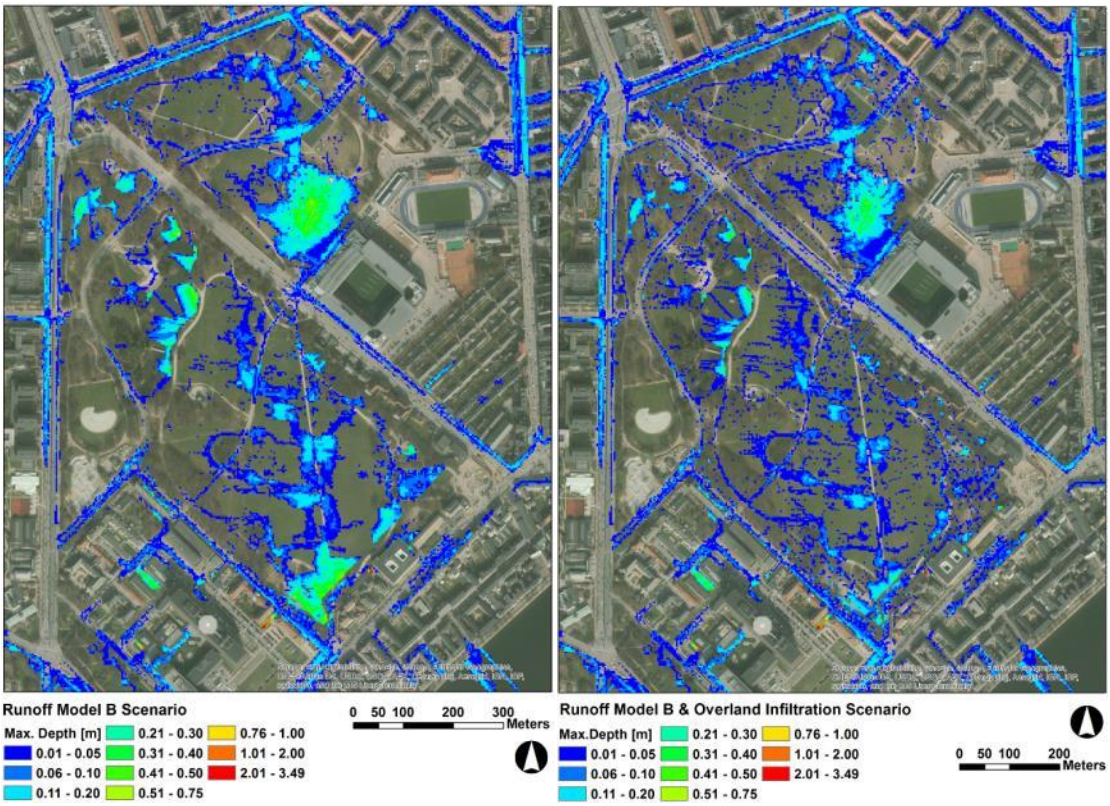
Storm Water Runoff from Green Urban Areas

Modellers' Guideline



CRC for
Water Sensitive Cities

Report

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The expert in WATER ENVIRONMENTS

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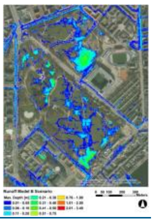
Storm Water Runoff from Green Urban Area

Summary for Modellers

Prepared for CRC for Water Sensitive Cities



Simulated urban flood in Fælledparken in Copenhagen

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1 Introduction

Aiming at making cities greener makes urban hydrology complex. In addition, climate change threatens with increased extreme rainfall intensities. Hence, old modelling assumptions must be revisited, paying more attention to the runoff from the cities' green areas and to urban flooding.

Simultaneously, the LIDAR technology delivers high precision digital elevation models. This has been followed by the development of modelling tools that enable detailed flood modelling. If the full benefit of these developments is to be exploited for modelling, better urban hydrology descriptions are needed, especially for simulating high return period flows. Together, these factors call for a systematic review of modelling of urban hydrology.

This document, representing a summary of a wider report "Modelling of Storm Water Runoff from Green Urban Areas" (DHI, January 2015), is a contribution to better understanding the issues and practices related to modelling of storm runoff from green areas in urban catchments during extreme rainfall events potentially causing urban flooding. The purpose is to provide a practical guideline to all those who apply urban flooding modelling for the analysis of urban flooding and for planning mitigation measures e.g. as part of climate change adaptation measures.

The report focuses on flood generating events and hence focus is on correct modelling of non-paved areas, rather than the modelling of green infrastructure functionality for loads levels below surcharging.

2 Green Areas in Urban Catchments under Extreme Rainfall Loads

Modelling of runoff from the green areas in urban catchments relates tightly to the analyses of urban drainage systems and urban flooding. The latter is actually an extension of the former, achieved by increasing the hydrological load beyond the design/service level of the drainage system and by broadening the physical system involved in the drainage process to include the catchments' entire surface. This is illustrated in Figure 2-1.

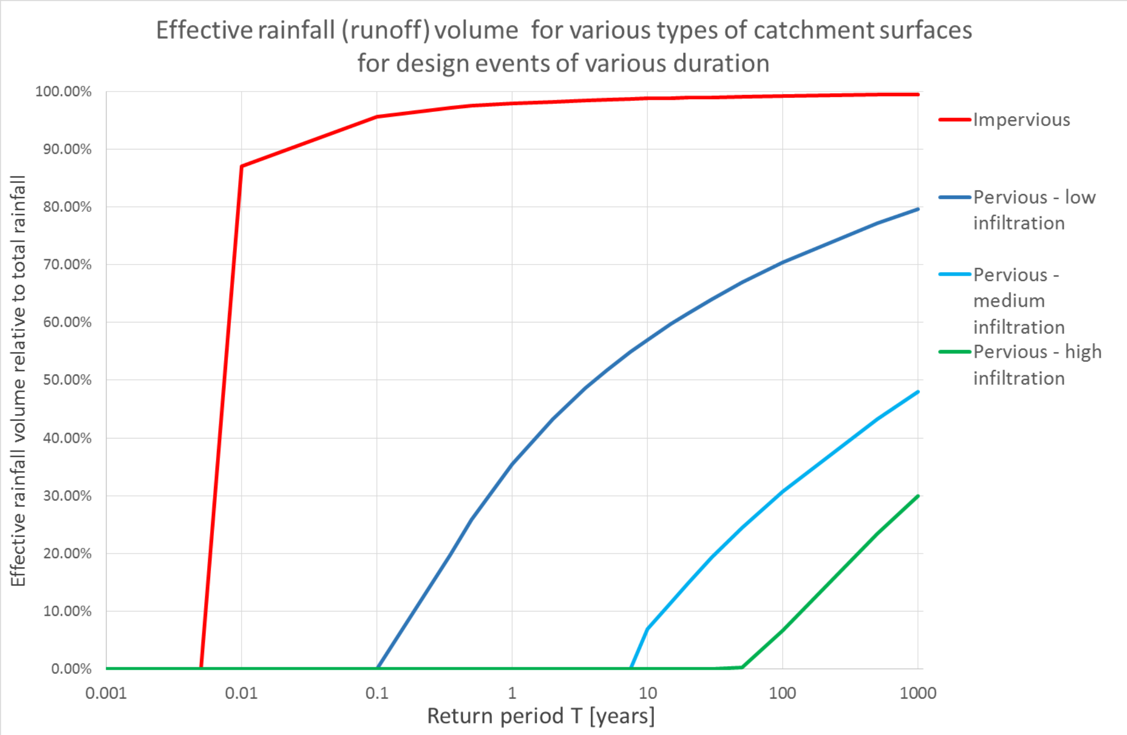

Figure 2-1 Relative contribution to runoff from various types of catchment surfaces as a function of rainfall event return period T, for designing rainfall events of the same durations (24 hours) and symmetric temporal profiles. Climate and soil variables are representative for Denmark (DHI, 2015).

Runoff response from truly impervious surfaces (red line in the graph in Figure 2-1) is reduced only by initial losses associated with wetting and surface storage. Typically these losses are limited, which means that already for very small rainfall events with short recurrence intervals runoff achieves 90% of the rainfall volume. With growing return period (i.e. growing design rainfall volume), the relative importance of this loss is reduced and the runoff approaches 100% for rare events. This situation, characterised by the full imperviousness of the contributing area, is typically included in the analyses of drainage systems loaded up to their design level.

Response from pervious areas depends on the size of the initial loss (vegetation cover and surface irregularity), the soil's initial moisture content and the soil infiltration capacity. The graph in Figure 2-1 includes illustrations for the response from three different surface and soil types: low infiltration capacity with no vegetation cover (dark blue), medium infiltration capacity with fair vegetation cover (light blue), and high infiltration capacity with dense vegetation cover (green).

According to the illustration, different pervious surfaces would start generating runoff for events with different return periods T, ranging between 0.1 and 50 years. One extreme is a bare unpaved surface with compact clayey soil that generates runoff already at a minor rain with return period of 1 month. On the other hand, sandy surface covered with dense vegetation (high trees with thick undergrowth) would start generating surface runoff for rainfall event with return period of 50 years or even higher.

Between the two extremes, there are realistic urban pervious surfaces – parks, gardens, etc. -, which will generate a significant amount of surface runoff under rainfall conditions well within the range included in the analysis of urban flooding, i.e. return periods between one and 1000 years. Therefore, this runoff must be included in the modelling analyses of flooding even though it is typically not included in typical urban drainage design situations focussing on service levels of surcharging. This is particularly important for catchments containing significant portions of green areas.

3 Analysis of urban storm water drainage systems vs. analysis of urban flooding

3.1 Documenting the Drainage System's Functionality beyond Design Level

The design/service level for urban drainage systems, in terms of flood protection, is defined typically by the return period for the design rainfall event. This implies that it should be appropriately documented that the system's design/service level is compliant with this request.

Simulation models, including a hydrological (precipitation-runoff) model and a hydrodynamic network model, are normally applied for the analyses. The precipitation-runoff model, typically accounting only for catchment areas connected to the drainage system, generates hydraulic load of the network. These areas are normally impervious and include building roofs, roads, sidewalks, parking lots, etc. Loads from the remaining parts of the catchment (pervious areas) are often neglected, i.e. it is assumed that the rainwater infiltrates and does not contribute to the load of the drainage system – certainly not by a significant amount during the critical time when surface runoff peaks.

The return period defining the service level of the urban storm water system depends on the type of the system, the socio-economic conditions prevalent in the urban catchment under consideration, as well as the local meteorological circumstances.

If the number of flood events exceeding the drainage system capacity is higher than the pre-defined service level, it is considered as irregular events – and the drainage system must be improved to contain the design load.

Nevertheless, even the systems that are 100% compliant with the design/service level are overloaded on rare occasions when the rain exceeds the design intensity and depth. Consequently, the drainage system will fail ”as per design” and urban flooding will develop, potentially causing material damage and traffic disruption, spreading pathogens and endangering human lives. In recent years, the frequency of such events has increased in Denmark, possibly because of the on-going climate change.

The consequences of flooding for events with return periods longer than the design event must be documented. This documentation must show the flooding extent, duration and water depths on the surface.

No firm set of rules setting an obligatory framework for urban flooding analysis exists on a global level, neither in terms of the selection of the reference rainfall, the definition of design/service level during extreme event or the modelling methodology. In practice, the involved parties define the criteria and the analysis methods according to the available data and some practical issues and influenced by loose national guidelines. This results in a wide range of service criteria and a number of more or less advanced modelling methods.

3.2 Modelling Approach

Extending the analysis to pervious surfaces also means extending the applied modelling methods and tools and a shifted focus from impervious surfaces connected to the drainage system to the entire catchment.

Modern modelling methods for analyses of urban sewer and drainage systems have developed and gradually improved during recent years, along with the advent of the modelling tools and the availability of the high-precision digital elevation models (DEMs). However, this development was incoherent both within Denmark and worldwide, leading to significant differences in methodological approaches for computation of runoff from green areas, which, in turn, reduces the reliability of the results. This situation arose unsurprisingly, as no “best practice” recommendations exist yet, leaving the modellers with a great deal of latitude, often with insufficiently documented effects of the applied assumptions and modelling techniques. Obviously, this calls for a systematic review, aimed at obtaining a streamlined and harmonised modelling practice of the runoff from green areas.

Today’s state-of-the-art is to apply a model cluster including a hydrological (precipitation-runoff) model, a hydrodynamic network model and a 2-dimensional surface (2D overland) hydrodynamic model.

The technical issues related to the urban flooding analysis, on the top of the urban drainage network analysis, include essentially the following:

- Generating the hydraulic loads from the pervious areas by realistically computing the dominant hydrological losses – initial loss and infiltration.
- Handling of the surplus loads from the impervious and pervious areas on the catchment surface.

The first issue can be solved by a range of lumped hydrological models or it can be done by the computation of hydrological losses directly in the 2D overland model. Choice of the method and the relevant modelling parameters has significant impact on the results. Therefore, a full understanding of the applied methods for the modelling of the runoff from green areas - with their advantages and drawbacks - is essential.

4 Modelling the physical urban water system

The physical system included in the model consists of the following components (subsystems):

- Catchment
- Drainage network
- Terrain surface

Some very different model types, which describe the relevant physical processes and the integration into a consistent model cluster, are used for the modelling of these subsystems.

The relevant processes in the model – surface runoff, network flows, surcharge, and flood propagation – are impacted by the model inputs, where precipitation is by far the most prominent.

The different models are mutually connected, allowing the water to move between them as in a real physical system (see Figure 4-1). The sketch shows the rainfall load, the exchange of water between the models as well as the water's departure from the modelled system.

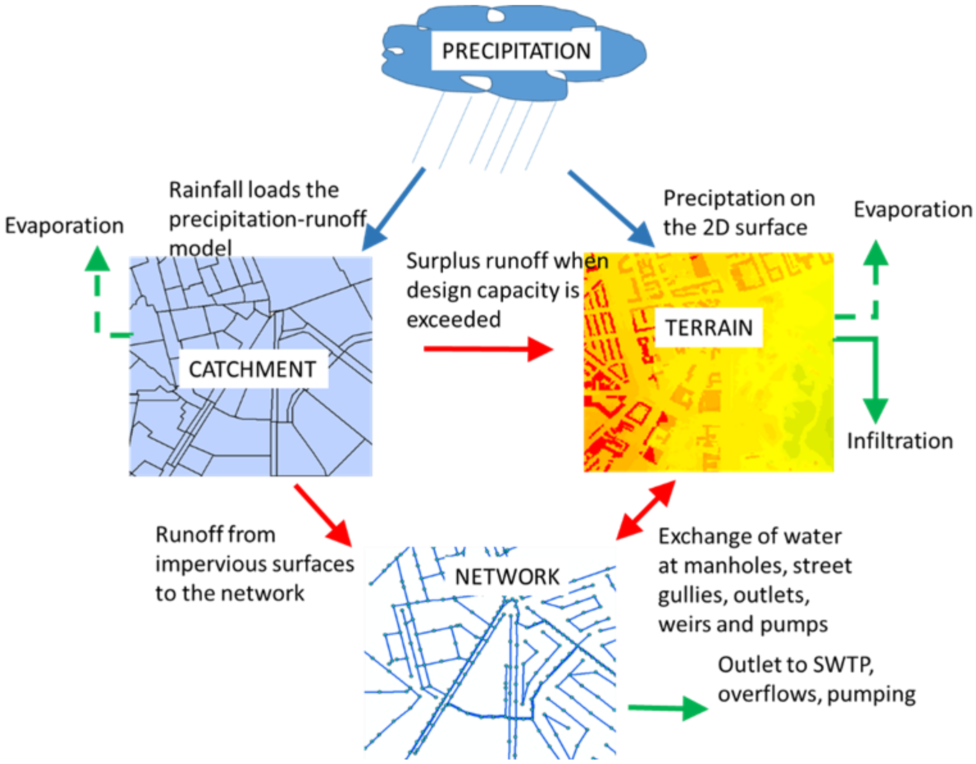

Figure 4-1 Links between the main components of the urban flood model

Modelling of each individual component and of the connections between them is well documented in the respective software manuals.

5 Rainfall for the analysis of urban flooding

Precipitation drives the runoff and the related processes in the models. Different rain events – synthetic or historical – result in different amounts of runoff and different runoff dynamics. Therefore, the choice of an appropriate rainfall for analysis, in terms of peak intensity, duration, total depth and temporal variation, is the first important task of the modelling process. This choice gets more complicated when the runoff from green areas is included in the model.

Normally, it is only the return period for the “service level” which is prescribed, while the choice of all other relevant parameters for the rainfall is left to the discretion of the modeller, based on the actual practice or some specific local conditions. When studying the consequences of rainfall events beyond the prescribed “design/service level” (i.e. with higher return periods than the design rainfall), rainfall events with various return periods can be applied, i.e. the definition of the rainfall is left to the involved parties.

The most popular type of synthetic rainfall profiles is the Chicago Design Storm (CDS). It is popular because a CDS profile of a certain duration and return period also includes the rainfalls of shorter durations with the same return period. This means that a single rainfall can test all parts of a complex drainage system, if its duration is sufficient for the most inert parts of the system. This means that CDS provides a rainfall load with a simultaneous occurrence of extreme events of various durations. This is unlikely to happen in reality, but is advantageous for the efficiency of the analysis. The alternative would be to perform a range of calculations for each return period with rainfall patterns that correspond to different concentration times of the sub-catchments, or the ultimate solution, being a complete analysis of a long rain series. With close-to-real-time simulations times, the latter is not a feasible option.

A CDS rainfall profile for a given area can be derived based on rainfall statistics for the area, usually processed as Intensity-Duration-Frequency (IDF) rainfall data. In Denmark, development of CDS profiles is supported by a dedicated spreadsheet application (DHI, 2012). CDS profiles valid for any location in Denmark can be developed for different regions as a function of the local average annual precipitation depth, different durations, return periods, profile asymmetry, temporal resolution and safety factors to account for the uncertainties due to future climate changes.

As long as the analysis only includes runoff from impervious areas, duration and asymmetry of the CDS, rainfall have no impact on the results of the analysis if the duration is longer than the minimum duration required for a system of given size. With inclusion of pervious areas (with the time varying infiltration process) and generation of runoff from these areas, the rainfall duration and asymmetry may have important effects on the modelling results. This is illustrated in Figure 5-1 and Figure 5-2.

Equally, in such a situation, the start conditions (initial level of saturation) affect the runoff simulation results.

Obviously, different assumptions of the rainfall duration and asymmetry as well as of the initial soil moisture may lead to important and potentially unacceptable differences in the modelling results. This may imply underestimating the effective runoff and its consequences or, on the other hand, overestimating the loads and unnecessary investments.

It stands clear that the choice of dominant parameters for the rainfall load should be agreed upon and harmonised in the planning process so that uniformity of the effective service level and optimisation of investments is secured.

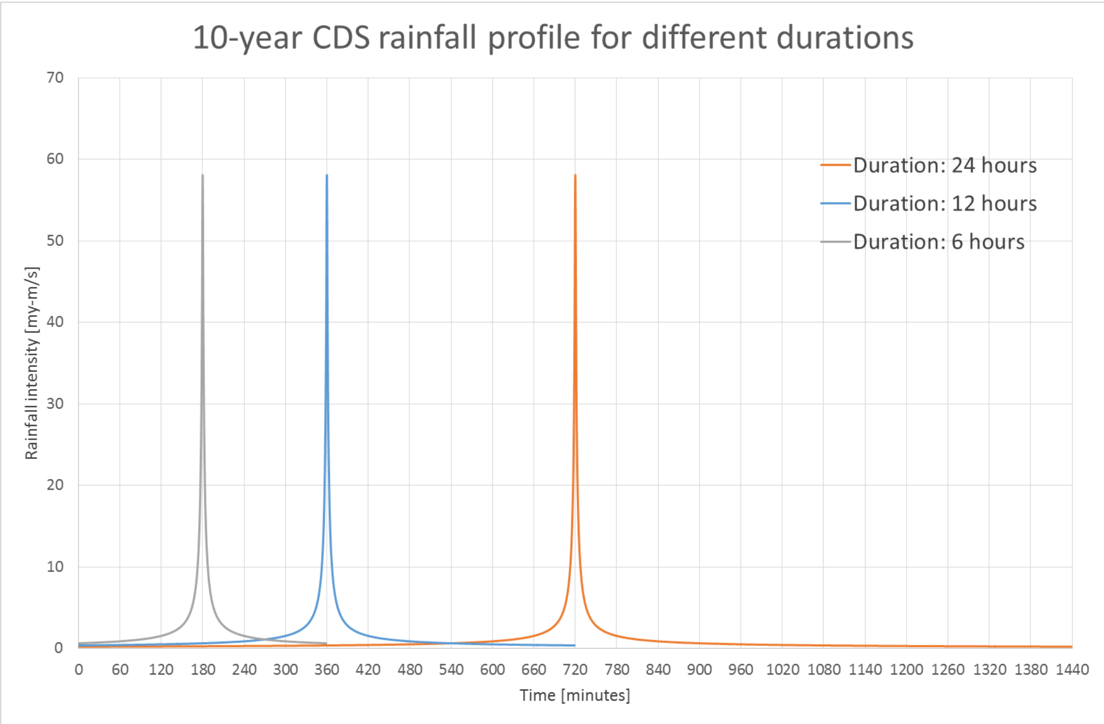

Figure 5-1 CDS rainfall profiles for a 10-year return period, with duration of 6, 12 and 24 hours.

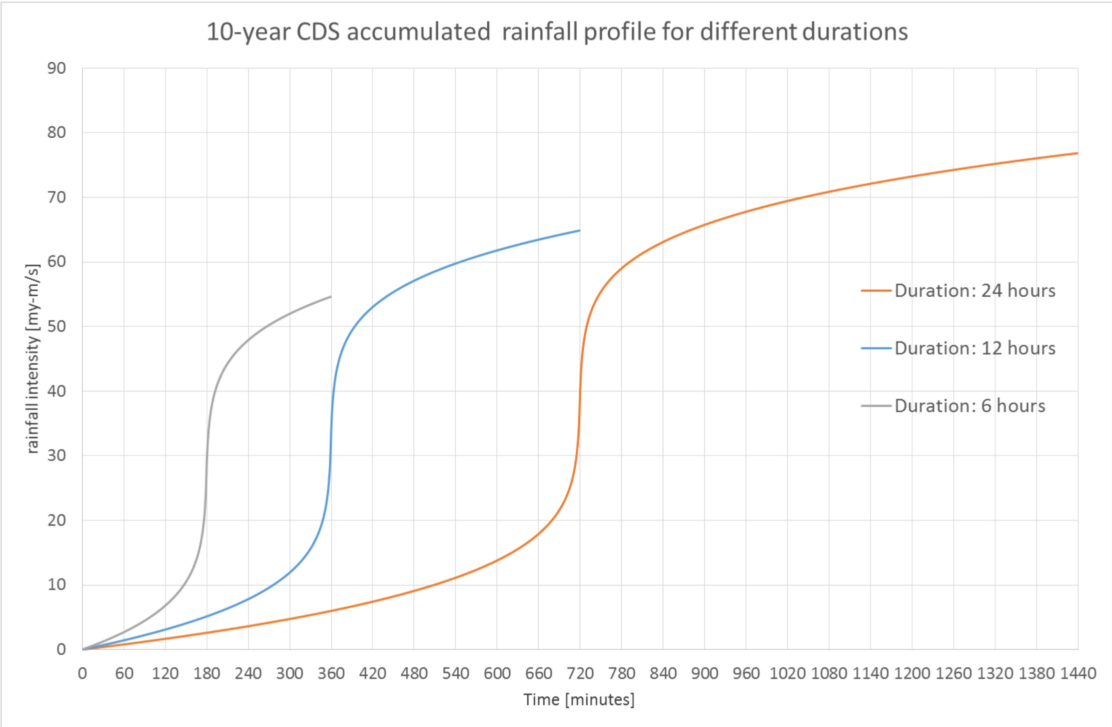

Figure 5-2 Accumulated rain depth for CDS profiles with durations of 6, 12 and 24 hours. The total rain depths are 54.6 mm, 64.9 mm and 76.8 mm, respectively. With symmetric profiles, this implies that in a 24-hour event, 11.1 mm of the rain accumulates before a 6-hour rain has started. These 11.1 mm rain contribute to a considerably larger soil saturation, i.e. to a smaller infiltration rate during peak rainfall intensity.

6 Hydrological modelling of runoff from pervious surfaces

The purpose of the hydrological (precipitation-runoff) modelling is the transformation of a representative precipitation to a runoff hydrograph at the connection to a hydraulic system. This transformation is calculated by a number of more or less complicated computations, which describe – fully or partially – a land phase of the hydrological cycle. Such a set of computations is named a hydrological model.

Runoff from a catchment occurs as surface runoff and/or as subsurface runoff. These two are very different processes with different physics and different importance. For urban flooding analysis, surface runoff is dominant and the only relevant runoff type. Subsurface runoff, which is dominant in natural catchments, is seldom of interest for urban flooding modelling.

Imperviousness of the catchment surface prevents the rainfall from infiltrating into the ground. Instead, the rainfall stays on the surface and runs off towards the connection to the drainage system, leading it away from the catchment.

During extreme events, also in pervious areas rainfall cannot completely infiltrate into the ground. Depending on the soil and surface hydraulic properties, part of the surface runoff is also generated on the pervious surfaces, contributing to the overall load of the drainage system. This part of the runoff is of special interest in this document.

Obviously, for the study of urban flooding, a hydrological model capable of simulating precipitation-runoff processes from both impervious and pervious surfaces is required. The focus on extreme events calls for a single-event analysis approach, with all model features related to continuous hydrological analysis being redundant.

Any selected surface precipitation-runoff model includes two distinct parts:

- **Calculation of the hydrological losses,** i.e. calculation of the part of precipitation that contributes to the surface runoff in the modelled system. This is usually termed 'effective precipitation'. The remaining part of the precipitation is "lost" from the model, either as a one-off loss in the beginning of the event or as a continuous loss.

- **Computation of surface runoff**, i.e. transformation of the effective precipitation to the surface runoff. This can be either done conceptually or physically based on the catchment's geographical extent, topography, surface morphology, etc.

6.1 Methods for computing infiltration

Infiltration is the most important hydrological process for a correct computation of surface runoff from pervious areas. The capability of a hydrological model to handle infiltration directly defines its usefulness to simulate surface runoff from pervious areas.

There are several relatively simple methods and empirical and theoretical equations for estimating infiltration. In practical precipitation-runoff modelling, several of these methods – on their own or in combination – are quite well known and included in different models, e.g.:

- Infiltration as part of initial loss;
- Infiltration as constant loss;
- Infiltration as proportional loss;
- Horton's equation;
- Green-Ampt method;
- Soil Conservation Service (SCS) method.

The first three methods are not dedicated specifically to infiltration, but are widely used as a (crude) approximation of the infiltration process because of historical developments. The methods can be applied in some of the MIKE URBAN precipitation-runoff models.

The SCS method is used as a de facto standard solution in the USA and is gaining popularity in New Zealand. It is available in MIKE URBAN in two forms, under the Unit Hydrograph (UHM) precipitation-runoff model.

The Green – Ampt method provides a modelling concept for the infiltration process, praised for its relative simplicity and is gaining popularity. MIKE URBAN, however, does not support it.

Another widely applied approach for modelling infiltration is Horton's formula (standard form), is available in MIKE URBAN MOUSE Runoff model B and C (DHI, 2014):

$$I_H(t) = I_{Imin} + (I_{Imax} - I_{Imin}) \cdot e^{-k_a \cdot t}$$

where:

$I_H(t)$ = Horton's infiltration (LT^{-1})

I_{Imin} = initial (maximum) infiltration capacity (LT^{-1})

I_{Imax} = final (minimum) infiltration capacity (LT^{-1})

k_a = empirical constant (time factor) (T^{-1})

t = time since the start of rainfall (T)

This approach describes the infiltration as an exponentially decaying process with large infiltration capacity in the beginning of an event. This capacity decreases in the course of an event due to increasing saturation of the soil and eventually approaches a (significantly lower) infiltration capacity for fully saturated soil.

In its standard form, Horton's formula describes the change of infiltration capacity during an event in dependence on the time from the beginning of the event, rather than the actual amount of rainfall. This issue is addressed in the integrated form of the Horton's equation, which is available in the MIKE URBAN MOUSE Runoff model B.

$$I_{I_{CUM}}(t_p) = \int_0^{t_p} I_H dt = I_{I_{min}} \cdot t_p + \frac{I_{Imax} - I_{Imin}}{k_a} \cdot (1 - e^{-k_a t_p})$$

where $I_{ICUM}(t_p)$ is the cumulative infiltration at "equivalent time" t_p, i.e. the area under the Horton's curve, under the assumption that the actual infiltration has been equal to the infiltration capacity I in the period from 0 to t. As this is only the case when the rain intensities are higher than the infiltration capacity, it must be corrected with:

$$I_{CUM}(t) = \int_0^t I_I dt$$

This means that the cumulative infiltration at time t is computed by means of an actually realised infiltration. At any time t, these two equations can be used to find the "equivalent time" t_p iteratively.

***

In principle, all these methods can be applied successfully for modelling infiltration. However, model structures that explicitly describe the infiltration process (such as Horton's formula or the Green and Ampt equations) are clearly more suitable from a technical viewpoint. In practice, the applications are also limited by actual software implementations.

Sometimes, these limitations can be by-passed by an appropriate pre-processing of the rainfall input.

7 Soil properties and field measurements of the soil infiltration capacity

The most important factors affecting infiltration are related to the physical properties of the soil. Among these, the most important factor is the actual porosity, which is determined by the soil type as well as the level of surface compacting. The latter has proven to be of crucial importance in urban areas, where pervious surfaces often have a compacted surface due to intensive pedestrian traffic.

Indirectly, the vegetation cover is also very important as a surface protection against excessive compacting and as a factor improving the soil's porosity and water conductivity.

Temperature can also play a very important role, if the soil freezes at low temperatures. Frozen soil filled with water is practically impermeable.

The soil properties are represented by the input parameters for the infiltration models. For illustration, literature values for Horton's parameters are presented in Table 7-1 and Table 7-2.

Extensive field measurements have shown that uncritical application of soil infiltration parameters from textbooks may lead to significant deviations when calculating the infiltration and surface runoff from urban pervious areas.

Most of the pervious areas in urban catchments are disturbed by urban development activities and by the active use of the area. This potentially affects the soil's infiltration properties significantly.

Table 7-1 Recommended values for Horton's initial infiltration capacity for different soil types, vegetation covers and initial moisture contents (Akan, 1993)

Soil type	Initial infiltration capacity (F_0)
	(mm/hour)
Dry sand with little or no vegetation	127
Dry loam with little or no vegetation	76.2
Dry clay with little or no vegetation	25.4
Dry sand with thick vegetation	254
Dry loam with thick vegetation	152
Dry clay with thick vegetation	51
Wet sand with little or no vegetation	43
Wet loam with little or no vegetation	25
Wet clay with little or no vegetation	7.6
Wet sand with thick vegetation	84
Wet loam with thick vegetation	51
Wet clay with thick vegetation	18

Table 7-2 Recommended values for final infiltration capacities and Horton's time factor (Akan, 1993)

Soil type	Final infiltration capacity (Fc) (mm/hour)	Horton's constant (1/hour)
Clay	0.00 - 1.3	4.14
Clayey loam	1.3 - 3.8	4.14
Loam	3.8 – 7.6	4.14
Sand and sandy loam	7.6 – 11.4	4.14

For example, the infiltration capacity of sandy soils depends mostly on the level of compaction, while soil moisture plays only a secondary role. This is in sharp contrast with the normally used values of Horton's parameters from the literature, where soil moisture plays a decisive role for all soil types. Infiltration capacity of clayey soils is affected by both soil moisture and compacting level. Based on the measurements, it has been found that dividing urban catchments in just four significant categories makes sense (see Table 7 3). The measurements show large variations also within the four groups, in particular for clayey soils.

Table 7-3 Summary of field measurements for soil infiltration capacity, divided in four categories. Note that the average rate of infiltration shows the averages over a two hours period. (Pit, 1999)

Soil category	Average rate of infiltration during 2 hours (mm/time)	Variation coefficient
Non-compacted sandy soil	414	0.4
Compacted sandy soil	64	0.2
Non-compacted, dry clay	220	1
Compacted clay, dry and saturated	20	1.5

Table 7-4 presents the Horton's parameters for the same four soil categories, derived from the measurements. All three parameters are found to vary widely even for the same soil category. This means that using the average values may generate results still very far from reality for the actual location.

Published values for Horton's parameters for various soil types, also shown in Table 7-4, appear to be significantly more conservative than the averages derived from the measurements. In practical application, this results in smaller infiltration and larger runoff.

Considering the wide range of measurement results and the large differences when comparing to literature values, we conclude that soil parameters could best be identified by an analysis of local measurements.

Table 7-4 Horton's parameters derived on the basis of field measurements (Pit, 1999)

Soil Category		f_0 (mm/hour)		fc (mm/hour)		k(/hour)	
		average	range	average	range	average	range
Sand	Observed non-compacted sandy soil	990	110-3710	381	10-640	576	60-1980
	Observed compacted sandy soil	380	3-2200	46	3-240	660	108-2220
	Published values for sandy soils	-	43-250	-	7.6-11	4.14	-
Clay	Non-compacted, dry clay	460	64-1500	170	3-610	528	-372*-1140
	Published values for dry clayey soils	-	30-50	-	0-1	4.14	
	Compacted clay, dry and saturated	86	0-1200	10	-15* - 170	336	0 - 2760
	Published values for saturated clayey soils	-	8-18	-	0-1	4.14	-

* Negative values appear because of imperfect fitting of the data to the Horton's infiltration formula

Similar results have been achieved by the measurements and soil parameter analyses in the Copenhagen park ”Fælledparken”. The measurements have been processed in a way that the two following parameters have been derived: initial loss due to the soil saturation and a constant infiltration capacity rate. Even though the number of measurements was significantly smaller than in the American study, the results confirm the pattern of large dispersion of results and higher average values for the final infiltration capacity than Horton's standard values.

The results for five measurement locations, which mainly differ by the type of vegetation and the traffic frequency, after processing in terms of initial loss and final constant infiltration capacity, are shown in Table 7-5. Please observe that the initial loss also accounts for the large infiltration capacity in the beginning of an event, before full saturation of the soil.

Table 7-5 Summary of the analysis results of the data from the field measurements in Fælledparken (Gregersen, Nava, 2014)

Location	Initial loss F_0 (mm)		Infiltration capacity f_c (mm/hour)	
	average	range	average	range
1	38.19	1.6 - 94.6	77.58	8.6 - 117
2	33.52	1.4 - 158.1	32.04	5.8 - 35.3
3	31.98	0.5 - 92.3	363.6	113.4 - 576.8
4	11.35	2.5 - 19.4	44.64	14.4 -132.8
5	43.72	0.3 - 165.3	119.88	20.2 - 325.4

In cases with no measurements available, modellers should apply standard values for the infiltration capacities.

8 Handling surface runoff from the pervious areas using MIKE URBAN

Surface runoff in MIKE URBAN is handled in two fundamentally distinct ways:

- Computation of runoff by one of the hydrological models and forcing it into the drainage system (i.e. 1D drainage network model) at the catchment connection point.
- Application of precipitation directly onto the 2D raster and computation of hydrological losses at a raster cell level.

In the first case, the runoff does not participate in the overland flow, except in cases of overload, when it surcharges. This works well for the surfaces actually connected to the drainage network and for the loads up to the drainage system's design level. At higher loads, a number of issues affecting the simulation accuracy arise, requiring a proper attention.

In the latter case, the precipitation is turned into runoff directly at the location where it hits the catchment surface. The runoff is routed by 2D dynamic flow equations over the catchment surface according to the terrain topography, thus reproducing the actual flow patterns accurately.

8.1 Application of Precipitation onto the 1D Sewer Model

8.1.1 Hydrological models for surface runoff in MIKE URBAN

MIKE URBAN MOUSE includes several surface runoff models:

- MOUSE Model A (Time-Area)
- MOUSE Model B (Kinematic wave)
- MOUSE Model C (Linear reservoir)
- MOUSE Unit Hydrograph Model (UHM)

All these models apply different methods for the computation of hydrological losses, including infiltration. Unfortunately, the current implementation does not allow application of different methods for hydrological losses across different models. Hence, the choice of model also implies the choice of method for the computation of the hydrological losses.

Some of the surface runoff models are more suitable for describing runoff from pervious areas than others. Model B is most suitable for the simulation of pervious areas because it permits the consideration of infiltration and is conceptually simple. All surface runoff models generate inflow only to the sewer network and thus need to be handled with care - in particular in large green areas - to avoid unrealistic overloading of the sewer network and shifts in flood locations.

In general, runoff from pervious areas can be described with the different surface models as follows:

MOUSE Model A has no specific method for the computation of infiltration. It can be approximated to be proportional to the rainfall intensity by specifying an appropriate hydrological reduction. A part of the infiltration in the saturation phase can be modelled as a fixed initial loss.

MOUSE Model B and **Model C** apply the Horton's infiltration equation. In MOUSE Model B it is possible to choose between ”Standard Horton” and ”Integrated Horton”. This choice is controlled by the MOUSE configuration file *dhiapp.ini*. In ”Standard Horton” the infiltration capacity only depends on the time elapsed since the start of the rain and not the rain intensity. In the “Integrated Horton” the infiltration capacity at a certain time depends on the actually infiltrated water amount since the start of rainfall.

MOUSE UHM can apply four different methods for calculation of the infiltration:

- Constant loss (defined as initial los (mm) and a continuous loss (mm/hour)
- Proportional loss (defined as ”runoff coefficient”)
- US Soil Conservation Service (SCS) method: based on the “SCS curve number” and ”antecedent moisture content”
- Generalised SCS method: based on the “SCS curve number” and directly defined initial loss (i.e. initial abstraction depth)

Additionally to these surface runoff models, **MOUSE RDII (NAM)** can be used, as it also generates surface runoff.

Model A and Model B can be coupled with MOUSE RDII (NAM). The purpose of this coupling is a computation of a continuous runoff from urban catchments. In the coupled modelling system, the surface runoff model focusses exclusively on the impervious areas, while MOUSE RDII takes over calculation from the pervious surfaces. The RDII component of the total runoff consists of surface runoff, interflow and base flow.

An overview of the available methods for hydrological losses in MIKE URBAN runoff models is presented in Table 8-1.

Simulations of runoff from pervious areas of a demo-catchment for various models have been demonstrated and extensively documented in report “Modelling of Storm Water Runoff from Green Urban Areas” (DHI, January 2015).

As an alternative to the computation of the hydrological losses connected to various runoff models in MIKE URBAN MOUSE, precipitation data can be pre-processed. This implies setting up of the computation with the preferred method for the hydrological losses in a spreadsheet or in a specially built external program.

The result of the pre-processing is a time series of effective precipitation that can be applied by any model, just with the built-in losses set to zero, or it can be applied directly on the 2D surface.

Table 8-1 Overview of the hydrological models for surface runoff in MIKE URBAN MOUSE

<table>
<tr><th colspan="2" rowspan="2">MOUSE OVERVIEW</th><th rowspan="2">MOUSE Model A</th><th rowspan="2">Mouse Model B</th><th colspan="2">Mouse Model C</th><th colspan="4">MOUSE UHM</th></tr>
<tr><th>C1</th><th>C2</th><th>Constant Loss</th><th>Proportional Loss</th><th>SCS method</th><th>SCS Generalized</th></tr>
<tr><td colspan="10">Beregning af hydrologiske tab</td></tr>
<tr><td>Loss type</td><td>category</td><td colspan="8"></td></tr>
<tr><td>Wetting</td><td>one-off</td><td rowspan="3">"initial loss"</td><td rowspan="2">"wetting"</td><td colspan="2" rowspan="3">"initial loss"</td><td rowspan="3">"initial loss"</td><td>N/A</td><td rowspan="3">"initial AMC"</td><td rowspan="3">"initial abstraction depth"</td></tr>
<tr><td>Interception</td><td>one-off</td><td>N/A</td></tr>
<tr><td>Surface storage</td><td>one-off</td><td>"storage"</td><td>N/A</td></tr>
<tr><td>Infiltration</td><td>continuous</td><td rowspan="2">"reduction factor"</td><td>Horton's equation</td><td colspan="2">Horton's equation</td><td rowspan="2">"constant loss"</td><td rowspan="2">"Runoff coefficient"</td><td colspan="2" rowspan="2">SCS Curve number</td></tr>
<tr><td>Evapo-transpiration</td><td>cntinuous</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td colspan="10">Computation of runoff</td></tr>
<tr><td colspan="2">Routing method</td><td>Time-area</td><td>Kinematic wave (Manning's formula)</td><td colspan="2">Linear reservoir</td><td colspan="4">Unit hydrograph (various implementations)</td></tr>
</table>

8.1.2 Connecting runoff to the Network Model

The standard model set-up features connecting of one catchment to one network node. That is, the runoff from the whole catchment area is loaded into a single network node. If the catchment is large, this may mean that runoff is so high that it creates hydraulic instability in the network model.

To load the network in a realistic way and to increase the model stability, the number of nodes and catchments should be large, i.e. model has to be discretized as detailed as possible.

Alternatively to the division of a large catchment into many small sub-catchments is the coupling of a single catchment area to more network nodes - typically those that lie within the catchment polygon. In this method, the total runoff hydrograph generated on the catchment is distributed according to specification, e.g. as uniform fractions to a set of nodes. This feature is available as a hidden and undocumented function in MIKE URBAN MOUSE.

8.2 Application of Precipitation Directly to the 2D Raster

The advanced solution for the modelling of surface runoff in the context of extreme event analysis is the application of the precipitation load directly on the terrain model 2D raster. However, similarly to the surface runoff models, all relevant losses have to be taken into account so that only the part of rain that remains on the terrain surface participates in the overland flow and flood propagation. Like before, the losses can here be divided in two main types:

- Initial loss
- Infiltration loss

In MIKE URBAN 2014, this approach requires pre-processing of the rainfall input to determine the effective precipitation during an event.

8.2.1 Initial loss on the 2D raster surface

If the surface is impervious, only the initial loss comprising wetting and surface storage is relevant. In addition to the surface type, the initial loss depends on the size of the 2D raster cell: smaller cells imply a more detailed surface model with a smaller surface storage capacity, and vice versa. Generally, for impervious areas both wetting and surface storage are relatively small (typically 0-1 mm) and not relevant.

For pervious areas, both initial loss and infiltration loss are relevant. Initial loss is larger than for impervious surfaces, due partially to the vegetation cover (interception) and partially to the generally rougher surface. It ranges up to 5 mm, which represents a noteworthy part of most of the rainfall events.

Partially, the initial loss is accounted for indirectly through the 2D model threshold value for changing the model cell status between dry and wet status (default value 2 or 3 mm). This means that overland flow from one cell to the other starts only after this threshold has been exceeded and stops when the water depth falls below the threshold. This has the same indirect effect on the surface flow volume balance as the initial loss of the same size.

For small grid sizes (< 2.0 x 2.0 m) this default value accounts for the initial loss for most types of surfaces, except for the areas with very thick vegetation, where interception loss is significant, i.e. where initial loss exceeds the threshold. In such cases, initial loss must be accounted for by pre-processing of the applied rainfall, by subtracting appropriate rainfall depth in the beginning of the event.

For larger grid sizes, additional initial loss may be added, accounting for the lost surface storage due to the ground elevation averaging when aggregating small cells into larger cells. This additional initial loss can be calculated as a function of the cell size, e.g. according to the equation:

$$P_k = S - S * e^{-0.04x}$$

where ***S*** is the theoretical water depth in the terrain model with grid cell size approaching zero. ***S*** is site specific and should be calculated by analysis of the actual elevation model. The calculated initial loss due to terrain cell aggregation must be included by pre-processing of the applied rainfall.

8.2.2 Infiltration on the 2D raster surface

Possibilities for the computation of infiltration of the 2D raster surface are limited with the actual implementation in the MIKEbyDHI software.

In **MIKE Urban 2014**, the only boundary condition for the 2D overland model surface is the precipitation. It can be specified as:

- Constant, applied uniformly over entire model area
- dfs0 time series, applied uniformly over entire model area
- dfs2 spatially-distributed time series

This actually represents a source in the MIKE21 2D overland model cells.

MIKE URBAN 2D surface is impervious and no losses can be specified directly. Instead, the rainfall load must be reduced accordingly (effective precipitation) to include for any initial loss beyond the default 2-3 mm and for infiltration.

It must be understood that the computation of infiltration in the pre-processing phase is based exclusively on the relation between the actual infiltration capacity and the rainfall intensity, but without taking into account the actual presence of the accumulated water on the terrain surface. This may lead to errors in evaluating the duration of the flood in the period after the end of rainfall.

This method can be improved by applying **MIKE FLOOD 2014** user interface for editing a 2D overland model setup from MIKE URBAN.

The improvement is achieved by using evaporation as replacement for the infiltration loss. Evaporation reduces the amount of water in the model cells with the specified intensity, which is equivalent to the infiltration capacity.

Evaporation can be defined in the same ways as precipitation, i.e. as a constant, as unique time series (dfs0) or as spatially distributed time series (dfs2). In most applications, a constant infiltration capacity is sufficiently accurate, but it should be applied with spatial variation reflecting variations of the surfaces across the model area.

An obvious advantage over the method with infiltration accounted for by effective precipitation is that the actual infiltration is related to the availability of water in any of the model cells, and not just related to the actual rainfall intensity.

The newest development in MIKE 21 rel. 2016 (to be released by the end of 2015) is the inclusion of a dedicated infiltration module. The solution is illustrated in Figure 8-1.

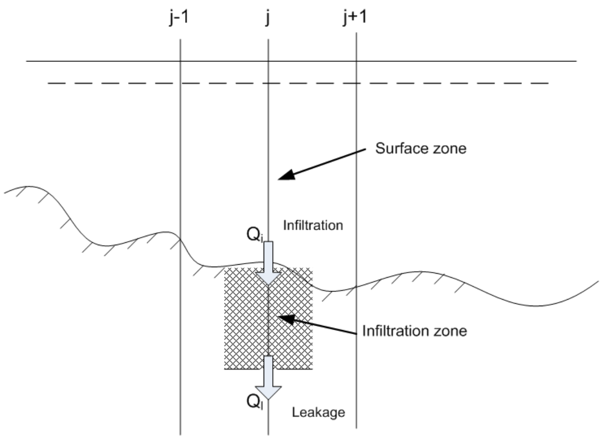

Figure 8-1 MIKE 21 infiltration module

Infiltration defines as:

- **Net infiltration rate**. This is equivalent to the use of evaporation in the current MIKE FLOOD 2014.
- **Constant infiltration,** where the infiltration from the surface into the unsaturated zone and further from the unsaturated to the saturated zone is described by a simplified infiltration model under the following assumptions:
    - Unsaturated zone has a constant, user specified porosity
    - Infiltration from surface into the unsaturated zone is calculated as a constant flow rate, corresponding to the infiltration capacity for unsaturated soil (e.g. Horton's initial infiltration capacity)
    - Flow from the unsaturated zone to the saturated zone is calculated as leakage with a constant flow rate, corresponding to the infiltration capacity for saturated soil (e.g. Horton's final infiltration capacity)

  Actual infiltration is limited by the availability of water on the surface.

  The infiltration model is defined by a file dfs2 fil (time constant, spatially distributed), containing five items:

    - Infiltration capacity (rate)
    - Porosity of unsaturated zone
    - Depth OR Level, describing the extent of the unsaturated zone
    - Leakage rate
    - Initial water content in the unsaturated zone.

8.2.3 Flow Routing on the 2D raster surface

Flow routing on the 2D surface is solved by the MIKE 21 2-dimensional dynamic flow model. The most relevant parameter affecting the computation is hydraulic resistance of the 2D surface (bed resistance), described by Manning's "n".

There is no extensive documentation on the Manning's "n" values for urban catchment surfaces. "n" values for the computation of "sheet flow" are given in Table 8-2 for certain specific surface types and for certain types of flood plains in Table 8-3.

Table 8-2 Manning's "n" for certain types of catchment surfaces (Engman, 1986)

Surface type		Manning's n
Smooth surfaces (concrete, rooftiles, asfalt, bare rock)		0.011
Fallow		0.05
Crops	Vegetation cover ≤ 20%	0.06
	Vegetation cover > 20%	0.17
Grassland	Short grass	0.15
	Thick grass	0.24
	Compact grass	0.41
Natural area		0.13
Forest	Little undergrowth	0.4
	Thick undergrowth	0.8

Table 8-3 Nishnabotna River: Flood-plain Manning's "n" values for water depths 0 – 1 m for different types of surfaces (Chow, 1986)

	Flood plain cover				
Surface/vegetation type	**Corn**	**Pasture**	**Meadow**	**Small grains**	**Brush and waste**
Manning's "n"	0.06 - 0.07	0.04 - 0.05	0.07 - 0.1	0.08 - 0.1	0.1 - 0.12

9 Practical strategies for the modelling runoff from green areas

In the modelling practice, different strategies may be applied, featuring various combinations of conceptual surface runoff models and 2D overland flow model for the simulation of runoff from catchments, including both impervious and pervious surfaces.

During extreme rainfall events, both drainage system and the catchment surface participate in the runoff (flow) and storage processes. One of the most important modelling tasks is to ensure that the hydrological loads from different parts of the catchment and the connection of this load to the model cluster are defined correctly and realistically.

9.1 Surface categorisation

An important step is splitting the catchment area into different categories in terms of modelling approach and treatment of the effective hydrological loadings. Accordingly, the first division is into **impervious** and **pervious** surface. Some hydrological models allow refinement of this division into more categories, e.g. with several types of pervious areas as in MOUSE model B.

The second criterion for the surface categorization is related to the connection of the surface to the drainage network: **connected** and **not connected** surfaces.

This lead to the following categories:

- Connected impervious surfaces
- Not connected impervious surfaces
- Not connected pervious surfaces

In this context, connected pervious surfaces do not exist as a separate category. Such areas, featuring sports grounds, porous road and parking lot surfaces with underground drains connected to the proper drainage network fall into the category of connected impervious surfaces, with their hydraulic functionality modelled as special features in the hydraulic network model.

An overview of the surface categories is shown in Table 9-1.

Table 9-1 Surface categories relative to imperviousness and connection to the drainage network

		Surface type			
		Impervious		**Pervious**	
Connetion to the drainage network	**Connected**	Type A	Roofs (including green roofs), road and parking lots (includingsolutions with porous surfaces), disconnected areas with local infiltration solutions (infiltration wells, swales, soakaways, etc.)	N/A	None
	Not connected	TypeB	Sports grounds , playing grounds, paved paths, etc. Without piped drainage	Type C	Private gardens, lawns, parks, etc.

In urban environment, the **impervious surfaces** (Type A) normally connect directly to the drainage network. Roofs and other impervious surfaces on a building lot are connected with a number of underground connections to the drainage network. Roads, parking lots and other similar surfaces also load the drainage network directly, through street gullies and other types of storm water intakes.

Some of the impervious surfaces may be furnished with low impact storm water drainage solutions, such as green roofs, porous road surfaces, infiltration sinks, swales, etc., which reduce the runoff by retention or by promoting local infiltration. Such solutions are effective for smaller rain events, but they are not designed for 100% effectivity during extreme events. In these cases, their retention and infiltration capacity is exceeded, and overflow to the drainage network occurs. Therefore, these areas should be treated as impervious connected area. Their hydraulic effect must be included through special functions in the network model, developed specifically for this purpose.

9.2 Modelling of runoff from different surface categories.

Technically, the most correct procedure is to model the runoff from **impervious connected areas** (Type A) as runoff hydrographs computed by a surface runoff model and connected to the drainage system as direct load to the network's nodes. Hydrological losses for "normal" impervious areas are small and the main task for the runoff is the runoff routing, according to the catchment size, geographical shape, topography and the connection location. In models with a detailed sub-catchment division, the routing also loses importance as the runoff dynamics and peak loads of the drainage system become similar to the rainfall.

As the connections have a limited physical size, i.e. limited hydraulic capacity, they need to be carefully modelled so that the model's functionality under extreme load is correctly captured.

Modelling of the hydrological load from impervious surfaces by coupling the precipitation directly on the 2D overland model surface is not recommended, as it contradicts the actual physical situation.

Impervious surfaces that are not connected to the drainage network (Type B) include e.g. paved pathways in parks, some types of sports grounds, non-permanent buildings, etc. – all impervious surfaces located away from a proper drainage system.

Pervious surfaces (Type C) are per definition not connected to the drainage network. They generate runoff only during extreme events and this runoff loads the drainage network accidentally, depending on the topographical conditions. Some of this runoff flows on the surface towards local terrain depressions, open ponds, lakes or to the sea, actually never loading the drainage network. The runoff that ends up in closed hollows finally infiltrates into the soil and/or evaporates.

Including these not connected surfaces into a surface runoff model with one or another method for handling infiltration loss is a widely adopted modelling practice. The reason for the popularity of this method is that it represents extrapolation of the well-known concepts applied in the modelling of drainage systems. The risk of introducing systematic errors in handling the model loads, imperviousness and hydrological losses is therefore minimal.

However, this method has also some serious drawbacks. Connecting green areas to the network model generates unrealistically high loading of the drainage network during extreme events, when runoff from these areas becomes a significant part of the total runoff. If the connection capacity is limited or if the drainage system surcharges due to local overload, the excessive runoff would spread on the 2D surface at and around the connection location. In reality, runoff from the not connected surfaces would flow towards the lower terrain, i.e. with a very different flow pattern and probably with a different result. This problem can be efficiently minimized by dividing the model area into a large number of small sub-catchments connected to a corresponding number of network nodes.

Another problem is related to large green areas without actual connection to the drainage network. In principle, this is the same problem as described above, but with an important difference that it cannot be minimized by a more detailed catchment delineation and network refinement. A standard solution is to connect such areas to an arbitrary node close to the area of concern and presumably at a topographically low position. However, this will result in an unrealistically high load of the drainage network locally and create a falsified image of the local flooding around the connection node, while the actual catchment surface appears to be dry.

The problem can be remedied and the error reduced by defining a fictive drainage network inside the ”green” catchments, which can receive the local runoff load and transfer it to the 2D overland model. This fictive network must have nodes with invert level just a few centimetres below the ground level. The links of the fictive network should have an insignificant transport and storage capacity. The green area should be divided into smaller sub-catchments e.g. using the ”catchment delineation” tool based on Thiesen polygons method, where each fictive node is allocated a polygon (sub-catchment) as a contributing fraction from the green catchment.

Alternatively, the detailed delineation can be substituted by coupling the original sub-catchments to multiple nodes.

As an alternative to the surface runoff models, the precipitation load on the not connected surfaces (both pervious and impervious) can be modelled directly by the 2D overland model, i.e. bypassing the surface runoff model. In a combination with a correct and detailed DEM and the flow routing calculated by a 2D overland model, this method produces highly accurate results.

The advantage of this method is that it opens the possibility to make very precise simulations of the runoff from larger green areas that are not connected to the drainage network. The method secures a realistic distribution of the rainfall load and a correct 2D flow dynamics according to the terrains topography. Also in ”ordinary” urban catchments, with distributed green surface between buildings and roads, this method contributes to the quality of results, particularly if the sub-catchments are relatively large.

The disadvantage of this method is that it is more complicated and requires a significant extension of the data processing skills. This may lead to increased risk of errors, which are not always readily detectable.

The simulation time is significantly longer, since all model cells directly loaded by rainfall are ”wet” and as such included as active in the simulation, throughout the rainfall duration.

A specific data required by this method is a 2D raster representing a spatial distribution of the not connected areas. This is created by subtracting the 2D raster representing the connected areas from the 2D raster for the entire catchment. This is illustrated in Figure 9-1.

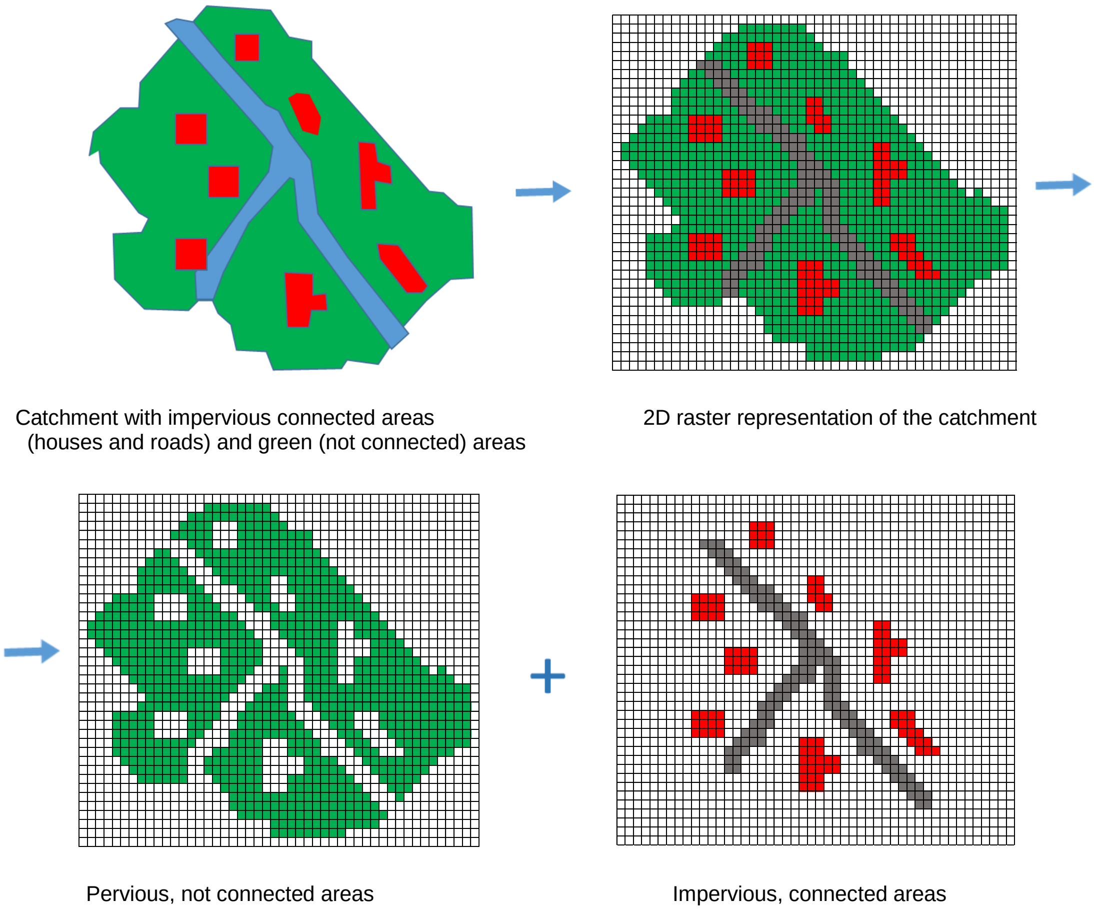

Figure 9-1 Schematization of a catchment to a 2D raster. The green raster cells are loaded by the rainfall directly to the 2D raster surface. Hydrological losses (infiltration) for these cells are defined according to the assumed infiltration properties of the soil. The red and green 2D raster cells define the catchment's imperviousness for the surface runoff model. Precipitation load on these cells is set to zero.

10 Recommended Methods for Modelling Storm Runoff from Urban Catchments including Runoff from Green Areas

The recommended methods for the modelling of storm runoff from urban catchments during extreme events, i.e. during urban flooding, include essentially two basic approaches to the modelling of runoff from green (pervious) areas:

1. **Application of a conceptual (lumped) hydrological model, including computation of all hydrological losses (initial loss and infiltration) and flow routing, for the entire catchment**

   or

2. **Application of a conceptual hydrological model, including computation of relevant hydrological losses (initial loss) and flow routing, for the impervious areas connected to the drainage network and rainfall load directly on the 2D overland model surface with adequate handling of hydrological losses (initial loss and infiltration) and 2D flow routing for the green (pervious) areas and disconnected impervious areas**

In both cases, inclusion of green areas in the model is considered as an extension of an existing model set-up for the impervious (connected) surfaces – in full consistency with the extension of the runoff contributing area.

10.1 Method 1

Obviously, **Method (1)** is relatively simple, as it represents an extrapolation of the standard modelling of the storm drainage systems, also to include pervious areas. There are, however, some issues associated with this method, which need to be handled accordingly in the model setup in order to minimize possible errors. Anyway, with a careful application, this approach is applicable for the most case analyses.

Within this method, the following choices of conceptual hydrological models should be pursued:

- **Time/area with initial loss (Model A):** MOUSE Surface runoff model A (or model C) for entire catchment;
- **Kinematic wave with Horton Infiltration (Model B):** MOUSE Surface runoff model B for entire catchment

The actual choice depends on the data availability, local practice and personal preferences.

From the technical point of view alone, **Model B** should be preferred, as it is conceptually simpler and more correct, with widely recognised treatment of the infiltration loss (Horton's infiltration model).

Model A requires the definition of separate catchment geometries for impervious and pervious areas. The treatment of infiltration is highly conceptualised by modelling the continuous infiltration loss as a single initial loss. The choice of model A may be conditioned by a strong confidence of the modellers for the application of the MOUSE Time-Area model.

10.2 Method 2

Method (2) applies the concept of loading the 2D model with rainfall and handling the infiltration loss directly on the 2D surface. This can potentially improve the accuracy of the results (relative to **Method 1**). However, additional needs related to the data availability, possibly increased data processing and maybe increased computation times, weighted against potential improvements, may be discouraging for some modellers. Therefore, Method 2 is recommended for cases where the benefit can be clearly justified and created through readily available data and technical expertise, without introducing additional risks for delays or technical ambiguities.

The following distinct methods, as extensions to the already discussed **Method A** and **Method B**, could be pursued:

- **Method A2D:** The time-area model (MOUSE surface runoff model A) or the linear reservoir model (MOUSE surface runoff model C) is used for impervious, connected areas, considering only initial loss. Precipitation is applied directly on the 2D flood model (MIKE FLOOD) for areas not connected to the drainage system (both pervious and impervious areas)
- **Method B2D:** The kinematic surface runoff model (MOUSE Surface runoff model B) is used for impervious, connected areas, in this case also considering only initial loss. Precipitation is applied directly on the 2D flood model (MIKE FLOOD) for areas not connected to the drainage system (both pervious and impervious areas)

The actual choice depends on the data availability, local practice and personal preferences.

As the conceptual runoff model treats impervious areas only, there is no clear technical “favourite”. Technically, runoff model A (Time-Area) and runoff model B (Non-linear reservoir or Kinematic wave) are equally applicable.

An overview of the four methods with their advantages and disadvantages is given in Table 10-1.

The technical details for these methods are summarised in Table 10-2, Table 10-3, Table 10-4 and Table 10-5.

For all four methods, the following remarks apply:

- The selected strategy should preferably be applied for the entire model area. Mixing of two or more strategies, e.g. A and A2D, is possible (A for ”normal” catchments, A2D for large green areas), but mixing of two concepts may be difficult to handle by a modeller and may subsequently cause inconsistent results
- The area included in the extent of 2D overland model must include as detailed a model of the drainage network and the contributing catchment area as practically possible. At outset, the model should include at least one node for each sub-catchment. If the correct description of the network requires many more nodes than there are sub-catchments, catchment connections to multiple nodes should be considered.
- All network nodes with one or more sub-catchments connected should be coupled with the 2D overland model. The flow capacity of this coupling should be limited to the design capacity.
- All other network nodes, except those in pressure mains, some closed structures and effectively sealed nodes, should be coupled with the 2D overland model. On these locations, the exchange of water between the network and the 2D surface will occur either because 2D overland flow will flow into the network or because water level in the network surcharges onto the surface.
- The choice of initial loss and infiltration capacity must be carefully evaluated and the most likely parameter values should be applied. In absence of reliable local field measurements, standard values from textbooks should be used. Any choice shall always be supported by prevalent reasoning. The modelling results should be supported by a sensitivity analysis with parameter values from within likely range of parameter values.

For methods A and B, the following specific remarks apply:

- Large green areas without drainage network, such as parks, should be treated with special care. If connected to a single network node, this may cause an unrealistically high local load of the drainage network and local flood around the point of connection. On the other hand, the actual capacity of the green area for the storage of surface water could remain unutilised. This shortcoming needs to be minimized to an acceptable level, e.g. by distributing the runoff from the green area to a number of nodes (based on topography).

Table 10-1 Overview of the simulation methods with lists of their advantages and disadvantages

<table>
<tr><th colspan="2" rowspan="3"></th><th colspan="2">Method for computing runoff from green areas</th></tr>
<tr><th>1</th><th>2</th></tr>
<tr><th>Conceptual model</th><th>Rain directly to 2D overland surface (2D)</th></tr>
<tr><td rowspan="8">Choice of conceptual runoff model</td><td rowspan="4">Kinematic wave with Horton's infiltration model (B)</td><td colspan="2">Advantages</td></tr>
<tr><td>(B)
• Simplicity: Extension of a well-known concept
• Widely accepted Horton's infiltration model</td><td>(B2D)
• Potentially the most accurate results, also for large green areas without drainage network</td></tr>
<tr><td colspan="2">Disadvantages</td></tr>
<tr><td>(B)
• Unrealistic local overload of the drainage network in case of large green areas
• First phase of flood propagation not realistic, with green area appearing dry</td><td>(B2D)
• Need for additional data
• Extra work on data processing
• Indirect handling of initial loss
• Longer simulation time</td></tr>
<tr><td rowspan="4">Time-Area with initial loss and reduction factor (A)</td><td colspan="2">Advantages</td></tr>
<tr><td>(A)
• Simplicity: Extension of a well-known concept for urban catchments hydrology</td><td>(A2D)
• Potentially the most accurate results, also for large green areas without drainage network</td></tr>
<tr><td colspan="2">Disadvantages</td></tr>
<tr><td>(A)
• Conceptualization of the infiltration process into initial loss and hydrological reduction
• Unrealistic local overload of the drainage network in case of large green areas
• First phase of flood propagation not realistic with green area appearing dry</td><td>(A2D)
• Need for additional data
• Extra work on data processing
• Indirect handling of initial loss
• Longer simulation time</td></tr>
</table>

Table 10-2 **Method A**: Summary of the method for modelling of surface runoff from urban catchments, including green areas, by the MOUSE surface runoff model A (Time-Area)

Method A: Time-Area with double catchments			
	Impervious areas		**Pervious surfaces (per definition not connected to the drainage network)**
	Connected to drainage network	**Not connected to drainage network**	
Catchment description	**Sub-catchment 1:** Describes the connected (impervious) part of the physical catchment	**Sub-catchment 2 :** Describes the non-connected part of the physical catchment, including non-connected impervious areas	
Connectivity to network model	Connected to a network node. Optionally, connected to multiple nodes	Connected to a network node. Optionally, connected to multiple nodes	
Model type	Time-Area (Model A)	Time-Area (Model A)	
Imperviousness	Actual imperviousness for the CONNECTED areas (roofs, roads, driveways, etc.) from GIS or imperviousness calculated as effectively contributing area	Calculates as 100% minus the imperviousness for sub-catchment 1	
Initial loss	0 - 1 mm	**Option 1:** Includes wetting (interception), surface storage and initial infiltration loss in the pre-saturation phase. E.g. with actual interception and surface storage loss of 6 mm, and soil properties corresponding to medium impermeability, total initial loss amounts to approx. 25 mm. The value may very significantly up or down, depending on the accepted assumptions and presence of impervious non-connected surfaces **Option 2:** Includes wetting (interception), surface storage and infiltration loss anticipated for the entire simulated event. The infiltration loss correspond to the total depth of the largest rainfall not generating any runoff. E.g. for certain site this may be estimated to a 10-year rainfall of a given duration. The value may vary significantly up or down, depending on the accepted model assumptions for the prevailing soil permeability properties and rainfall duration and presence of impervious non-connected surfaces	
Hydrological reduction	1.00	**Option 1:** To be defined based on the assumed soil infiltration capacity and presence of impervious non-connected surfaces. Depends also on the applied rainfall, which is a significant drawback for the scientific and technical validity of the method. **Option 2:** 1.00. This means that all rainfall beyond the actual initial loss and the anticipated total infiltration (included in the definition of initial loss) will be transformed into runoff. E.g. If the initial loss has been set to consume the total 10-year rain, simulation with a 100-year rain will generate a runoff volume corresponding to the difference between a 10-year and a 100-year rainfall of the same duration.	
Infiltration	N/A	Included in the initial loss and reductions factor	
Concentration time Tc	According to MIKE URBAN "Catchment processing tool" med v = 0.2 - 0.3 m/s	Value for impervious part of the catchment, multiplied by factor 3-5	
Precipitation load	Total precipitation for all sub-catchments		

Table 10-3 **Method B**: Summary of the method for modelling of surface runoff from urban catchments, including green areas, by the MOUSE surface runoff model B (Kinematic Wave)

<table>
<tr><th colspan="4">Method B: Kinematic Wave</th></tr>
<tr><th rowspan="2"></th><th colspan="2">Impervious areas</th><th rowspan="2">Pervious surfaces (per definition not connected to the drainage network)</th></tr>
<tr><th>Connected to drainage network</th><th>Not connected to drainage network</th></tr>
<tr><td>Catchment description</td><td>Impervious connected areas described as a combination of contributing impervious areas (steep and/or flat). May be simplified to just one impervious surface category.</td><td colspan="2">ALL pervious areas described as a combination of contributing pervious areas (low, medium and large infiltration capacity). May be simplified to just one pervious surface category.</td></tr>
<tr><td>Connectivity to network model</td><td colspan="3">Connected to a network node. Optionally, connected to multiple nodes</td></tr>
<tr><td>Model type</td><td>Kinematic wave (Model B) - without infiltration</td><td colspan="2">Kinematic wave (Model B) - with Integrated Horton's infiltration</td></tr>
<tr><td>Imperviousness</td><td>Actual physical imperviousness for the connected areas (roofs, roads, driveways, etc.) from GIS or imperviousness calculated as effectively contributing area, possibly divided to "Impervious Flat" and "Impervious Steep"</td><td colspan="2">Calculates as 100% minus the real physically impervious area, possibly divided to "Low pervious", "Medium pervious" and "High pervious". If present, non-connected impervious areas to be included by proportional weighting the hydrological parameters (see below)</td></tr>
<tr><td>Wetting</td><td>Default value</td><td colspan="2">Includes also interception. Shall be adjusted according to vegetation type (1 -3 mm). If present, non-connected impervious areas to be included with zero wetting by proportional weighting</td></tr>
<tr><td>Storage</td><td>0 - 1 mm</td><td colspan="2">Shall be adjusted according to surface type (1 -5 mm). If present, non-connected impervious areas to be included with storage 0-1 mm, by proportional weighting</td></tr>
<tr><td>Hydraulic resistance (Manning's "n")</td><td>Manning's "n": 0.011 - 0.020</td><td colspan="2">Manning's "n": 0.05 - 0.1</td></tr>
<tr><td>Slope</td><td colspan="3">Estimated according to catchment topography</td></tr>
<tr><td>Length</td><td colspan="3">Estimated according to catchment size and shape</td></tr>
<tr><td>Infiltration</td><td>N/A</td><td colspan="2">Integrated Horton's infiltration, parameters to be taken from textbooks or based on local measurements. If present, non-connected impervious areas to be included with zero infiltration by proportional weighting</td></tr>
<tr><td>Precipitation load</td><td colspan="3">Total precipitation for all sub-catchments</td></tr>
</table>

Table 10-4 **Method A2D**: Summary of the method for modelling of surface runoff from impervious urban areas by the MOUSE surface runoff model A and inclusion of green (pervious) areas by loading precipitation directly to the 2D raster

Method A2D: Time-Area + Rainfall directly on 2D surface			
	Impervious areas		**Pervious surfaces (per definition not connected to the drainage network)**
	Connected to drainage network	**Not connected to drainage network**	
Catchment description	Model A catchment: Describes the impervious part of the physical catchment area, with CONNECTED impervious areas	2D surface, includes all 2D model cells outside the connected impervious areas	
Connectivity to network model	Connected to a network node. Optionally, connected to multiple nodes	Indirectly, through 2D surface and network model coupling	
Model type	Time-Area (Model A)	2D	
Imperviousness	Actual physical imperviousness for the CONNECTED areas (roofs, roads, etc.) from GIS	Model cells defined 100% impervious by excluding from the specification of evaporation or infiltration	Model cells get allocated evaporation or infiltration, according to the expected initial loss and/or infiltration capacity
Initial loss	0 - 1 mm	Included in drying/wetting	**MIKE URBAN 2014**: Includes via effective precipitation, to account for wetting, interception and surface storage. With larger 2D raster cells, must be increased to compensate for elevation averaging
			MIKE FLOOD 2014: Includes via effective precipitation, to account for wetting, interception and surface storage. With larger 2D raster cells, must be increased to compensate for elevation averaging
			MIKE FLOOD 2016: Includes via effective precipitation, to account for wetting, interception and surface storage. With larger 2D raster cells, must be increased to compensate for elevation averaging
Hydrological reduction	1	N/A	N/A
Infiltration	N/A	**MIKE URBAN 2014**: N/A	**MIKE URBAN 2014**: includes via effective precipitation (i.e. reduced total precipitation) for model cells which belong to this type of surface
		MIKE FLOOD 2014: for the model cells belonging to this type of surface, evaporation sets to zero in the dfs2 file	**MIKE FLOOD 2014**: includes as constant evaporation (5 mm/h - 50 mm/h) for model cells which belong to this type of surface
		MIKE FLOOD 2016: for the model cells belonging to the type of surface, defines as input for MIKE21 infiltration module with zero infiltration capacity	**MIKE FLOOD 2016**: defines as input for MIKE21 infiltration module for model cells which belong to this type
Concentration time Tc	According to MIKE URBAN "Catchment processing tool" with v = 0.2 - 0.3 m/s	N/A	N/A
Hydraulic resistance (Manning's "n")	N/A	Manning's "n": 0.013 - 0.020	Manning's "n": 0.05 - 0.1
Precipitation load	Total precipitation	**Total precipitation** in a dfs2 file, for model cells which belong to this type of surface	MIKE FLOOD 2014: **Effective precipitation** (i.e. total precipitation reduced by initial loss and infiltration) in a dfs2 file, for model cells which belong to this type of surface
			MIKE FLOOD 2014: **Effective precipitation** (i.e. total precipitation reduced by initial loss) in a dfs2 file, for model cells which belong to this type of surface
			MIKE FLOOD 2016: **Effective precipitation** (i.e. total precipitation reduced by initial loss) for model cells which belong to this type of surface

Table 10-5 **Method B2D**: Summary of the method for modelling of surface runoff from impervious urban areas by the MOUSE surface runoff model B and inclusion of green (pervious) areas by loading precipitation directly to the 2D raster

<table>
<tr><th colspan="4">Method B2D: Kinematic Wave + Rainfall directly on 2D surface</th></tr>
<tr><th rowspan="2"></th><th colspan="2">Impervious areas</th><th rowspan="2">Pervious surfaces (per definition not connected to the drainage network)</th></tr>
<tr><th>Connected to drainage network</th><th>Not connected to drainage network</th></tr>
<tr><td>Catchment description</td><td>Model B catchment: Describes the impervious part of the physical catchment area, with CONNECTED impervious areas, pervious area set to zero</td><td colspan="2">2D surface, includes all 2D model cells outside the connected impervious areas</td></tr>
<tr><td>Connectivity to network model</td><td>Connected to a network node. Optionally, connected to multiple nodes</td><td colspan="2">Indirectly, through 2D surface and network model coupling</td></tr>
<tr><td>Model type</td><td>Kinematic wave (Model B) - without infiltration</td><td colspan="2">2D</td></tr>
<tr><td>Imperviousnes s</td><td>Actual physical imperviousness for the CONNECTED areas (roofs, roads, etc.) from GIS, possibly divided to "Impervious Flat" and "Impervious Steep"</td><td>Model cells defined 100% impervious by excluding from the specification of evaporation or infiltration</td><td>Model cells get allocated evaporation or infiltration, according to the expected initial loss and/or infiltration capacity</td></tr>
<tr><td rowspan="2">Wetting</td><td rowspan="2">Default value</td><td rowspan="3">Included in drying/wetting</td><td>MIKE URBAN 2014: Includes via effective precipitation, to account for wetting, interception and surface storage. With larger 2D raster cells, must be increased to compensate for elevation averaging</td></tr>
<tr><td>MIKE FLOOD 2016: Includes via effective precipitation, to account for wetting, interception and surface storage. With larger 2D raster cells, must be increased to compensate for elevation averaging</td></tr>
<tr><td>Storage</td><td>0 - 1 mm</td><td>MIKE FLOOD 2014: Includes via effective precipitation, to account for wetting, interception and surface storage. With larger 2D raster cells, must be increased to compensate for elevation averaging</td></tr>
<tr><td>Hydraulic resistance (Manning's "n")</td><td>Manning's "n": 0.013 - 0.020</td><td>Manning's "n": 0.013 - 0.020</td><td>Manning's "n": 0.05 - 0.1</td></tr>
<tr><td>Slope</td><td>Estimated</td><td colspan="2">N/A</td></tr>
<tr><td>Length</td><td>Estimated according to the catchment size, can be used a calibration parameter</td><td colspan="2">N/A</td></tr>
<tr><td rowspan="3">Infiltration</td><td rowspan="3">N/A</td><td>MIKE URBAN 2014: N/A</td><td>MIKE URBAN 2014: includes via effective precipitation (i.e. reduced total precipitation) for model cells which belong to this type of surface</td></tr>
<tr><td>MIKE FLOOD 2014: for the model cells belonging to this type of surface, evaporation sets to zero in the dfs2 file</td><td>MIKE FLOOD 2014: includes as constant evaporation (5 mm/h - 50 mm/h) for model cells which belong to this type of surface</td></tr>
<tr><td>MIKE FLOOD 2016: for the model cells belonging to the type of surface, defines as input for MIKE21 infiltration module with zero infiltration capacity</td><td>MIKE FLOOD 2016: defines as input for MIKE21 infiltration module for model cells which belong to this type</td></tr>
<tr><td rowspan="3">Precipitation load</td><td rowspan="3">Total precipitation</td><td rowspan="3">Total precipitation in a dfs2 file, for model cells which belong to this type of surface</td><td>MIKE FLOOD 2014: Effective precipitation (i.e. total precipitation reduced by initial loss and infiltration) in a dfs2 file, for model cells which belong to this type of surface</td></tr>
<tr><td>MIKE FLOOD 2014: Effective precipitation (i.e. total precipitation reduced by initial loss) in a dfs2 file, for model cells which belong to this type of surface</td></tr>
<tr><td>MIKE FLOOD 2016: Effective precipitation (i.e. total precipitation reduced by initial loss), for model cells which belong to this type of surface</td></tr>
</table>

11 Conclusions

Accurate modelling of the runoff from green areas under extreme rainfall loads and urban flooding is possible with existing software. However, inclusion of green areas introduces complexity in the modelling through a number of issues that are usually not important when dealing with impervious urban surfaces alone. Therefore, caution must be applied when choosing the modelling approach, rainfall loads and the key model parameters. In general, a new design standard must be established. This modellers' guideline is a step towards achieving such a standard.

12 List of References

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