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HS2.2.1: Models and Data: Understanding and representing spatio-temporal dynamics of hydrological processes

Distributed hydrological modelling using spatiotemporally varying velocities

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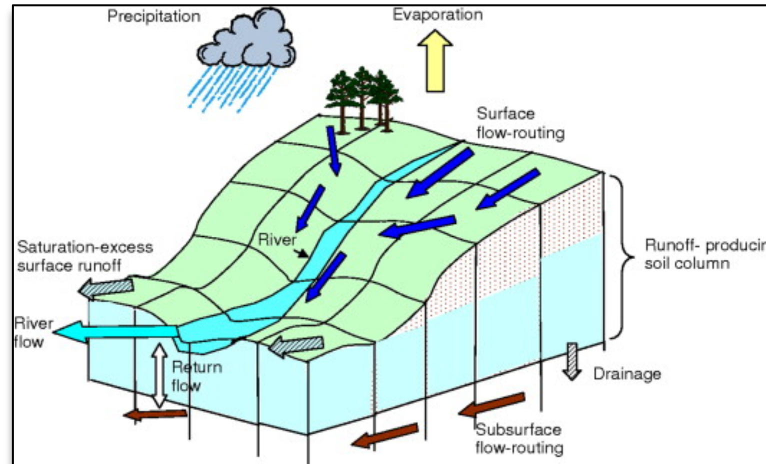
Presentation available online: www.itia.ntua.gr/2026/

Hydrological models

- Hydrological models
  - Black box
  - Conceptual
  - Deterministic
    - Lumped
    - Semi-distributed
    - Distributed



Example of a distributed hydrological model

Parameterization approaches

Lumped model

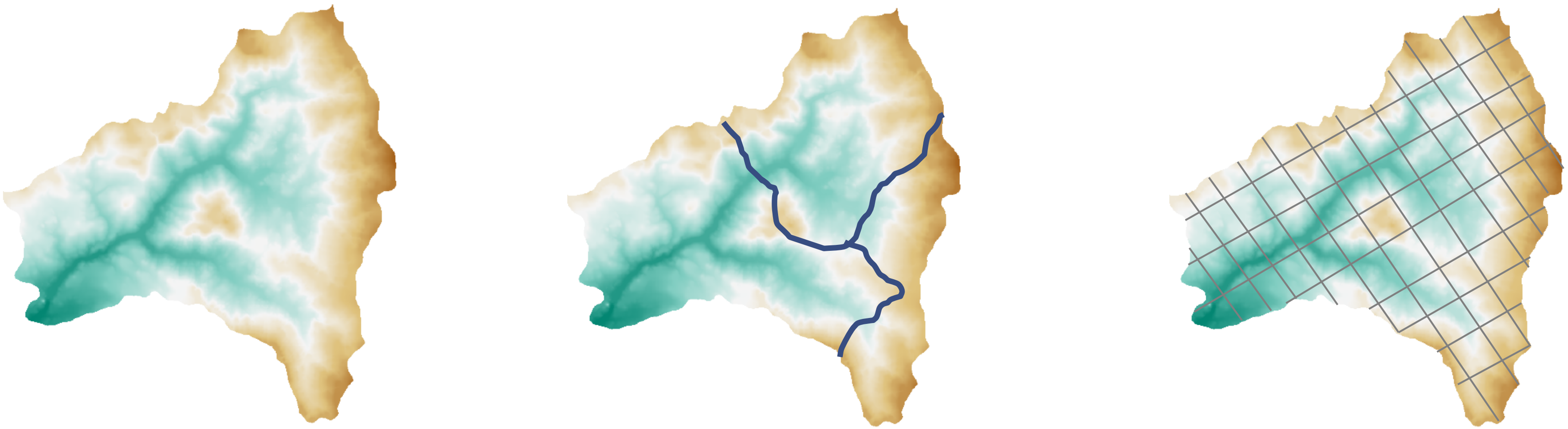
Same parameter values for the entire basin

Semi-distributed model

Parameters assigned to large spatial entities (typically, sub-basins)

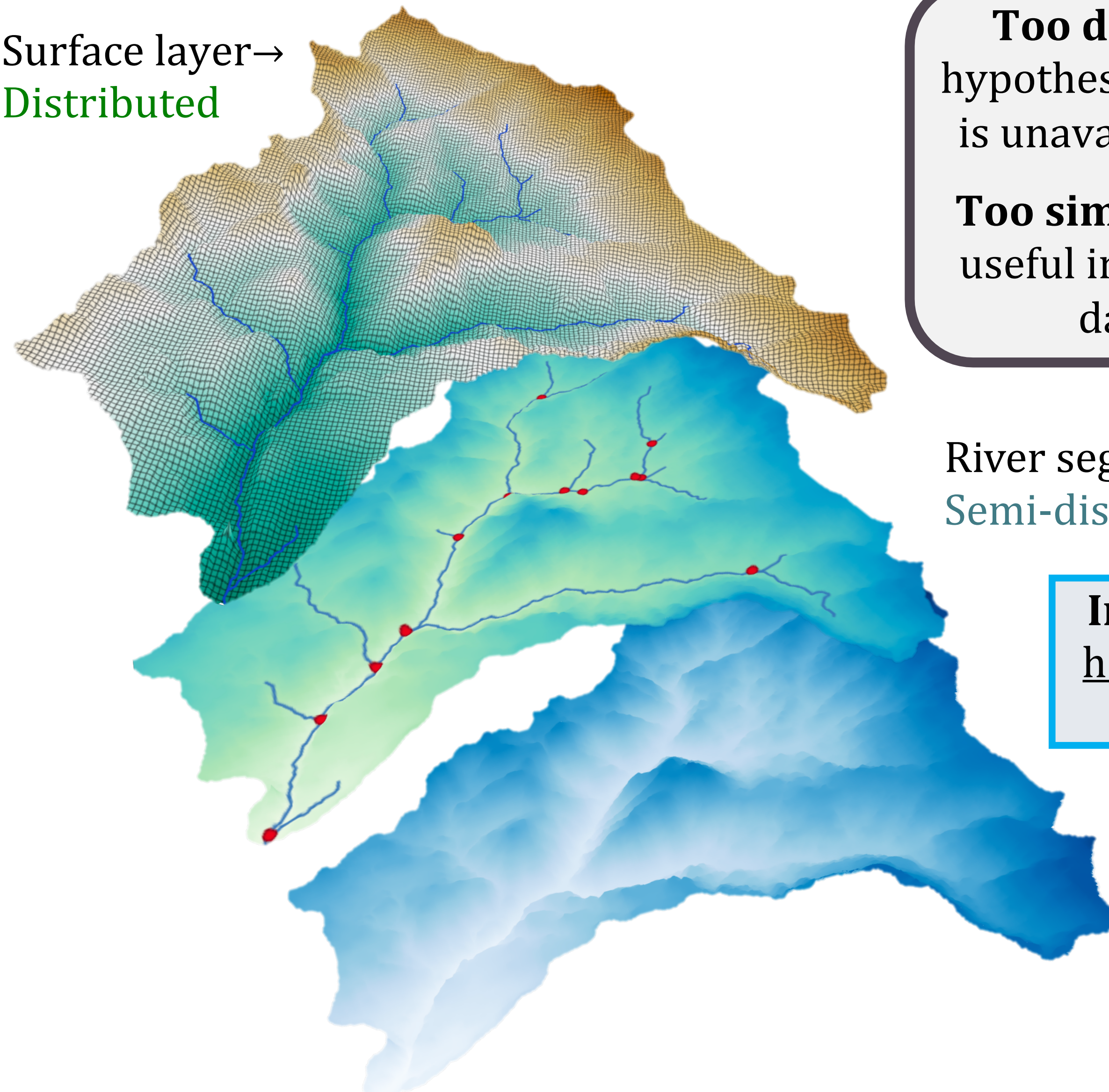
Distributed model

Parameter values varying per cell



Hybrid modelling approach

Surface layer→ Distributed



Too detailed models: need to hypothesize distributed data, which is unavailable at this specific scale

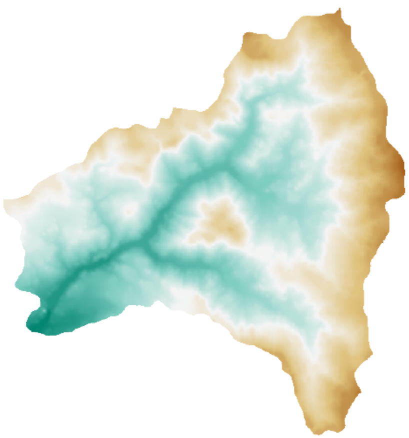
Too simple models: risk of losing useful information by aggregating data to coarser scales

River segment layer → Semi-distributed

Innovation: use of different heterogenous detail levels of available data

Aquifer layer → Lumped

Distributed approach



Surface Layer

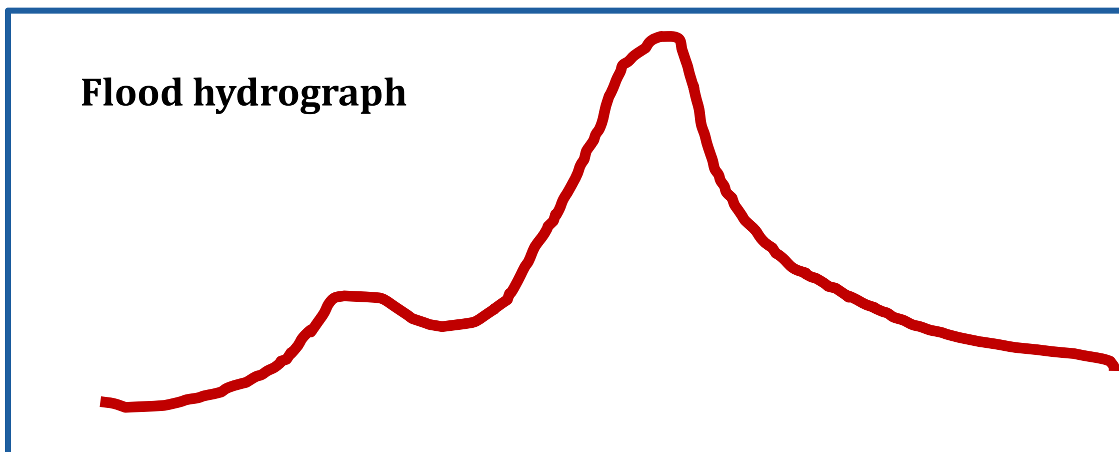
Effective rainfall

Revised method for CN assessment
(Savvidou et al., 2018)

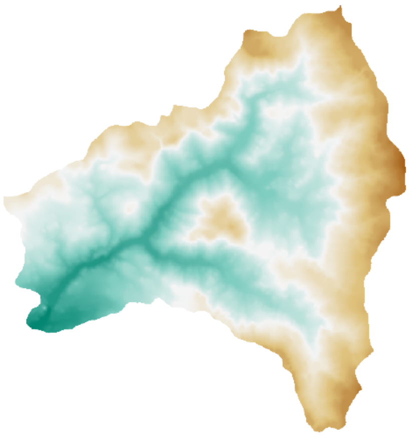
$$CN = 10 + 9 \times i_{PERM} + 6 \times i_{VEG} + 3 \times i_{SLOPE}$$

i_{PERM} ➔ Permeability (soil, geology)
i_{VEG} ➔ Land use/ cover(vegetation)
i_{SLOPE} ➔ Drainage capacity (slope, structures)

Simulation model for rainfall event ➞ **Distributed approach**



Semi-distributed approach



Transformation of the effective rainfall into a hydrograph in the outlet→ **Isochronous method**

Discrete types of surface runoff

Channel flow along the river network
- Slope
- Roughness

Overland flow across the catchment's terrain
- Slope
- Roughness
- Geometry
- Discharge

Calculation of overland velocity

$$V_o = k\,J^{1/2}$$

J: terrain slope

k: coefficient associated with land use/cover characteristics

Land cover type	k (ft/s)	k (m/s)
Dense underbrush	0.7	0.2
Light underbrush	1.4	0.4
Heavy ground litter	2.5	0.8
Bermuda grass	1.0	0.3
Dense grass	1.5	0.5
Short grass	2.1	0.6
Short grass pasture	7.0	2.1
Conventional tillage with residue	1.2	0.4
Conventional tillage no residue	2.2	0.7
Agricultural, cultivated, straight row	9.1	2.8
Agricultural, cultivated, contour or strip cropped	4.6	1.4
Agricultural, trash fallow	4.5	1.4
Rangeland	1.3	0.4
Alluvial fans	10.3	3.1
Grassed waterway	15.7	4.8
Small upland gullies	23.5	7.2
Paved area	20.8	6.3
Paved gutter	46.3	14.1

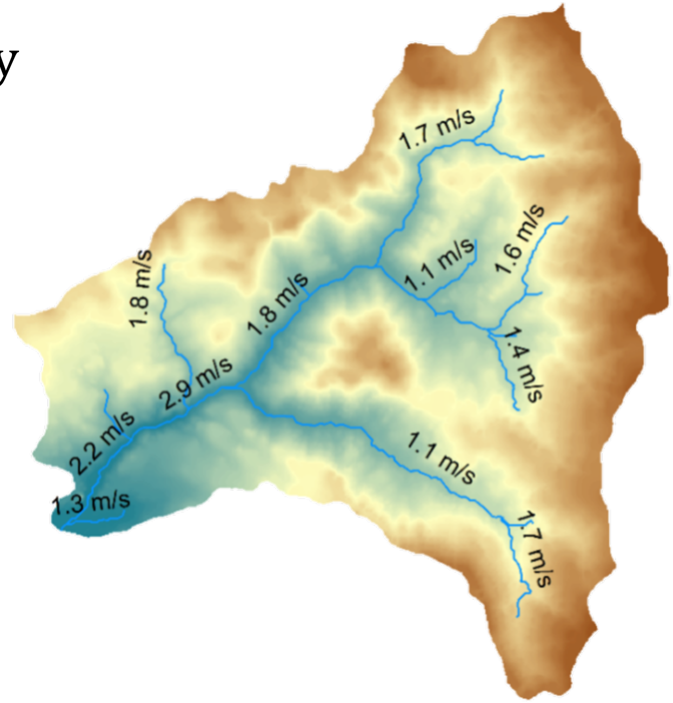
Recommended k values per land cover type (adapted from McCuen, 1997)

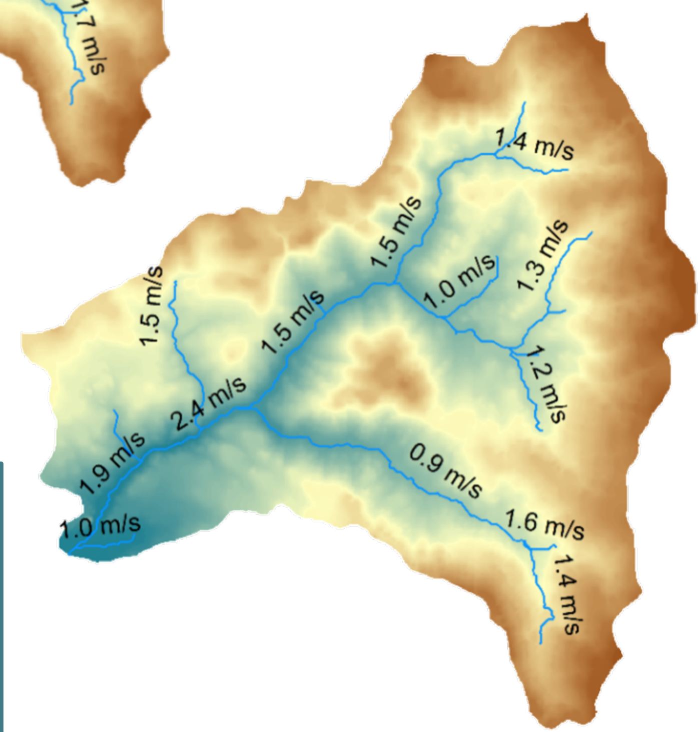
+ Correction formula of steep slopes (Grimaldi *et al.*, 2012):

$$J' = 0.05247 + 0.06363J - 0.182\, e^{-62.38J}$$

Estimation of channel velocities

- Velocity: hydraulic quantity
- Depending on:
  - River geometry
  - Hydraulic properties
  - **Discharge**
- Spatially & temporally varying





Assignment of varying velocities across the river network of Nedontas, for two flood events

Most of known literature approaches➔ **oversimplified assumption of a spatially and temporally constant value of velocity**

Spatial variability of velocity➔ different *V* for each segment of the river network

Time variability➔ different concentration times for each event ➔ different velocities in the river

Estimation of channel velocities

$$V_i = \frac{1}{n_i} R_i^{2/3} \; J_i^{1/2}$$

$$R_i^{2/3} = c$$ → Lumped parameter for the entire basin

$$t_u = \frac{L_u}{V_u} = \frac{L_u}{k_u \, J_u^{1/2}}$$ → Time of concentration of the most upstream sub-basin

$$t_r = t_c - t_u$$ → Total travel time across the longest river course

$$t_r = \frac{L_1}{V_1} + \frac{L_2}{V_2} + \cdots + \frac{L_N}{V_N}$$ → N: set of segments of the main channel

$$t_r = \frac{1}{c}\left(\frac{n_1 L_1}{J_1^{1/2}} + \frac{n_2 L_2}{J_2^{1/2}} + \cdots + \frac{n_N L_N}{J_N^{1/2}}\right)$$

$$c = \frac{1}{t_c - t_u}\left(\frac{n_1 L_1}{J_1^{1/2}} + \frac{n_2 L_2}{J_2^{1/2}} + \cdots + \frac{n_N L_N}{J_N^{1/2}}\right)$$

Varying time of concentration t_c

Different in every episode

$$t_c = t_0 \, i_e^{-\beta}$$

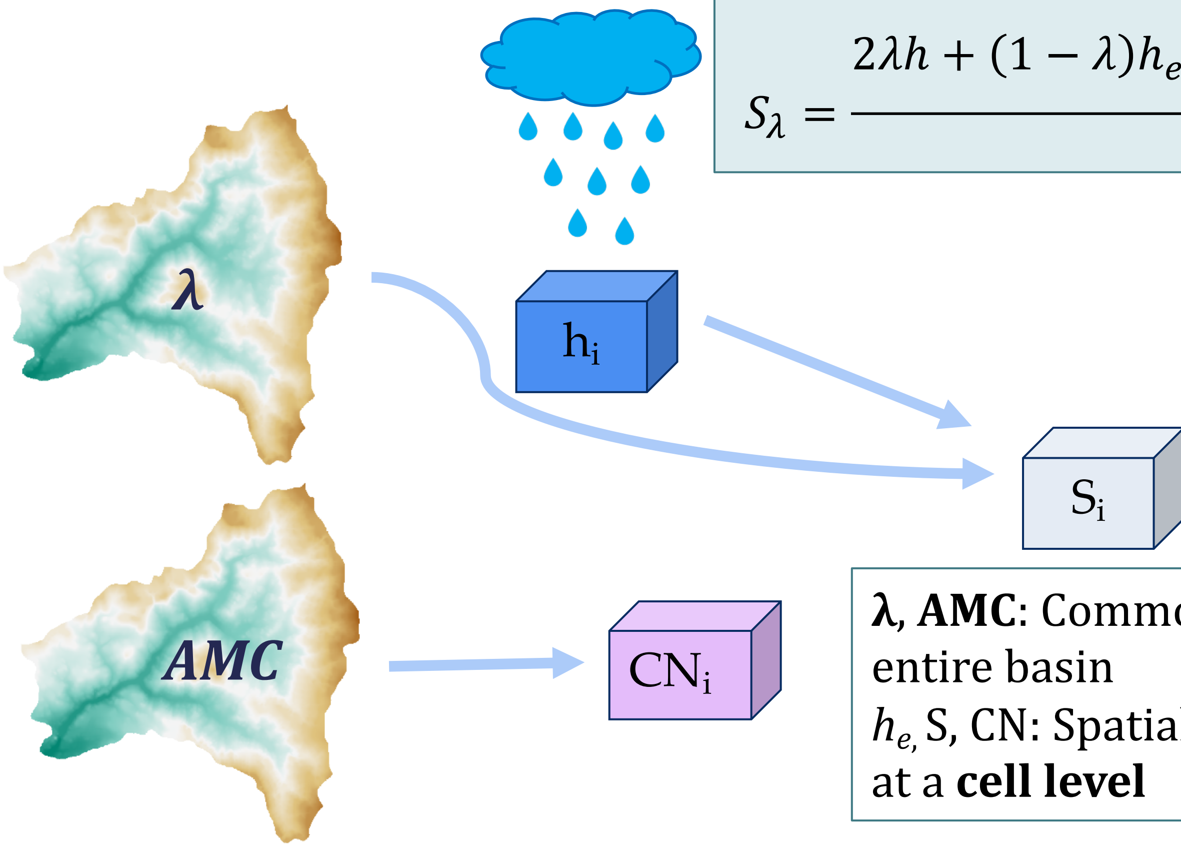
Michailidi et al. (2018)

Lumped approach

Standard value for initial abstraction ratio λ according to SCS: 0.20
Standard values in small catchments with steep slopes: ≤ 0.05

} **Need for adjustment**

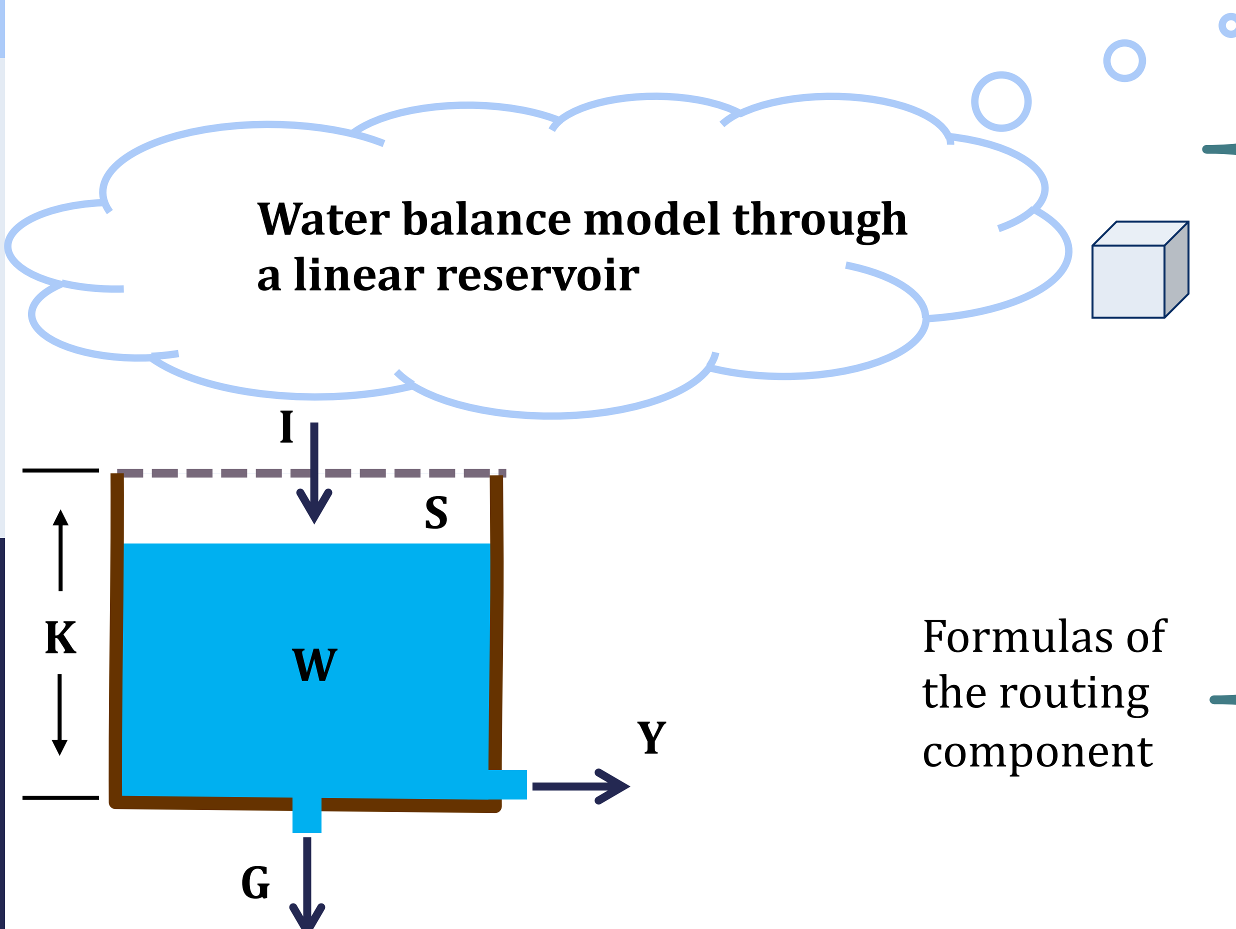
$$S_\lambda = \frac{2\lambda h + (1-\lambda)h_e - \sqrt{h_e[h_e(1-\lambda)^2 + 4\lambda h]}}{2\lambda^2}$$



λ, AMC: Common parameters for the entire basin
h_e, S, CN: Spatially – varying parameters at a **cell level**

Enhanced model version

- **Subsurface flow →** Dominating component of a flood hydrograph
- Need for separation?
- **Empirical model →** subsurface flow simulation



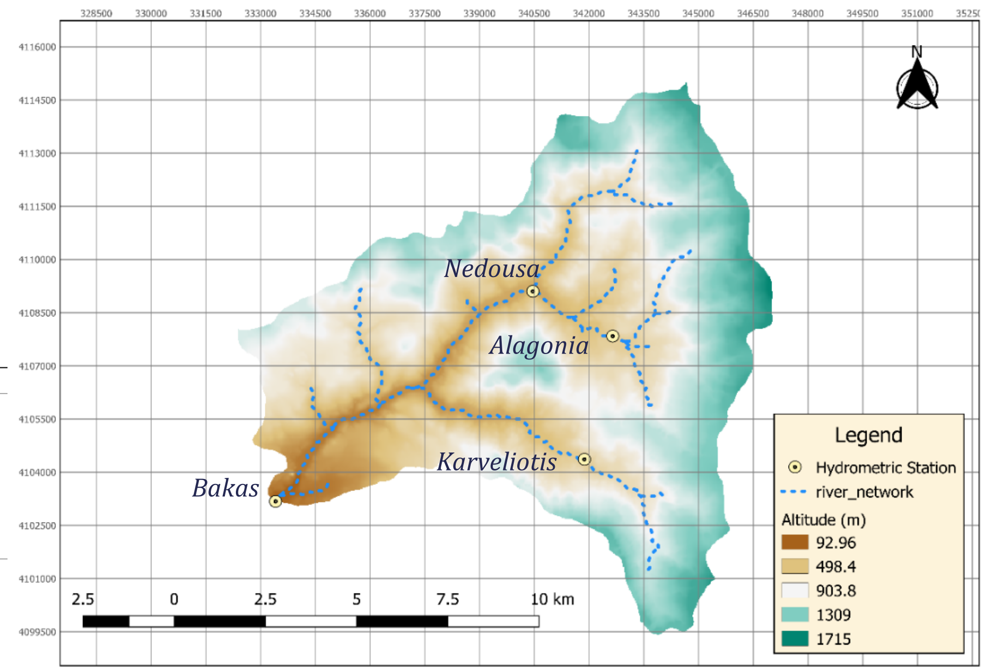
$$
\begin{cases}
W_t = W_{t-1} + I_t - Y_t - G_t \\
K = W_0 + S_0 \\
S_t = K - W_{t-1} \\
Y_t = \kappa \, W_t \\
G_t = \mu \, W_t
\end{cases}
$$

Formulas of the routing component

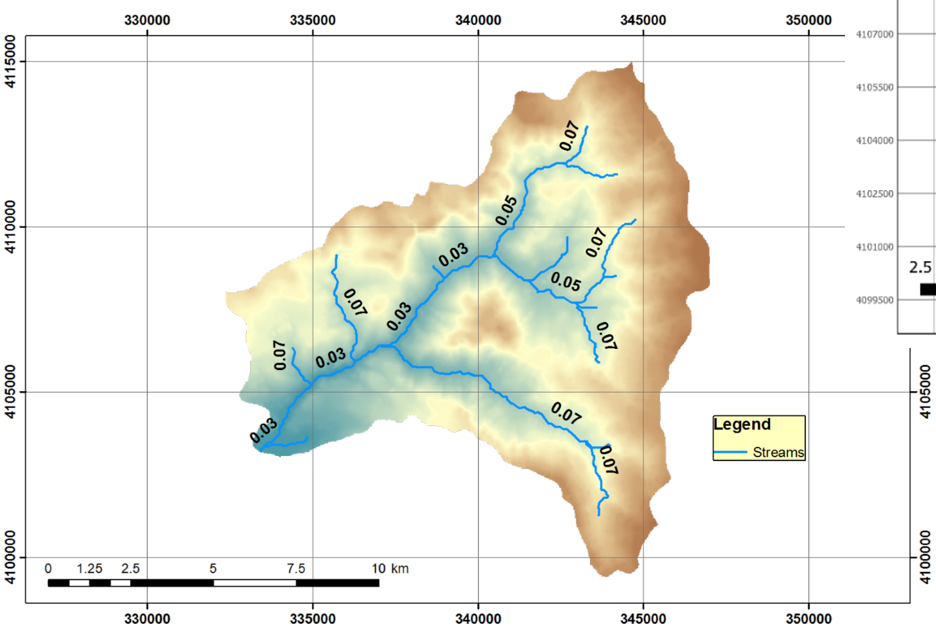
$$
\begin{cases}
Q_t = \varphi \, X_t \\
X_t = X_{t-1} + H_{et} - Q_t \\
R_t = Y_{t-\delta} + Q_{t-\tau}
\end{cases}
$$

Study area– Nedontas river basin

- Western Peloponnese, crosses the city of Kalamata (food prone area)
- River basin properties:
  - $A = 119.3\ \text{km}^2$
  - $z_{\text{min}} = 93$ m
  - $z_{\text{max}} = 1715$ m



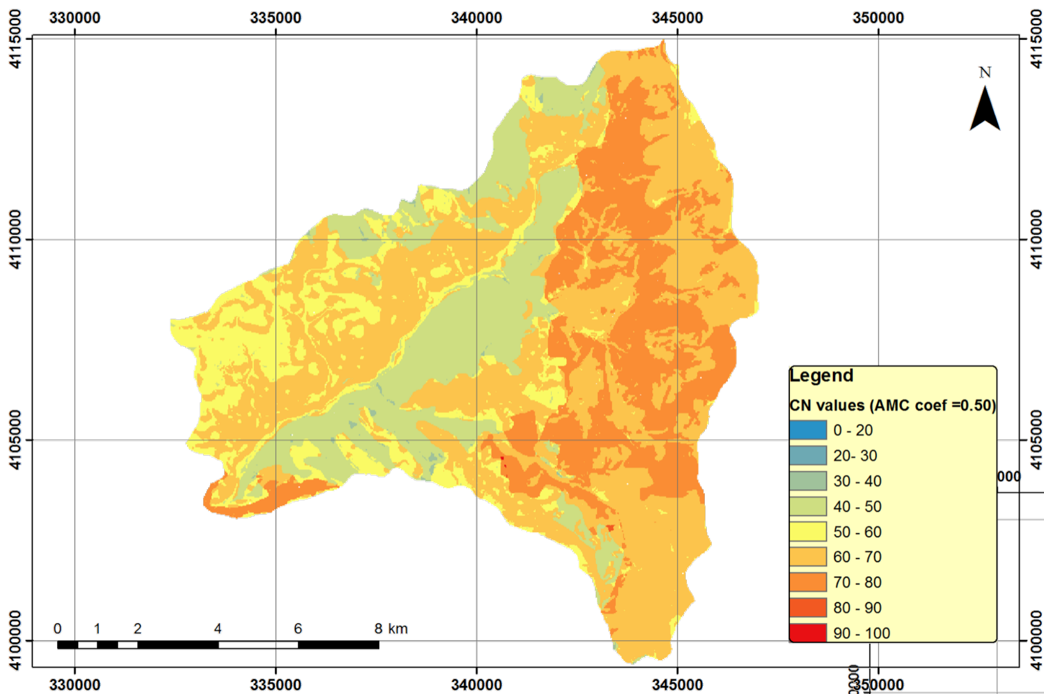
DEM of study area



Manning's coefficient values across stream segments

- Major tributaries: Nedousa, Alagonia, Karveliotis
- Estimation of Manning's coefficients macroscopically by means of satellite imagery interpretation
- $t_0 = 3.1$ h, $\beta = 0.193$

Study area– Nedontas river basin

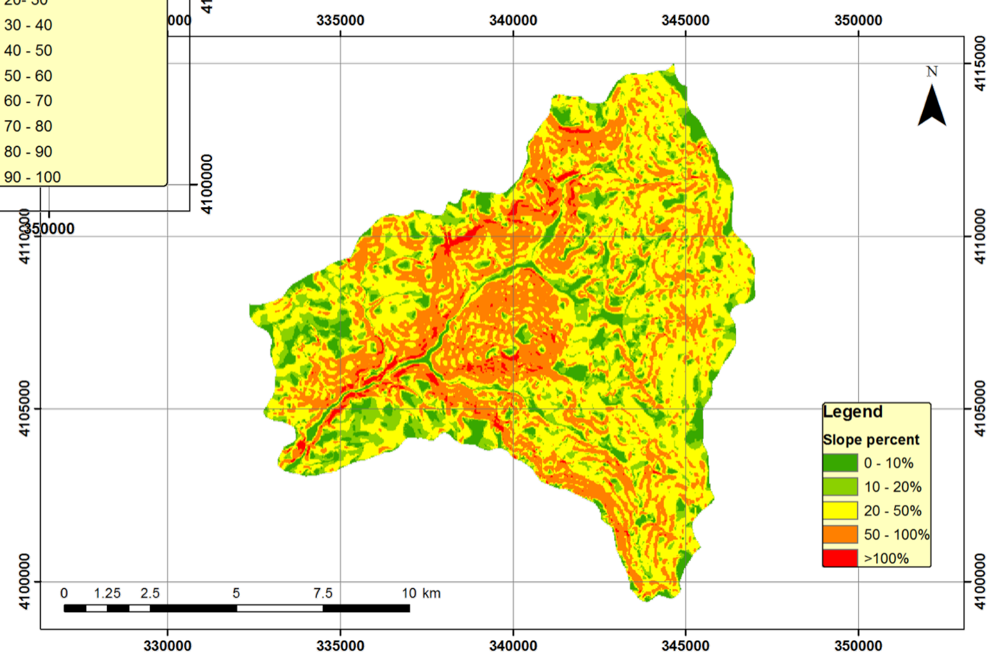


CN values for AMC II conditions (Savvidou et al., 2018)

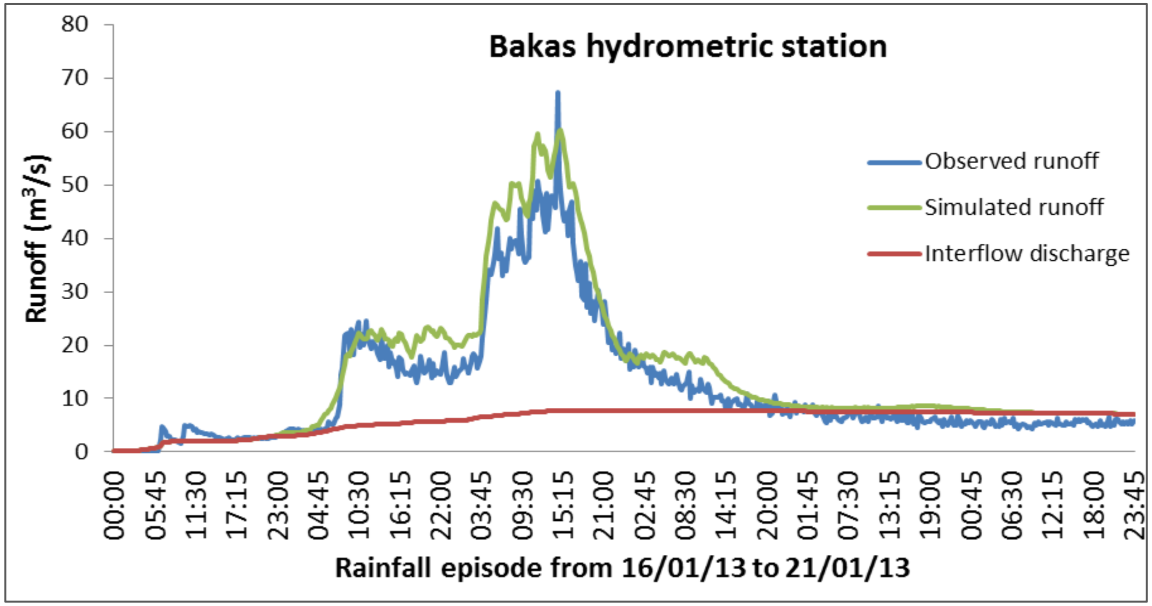
- Mean CN = 62.5

- Steep slopes, mean value 49%

Slope classification



Results of lumped model – Event A

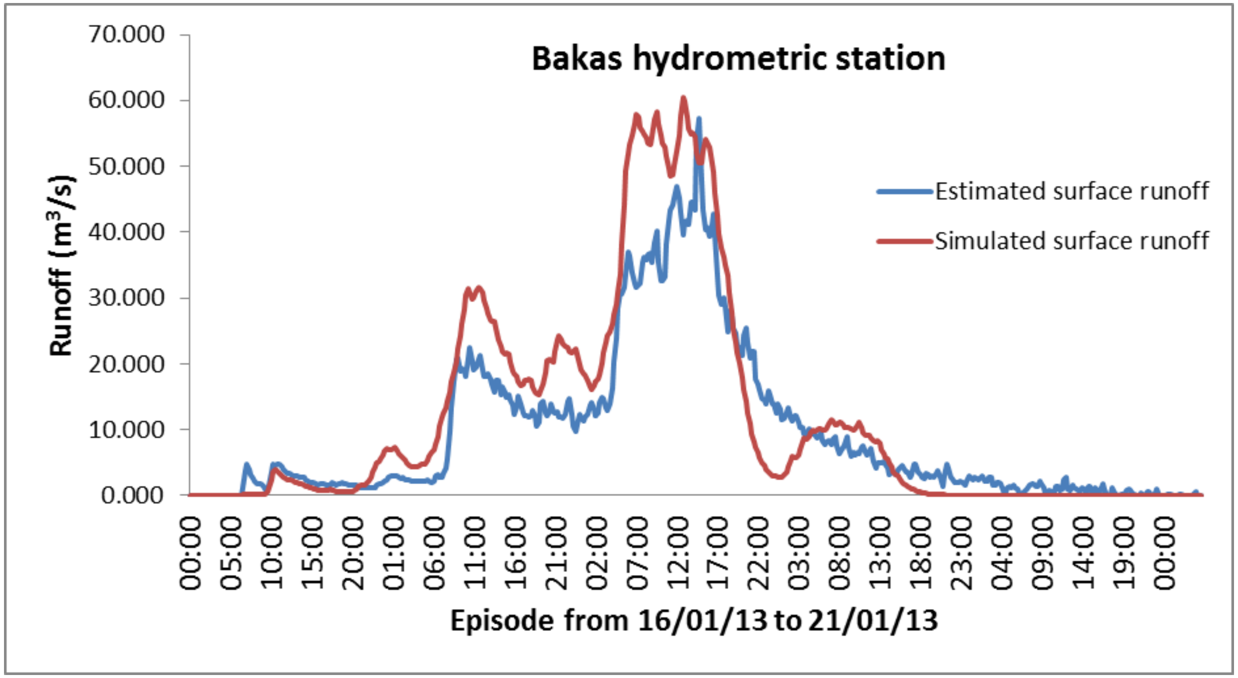


Parameter	Value
CN	41.3
λ	0.0745
κ	0.0004
μ	0
W_0	12.8 mm
$\delta - \tau$	2 hours
φ	0.0570

- Nash-Sutcliffe Efficiency Metric
- $PEV = 100\left|\frac{V_0 - V_M}{V_0}\right|$
- $PERF = 100\left|\frac{Q_{0(PEAK)} - Q_{M(PEAK)}}{Q_{0(PEAK)}}\right|$
- $\Delta T_{PF} = |Tpeak_{obs} - Tpeak_{sim}|$

Metric	Value
NSE	0.946
PEV	-22.1%
$PEPF$	+10.6%
ΔT_{PF}	+45 min

Results of distributed surface model– Event A



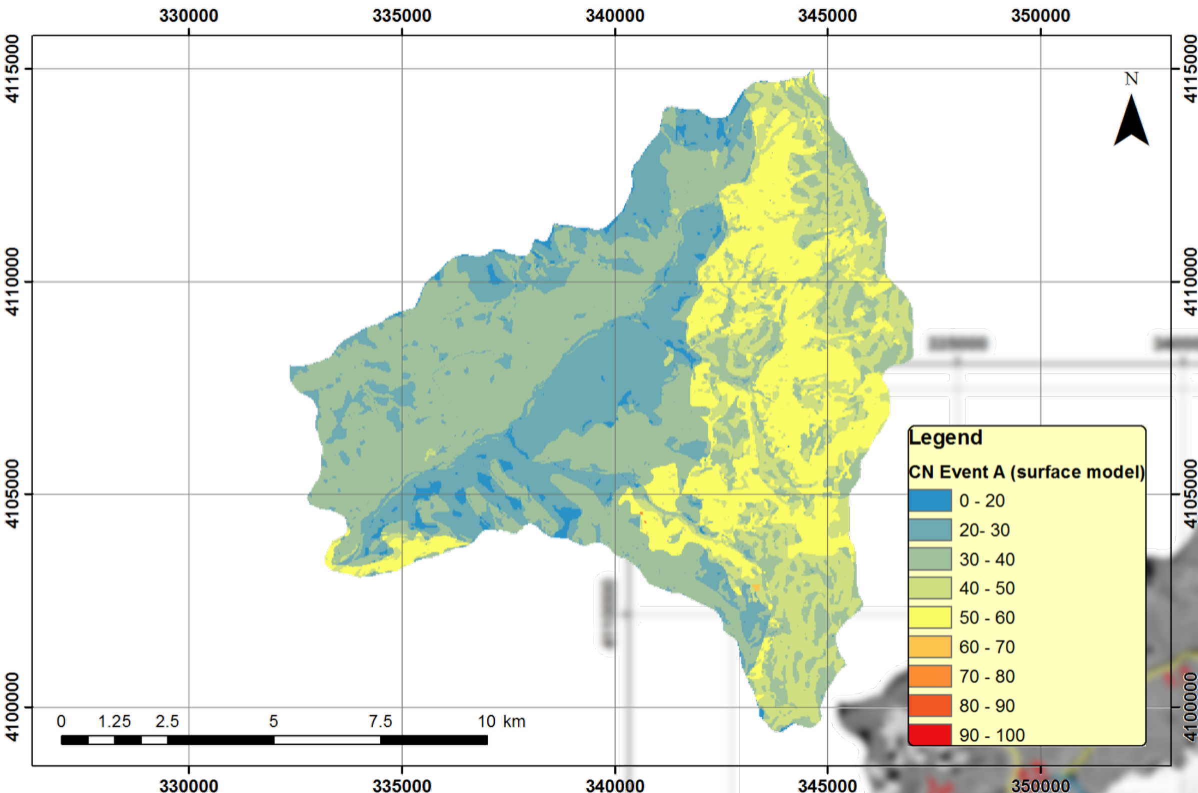
Parameter	Value
λ	0.050
AMC	0.005

Model parameters after optimization

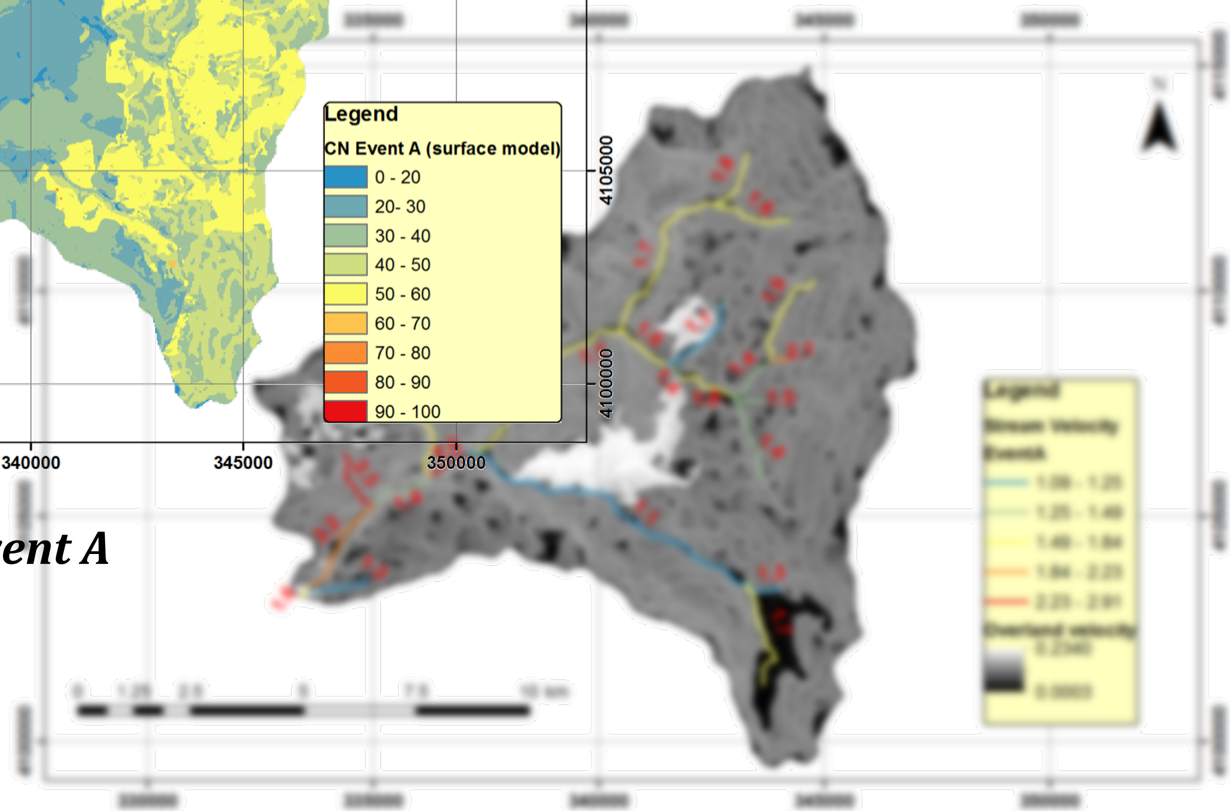
- Nash-Sutcliffe Efficiency Metric
- $PEV = 100\left|\frac{V_0 - V_M}{V_0}\right|$
- $PERF = 100\left|\frac{Q_{0(PEAK)} - Q_{M(PEAK)}}{Q_{0(PEAK)}}\right|$
- $\Delta T_{PF} = |Tpeak_{obs} - Tpeak_{sim}|$

Metric	Value
NSE	0.050
PEV	-21.4%
PEPF	-5.57%
ΔT_{PF}	-120 min

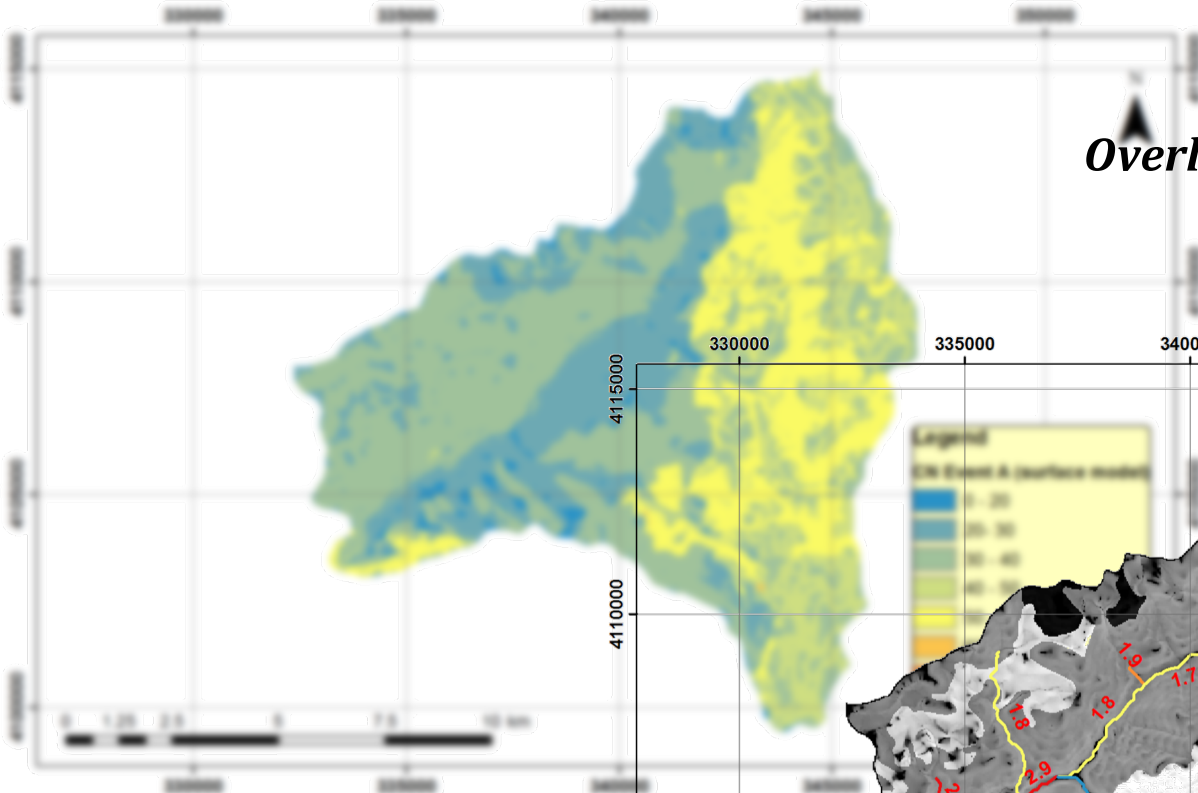
Results of surface model– Event A



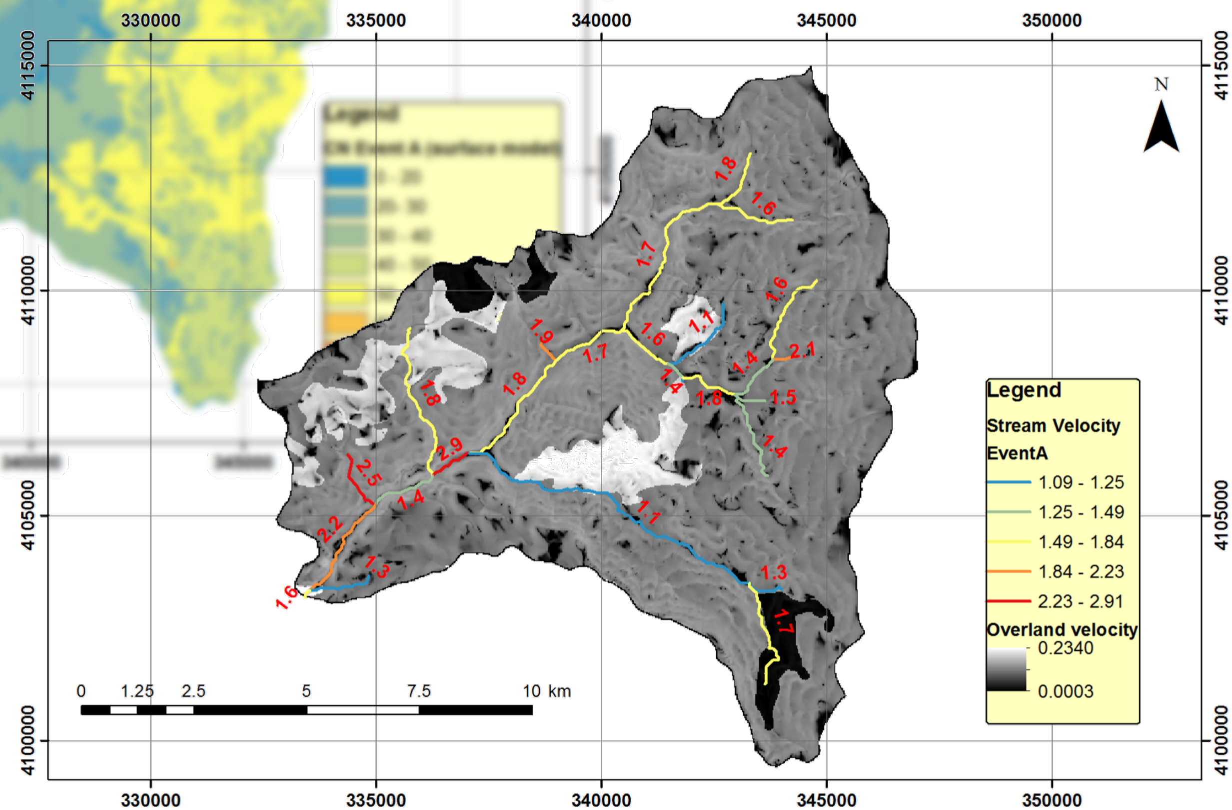
Adjusted CN values for Event A



Results of surface model– Event A

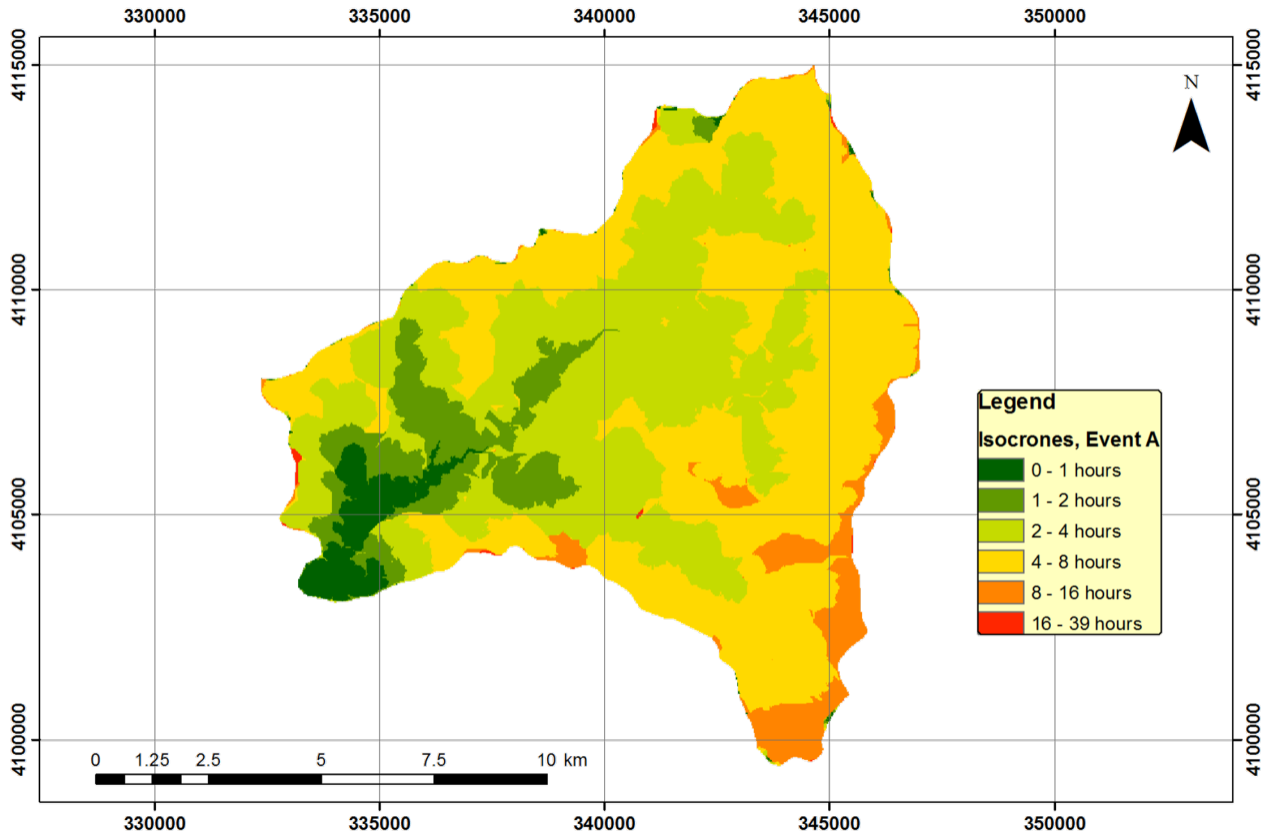


Overland and channel velocities of Event A



Time of concentration: 3.69 h

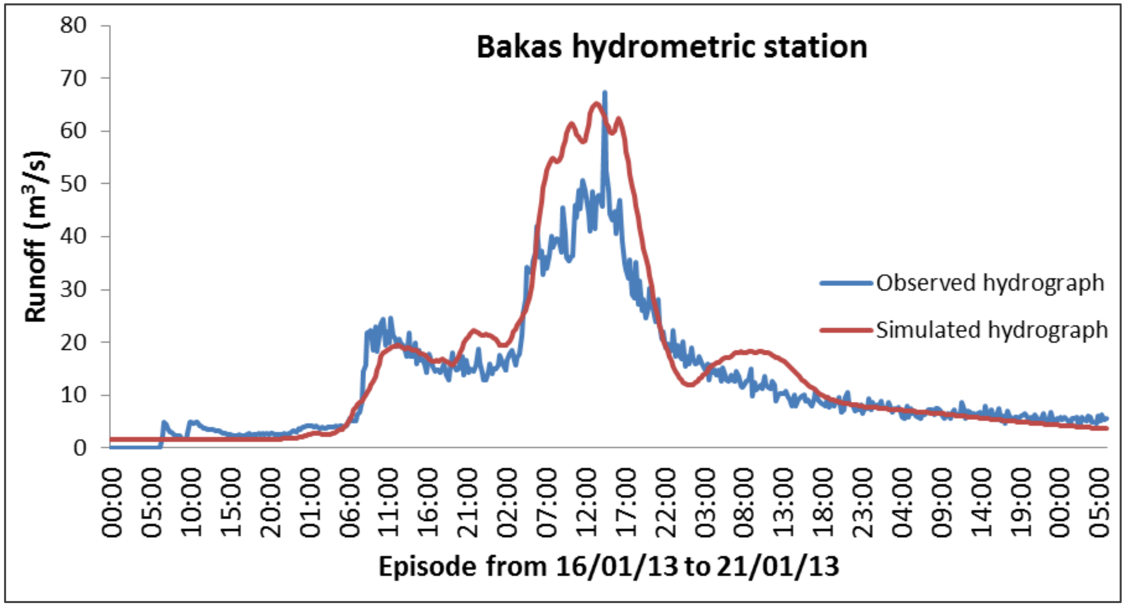
Results of surface model– Event A



Isochrones of Event A

Mean travel time: 5.70 h

Results of distributed complete model

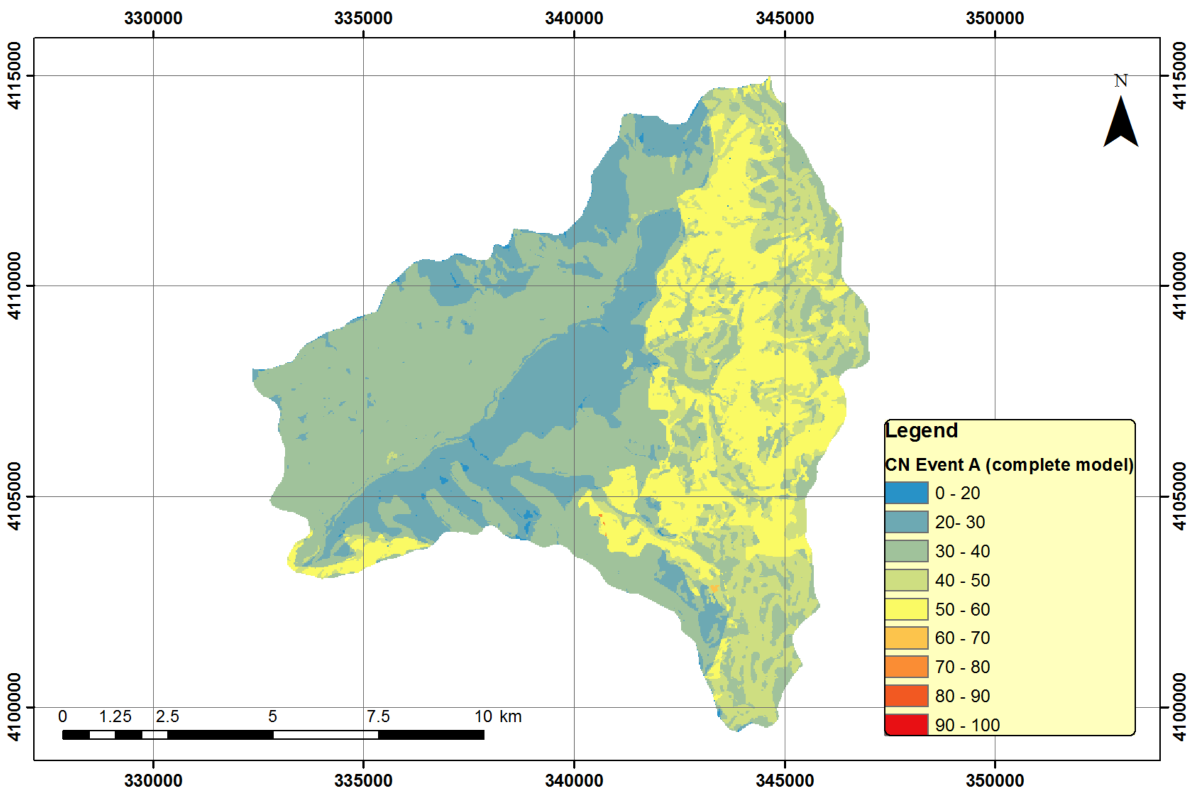


Parameter	Value
λ	0.245
AMC	0.034
κ	0.00078
μ	0.0061
W_0	16.50 mm
δ	9.25 hours

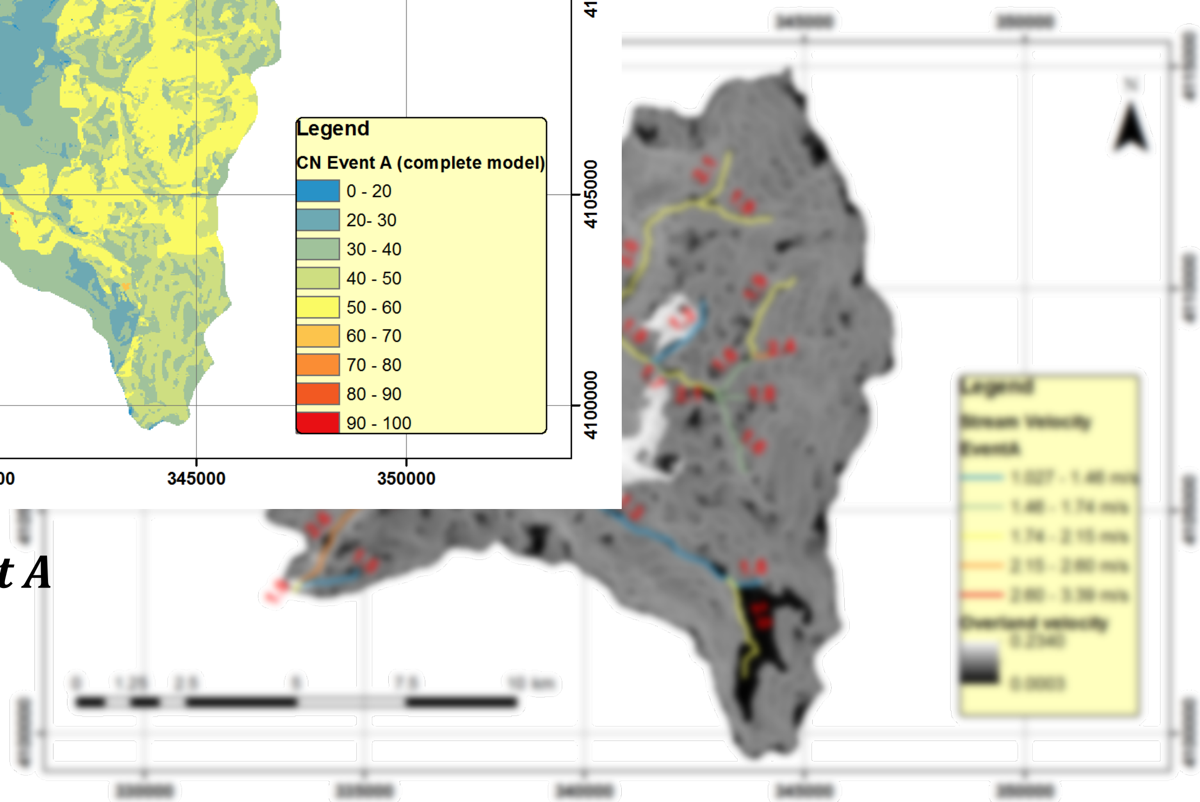
Metric	Value
NSE	0.865
PEV	-15.4%
$PEPF$	+3.0%
ΔT_{PF}	-1 hour

- Nash-Sutcliffe Efficiency Metric
- $PEV = 100\left|\frac{V_0 - V_M}{V_0}\right|$
- $PERF = 100\left|\frac{Q_{0(PEAK)} - Q_{M(PEAK)}}{Q_{0(PEAK)}}\right|$
- $\Delta T_{PF} = |Tpeak_{obs} - Tpeak_{sim}|$

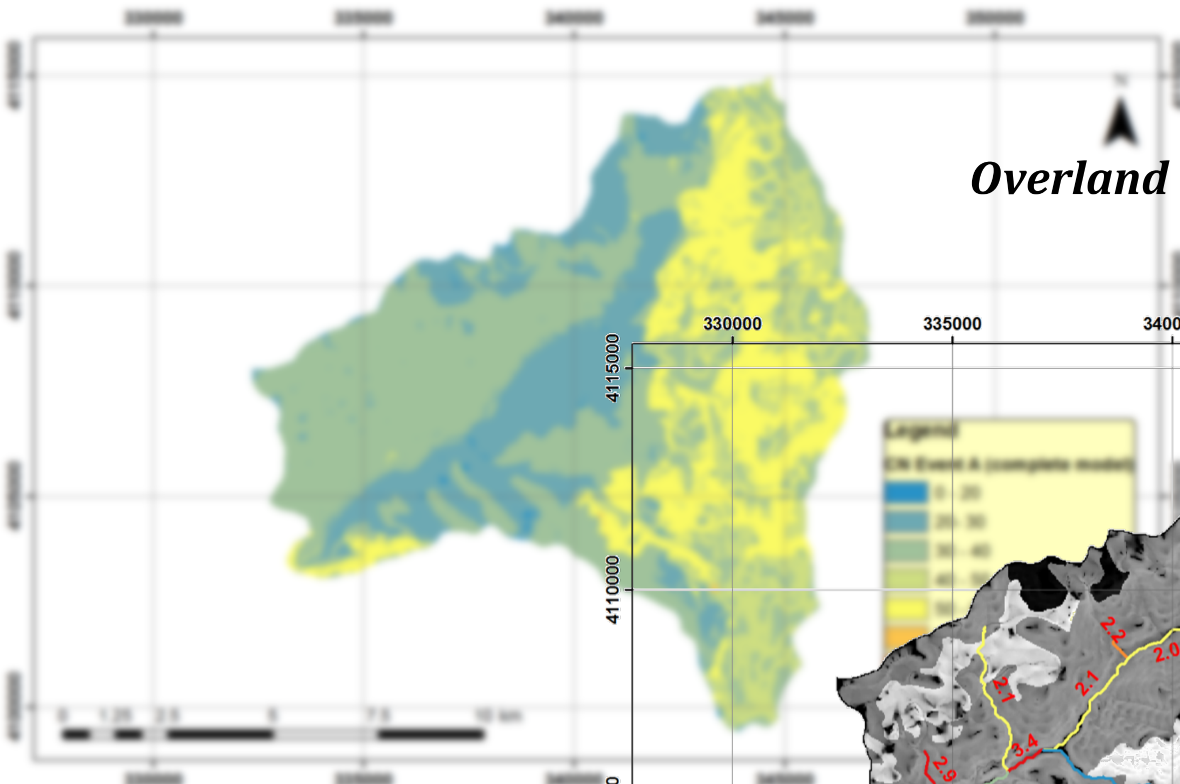
Results of distributed complete model



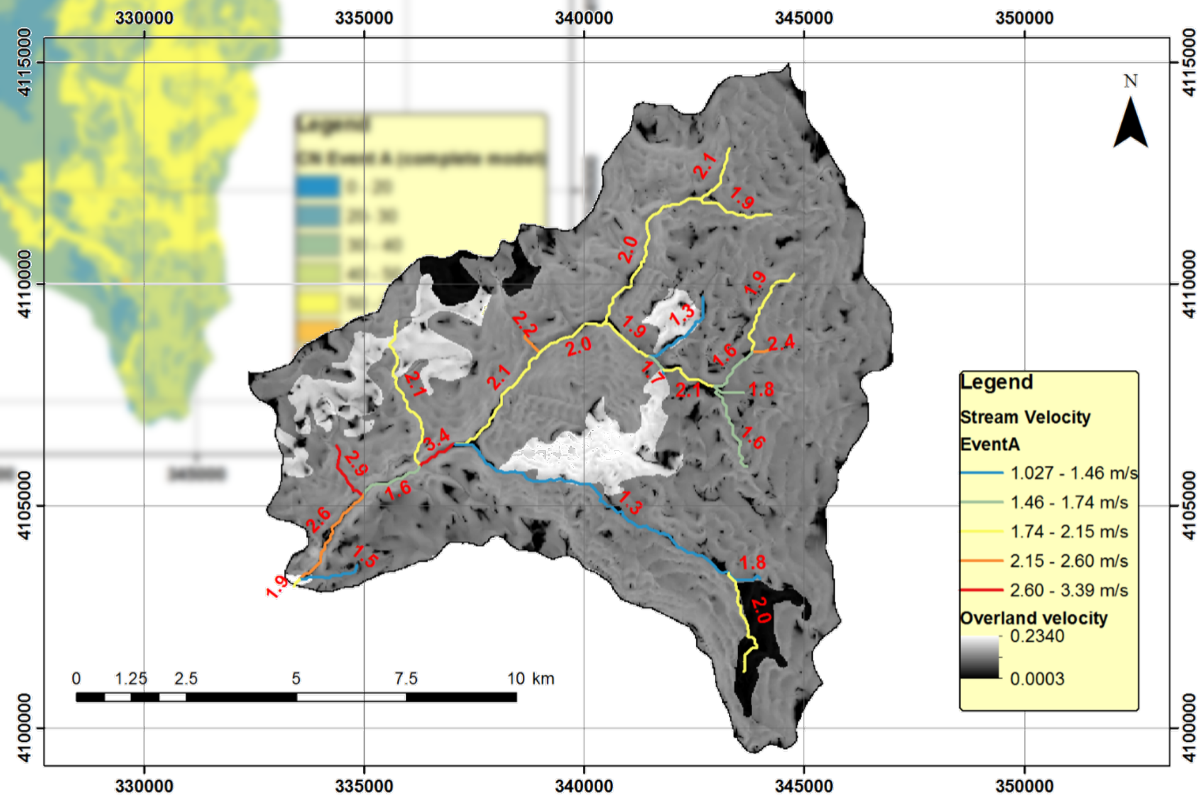
Adjusted CN values for Event A



Results of distributed complete model

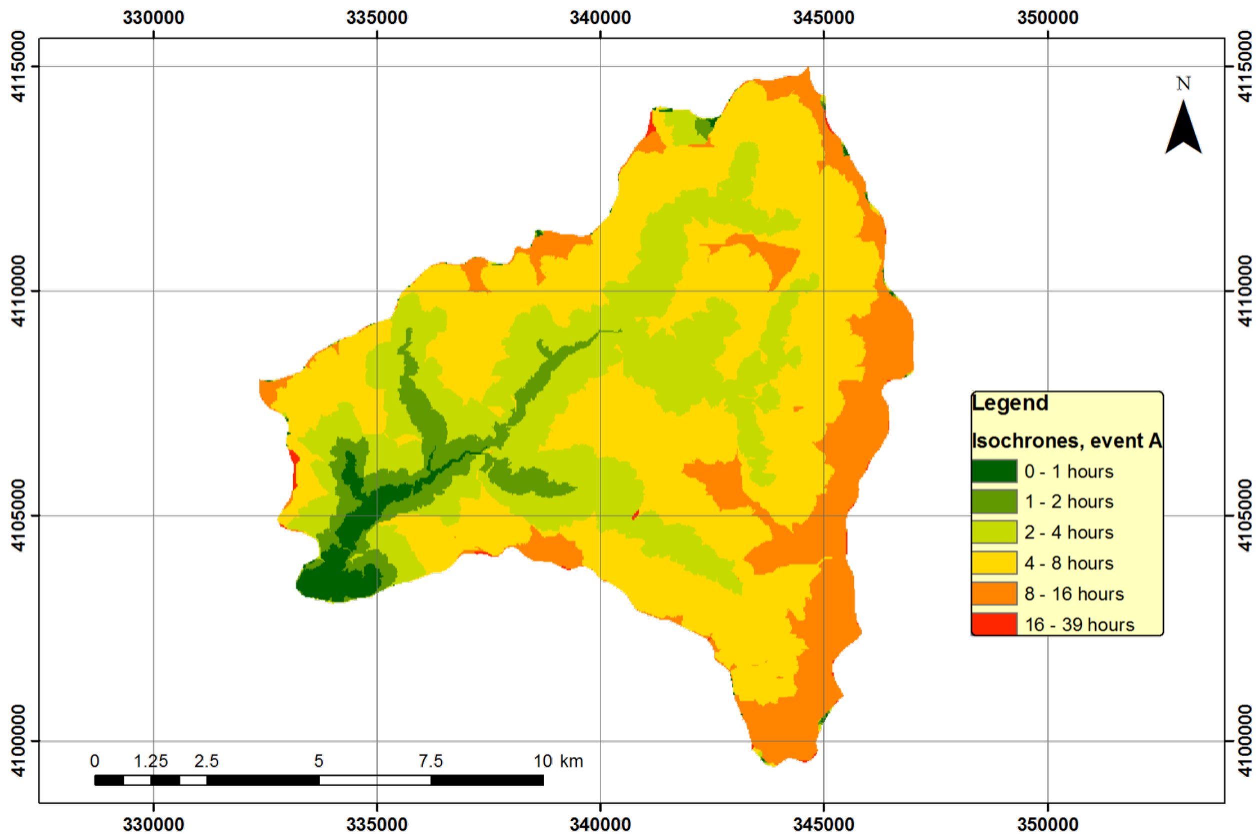


Overland and channel velocities of Event A



Time of concentration:
3.59 h

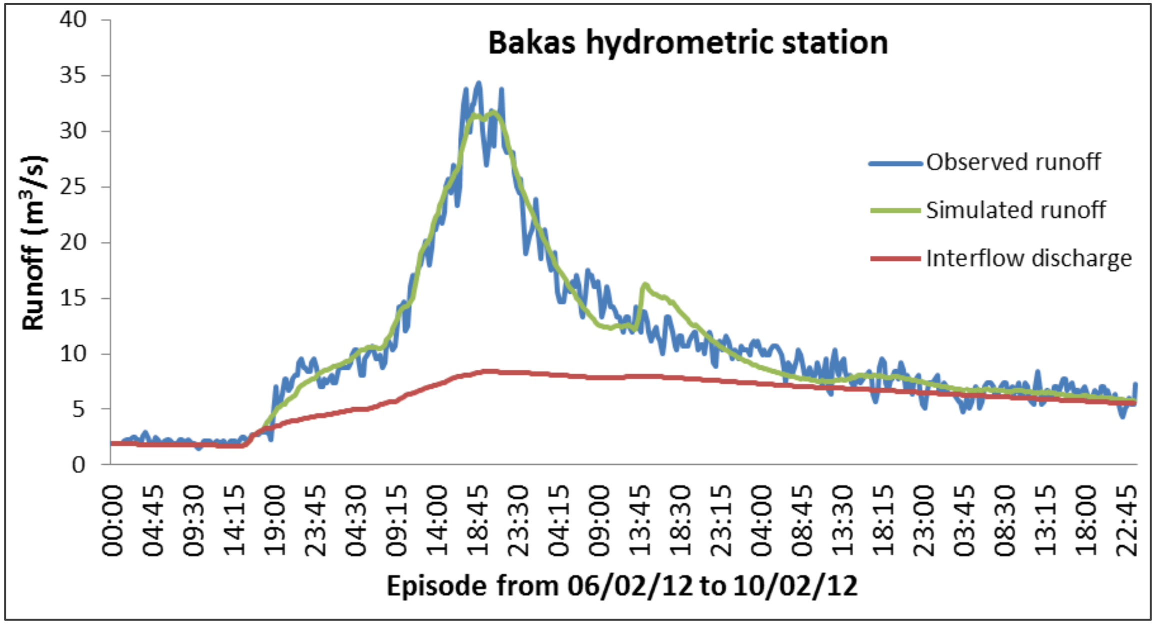
Results of distributed complete model



Isochrones of Event A, complete model

Mean travel time: 5.34 h

Results of lumped model – Event B

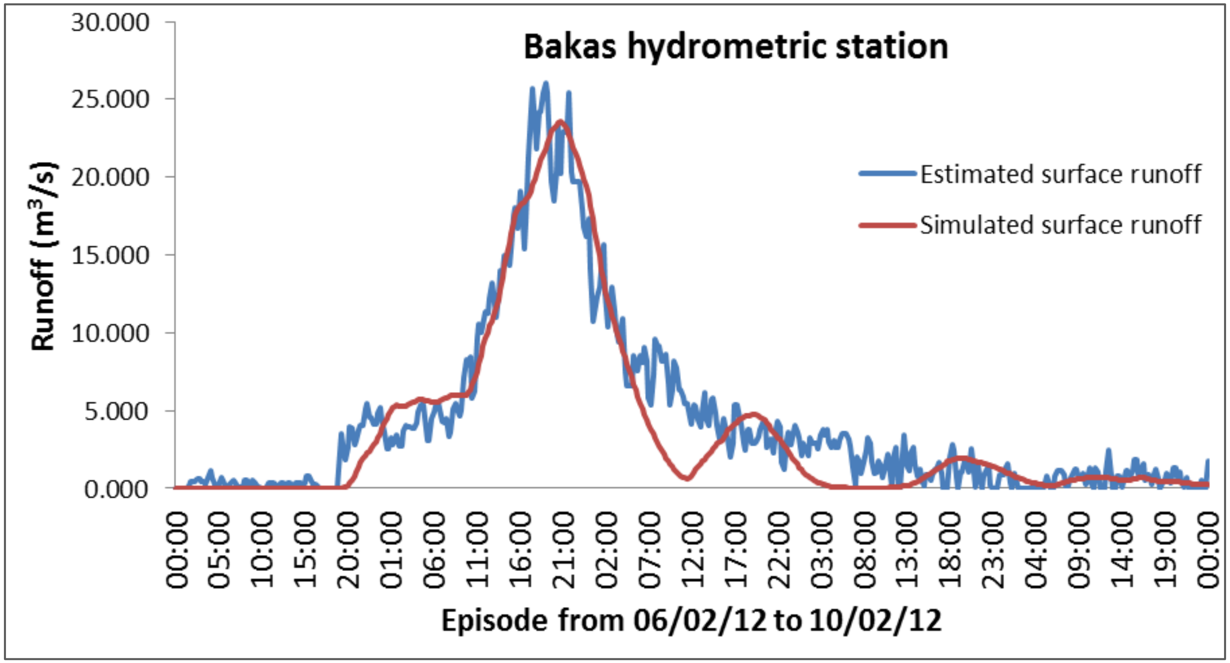


Parameter	Value
CN	54.1
λ	0.0010
κ	0.0007
μ	0.0011
W_0	19.9 mm
$\delta - \tau$	2 hours
φ	0.0384

- Nash-Sutcliffe Efficiency Metric
- $PEV = 100\left|\frac{V_0 - V_M}{V_0}\right|$
- $PERF = 100\left|\frac{Q_{0(PEAK)} - Q_{M(PEAK)}}{Q_{0(PEAK)}}\right|$
- $\Delta T_{PF} = |Tpeak_{obs} - Tpeak_{sim}|$

Metric	Value
NSE	0.957
PEV	-0.34%
$PEPF$	+7.76%
ΔT_{PF}	+105 min

Results of distributed surface model– Event B



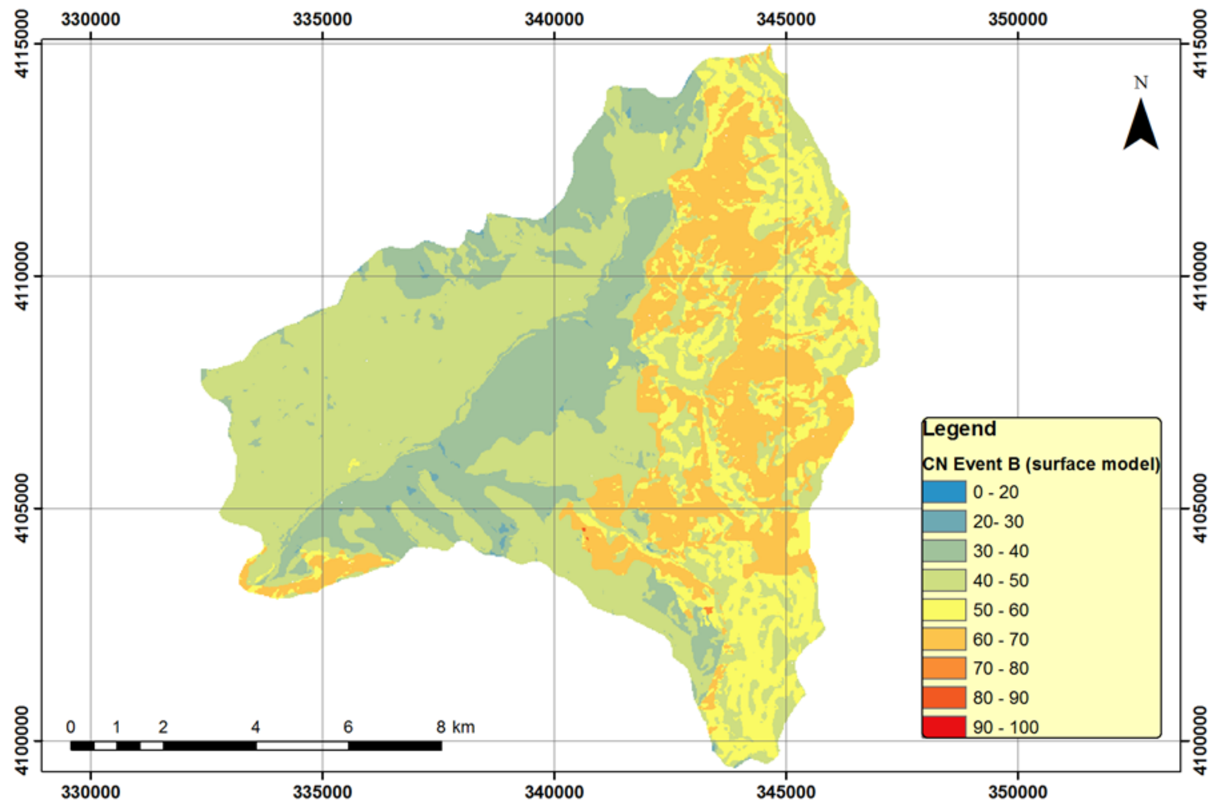
Parameter	Value
λ	0.011
AMC	0.233

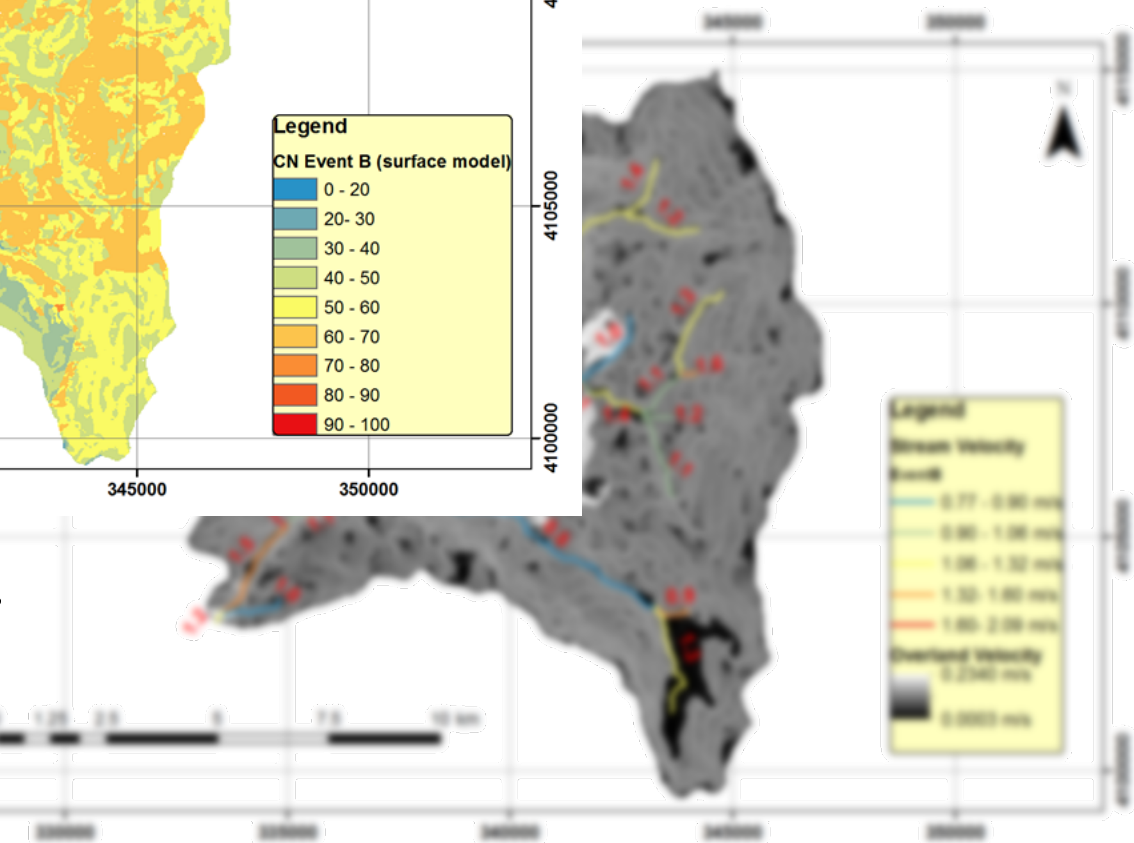
Model parameters after optimization

- Nash-Sutcliffe Efficiency Metric
- $PEV = 100\left|\frac{V_0 - V_M}{V_0}\right|$
- $PERF = 100\left|\frac{Q_{0(PEAK)} - Q_{M(PEAK)}}{Q_{0(PEAK)}}\right|$
- $\Delta T_{PF} = |Tpeak_{obs} - Tpeak_{sim}|$

Metric	Value
NSE	0.901
PEV	9.62%
$PEPF$	+14.99%
ΔT_{PF}	+120 min

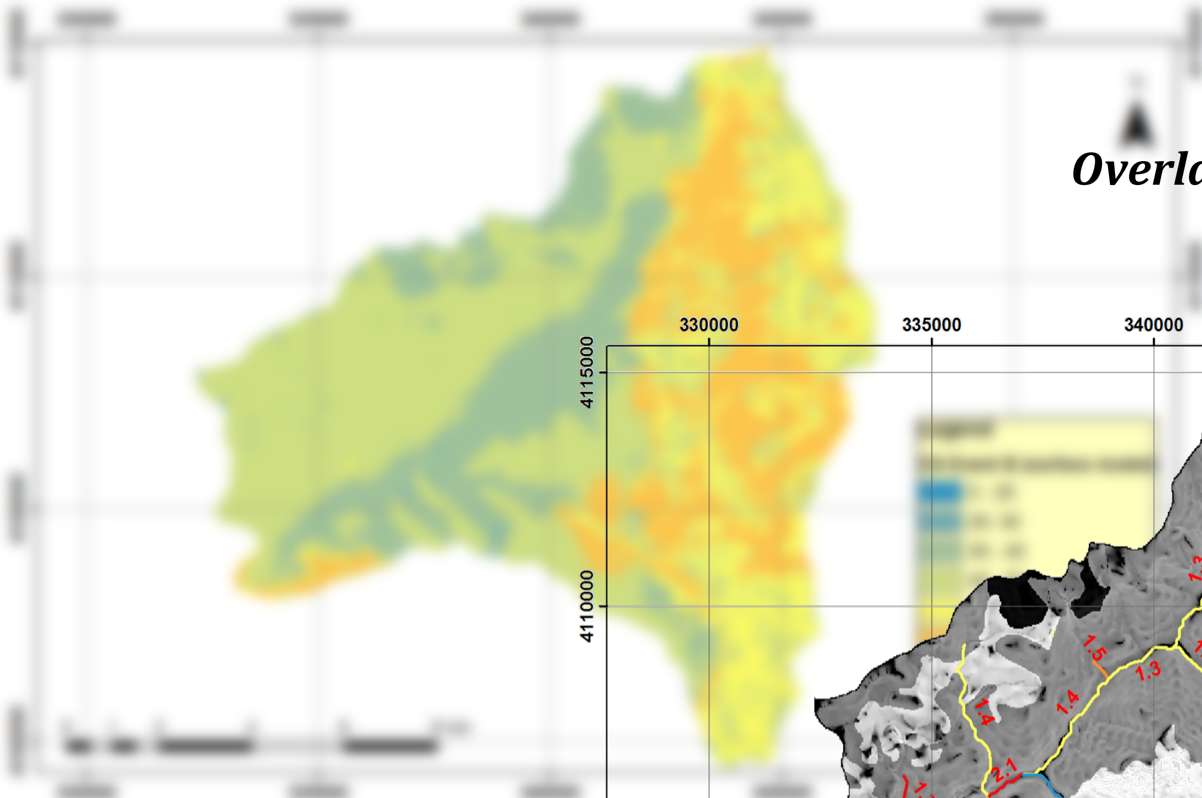
Results of distributed complete model



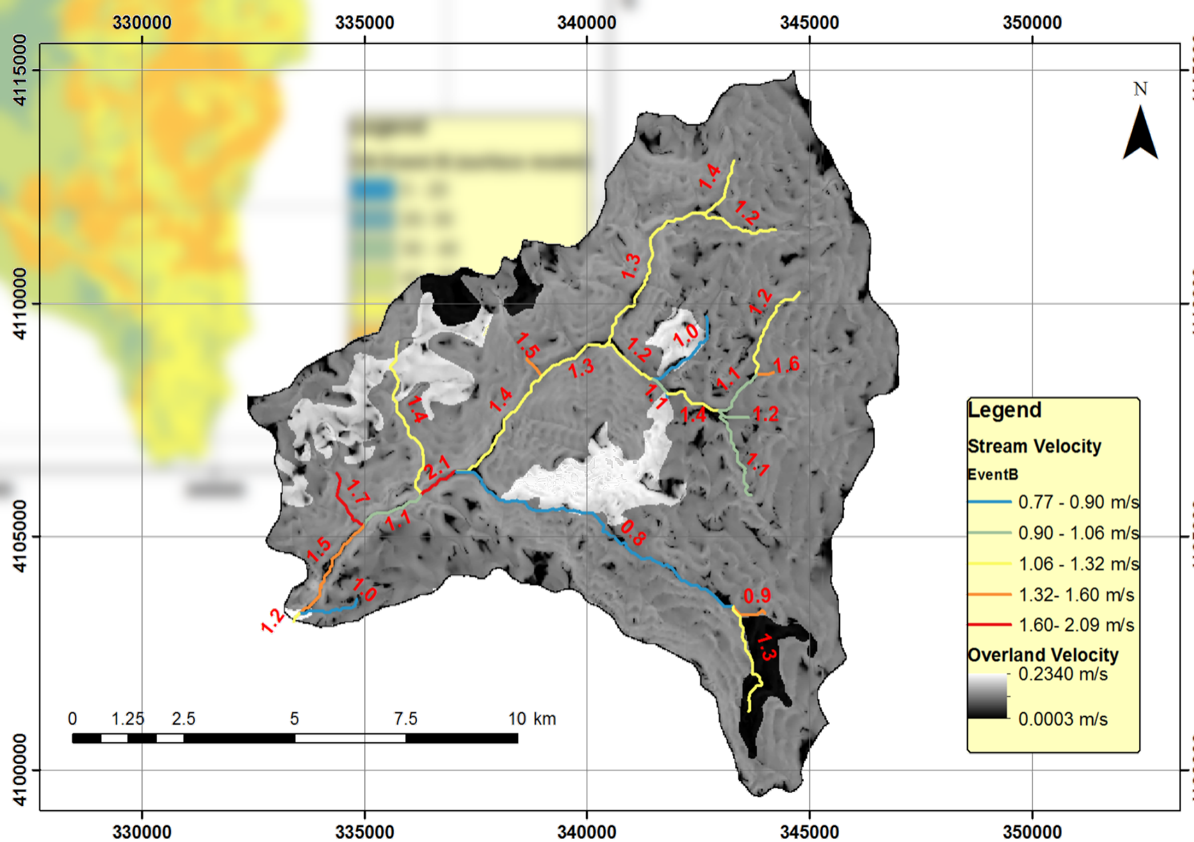


Adjusted CN values for Event B

Results of distributed complete model

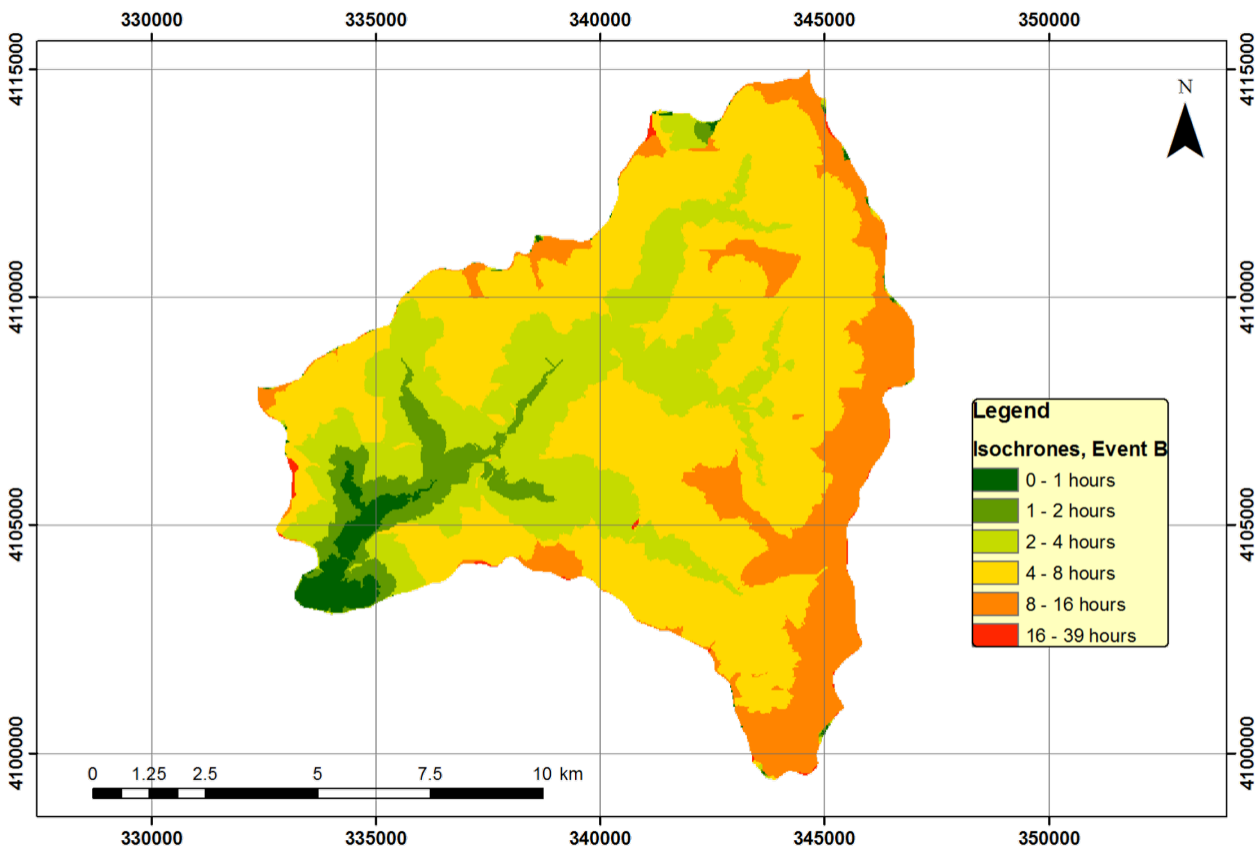


Overland and channel velocities of Event B



Time of concentration:
4.22 h

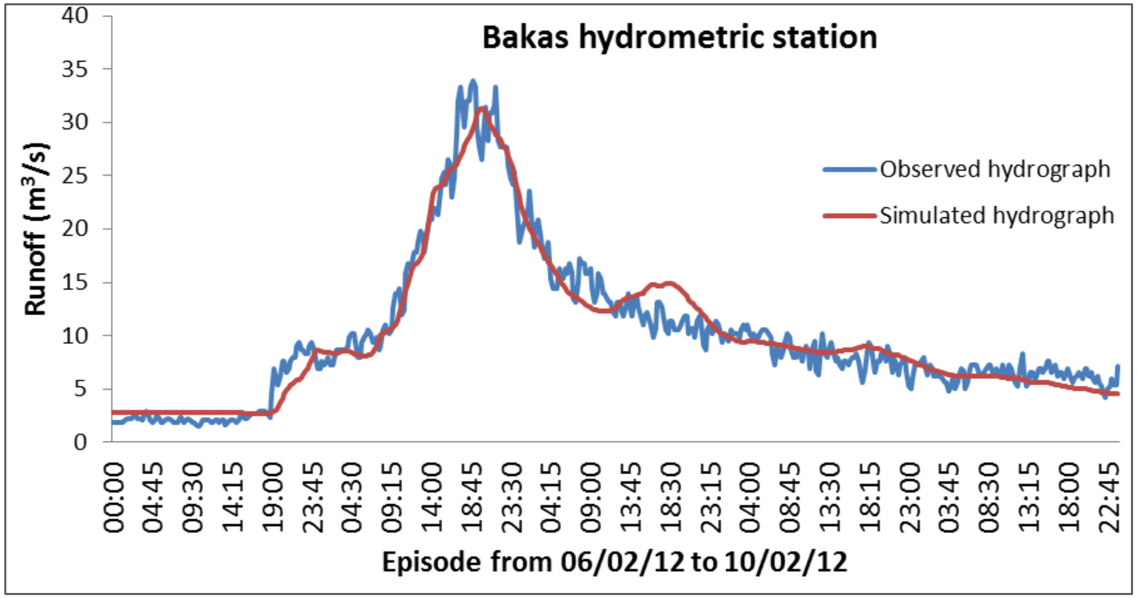
Results of distributed complete model



Isochrones of Event B

Mean travel time: 6.15 h

Results of distributed complete model

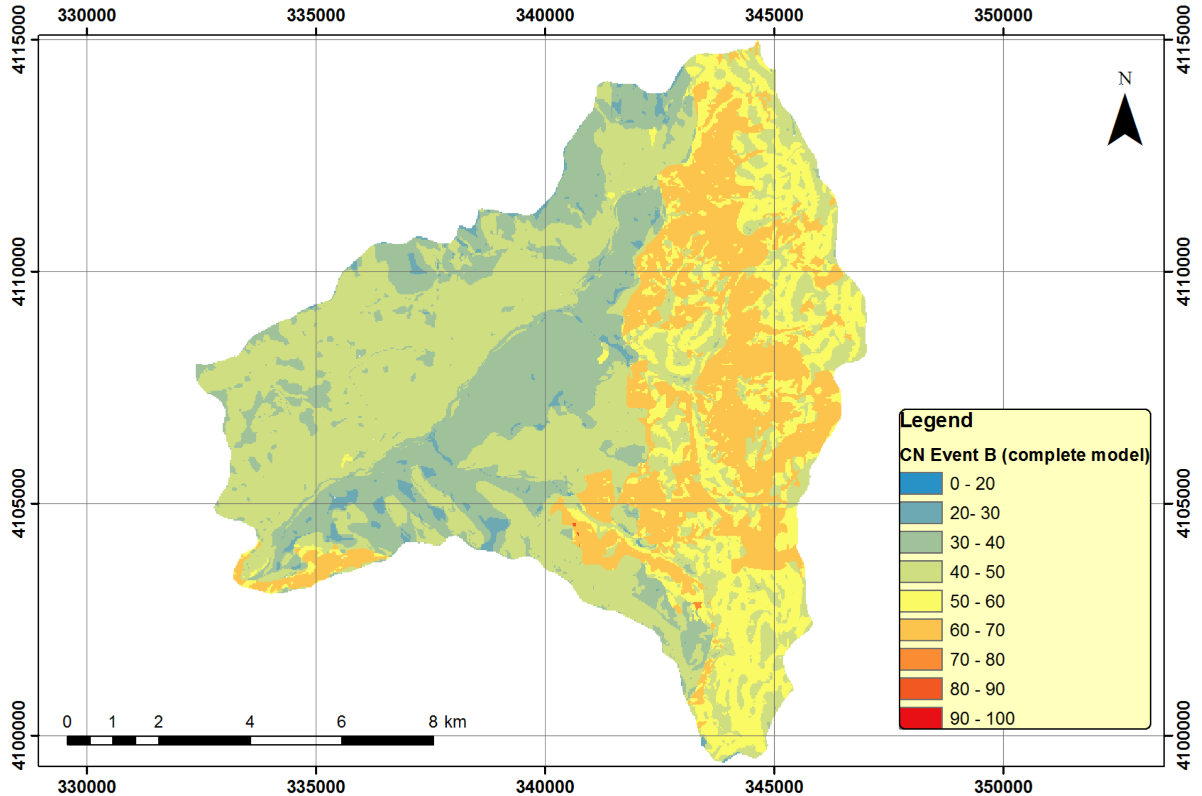


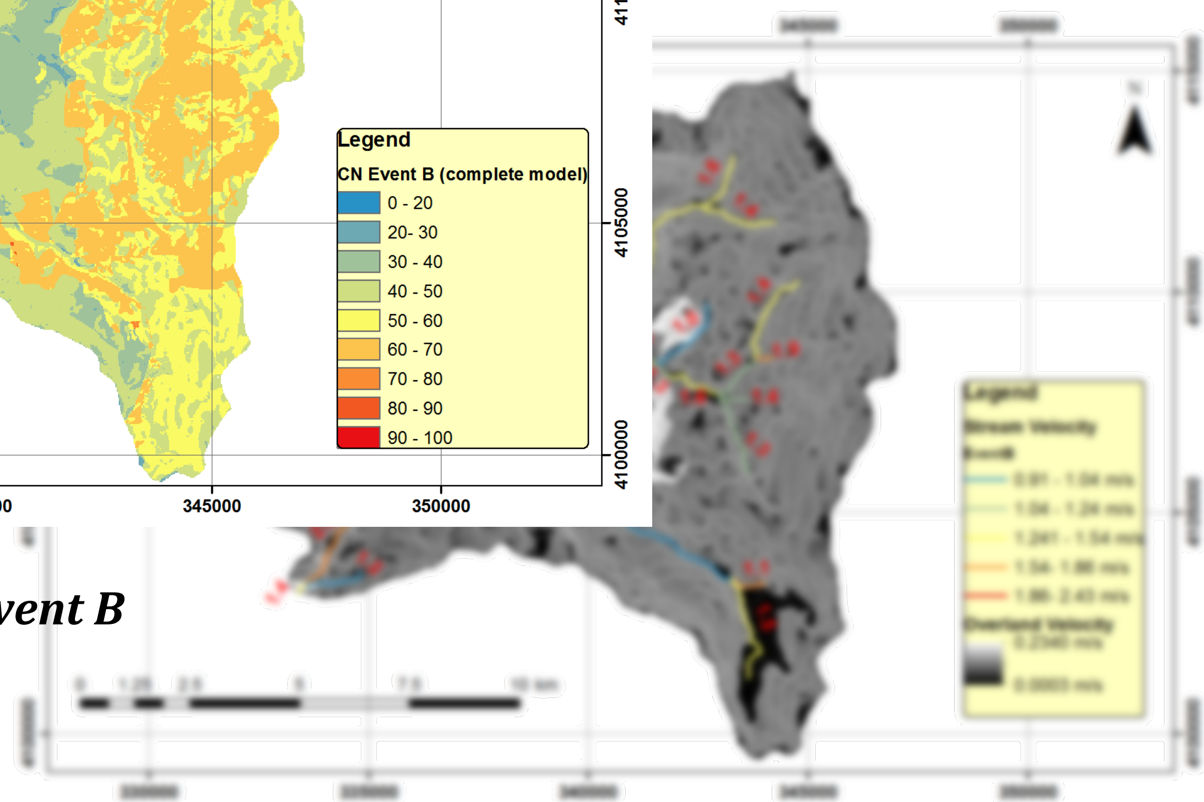
Parameter	Value
λ	0.0005
AMC	0.209
κ	0.0012
μ	0.0038
W_0	16.48 mm
δ	15.5 hours

- Nash-Sutcliffe Efficiency Metric
- $PEV = 100\left|\frac{V_0 - V_M}{V_0}\right|$
- $PERF = 100\left|\frac{Q_{0(PEAK)} - Q_{M(PEAK)}}{Q_{0(PEAK)}}\right|$
- $\Delta T_{PF} = |Tpeak_{obs} - Tpeak_{sim}|$

Metric	Value
NSE	0.865
PEV	-15.4%
$PEPF$	+3.0%
ΔT_{PF}	+1 hour

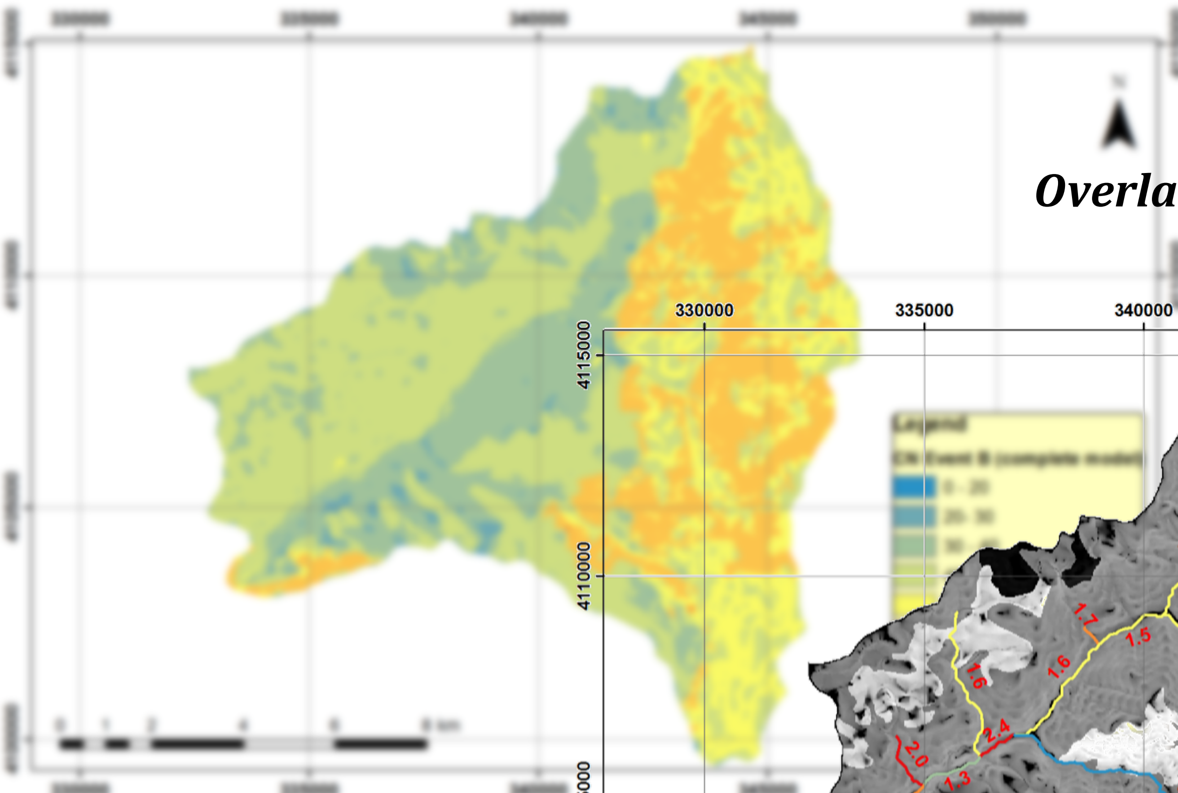
Results of distributed complete model



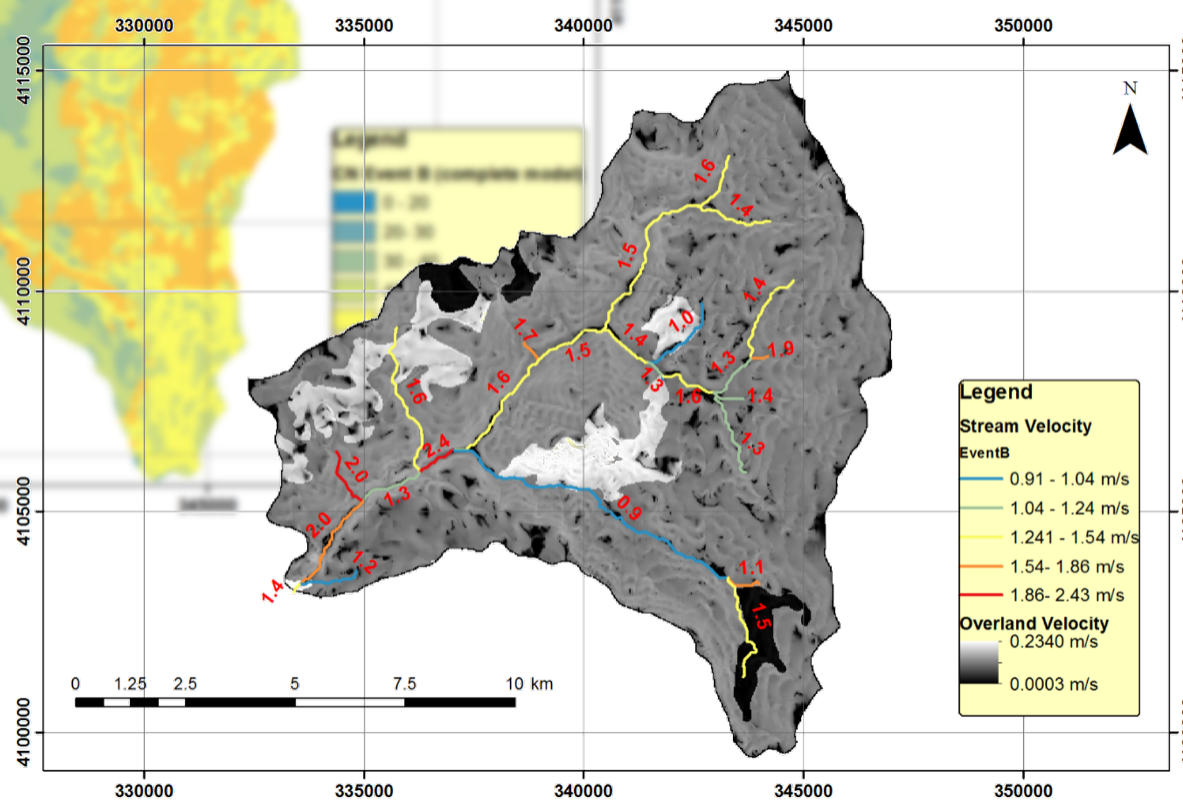


Adjusted CN values for Event B

Results of distributed complete model

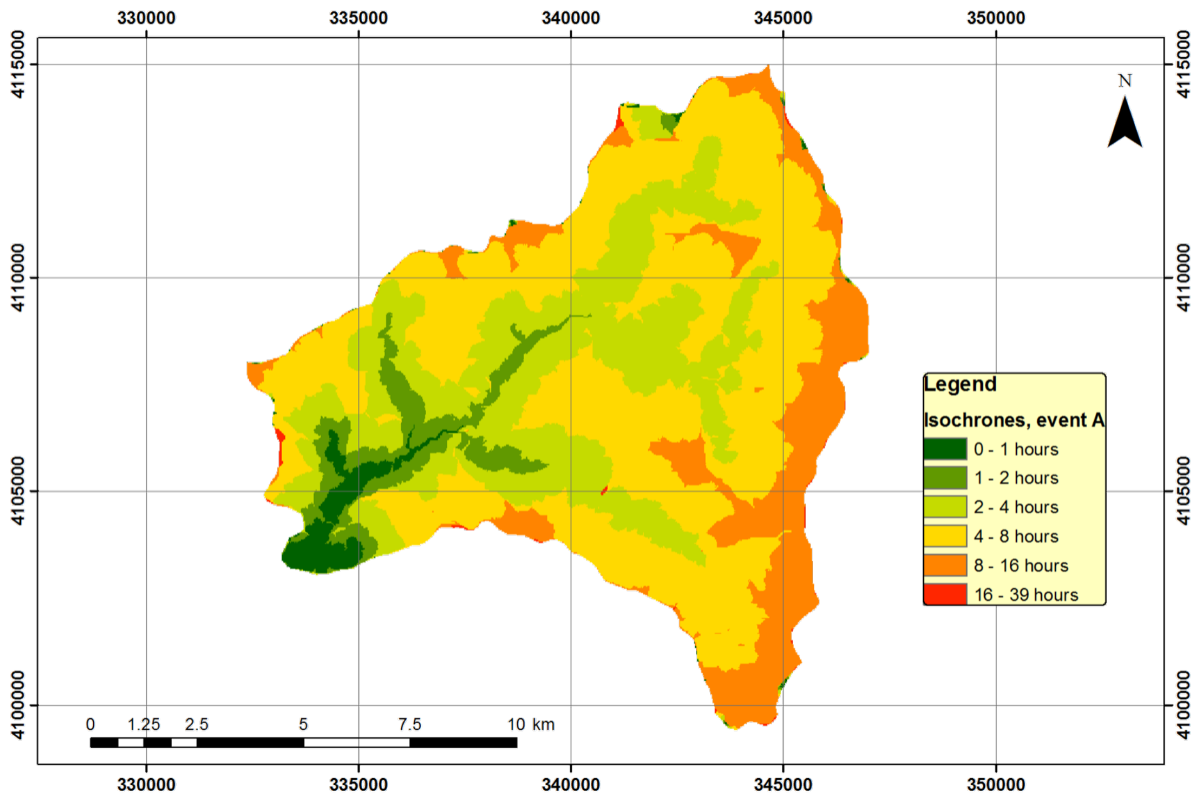


Overland and channel velocities of Event B



Time of concentration: 3.77 h

Results of distributed complete model



Isochrones of Event B, complete model

Mean travel time: 5.84 h

Conclusions

Incorporating multiple and modern **innovations** into a framework:

- **GIS- based approach** for automatic mapping of the so-called **reference CN.**
- Adjusting the CN to **any antecedent soil moisture conditions** and **any initial abstraction ration**.
- **Varying time** of concentration within runoff routing.
- Possibility for routing procedure with satisfactory accuracy **without employing a hydraulic model.**
- Representation of the **subsurface flow** through a soil moisture accounting tank and the **time varying maximum potential retention**.
- Parsimonious formulation, few parameters.
- Coupling various computational and programming tools, open source code, useful for the modern hydraulic engineer for various uses.
- Development of a software with augmented capabilities in data handling, data pre-processing, geo-spatial analysis, hydrological simulation, optimization and visualization of results.

Proposals for future research

- Comparison results with commercial hydraulic packages.
- Coupling a distributed rainfall – runoff model with a hydraulic one.
- Calculating discharge in every node of the river network.
- Dynamic adjustment of the time of concentration within the simulated event.
- Multiple flood events.
- Multiple basins with different characteristics.

Article under review:

Risva *et al.*, Lumped vs. distributed, conceptual vs. physically-based, event-based vs. continuous: Antithesis or synthesis?, Water (2020, submitted)

Special Issue: *Hydrologic, Hydraulic and Geomorphic Modeling for Small and Ungauged Basins*

References

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