seen in figure 6, there are very minor differences between the 5-minute block and the 10-minute block, with the simulated runoff for both block lengths largely overlapping and resulting in the same CN-curve.

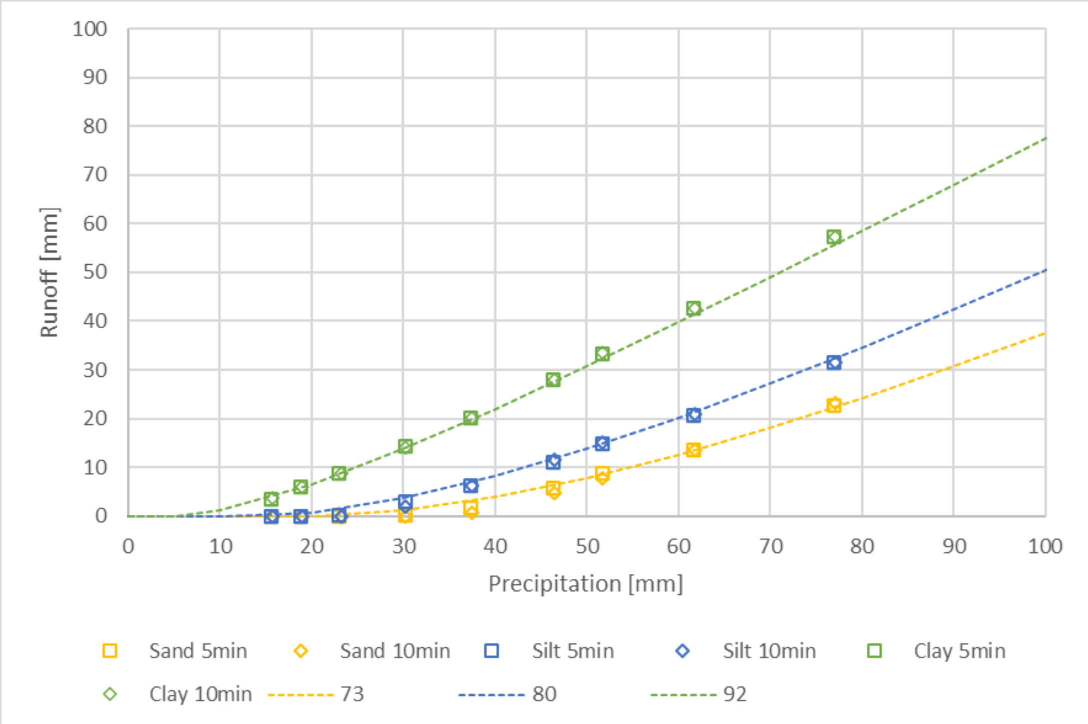

Figure 6 Results from sensitivity analysis of the chosen block length. The block length chosen for all previous simulations has been 5 minutes, here compared to a 10-minute block length. Only one CN-curve is plotted for each soil type, as the simulated runoff is very similar for the two block rain lengths.

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 analysing 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.

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 rains 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 5-10 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 dynamic 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 7 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 median CN curve.

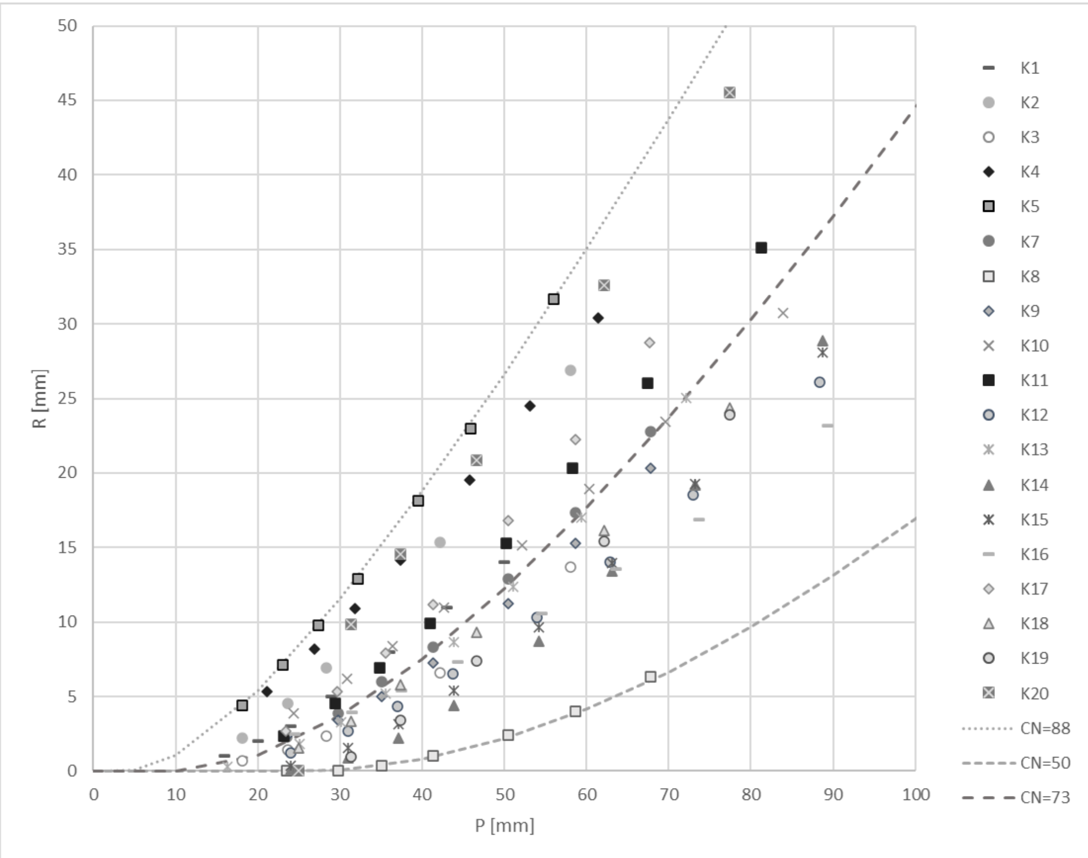

Figure 7 Results of simulations of surcharge from urban sewer systems given local CDS-events, presented in mm (cumulated volume of surcharge during each event divided with the sum of artificial area connected to the sewer system). The three CN-p curves reflect the curves that match the best performing 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 urban zones.

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 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 naturally 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 the exceeds the required performance, demonstrating that this assumption does not fit the sewer simulations very well.

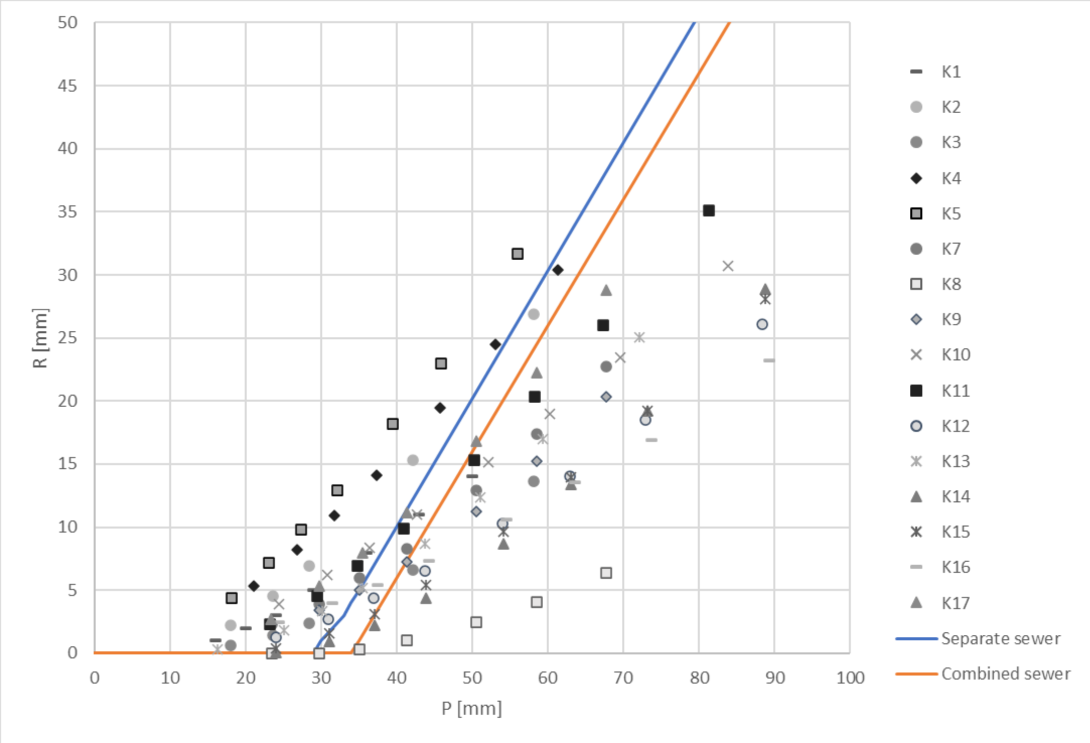

Figure 8 The same results as in the previous figure, here plotted with lines indicating the general performance assumption for Danish drainage systems (initial loss of 29/34 mm and runoff coefficient = 1).

For artificial surfaces outside of urban zones, the type of drainage system used to manage runoff, if any, is not known, and may in many instances simply constitute of assuring that artificial surfaces slope away from buildings and towards the nearest natural surface. Hence, for artificial surfaces outside of urban zones, we convert 100% of the rainfall to surface runoff.

For unpaved roads, we assume that these are not connected to any sewer 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 soil type below is applied.

4.0.1 Sweden

In Sweden, we use the dataset Tätorter from SCB, assuming the artificial surfaces within an urban zone are connected to a sewer system, while artificial surfaces outside an urban zone are not.

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, converting all rainfall to runoff results in puddles forming on the nearby natural areas already at very small rainfall depths (since rainfall cannot infiltrate once it has left the model cell that it landed on). 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 most 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, although 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 lower of 0.8 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	21/9-2023	1. A few SGU soil types have been regrouped. 2. A few soil groups have been assigned updated CN-p values.

5.1 Changes between version 1.1 and version 1.0

A few small changes have been made to the RRM compared to the first release (version 1.0).

Soil type grouping: a few SGU soil types have been moved to a new soil group, as specified in the table below.

Table 8 Soil types which have been moved to a new soil group compared to version 1.0.

SGU soil type	Moved from group	Moved to group
Rösberg	Bedrock	Block
Talus	Gravel	Block
Klapper	Sand	Block
Kalktuff	Bedrock	Clay
Moränlera eller lerig morän	Clay	Coarse clay
Moränlera	Clay	Coarse clay

Skaljord	Sand	Gravel
Svämsediment	Sand	Silt

CN-p values: the Horton parameters for a few soil types have been updated (due to improved knowledge base), which has resulted in slightly modified CN-p values. Furthermore, all soil types that formerly had set their runoff to zero, have been changed to CN-p 30 (to better align with the original CN method). See table below for details.

Table 9 Soil types which have received new CN-p values compared to version 1.0.

Soil type	High compaction		Low compaction	
	CN-p in version 1.0 (λ)	**CN-p (λ)**	CN-p in version 1.0 (λ)	**CN-p (λ)**
Rocks/blocks	0	**30 (0.2)**	0	**30 (0.2)**
Gravel	0	**30 (0.2)**	0	**30 (0.2)**
Sand			0	**30 (0.2)**
Fine sand			0	**30 (0.2)**
Silt			68 (0.4)	**73 (0.3)**
Coarse clay			74 (0.4)	**77 (0.3)**
Clay				
Fine clay				
Gyttja/peat	76 (0.2)	**82 (0.3)**	0	**67 (0.3)**
Bedrock				

6. Acknowledgements

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