

# Modelling of runoff from green urban areas

Berislav Tomicic

# Introduction

- Guideline: "Modelling of Storm Water Runoff from Green Urban Areas", DHI, 2015
  - Focus on flood generating events and correct modelling of non-paved areas (not LID infrastructure)
  - Motivation: Need for a "common standard" for modelling

# Example 1: On-Shore Gas Terminal Site

Area: approx. 45 hectares



# Climate and Hydrology

Climate data for Kyaukpyu

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high °C (°F)	26.3 (79.3)	27.4 (81.3)	29.4 (84.9)	31.8 (89.2)	32.4 (90.3)	29.4 (84.9)	28.7 (83.7)	28.7 (83.7)	29.9 (85.8)	30.5 (86.9)	29.3 (84.7)	27.2 (81)	29.25 (84.64)
Average low °C (°F)	17.4 (63.3)	18.1 (64.6)	21.1 (70)	24.2 (75.6)	25.5 (77.9)	24.4 (75.9)	24.1 (75.4)	24.3 (75.7)	23.0 (73.4)	24.4 (75.9)	22.8 (73)	19.2 (66.6)	22.38 (72.27)
Average precipitation mm (inches)	5 (0.2)	8 (0.31)	3 (0.12)	32 (1.26)	253 (9.96)	1,012 (39.84)	1,232 (48.5)	989 (38.94)	575 (22.64)	270 (10.63)	89 (3.5)	13 (0.51)	4,481 (176.41)

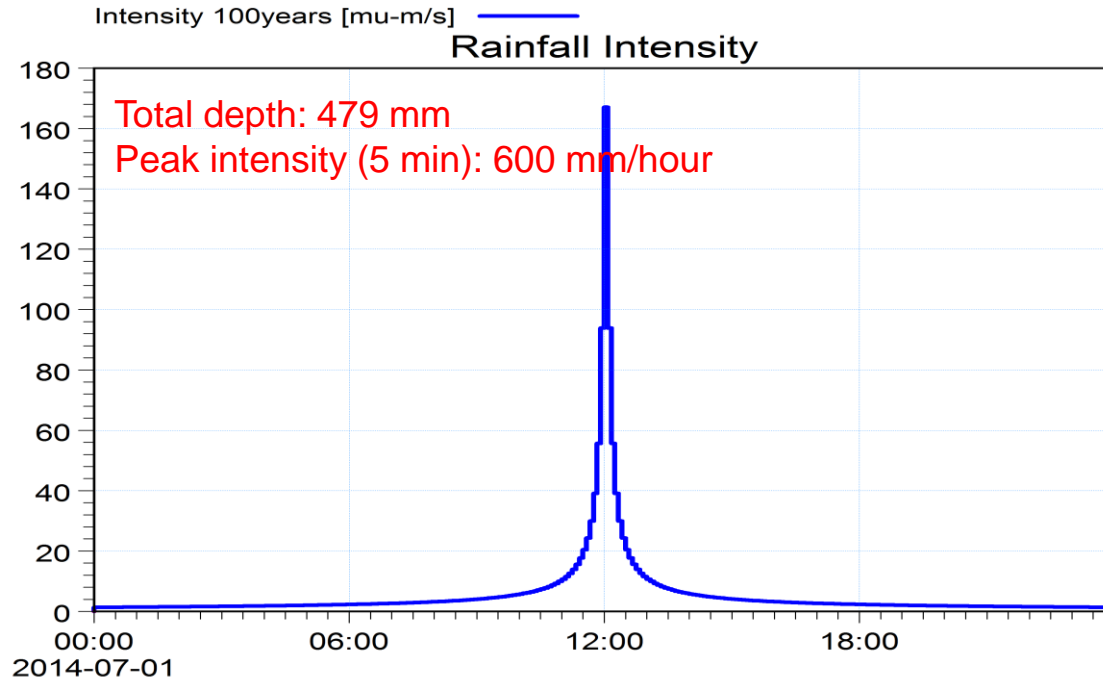
Source: NOAA (1961–1990) <sup>[4]</sup>

4,500 mm rainfall per year, 3,200 mm only in June, July and August!!!

# I-D-F Rainfall Statistics

Duration	Rainfall Depth (mm)				
	1-year	5-years	10-years	50-years	100-years
15min	31	46	55	85	103
30min	43	67	81	128	157
60min	60	93	112	170	204
24hr	205	300	341	438	479

# Rainfall profile: Symmetric Chicago Design Storm (CDS), 24 h duration, for various return periods



# Impervious and pervious areas, runoff coefficient ("Rational method")

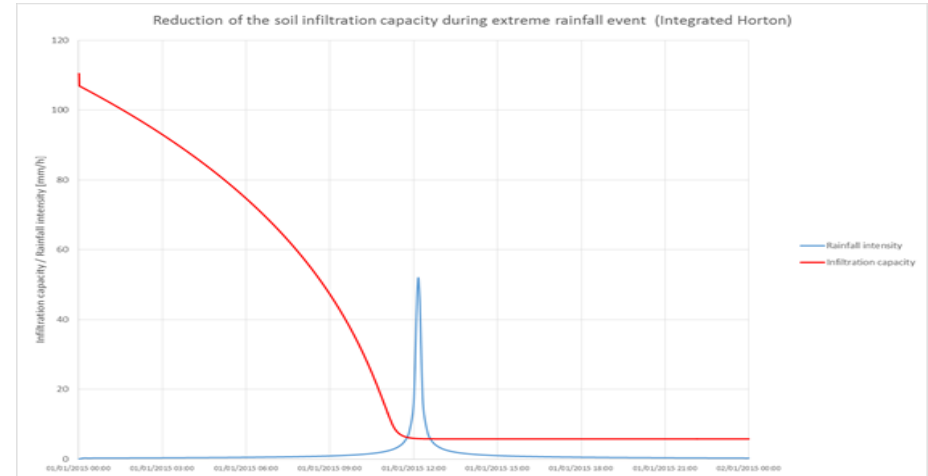
Land use type	Area [ha]	% of total	Runoff coefficient	Contributing area [ha]
<b>Buildings</b>	1.93	4.29%	0.95	1.83
<b>Roads</b>	2.21	4.92%	0.95	2.10
<b>Canals &amp; Drains</b>	1.66	3.70%	1.00	1.66
<b>Gravel</b>	1.90	4.22%	0.50	0.95
<b>Unpaved</b>	37.21	82.86%	0.30	11.16
<b>Total</b>	<b>44.91</b>	<b>100.00%</b>	<b>0.39</b>	<b>17.71</b>

# Hydrological Losses - Soil Properties (Parameters in Horton's equation)

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

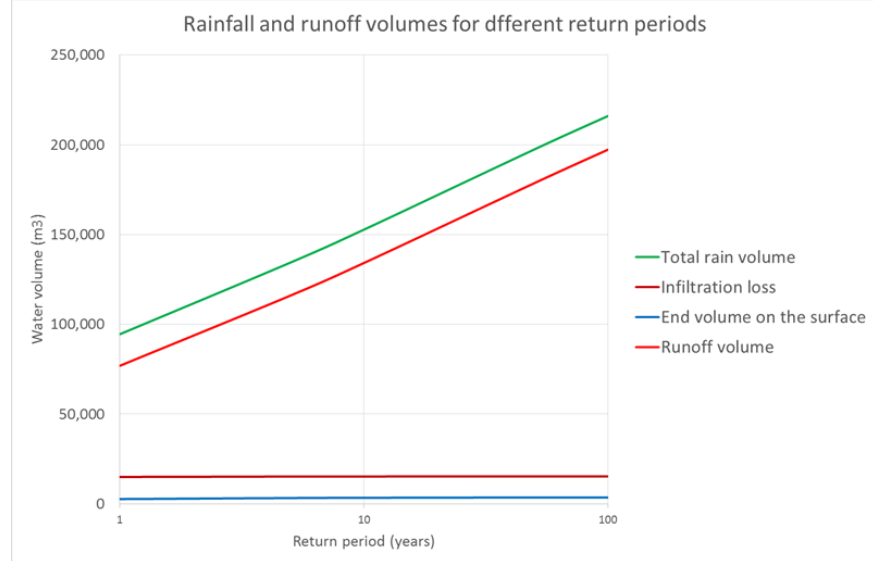
Soil type	Initial infiltration capacity ( $F_0$ )
	(mm/hour)
Dry sand with little or no vegetation	127
Dry loam with little or no vegetation	76.2
Dry clay with little or no vegetation	25.4
Dry sand with thick vegetation	254
Dry loam with thick vegetation	152
Dry clay with thick vegetation	51
Wet sand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

Soil type	Final infiltration capacity ( $F_c$ )	Horton's constant
	(mm/hour)	(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



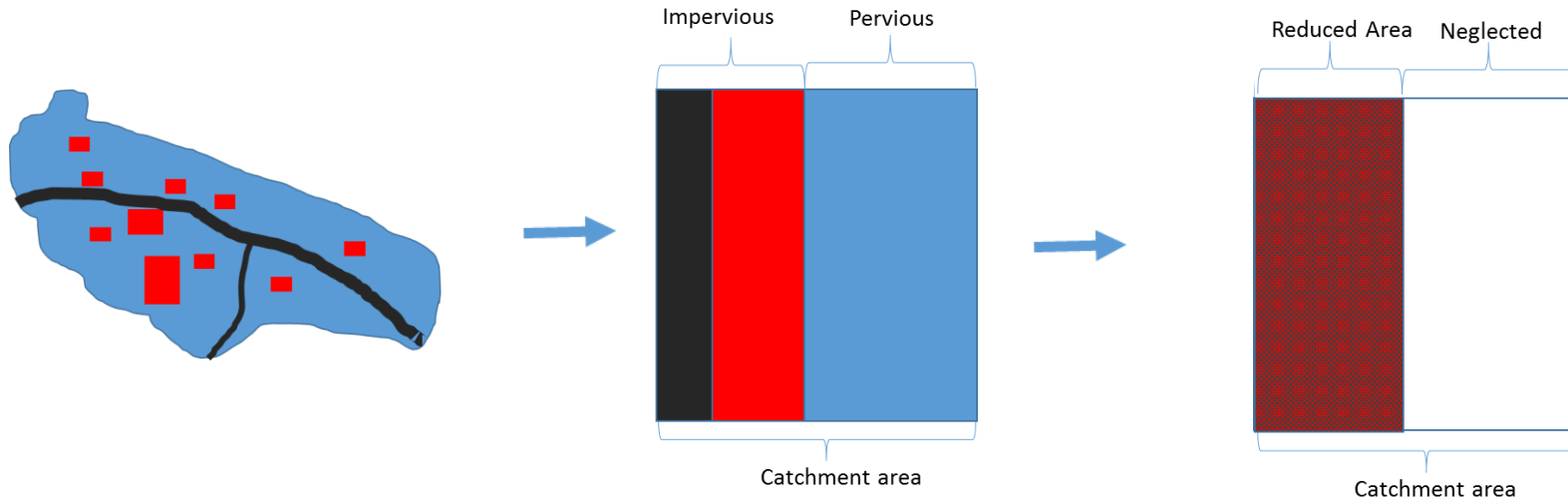


Return period	Total rain depth	Catchment area	Total rain volume	Infiltration loss	End volume on the surface	Runoff volume	
	[mm]	[ha]	[m <sup>3</sup> ]	[m <sup>3</sup> ]	[m <sup>3</sup> ]	[m <sup>3</sup> ]	[% of total]
1 year	210.5	44.909	94,533	14,957	2,655	76,933	81.38%
5 years	299.4	44.909	134,438	15,174	3,210	116,052	86.32%
10 years	340.2	44.909	152,761	15,226	3,355	134,179	87.84%
50 years	439.8	44.909	197,485	15,280	3,515	178,689	90.48%
100 years	481.1	44.909	216,055	15,263	3,470	197,323	91.33%



## EXAMPLE 2: Copenhagen

- Time-Area model: concept of "reduced area" (contributing area)
- Applicable for impervious areas & drainage system analyses



# Rain Recurrence-Dependent Model Parameters

## Extension of the "reduced area" concept for impervious areas

*Afløbstider og initialtab*

*Hydrologisk reduktionsfaktor*

Gentagelsesperiode	Reduktionsfaktor
T=2	0,7-0,9
T=5	0,8-0,9
T=10	0,8-1,0
T=50	0,9-1,0
T=100	1,0

Overfladetype	Afløbstid [min]	Initialtab [mm]
Bygninger	7	0,6
Veje	7	0,6
Diverse befæstede arealer	7	0,6
Jernbane	Beregnes 1 m/s	10
Drænede grønne arealer *	Beregnes 0,5 m/s	30
Udrænede grønne arealer *	Beregnes 0,1 m/s	30
Søer og våde arealer	0	0

*Befæstelsesgrader*

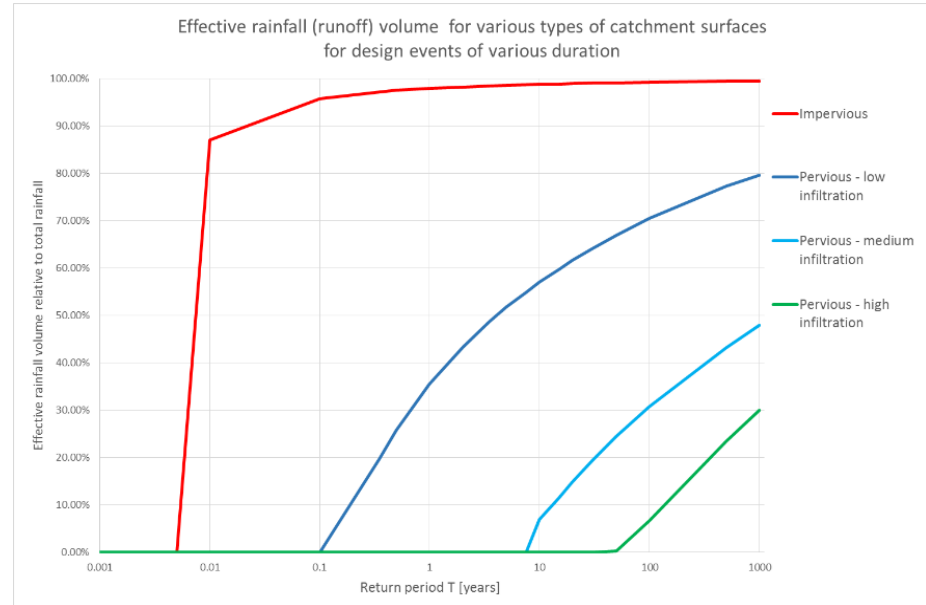
Overfladetype	Befæstelsesgrad	
	T=10	T=100
Bygninger	95	100
Veje	95	100
Diverse befæstede arealer	90	100
Jernbane	10	50
Drænede grønne arealer *	5	50
Udrænede grønne arealer *	5	50
Søer og våde arealer	100	100

# Key for Understanding

- Fundamental shift of focus
  - Drainage system ( $F \leq 10$  years)  $\rightarrow$  runoff from the contributing area
  - Urban flooding ( $F > 10$  years)  $\rightarrow$  Runoff from entire catchment

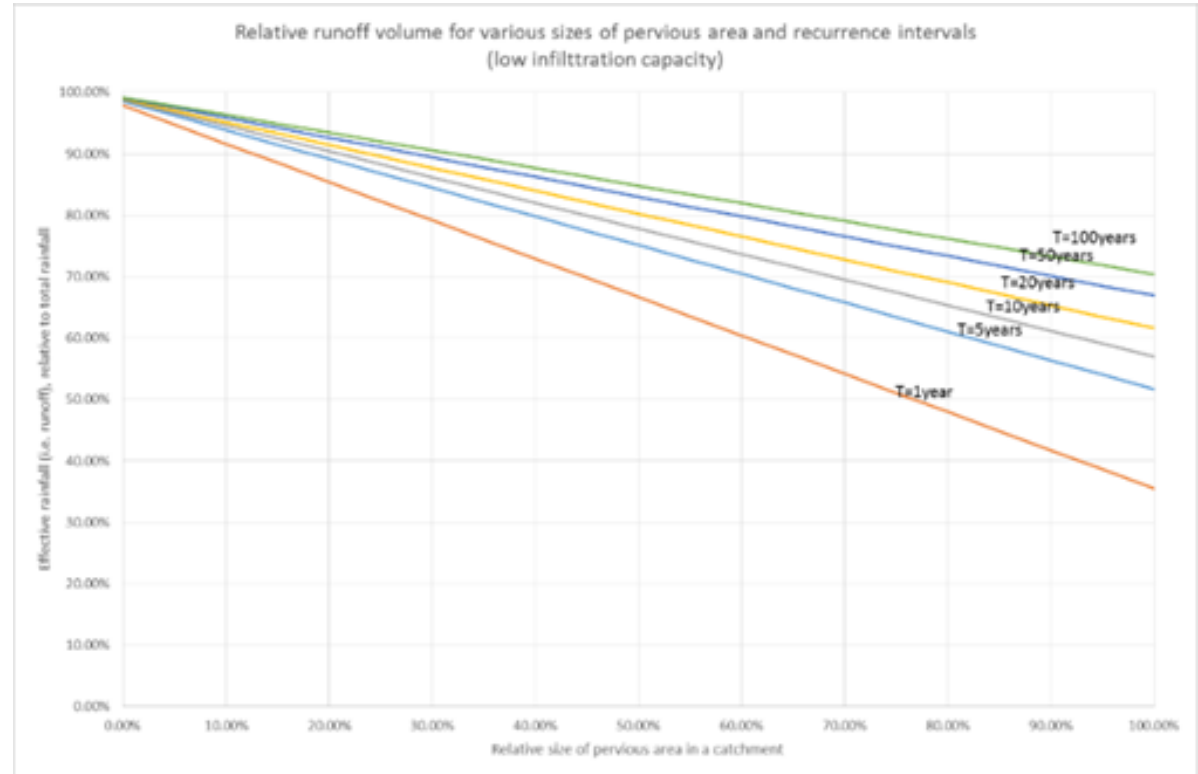
# Green Areas (pervious) in Urban Catchment under Extreme Rainfall

- Runoff from:
  - Impervious areas
  - Pervious areas



# Green Areas in Urban Catchment under Extreme Rainfall

- Runoff from:
  - Impervious areas
  - Pervious areas

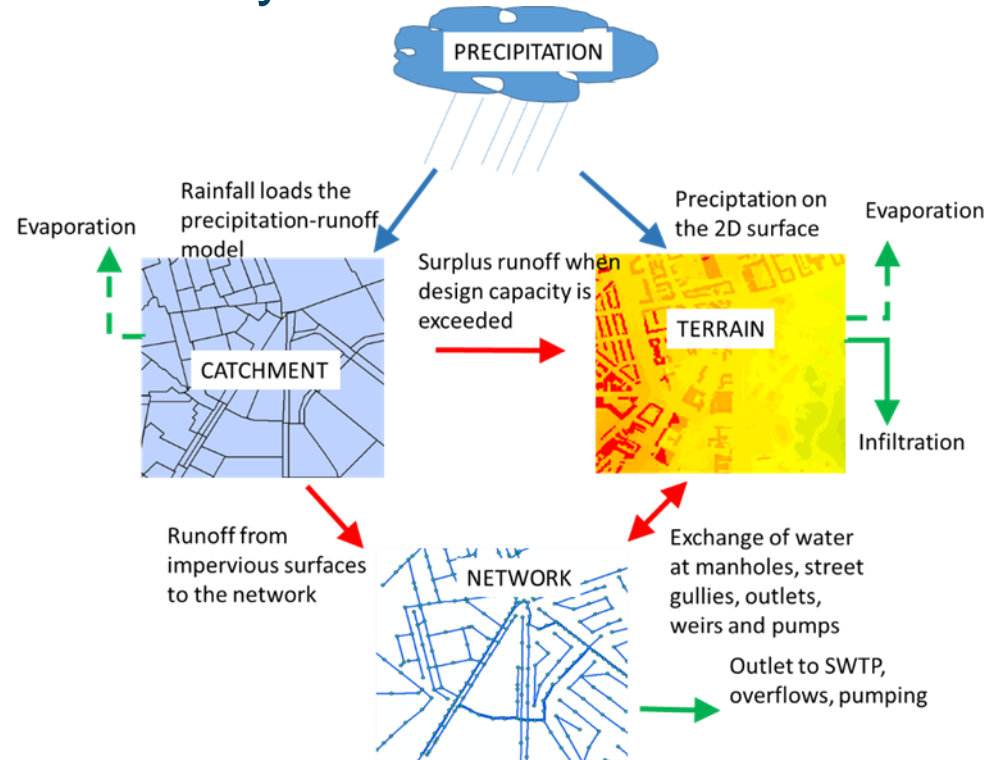


# Modelling approach – extending analysis to pervious surfaces

- Recent years developments
  - Enhancement of applied modelling methods and tools
  - Availability of digital terrain models (DEM)
- However – the development was incoherent within Denmark and worldwide => no "best practise" recommendation for modelling runoff from green areas

# Modelling of the urban water system

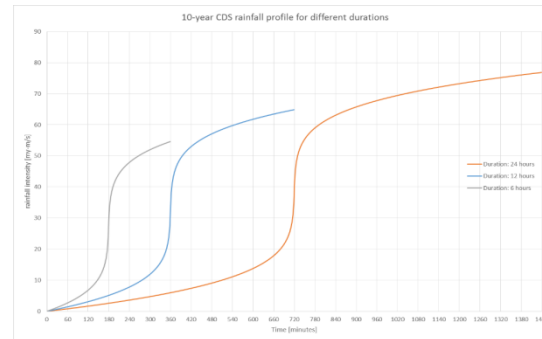
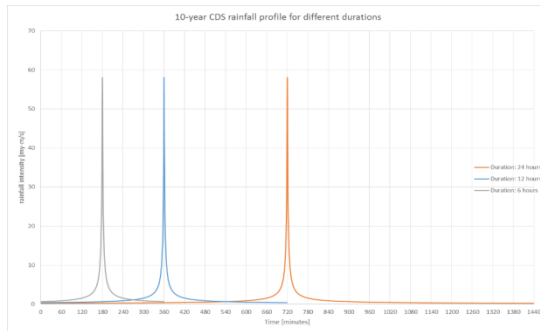
- Catchment
- Drainage system
- Terrain surface





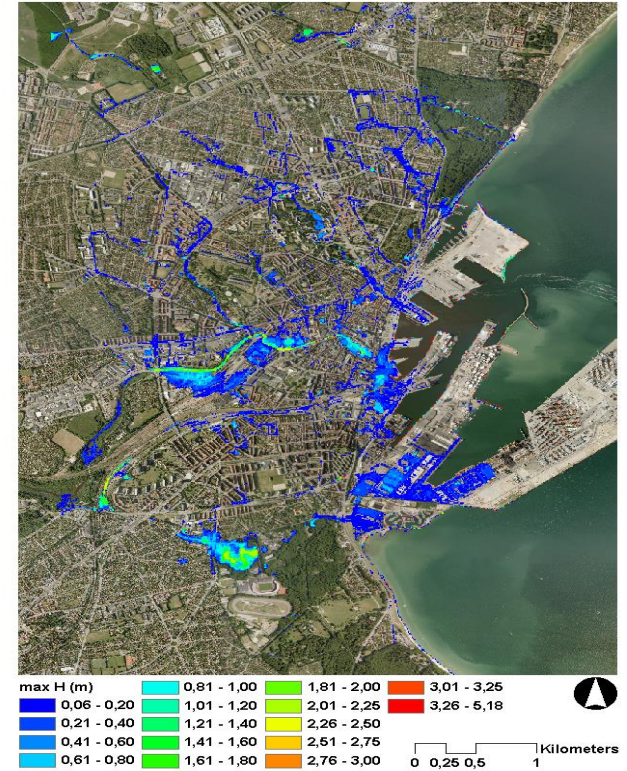
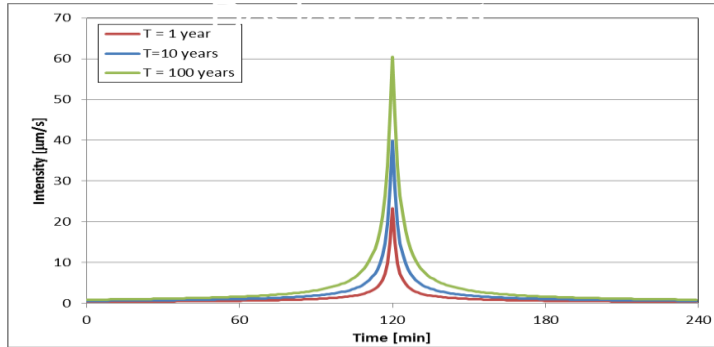
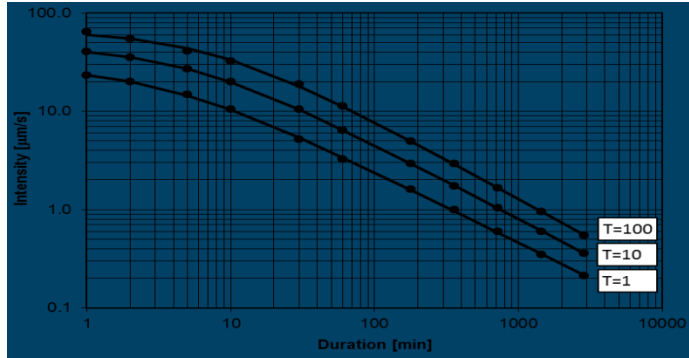
# Precipitation

- Service Level – 10 year return period
- Selection of rainfall
  - Synthetic rainfall profiles - Chicago Design Storm – CDS
  - Climate change projection of rainfall (factor)
  - Duration and Assymetry of CDS rainfall



# Design event approach

IDF curve



# Hydrological Modelling of runoff from pervious surfaces

- Precipitation-runoff models
  - Hydrological losses
  - Surface runoff (routing)

# Hydrological Losses - Methods

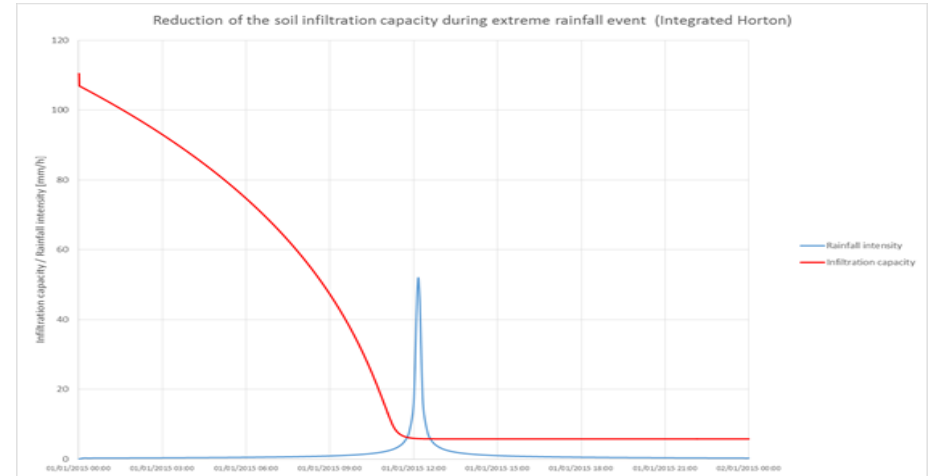
- Infiltration as constant loss
  - Infiltration as part of initial loss
  - Infiltration as proportional loss
  - Horton's equation
  - Soil Conservation Service (SCS) method
  - Green-Ampt method
- } • Model A
- Model B
- UHM

# Hydrological Losses - Soil Properties (Parameters in Horton's equation)

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

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

Soil type	Final infiltration capacity ( $F_c$ )	Horton's constant
	(mm/hour)	(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



# Hydrological models for surface runoff in MIKE URBAN

- MOUSE Model A (Time-Area)
- MOUSE Model B (Kinematic Wave+Horton)
- MOUSE Model C (Linear Reservoir+Horton)
- MOUSE Unit Hydrograph Model (UHM)
  
- MIKE 21 – 2D

# Model A – Time Area

- Reduction factor
  - Initial loss
- 
- Control volume balance
- 
- Concentration time
  - Shape of time/area curve
- 
- Control flow routing

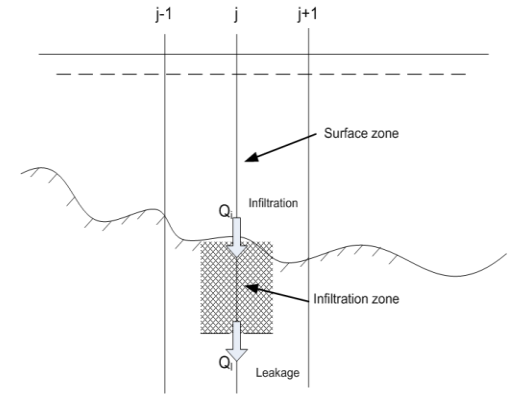
# Overview of MIKE URBAN runoff models

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

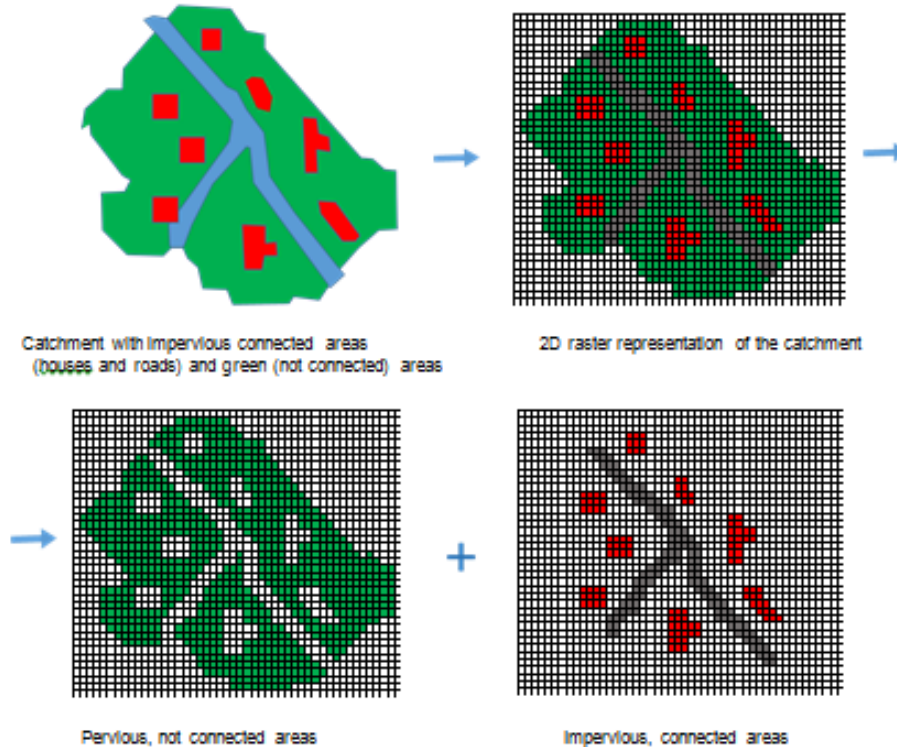


# Apply precipitation directly on 2D

- Initial loss on 2D raster surface
- Infiltration on 2D raster surface
  - Constant, applied uniformly over entire model area
  - dfs0 time series, applied uniformly over entire model area
  - dfs2 spatially-distributed time series



# Schematisation of catchments in 2D raster



# Recommendation

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

# Recommendation

- Method 1
  - Kinematic wave with Horton Infiltration (Model B): MOUSE Surface runoff model B for entire catchment
  - Time/area with initial loss (Model A): MOUSE Surface runoff model A (or model C) for entire catchment;
- Method 2
  - Method (2) applies the concept of loading the 2D model with rainfall and handling the infiltration loss directly on the 2D surface.

# Recommendation

- 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)

# Recommendation

		Method for computing runoff from green areas	
		1	2
		Conceptual model	Rain directly to 2D overland surface (2D)
Choice of conceptual runoff model	Kinematic wave with Horton's infiltration model (B)	Advantages	
		(B) <ul style="list-style-type: none"> <li>Simplicity: Extension of a well-known concept</li> <li>Widely accepted Horton's infiltration model</li> </ul>	(B2D) <ul style="list-style-type: none"> <li>Potentially the most accurate results, also for large green areas without drainage network</li> </ul>
		Disadvantages	
		(B) <ul style="list-style-type: none"> <li>Unrealistic local overload of the drainage network in case of large green areas</li> <li>First phase of flood propagation not realistic, with green area appearing dry</li> </ul>	(B2D) <ul style="list-style-type: none"> <li>Need for additional data</li> <li>Extra work on data processing</li> <li>Indirect handling of initial loss</li> <li>Longer simulation time</li> </ul>
	Time-Area with initial loss and reduction factor (A)	Advantages	
		(A) <ul style="list-style-type: none"> <li>Simplicity: Extension of a well-known concept for urban catchments hydrology</li> </ul>	(A2D) <ul style="list-style-type: none"> <li>Potentially the most accurate results, also for large green areas without drainage network</li> </ul>
		Disadvantages	
		(A) <ul style="list-style-type: none"> <li>Conceptualization of the infiltration process into initial loss and hydrological reduction</li> <li>Unrealistic local overload of the drainage network in case of large green areas</li> <li>First phase of flood propagation not realistic with green area appearing dry</li> </ul>	(A2D) <ul style="list-style-type: none"> <li>Need for additional data</li> <li>Extra work on data processing</li> <li>Indirect handling of initial loss</li> <li>Longer simulation time</li> </ul>

# Recommendation

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	<b>Sub-catchment 1:</b> Describes the connected (impervious) part of the physical catchment	<b>Sub-catchment 2 :</b> 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	<b>Option 1:</b> 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 <u>impermeability</u> , total initial loss amounts to approx. 25 mm. The value may vary significantly up or down, depending on the accepted assumptions and presence of impervious non-connected surfaces  <b>Option 2:</b> 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	<b>Option 1:</b> 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.  <b>Option 2:</b> 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		

# Recommendation

Method B: Kinematic Wave			
	Impervious areas		Pervious surfaces (per definition not connected to the drainage network)
	Connected to drainage network	Not connected to drainage network	
Catchment description	Impervious connected areas described as a combination of contributing impervious areas (steep and/or flat). May be simplified to just one impervious surface category.	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.	
Connectivity to network model	Connected to a network node. Optionally, connected to multiple nodes		
Model type	Kinematic wave (Model B) - without infiltration	Kinematic wave (Model B) - with Integrated Horton's infiltration	
Imperviousness	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"	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)	
Wetting	Default value	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	
Storage	0 - 1 mm	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	
Hydraulic resistance (Manning's "n")	Manning's "n": 0.011 - 0.020	Manning's "n": 0.05 - 0.1	
Slope	Estimated according to catchment topography		
Length	Estimated according to catchment size and shape		
Infiltration	N/A	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	
Precipitation load	Total precipitation for all sub-catchments		



# Recommendation

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	<b>MIKE URBAN 2014:</b> 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 <b>MIKE FLOOD 2014:</b> 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 <b>MIKE FLOOD 2016:</b> 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	<b>MIKE URBAN 2014:</b> N/A	<b>MIKE URBAN 2014:</b> includes via effective precipitation (i.e. reduced total precipitation) for model cells which belong to this type of surface
		<b>MIKE FLOOD 2014:</b> for the model cells belonging to this type of surface, evaporation sets to zero in the dfs2 file	<b>MIKE FLOOD 2014:</b> includes as constant evaporation (5 mm/h - 50 mm/h) for model cells which belong to this type of surface
		<b>MIKE FLOOD 2016:</b> for the model cells belonging to the type of surface, defines as input for MIKE21 infiltration module, with zero infiltration capacity	<b>MIKE FLOOD 2016:</b> 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	<b>Total precipitation</b> in a dfs2 file, for model cells which belong to this type of surface	<b>MIKE FLOOD 2014: Effective precipitation</b> (i.e. total precipitation reduced by Initial loss and Infiltration) in a dfs2 file, for model cells which belong to this type of surface <b>MIKE FLOOD 2014: Effective precipitation</b> (i.e. total precipitation reduced by Initial loss) in a dfs2 file, for model cells which belong to this type of surface <b>MIKE FLOOD 2016: Total precipitation,</b>

# Recommendation

Method B2D: Kinematic Wave + 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 B catchment: Describes the impervious part of the physical catchment area, with CONNECTED impervious areas, pervious area set to zero	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	Kinematic wave (Model B) - without infiltration	2D	
Imperviousness	Actual physical imperviousness for the CONNECTED areas (roofs, roads, etc.) from GIS, possibly divided to "Impervious Flat" and "Impervious Steep"	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
Wetting	Default value	Included in drying/wetting	<b>MIKE URBAN 2014:</b> 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
			<b>MIKE FLOOD 2016:</b> 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
Storage	0 - 1 mm		<b>MIKE FLOOD 2014:</b> 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
Hydraulic resistance (Manning's "n")	Manning's "n": 0.013 - 0.020	Manning's "n": 0.013 - 0.020	Manning's "n": 0.05 - 0.1
Slope	Estimated	N/A	
Length	Estimated according to the catchment size, can be used as a calibration parameter	N/A	
Infiltration	N/A	<b>MIKE URBAN 2014:</b> N/A	<b>MIKE URBAN 2014:</b> includes via effective precipitation (i.e. reduced total precipitation) for model cells which belong to this type of surface
		<b>MIKE FLOOD 2014:</b> for the model cells belonging to this type of surface, evaporation sets to zero in the dfs2 file	<b>MIKE FLOOD 2014:</b> includes as constant evaporation (5 mm/h - 50 mm/h) for model cells which belong to this type of surface
		<b>MIKE FLOOD 2016:</b> for the model cells belonging to the type of surface, defines as input for MIKE21 infiltration module with zero infiltration capacity	<b>MIKE FLOOD 2016:</b> defines as input for MIKE21 infiltration module for model cells which belong to this type
Precipitation load	Total precipitation	Total precipitation in a dfs2 file, for model cells which belong to this type of surface	<b>MIKE FLOOD 2014: Effective precipitation</b> (i.e. total precipitation reduced by initial loss and infiltration) in a dfs2 file, for model cells which belong to this type of surface
			<b>MIKE FLOOD 2014: Effective precipitation</b> (i.e. total precipitation reduced by initial loss) in a dfs2 file, for model cells which belong to this type of surface
			<b>MIKE FLOOD 2016: Total precipitation</b> , for model cells

# Conclusion

- 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.