SIMULATION METHODS FOR WATERSHED MANAGEMENT

Introduction to hydrological modeling

Topics

- Principles of hydrological modelling
- Description and types of models
- Effective rainfall (precipitation loss) calculation or indirect methods for its calculation – Soil Conservation Service – Curve Number method (SCS-CN)
- Catchment hydrologic response calculation – unit hydrograph (UH) method

Model - definition

- General definition:
  - Generalized and simplified representation of some real phenomenon or real system
  - Describe transformation of model inputs into model outputs with respect to model parameters or characteristics
- Mathematical model:
  - Set of mathematical equations describing given phenomenon in a numeric (quantitative) way

$$y = f\left(x_1, x_2, \ldots, x_n; p_1, p_2, \ldots, p_m\right) + \varepsilon$$

Models - division

- Models can be divided into groups according to different characteristics
  - Theoretical vs. Conceptual vs. Empirical
  - Distributed vs. Semi-distributed vs. Lumped
  - Linear vs. Non-linear
  - Time-variant vs. Time-invariant
  - Stochastic vs. Deterministic

Theoretical, conceptual and empirical models

- Theoretical models (white box, physically-based)
  - Use most important laws governing the phenomena
  - Logical structure similar to the real-world system
- Conceptual models (grey box)
  - Intermediate between theoretical and empirical
  - Consider physical laws but in highly simplified form
- Empirical models (black box, input-output)
  - Do not consider basic physical processes

Distributed, semi-distributed and lumped models

- Distributed models
  - Whole catchment is divided into elementary unit areas in which processes are calculated
  - Rasters, grids, hexagonal nets
- Semi-distributed models
  - Catchment is divided into sub-catchments in which processes are calculated and then routed through drainage network connecting them
- Lumped models
  - Describe the catchment as a whole
  - Catchment is described by parameters which do not consider spatial distribution

Linear and non-linear models

- Linear models
  - Hold the principle of superposition
- Non-linear models
  - Do not hold the principle of superposition

$$y_1 = f(x_1) \qquad y_2 = f(x_2)$$

if $y_1 + y_2 = f(x_1 + x_2)$ then the model is linear in system theory sense

if $y_1 + y_2 \neq f(x_1 + x_2)$ then the model is non-linear in system theory sense

Time-variant and time-invariant models

- Time-variant models
  - The input-output relationship changes with time
- Time-invariant models
  - The input-output relationship is not changing with time

$$y = f\left(x_1, x_2, \dots, x_n; \underbrace{p_1, p_2, \dots, p_m}_{\text{At least one of model parameters varies in time}}\right) + \varepsilon$$

$$p_i = f(t)$$

Stochastic and deterministic models

- Stochastic models
  - At least one variable or parameter is regarded as random having probability distribution
  - The model returns different output values for the same input when applied repeatedly
- Deterministic models
  - No variables or parameters are random having probability distribution
  - Application of the model returns always same output for the same inputs

SCS-CN method - introduction

- Developed at USDA in the middle of 20th century – institution Soil Conservation Service (SCS) – now NRCS (Natural Resources Conservation Service)
- Dedicated for calculation of effective rainfall (depth of direct runoff)
- Works with most important catchment characteristics with an influence on rainfall-runoff process

SCS-CN method – basic principles

- Mass conservation law
- Assumption of equality of ratio between actual direct runoff value and precipitation total and ratio between actual infiltratio and maximum potential retention
- Assumption of intial loss amount given by a part of maximum potential retention

Mass conservation law

$$P = I_a + F + Q$$

- P – precipitation
- I_a – initial loss, initial abstraction (short term losses – interception, depression storage etc.)
- F – infiltration
- Q – runoff

All in units of legth

Assumption of ratios equality

$$\frac{Q}{P - I_a} = \frac{F}{S}$$

- P – precipitation
- I_a – initial loss, initial abstraction (short term losses – interception, depression storage etc.)
- F – infiltration
- Q – runoff
- S – maximum potential retention

All in units of length

Assumption of relationship between I_a a S

$$I_a = \lambda \cdot S$$

- I_a – initial loss, initial abstraction (short term losses – interception, depression storage etc.)
- S – maximum potential retention
- λ – regional parameter which depends mainly on geology and climatic conditions (mostly considered as 0.2)

All in units of legth

Derivation

- From mass conservation law and assumption of equality ratios:

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

Derivation

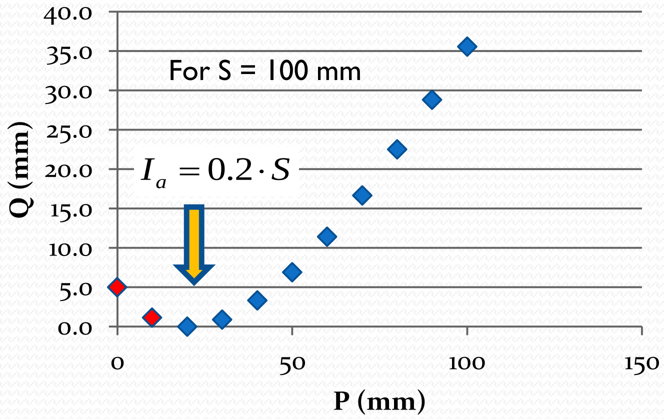
- After substitution of relationship between I_a a S:

$$Q = \frac{(P - 0.2 \cdot S)^2}{P + 0.8 \cdot S}$$

for: $P \geq 0.2 \cdot S$

for: $P < 0.2 \cdot S$

$$Q = 0$$



Maximum potential retention

- *S* can vary theoretically from 0 to ∞, therefore *CN* parameter is introduced to vary between 0 100
- Maximum potential retention is then expressed as:

$$S = \frac{1000}{CN} - 10 \qquad [\text{inch}]$$

Inches are used according to the method origin

Maximum potential retention

- In metric units (SI) the equation changes to:

$$S = 25.4 \cdot \left(\frac{1000}{CN} - 10 \right) \qquad [\mathrm{mm}]$$

Real CN values vary from 40 to 98

CN parameter

- Value of *CN* is based on combination of land use type and hydrological soil group with respect to antecedent precipitation index
- *CN* values can be found in tables for moderate antecedent precipitation index - API II
- *CN* values for other APIs (API I and API III) must be recalculated from the value of *CN* for API II
  - API I – precipitation less than 1.3 cm in dormant season and less than 3.6 cm in growing season in preceeding 5 days
  - API III – precipitation more than 2.8 cm in dormant season and less than 5.3 cm in growing season in preceeding 5 days

CN - values

LU code	Land use	Hydrological soil group			
		A	B	C	D
100	urban areas	61	75	83	87
110	residential areas	61	75	83	87
113	gardens	57	73	82	86
114	parks/lawns	39	61	74	80
120	communications	82	89	92	93
121	streets/roads	82	89	92	93
122	paths	72	82	87	89
123	railway	72	82	87	89
130	industrial areas	81	88	91	93
200	arable land - maize	72	81	88	91
255	small grain	63	75	83	87

Note: values used for purposes of EMTAL project

Graphic representation

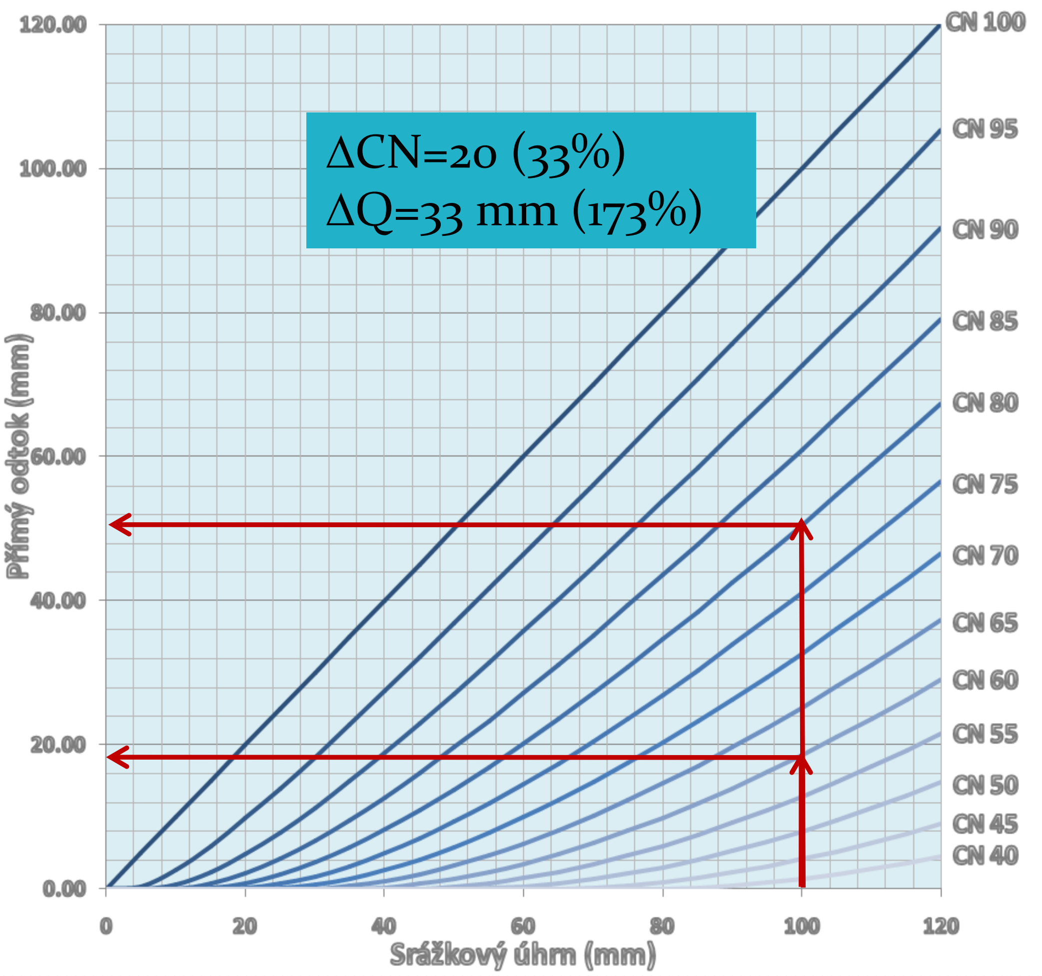
Precipitation total
100 mm

Park/HSG B
→ CN=61

Q=19 mm

Maize/HSG B
→ CN=81

Q=52 mm



ΔCN=20 (33%)
ΔQ=33 mm (173%)

Hydrologic soil groups

Hydrologic soil group	Infiltration rate from inch/hr (cm/d)	Infiltration rate to inch/hr (cm/d)
A	0.30 (18.29)	0.45 (27.43) and more
B	0.15 (9.14)	0.30 (18.29)
C	0.05 (3.05)	0.15 (9.14)
D	0.00	0.05 (3.05)

Antecedent precipitation index

API	Precipitation total in last 5 days (cm)	
	Dormant season	Growing season
I	Less than 1.3	Less than 3.6
II	1.3 to 2.8	3.6 to 5.3
III	More than 2.8	More than 5.3

Antecedent precipitation index

- *CN* values calculation for other antecedent precipitation indexes

$$CN_{I} = \frac{CN_{II}}{2.281 - 0.01281 \cdot CN_{II}}$$

$$CN_{III} = \frac{CN_{II}}{0.427 + 0.00573 \cdot CN_{II}}$$

CN values for heterogeneous areas

- In case of area heterogeneity the final value of *CN* is calculated as weighted average

$$CN = \frac{\sum (CN_i \cdot A_i)}{\sum A_i}$$

Advantages of the method

- Simple conceptual method for calculation of direct runoff
- Well documented, introduced and widely used method; a lot of empirical data is available
- The method has only one parameter – parameter *CN*
- For given cases produces relevant outputs
- Works with most factors with important influence on direct runoff forming

Disadvantages of the method

- Method does not consider slopes
- Soil characeteristics are considered only roughly
- Soil profile saturation is considered only by three states
- Method is developped in conditions of USA – needs validation when used in other regions, sometimes recalibration is also needed
- Method originaly does not consider precipitation distribution in time
- Method is not suitable for small precipitation totals