11th World Congress of the European Water Resources Association on "Managing Water Resources for a Sustainable Future"
Madrid, Spain, 25-29 June 2019

Development of a distributed hydrological software application employing novel velocity-based techniques

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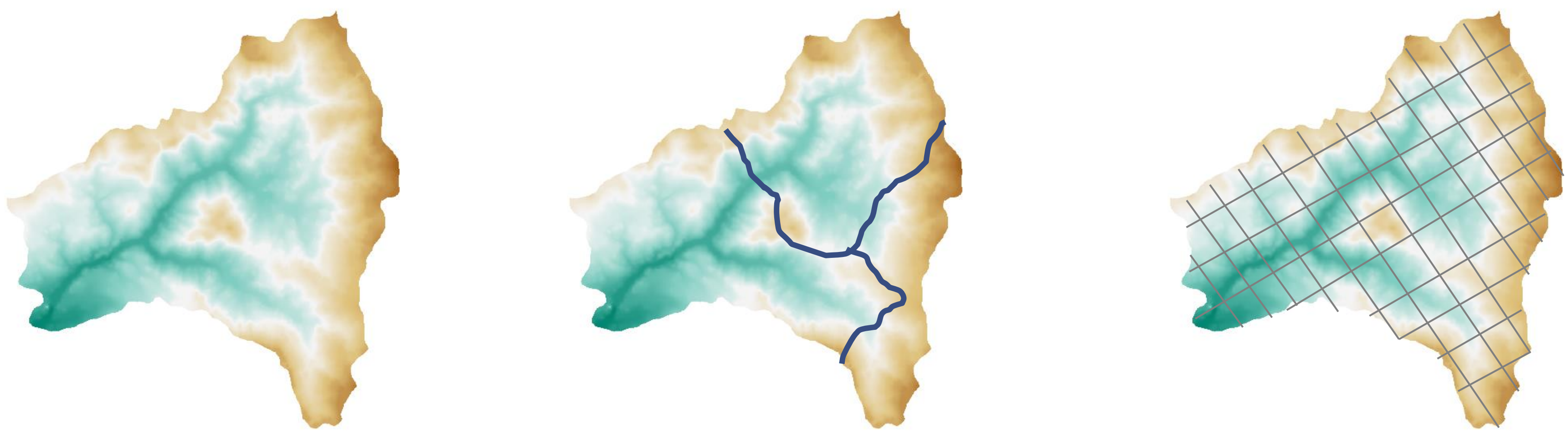
Physically based hydrological models

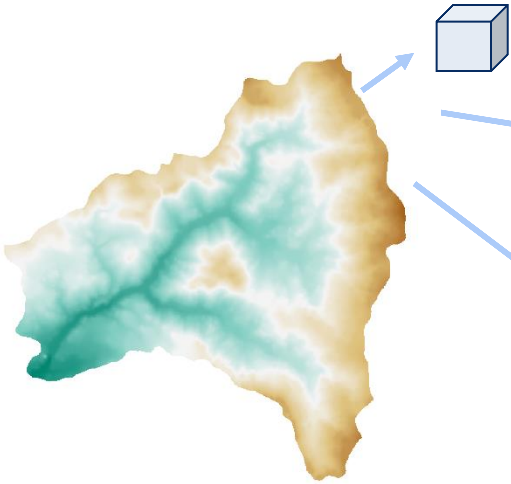
Lumped model → Same parameters for the basin

Semi – distributed model → Parameters in large spatial entities (e.g. subasins)

Distributed model → Parameters per cell



Model framework overview



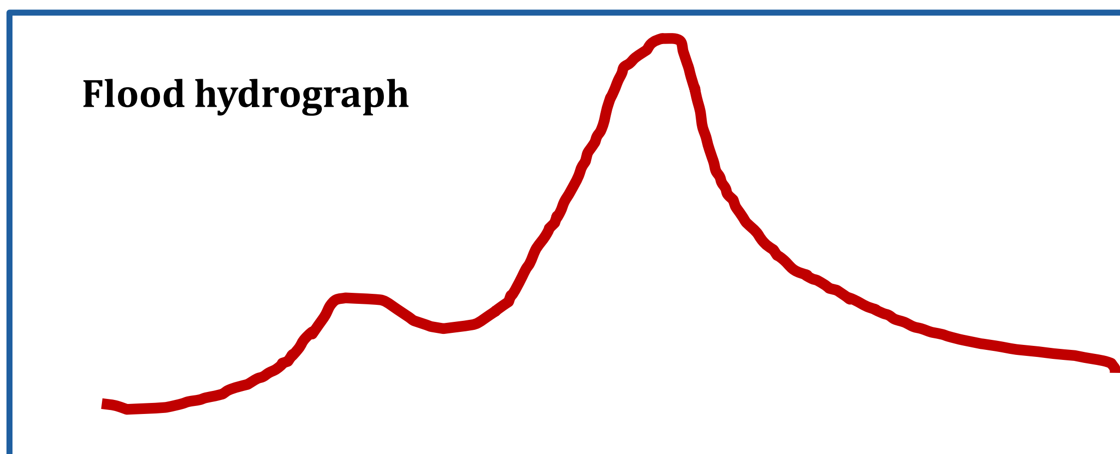
Effective rainfall

Discrete types of surface runoff

Overland flow across the catchment's terrain

Channel flow along the river network

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



Calculation of the effective rainfall

$$h_e = \begin{cases} 0 & h \leq h_{a0} \\ \dfrac{(h - h_{a0})^2}{h - h_{a0} + S} & h > h_{a0} \end{cases}$$

$$h_{a0} = \lambda S$$

$$S = 254\left(\frac{100}{CN} - 1\right)$$

Natural Resources Conservation Service Curve Number (NRCS-CN)

Land cover	Hydrologic soil group			
	A	B	C	D
Cultivated areas	62-72	71-81	78-88	81-91
Pasture areas	30-68	58-79	71-86	78-89
Forests	25-45	55-66	70-77	77-83

CN ranges across rural areas or AMC II conditions (adapted by Koutsoyiannis , 2011)

A: High rate of infiltration
B: Moderate rate of infiltration
C: Low rate of infiltration
D: Very low rate of infiltration

Shortcomings of NRCS- CN method

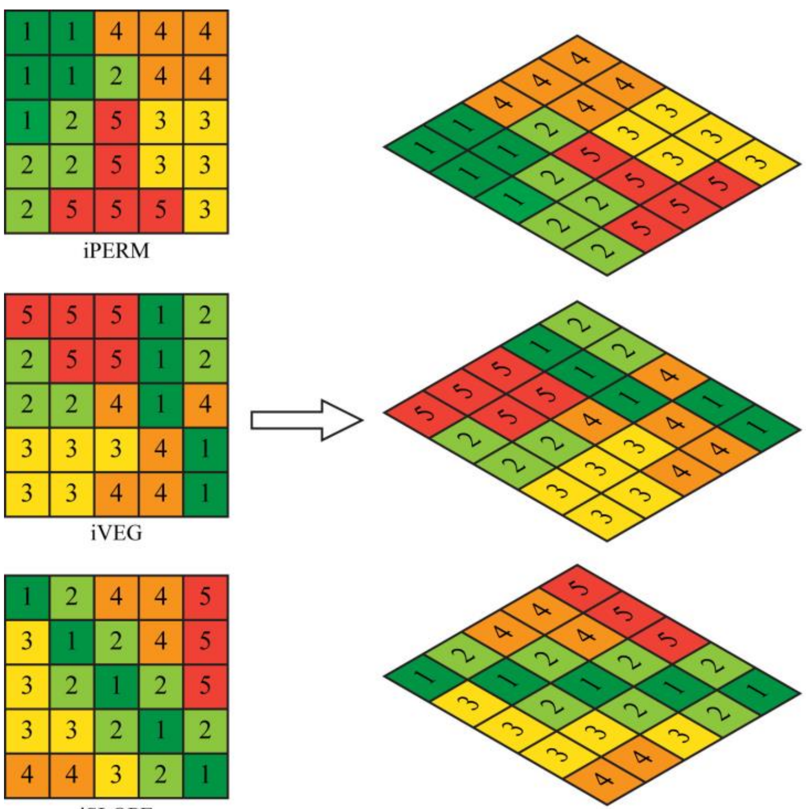
- Not accounting for the effect of slope on flood runoff generation (CN originally calculated in small agricultural watersheds).
- Standard classicifation does not cover the entire range of permeability characteristics (e.g.. Limestone, dolomite, karst)
- Subjectivity in the determination of representative parameter values.

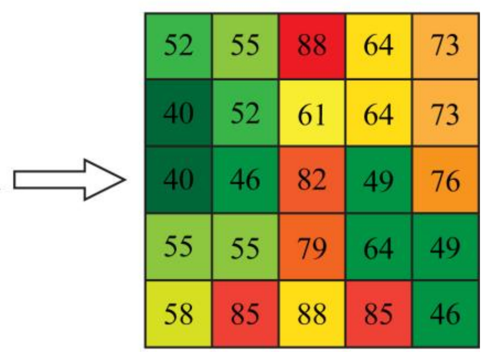
Revised method for the CN assessment

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

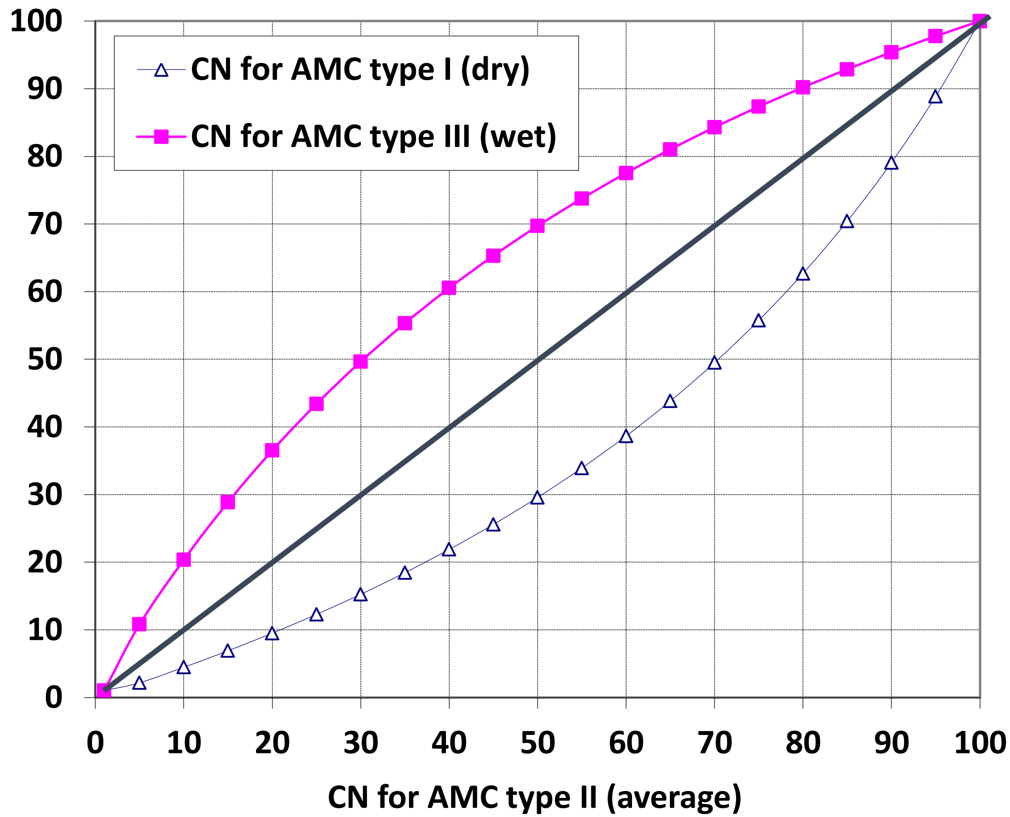
i_{PERM} ➔ Permeability (soil, geology)
i_{VEG} ➔ Land use/ cover(vegetation)
i_{SLOPE} ➔ Drainage capacity (slope, structures)

Layers of geographic information for permeability classes, vegetation density classes and drainage capacity classes ; (b) layer overlay; (c) CN parameter map (Savvidou et al., 2018).





Adaptation to antecedent conditions



For the antecedent soil moisture conditions (AMC) types I and II NRCS-CN uses the following conversion formulas (AMC):

$$CN_I = \frac{4.2CN_{II}}{10 - 0.058CN_{II}} \qquad CN_{III} = \frac{23CN_{II}}{10 + 0.13CN_{II}}$$

Adaptation to antecedent conditions

For **any** antecedent soil moisture conditions (AMC):

$$CN_{AMC} = \begin{cases} CN_{II} - \dfrac{CN_{II} - CN_{I}}{0.4}\left(0.5 - AMC_{coef}\right), AMC_{coef} < 0.5 \\ CN_{III} + \dfrac{CN_{III} - CN_{II}}{0.4}\left(AMC_{coef} - 0.5\right), AMC_{coef} \geq 0.5 \end{cases}$$

For a better representation of the inherent variability of the soil moisture, we implement a continuous classification of the AMC. Assuming:
Type I: 0.1
Type II: 0.5
Type III: 0.9

Adjustment of maximum potential retention S

Need for adjustment!

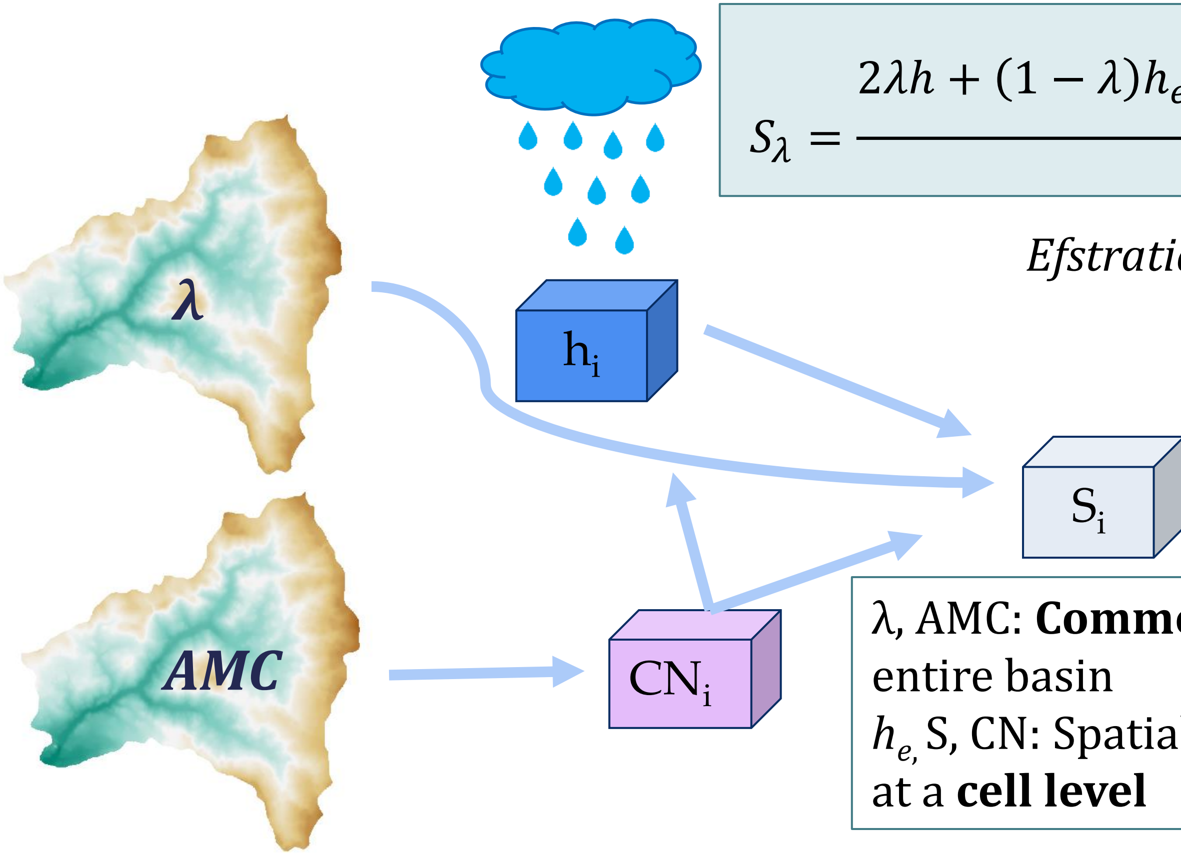
Standard value for initial abstraction ratio λ according to SCS: 0.20
Standard values in small catchments with steep slopes: ≤ 0.05

$$S_{0.20} = 254\left(\frac{100}{CN_{0.20}} - 1\right)$$

$$h_{a0} = 0.20\,S,\ h_e = \cdots$$

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

Efstratiadis et al., 2014



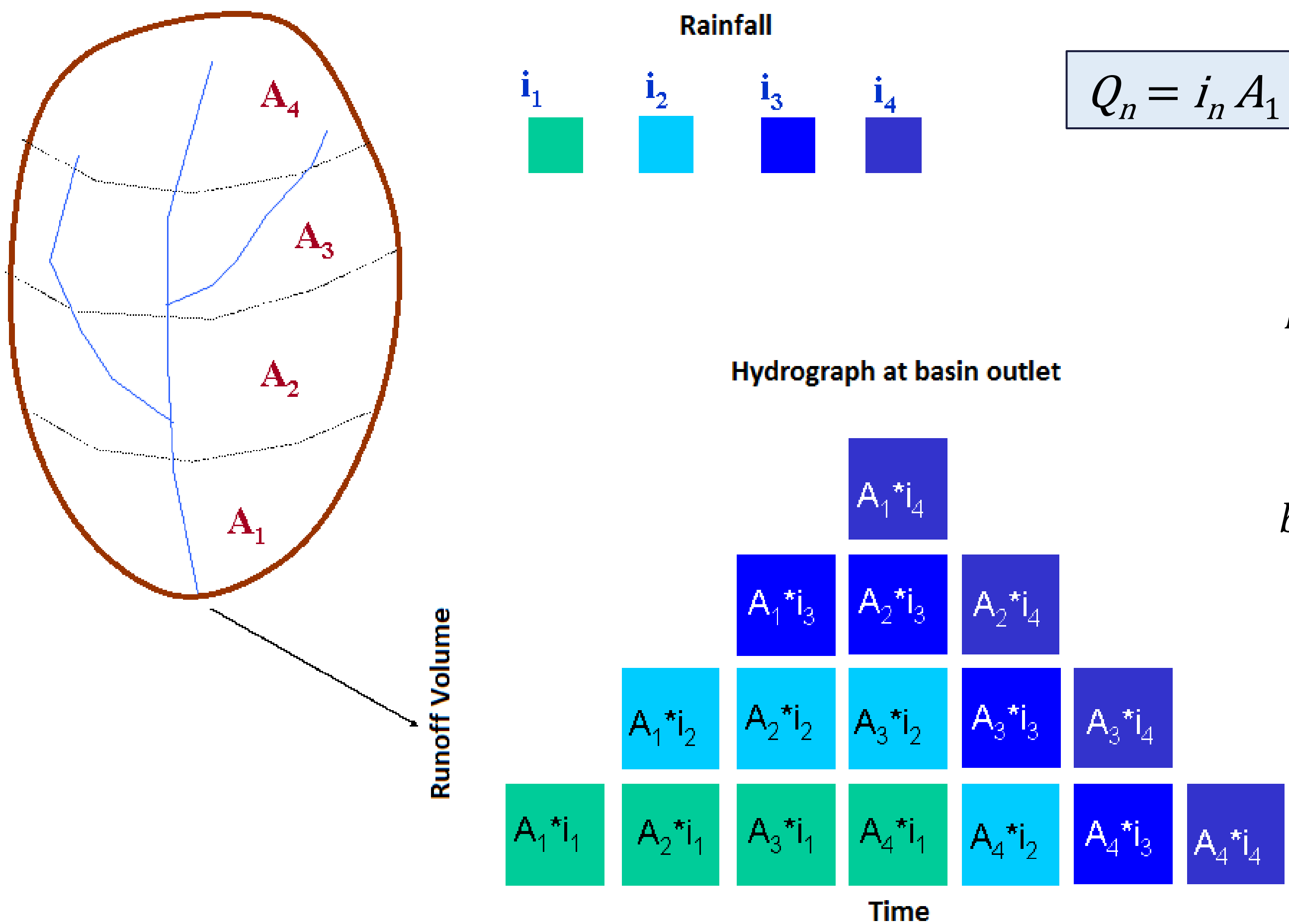
λ, AMC: **Common** parameters for the entire basin
h_e, S, CN: Spatially – varying parameters at a **cell level**

Isochronous method

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

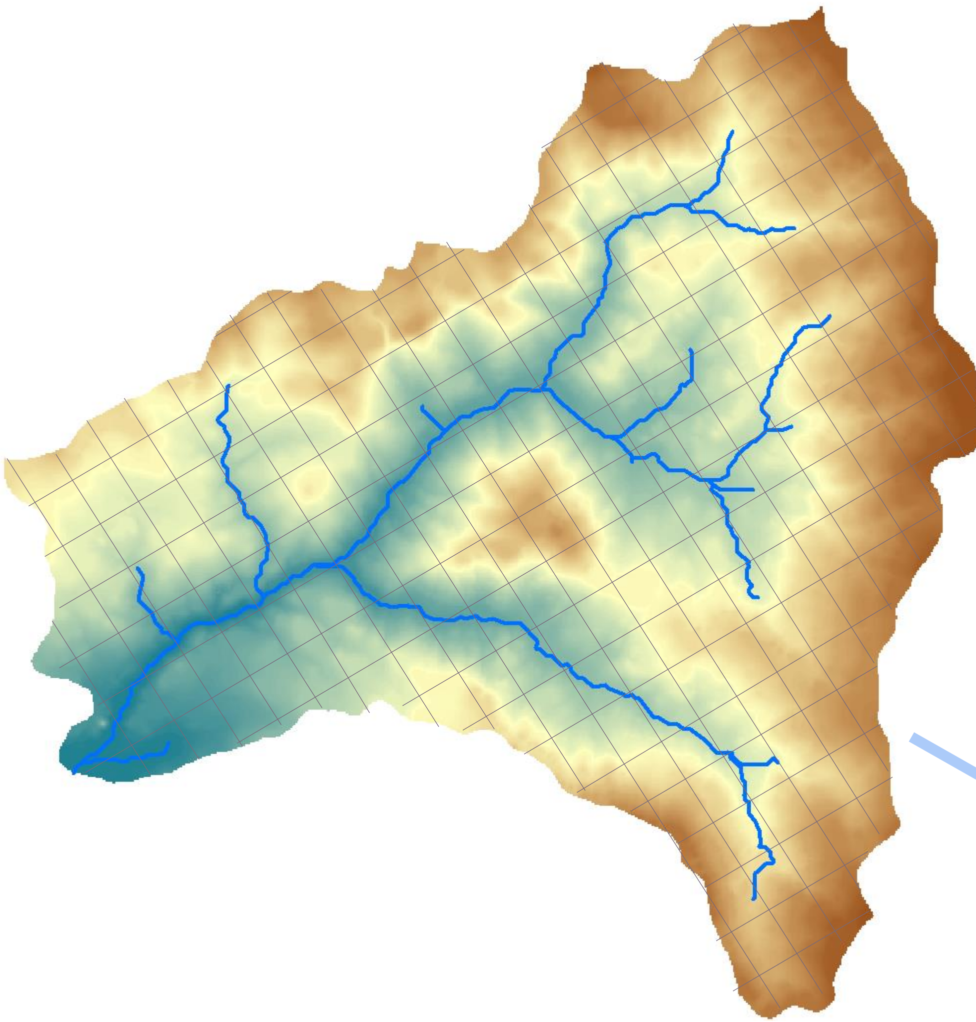
The outlet runoff at each step:

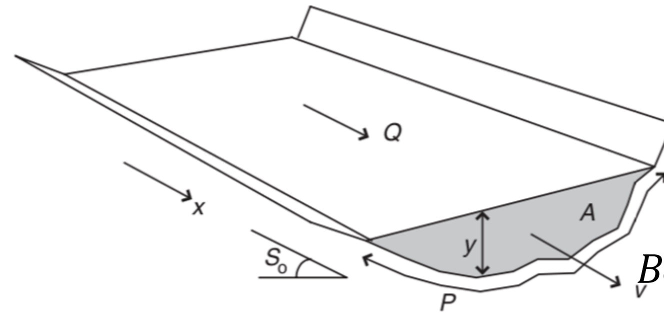
$$Q_n = i_n A_1 + i_{n-1} A_2 + \dots + i_1 A_n$$



Example of the mechanism of hydrograph creation using the isochrones method, in a hypothetical basin of four zones of equal area with equal effective rainfall intensity.

Estimation of velocities

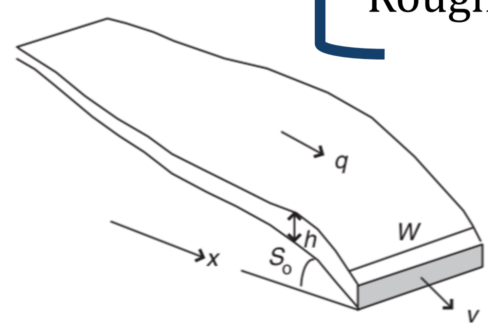




Beven, 2002

River flow
- Slope
- Roughness
- Geometry
- Discharge

Overland flow
- Slope
- Roughness



Calculation of overland velocity

Sheet-flow equation:

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

J: Slope (%)
k: Roughness coefficient

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

Categories of land cover and proposed k values(adapted fromMcCuen, 1998)

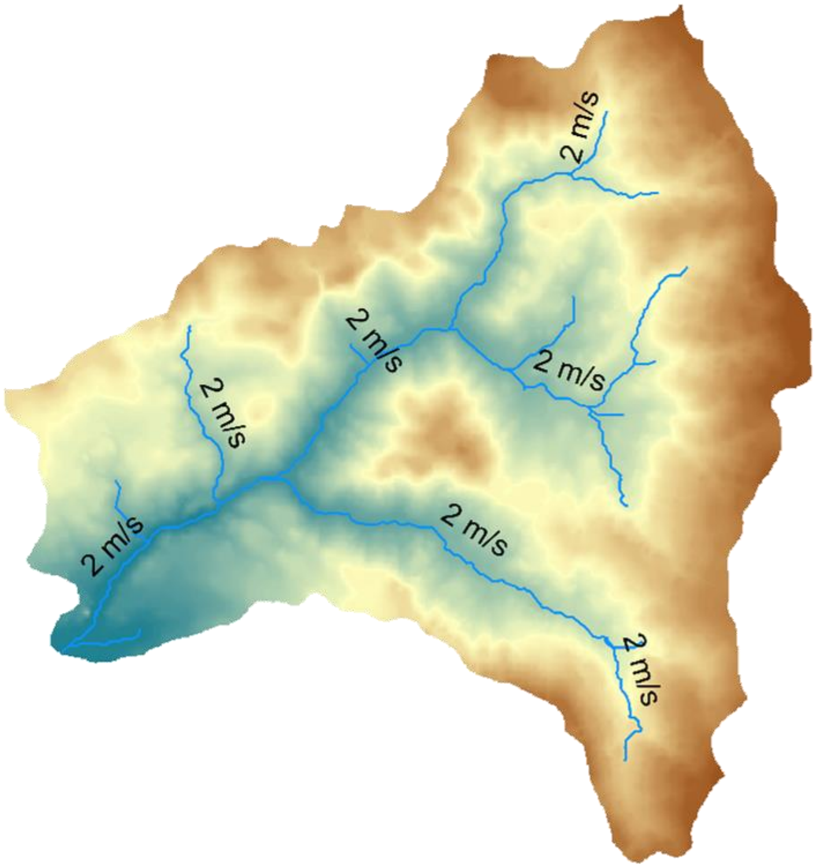
Correction formula of steep slope:

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

Grimaldi et al., 2012

Estimation of channel velocities

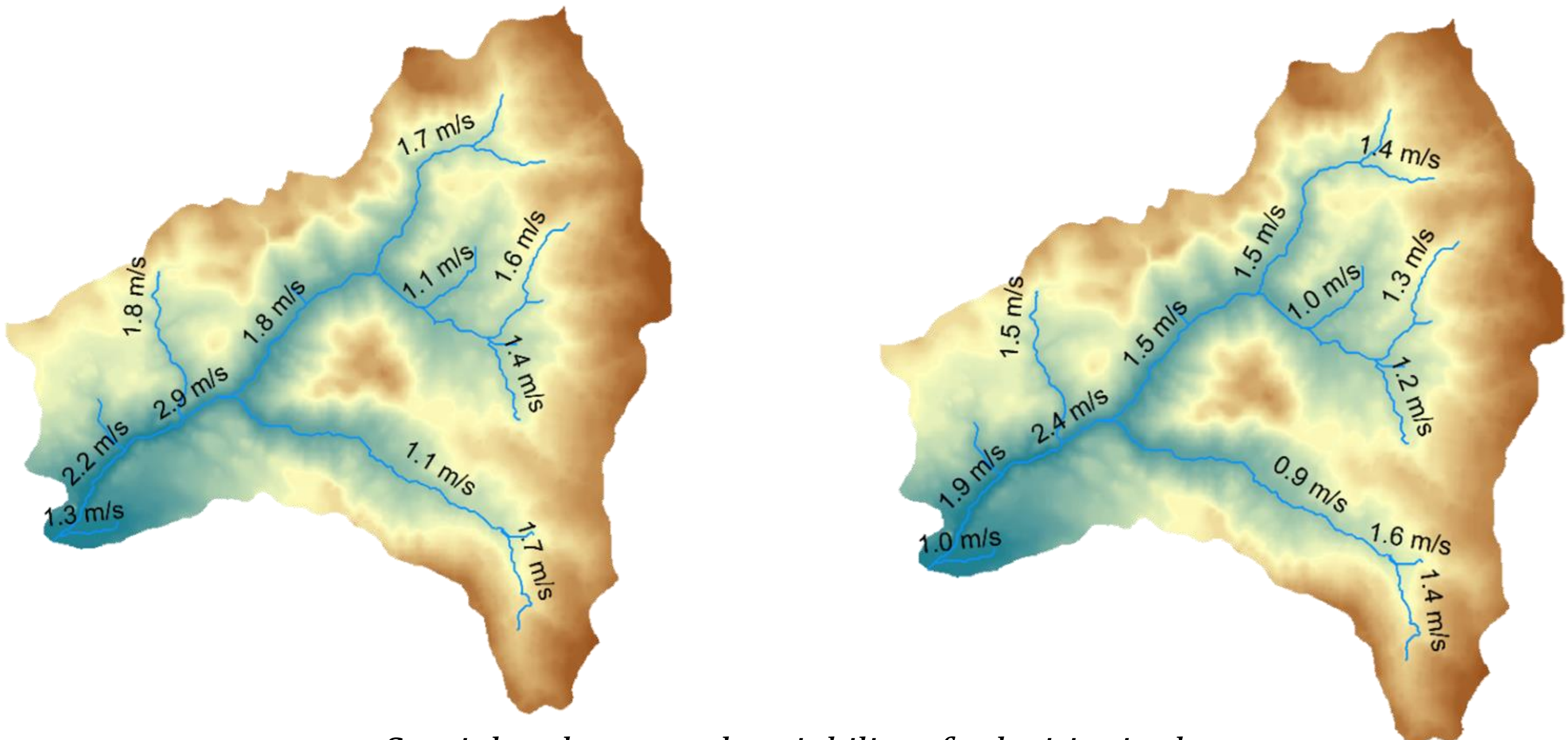
- Velocity: hydraulic quantity
- Depending on:
  - Geometry
  - Hydraulic characteristics
  - **Discharge**
- Spatially and temporally varying



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

Estimation of channel velocities

Spatial variability → in every segment of the river network
Temporal variability→ different concentration times in every episode→ different velocities in the river



Spatial and temporal variability of velocities in the river network in two distinct flood episodes

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

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

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

Varying time of concentration t_c

↓

Differs by episode

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

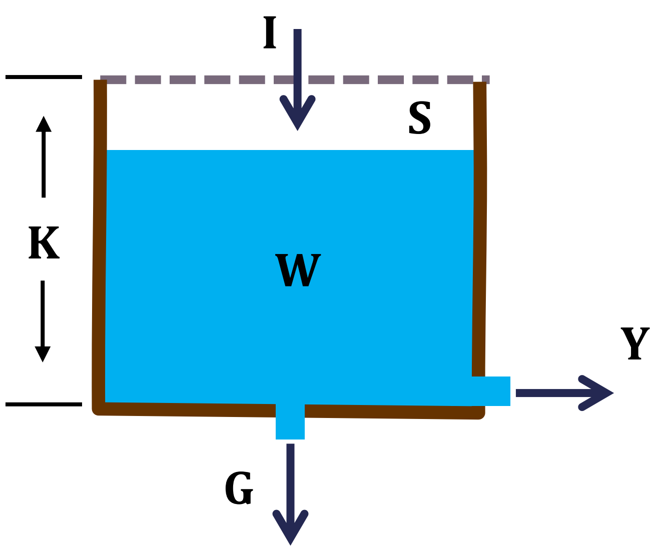
Michailidi et al. (2018)

Enhanced model version

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

Water balance model through a linear reservoir

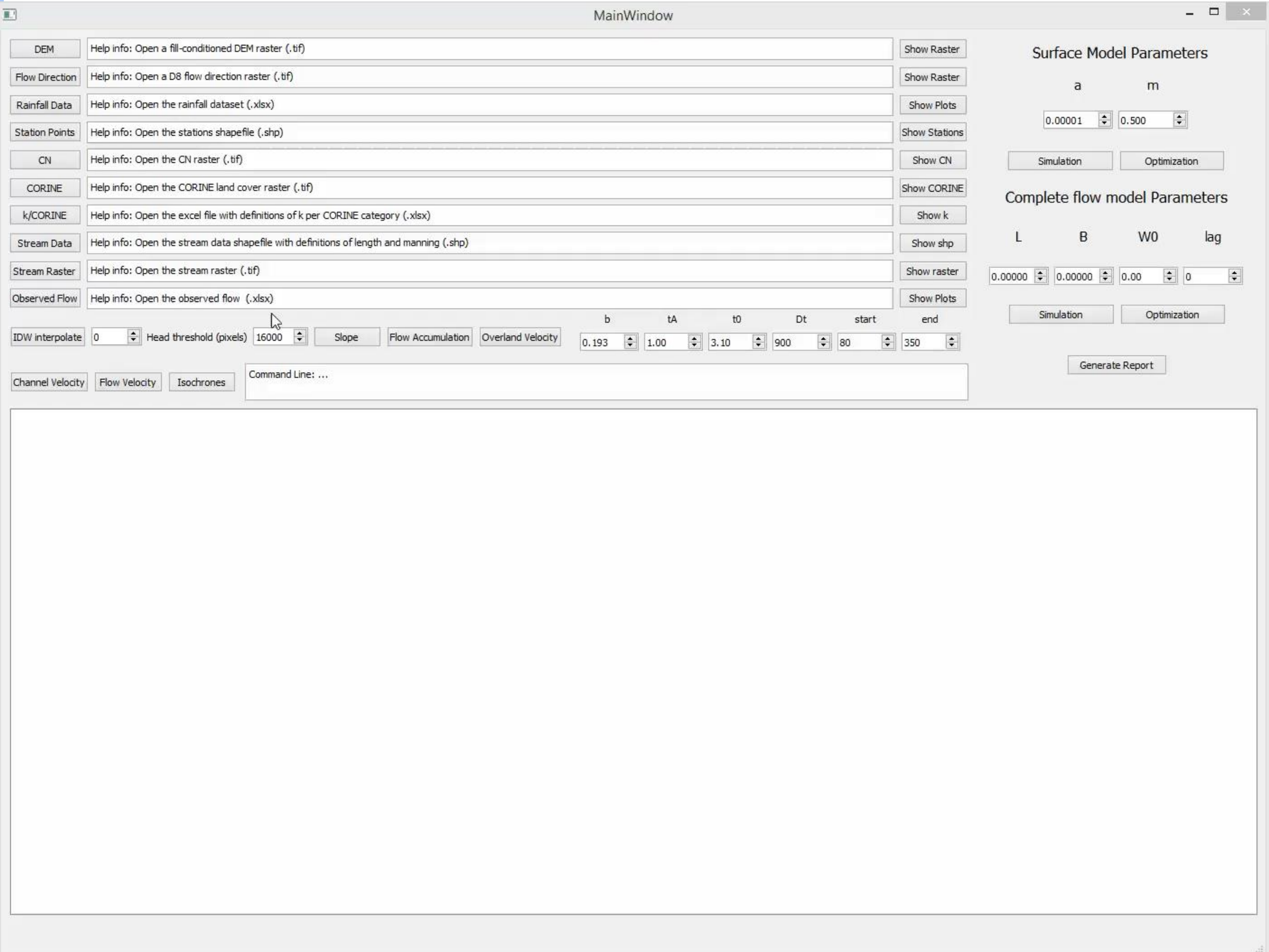
$$
\begin{cases}
W_t = W_{t-1} + I_t - Y_t - G_t \\
K = W_0 + S_0 \\
S_t = K - W_{t-1} \\
Y_t = \kappa \, W_t \\
G_t = \mu \, W_t
\end{cases}
$$



Formulas of the routing component

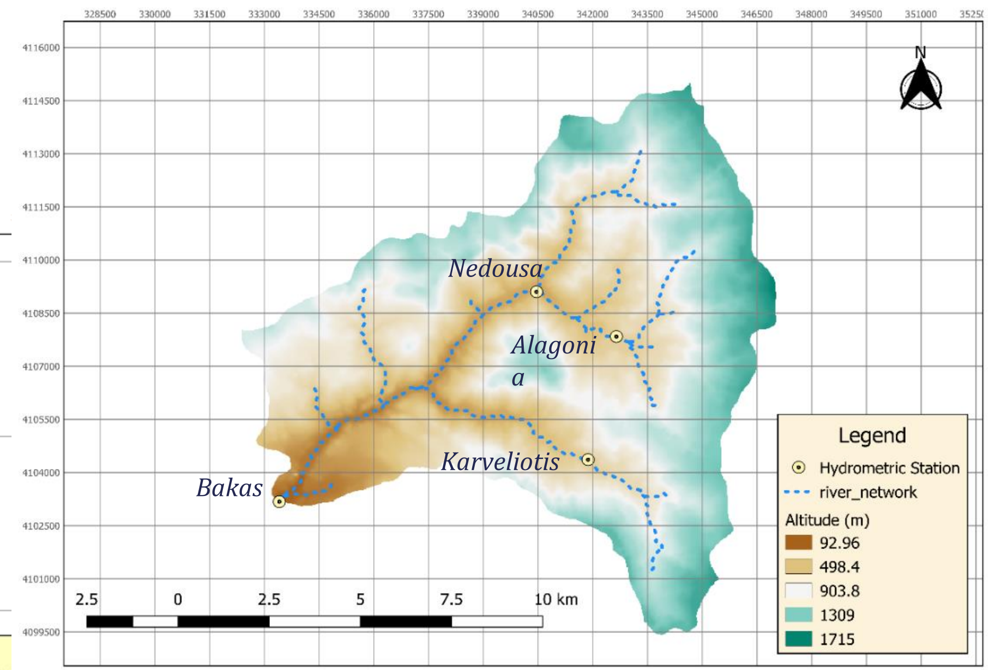
$$
\begin{cases}
Q_t = \varphi \, X_t \\
X_t = X_{t-1} + H_{et} - Q_t \\
R_t = Y_{t-\delta} + Q_{t-\tau}
\end{cases}
$$

Software implementation

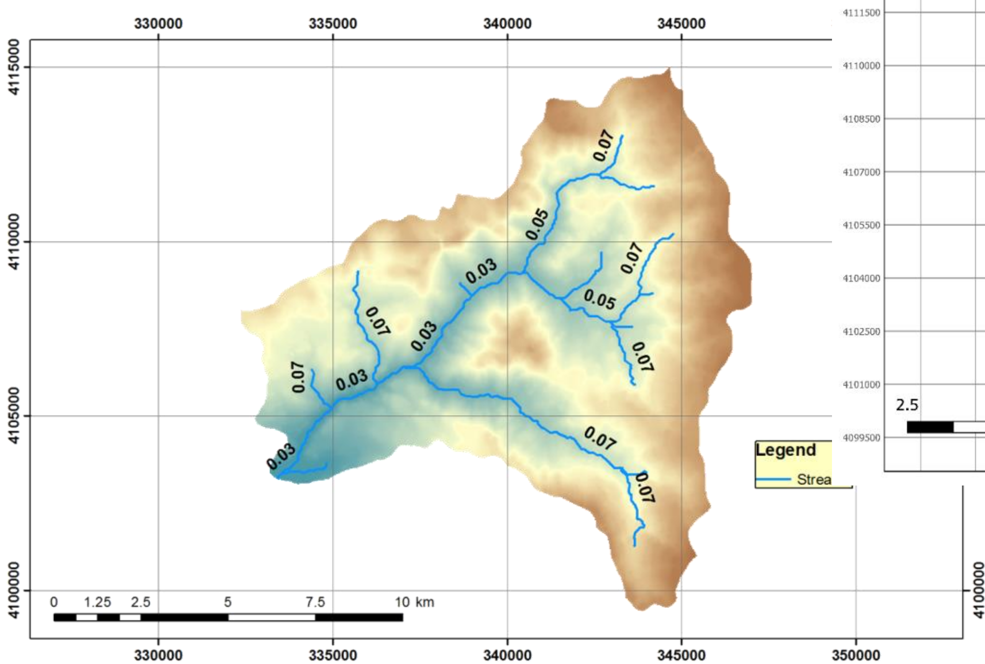

MainWindow
DEM
Help info: Open a fill-conditioned DEM raster (.tif)
Show Raster
Flow Direction
Help info: Open a D8 flow direction raster (.tif)
Show Raster
Rainfall Data
Help info: Open the rainfall dataset (.xlsx)
Show Plots
Station Points
Help info: Open the stations shapefile (.shp)
Show Stations
CN
Help info: Open the CN raster (.tif)
Show CN
CORINE
Help info: Open the CORINE land cover raster (.tif)
Show CORINE
k/CORINE
Help info: Open the excel file with definitions of k per CORINE category (.xlsx)
Show k
Stream Data
Help info: Open the stream data shapefile with definitions of length and manning (.shp)
Show shp
Stream Raster
Help info: Open the stream raster (.tif)
Show raster
Observed Flow
Help info: Open the observed flow (.xlsx)
Show Plots
IDW interpolate
0
Head threshold (pixels)
16000
Slope
Flow Accumulation
Overland Velocity
b
tA
t0
Dt
start
end
0.193
1.00
3.10
900
80
350
Channel Velocity
Flow Velocity
Isochrones
Command Line: ...
Surface Model Parameters
a
m
0.00001
0.500
Simulation
Optimization
Complete flow model Parameters
L
B
W0
lag
0.00000
0.00000
0.00
0
Simulation
Optimization
Generate Report

Study area– Nedontas river basin

- Water Department of Western Peloponnese. Nedontas passed through the city of Kalamata.
- Area: 119.3km^2
- H_{min}: 93m
- H_{max}: 1715m



DEM of the study area

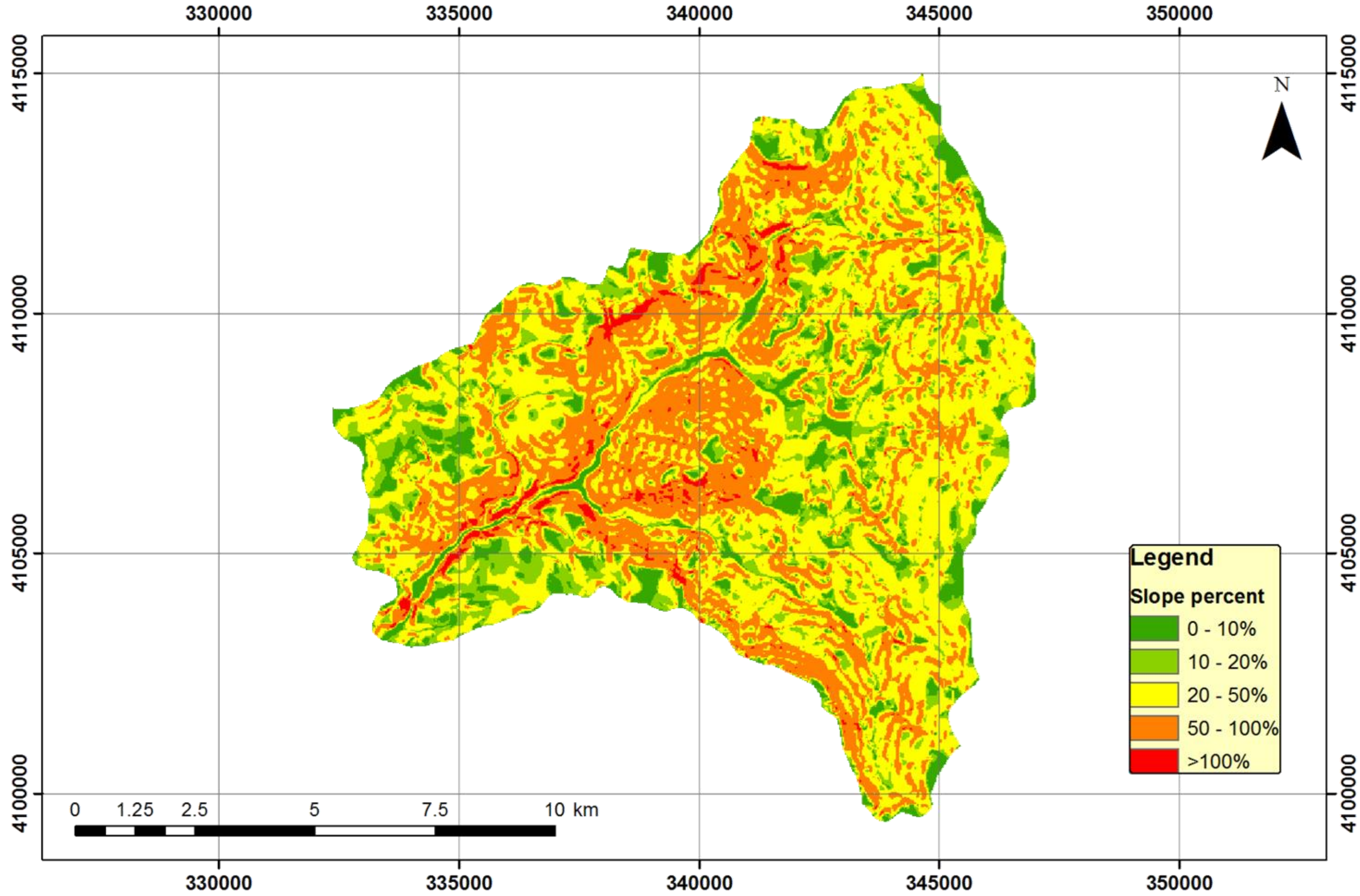


Manning values of the stream segments

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

Study area– Nedontas river basin

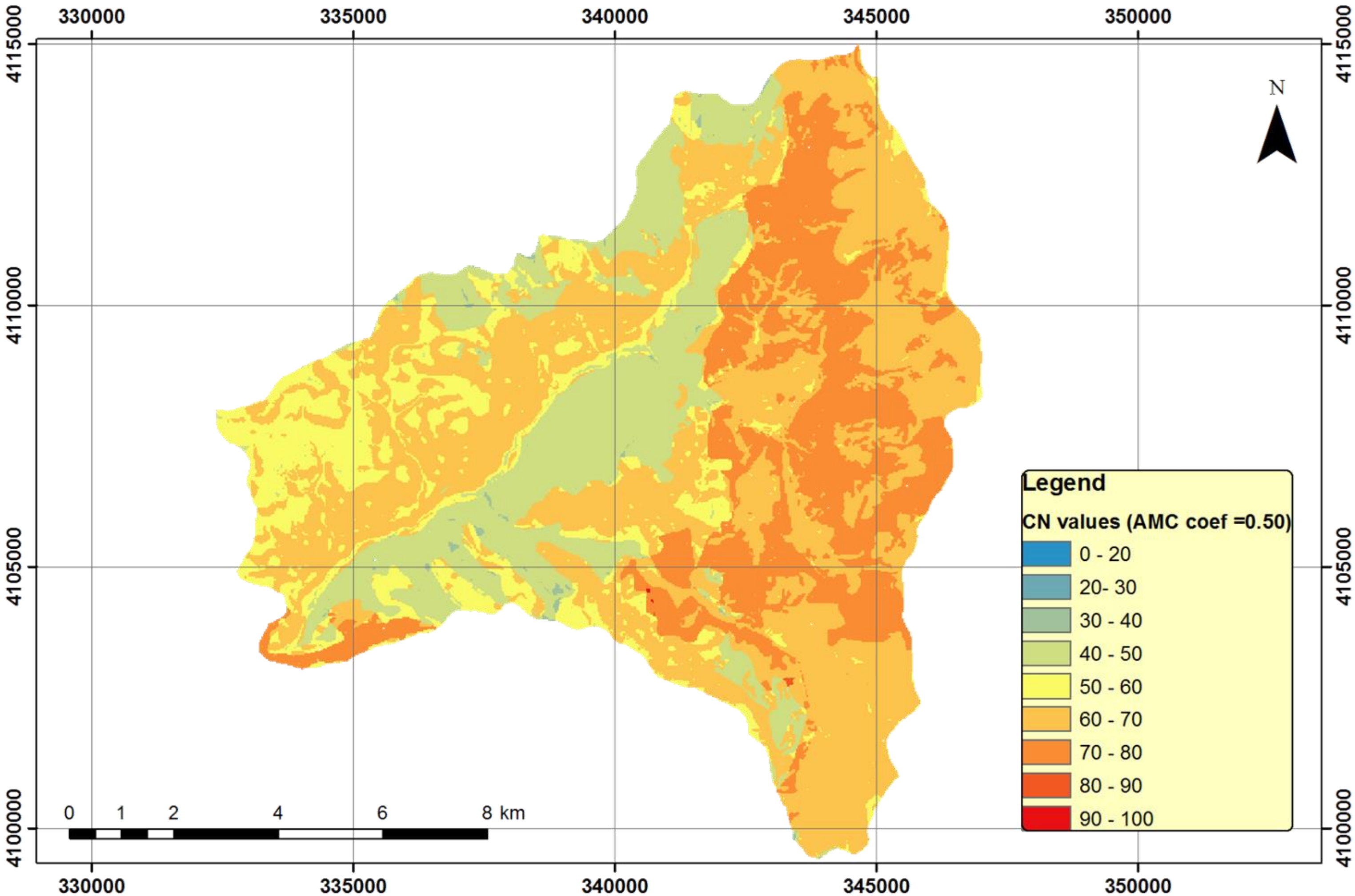
- Steep slopes, mean value 49%



Slope classification

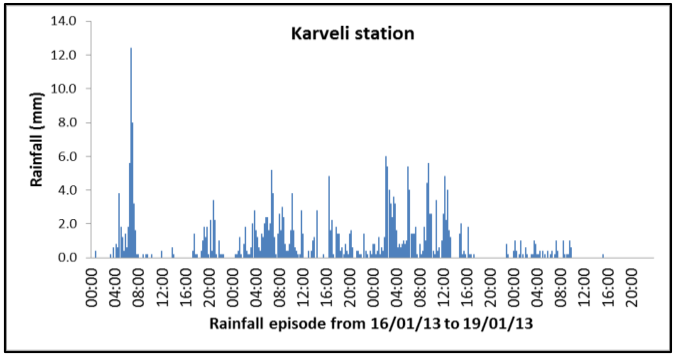
Study area– Nedontas river basin

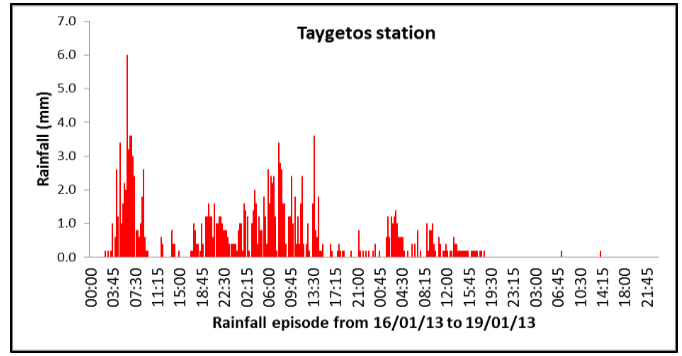
- Mean CN= 62.5

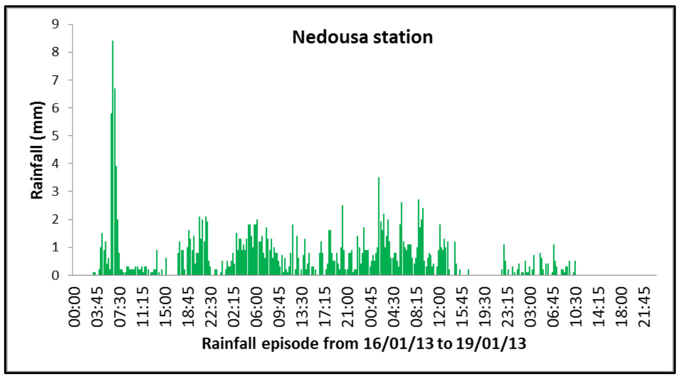


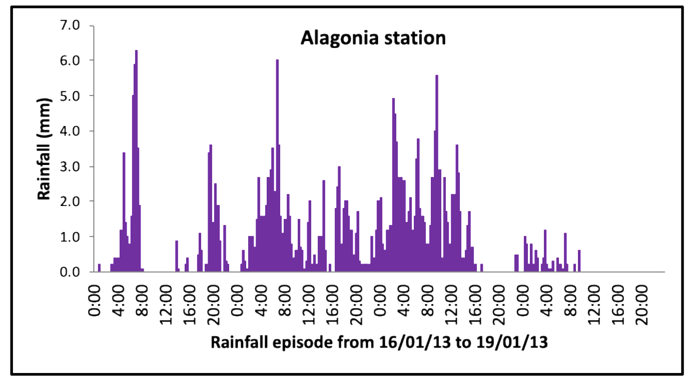
CN values for AMC II conditions (Savvidou et al., 2018)

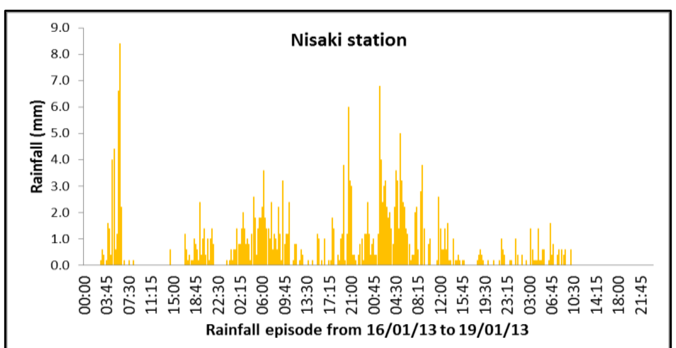
Event A: 16/1/13 - 19/1/13

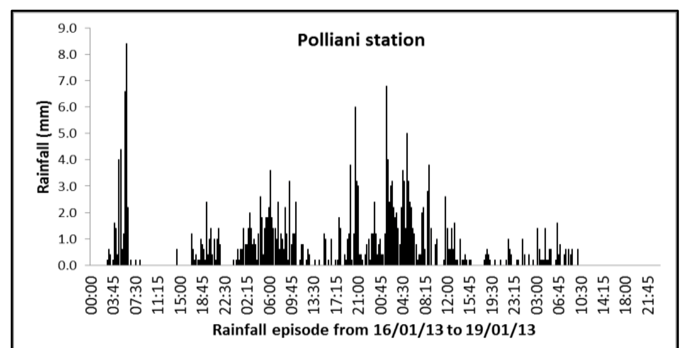






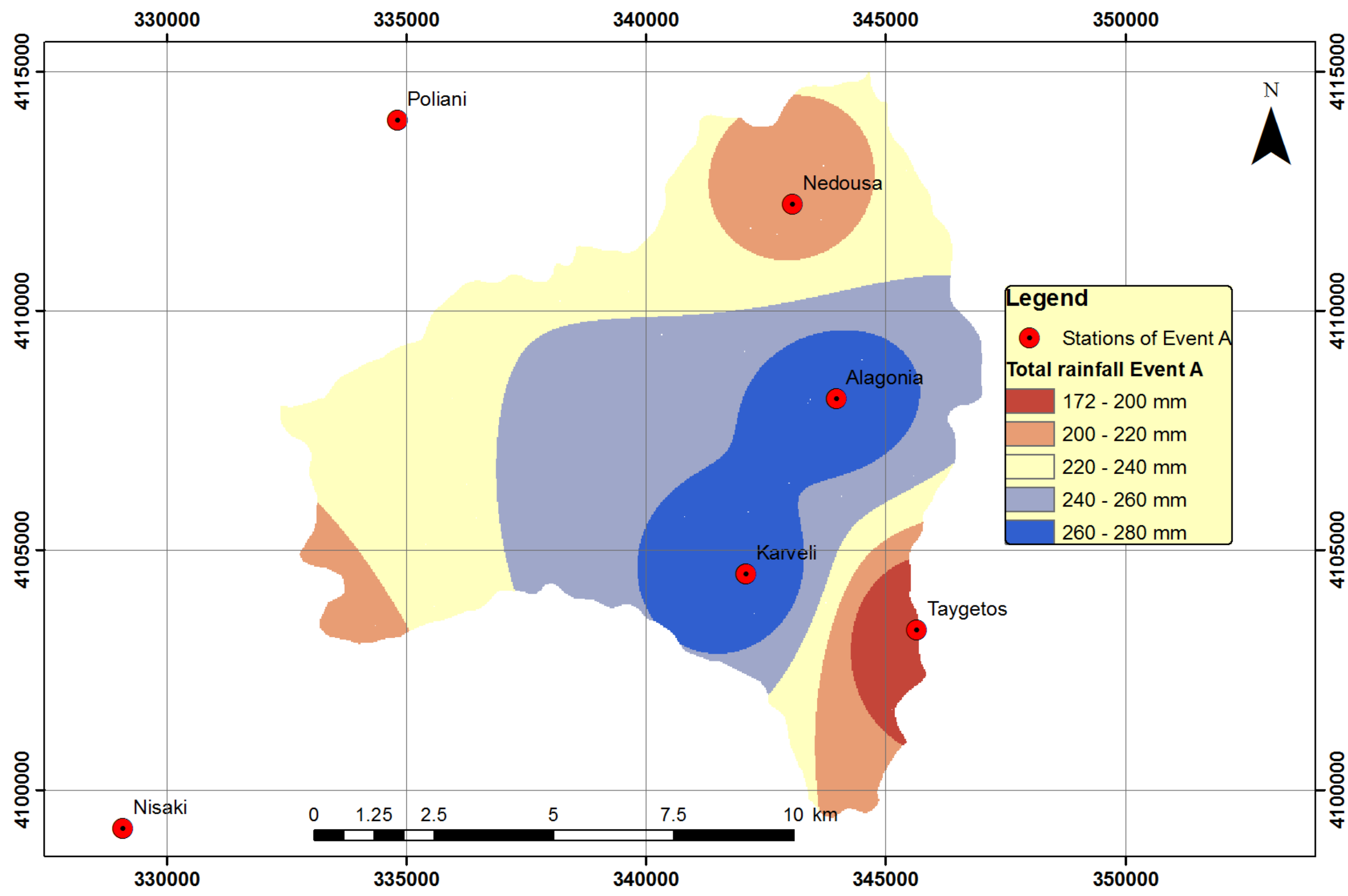




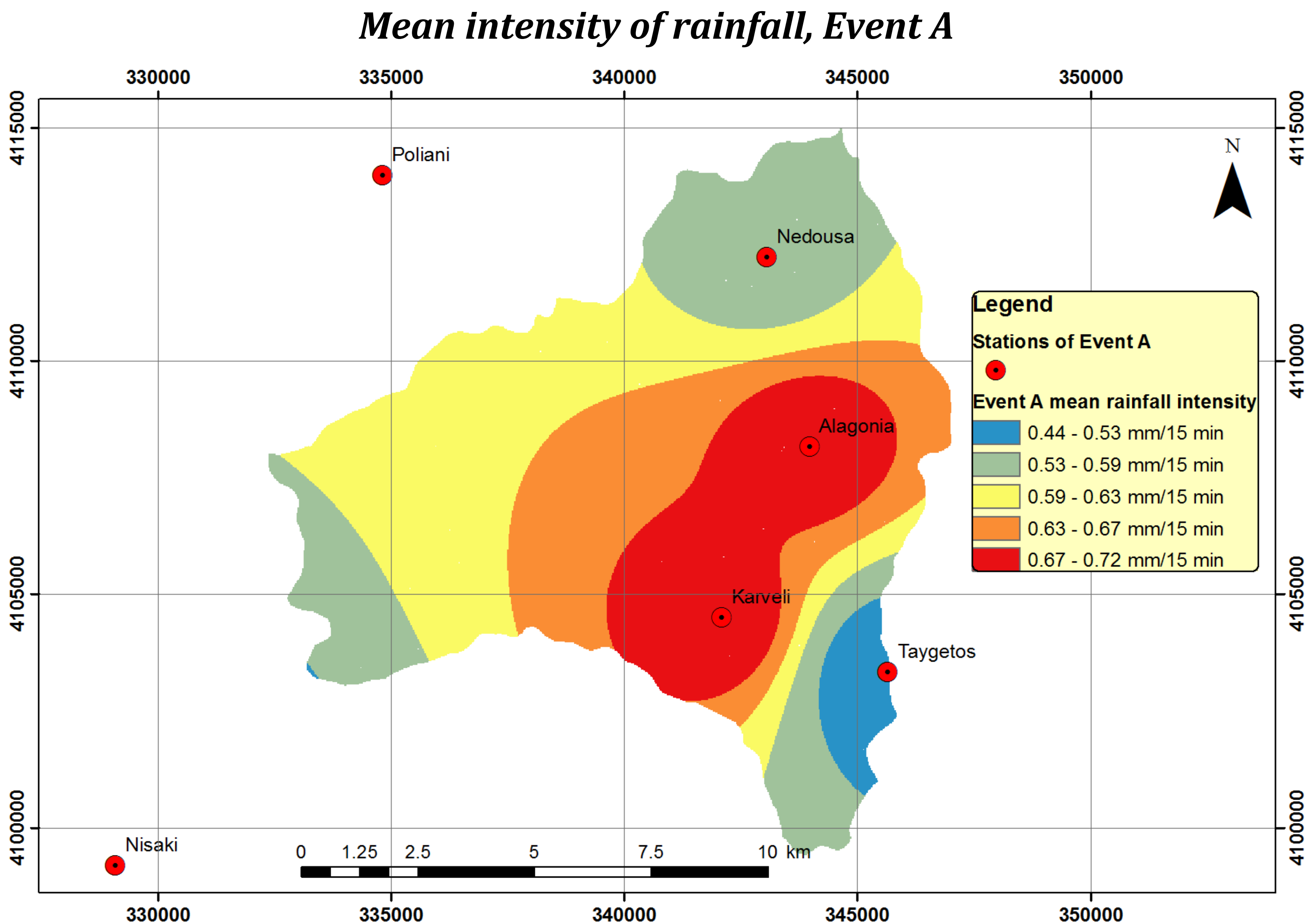


Spatial interpolation of rainfall – Event A

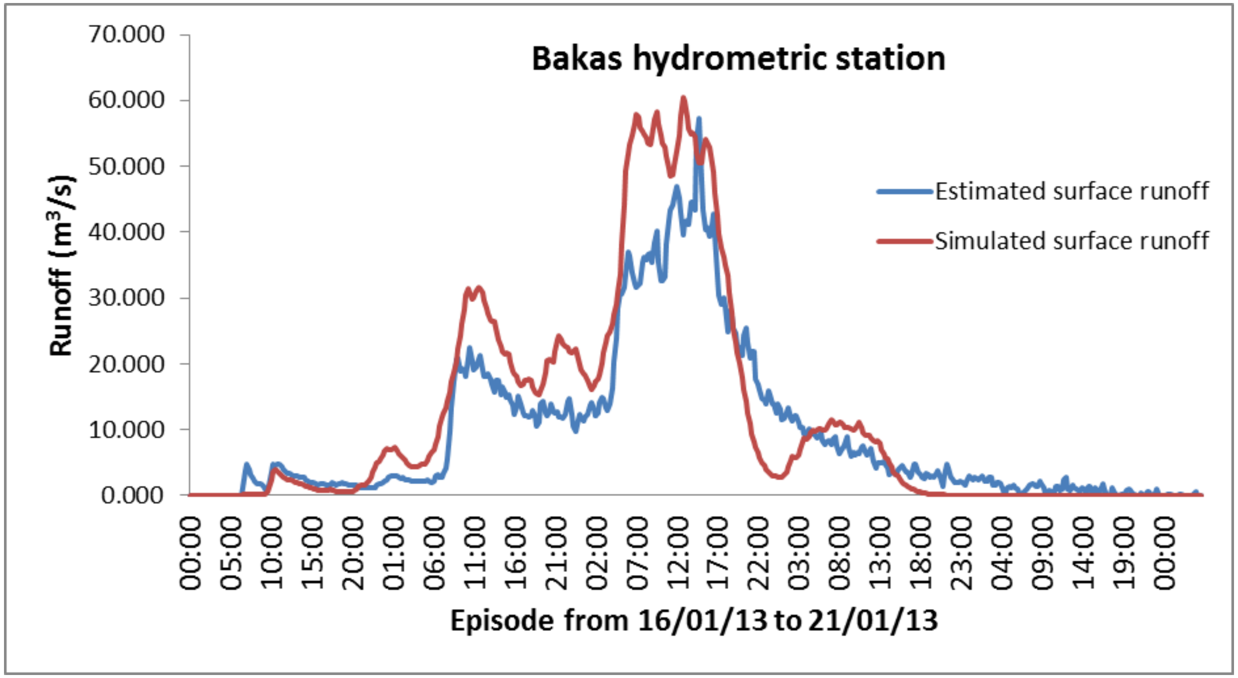
Total rainfall in mm of Event A



Spatial interpolation of rainfall – Event A



Results of surface model– Event A



Parameter	Value
λ	0.050
AMC	0.005

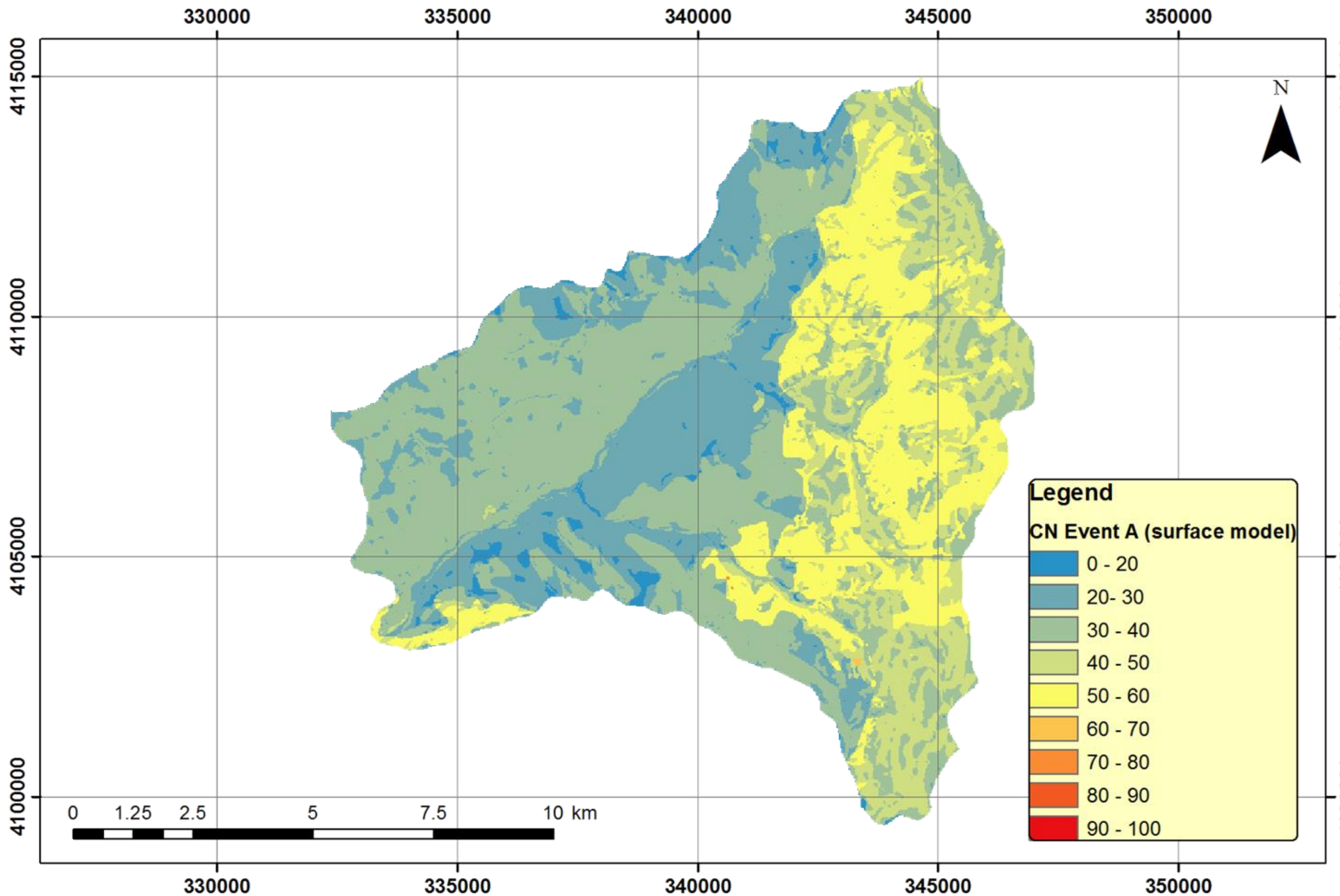
Model parameters after optimization

- 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	0.704
PEV	-21.4%
PEPF	-5.57%
ΔT_{PF}	+120 min

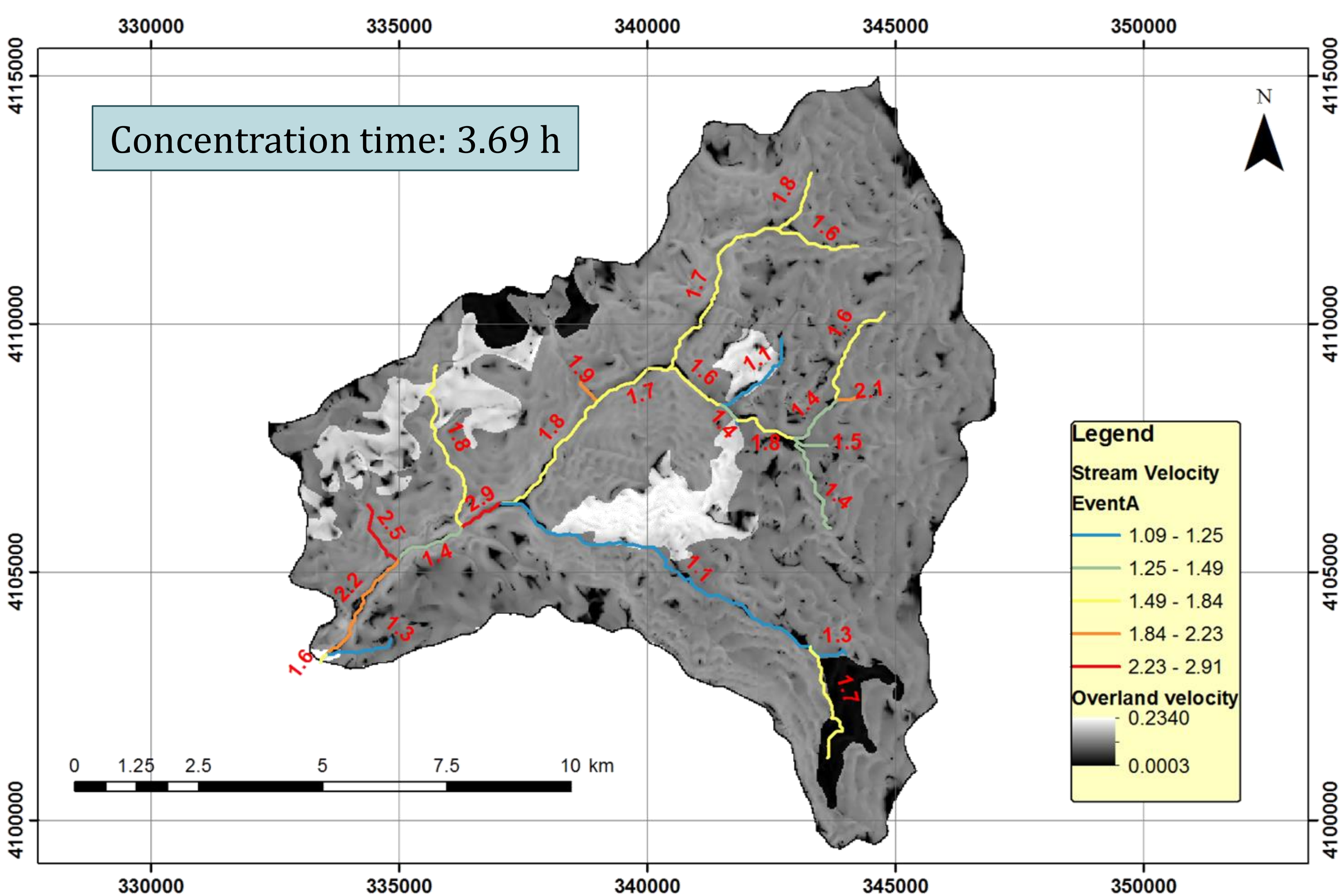
Results of surface only model– Event A

Adjusted CN values for Event A



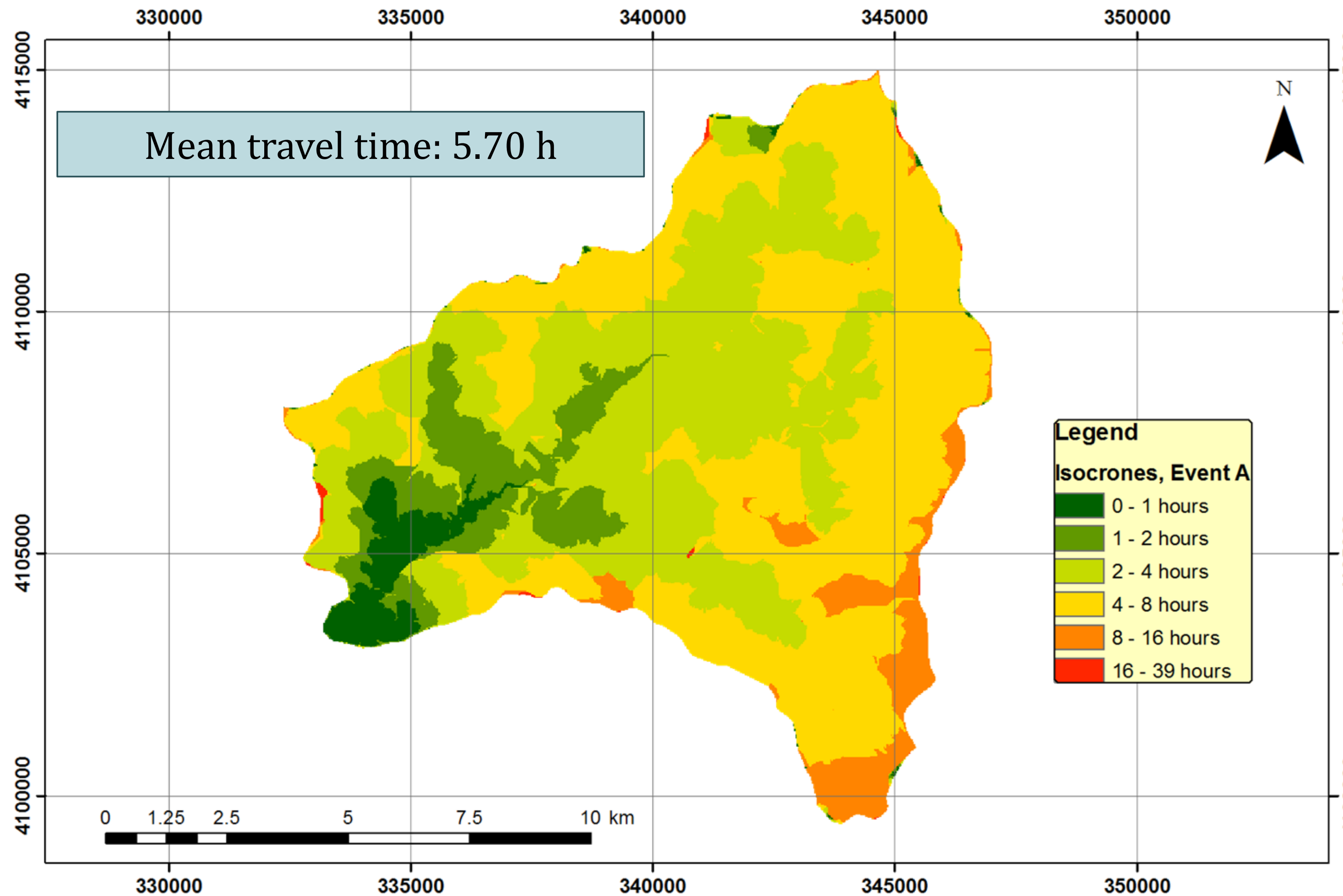
Results of surface model– Event A

Overland and channel velocities of Event A

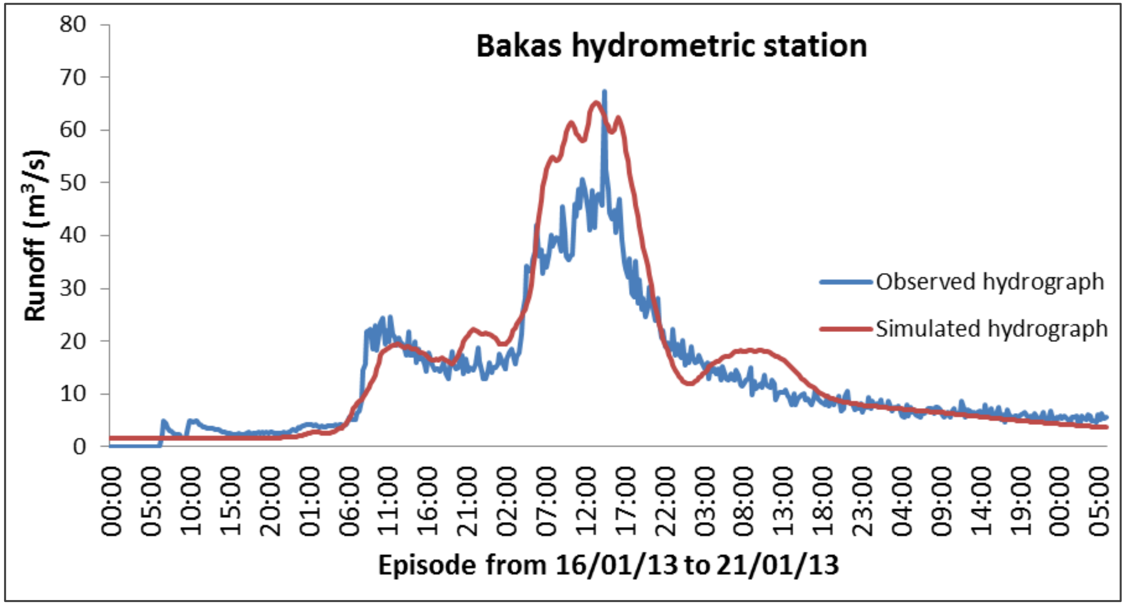


Results of surface model– Event A

Isochrones of Event A



Results of enhanced model – Event A



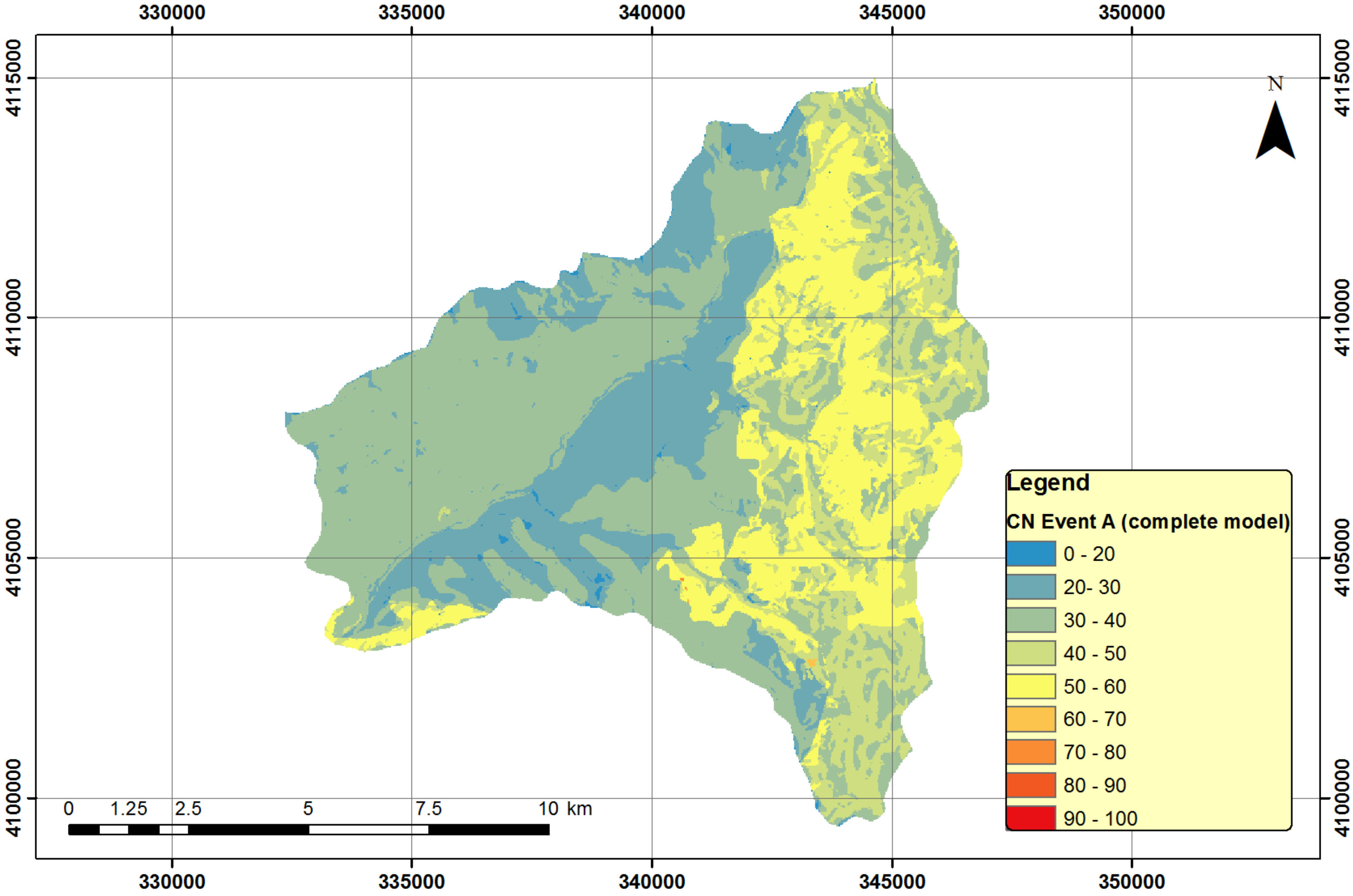
Parameter	Value
λ	0.245
AMC	0.034
κ	0.00078
μ	0.0061
W_0	16.50 mm
δ	9.25 hours

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

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

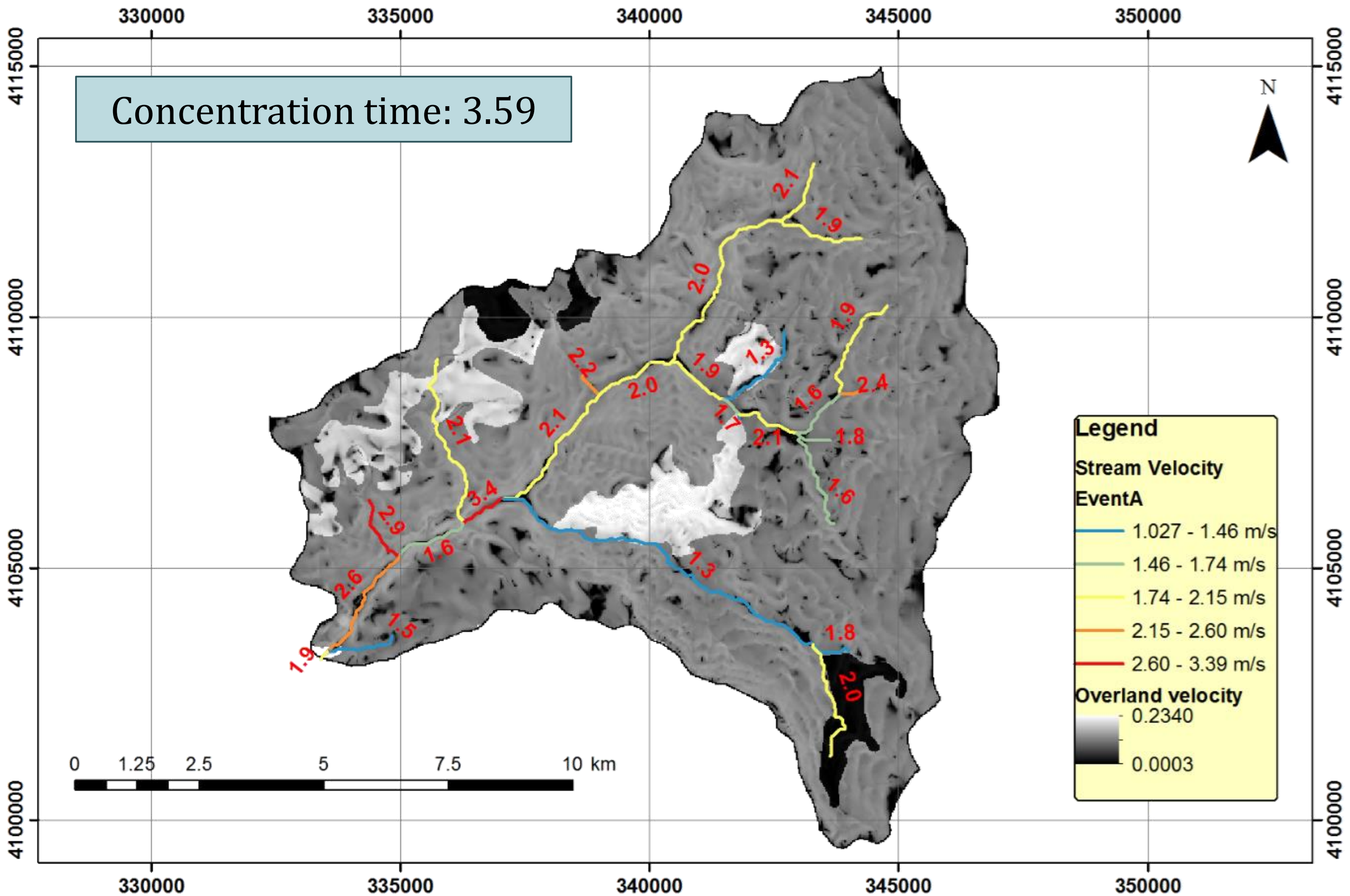
Results of enhanced model - Event A

Adjusted CN values for Event A



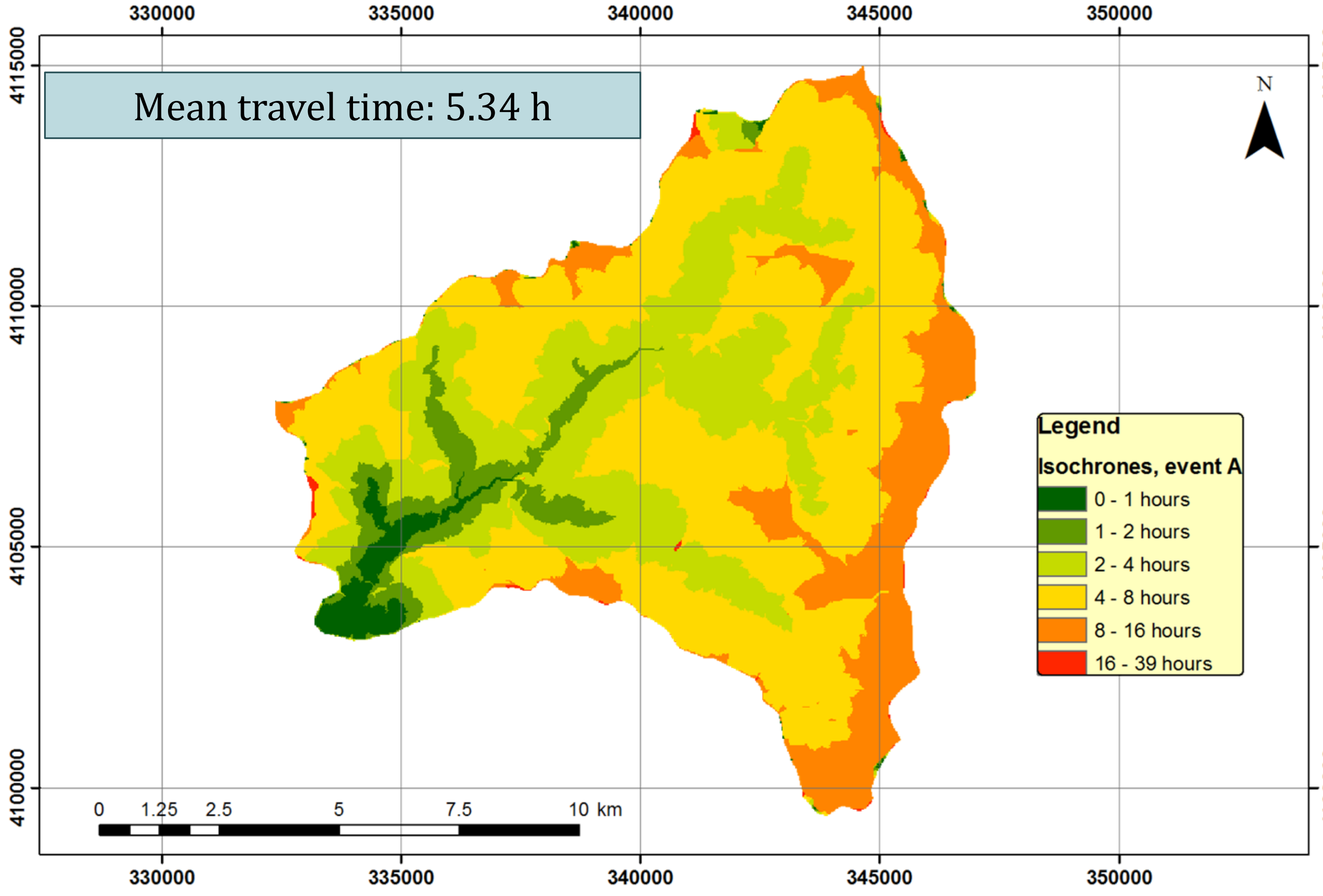
Results of enhanced model – Event A

Overland and channel velocities of Event A

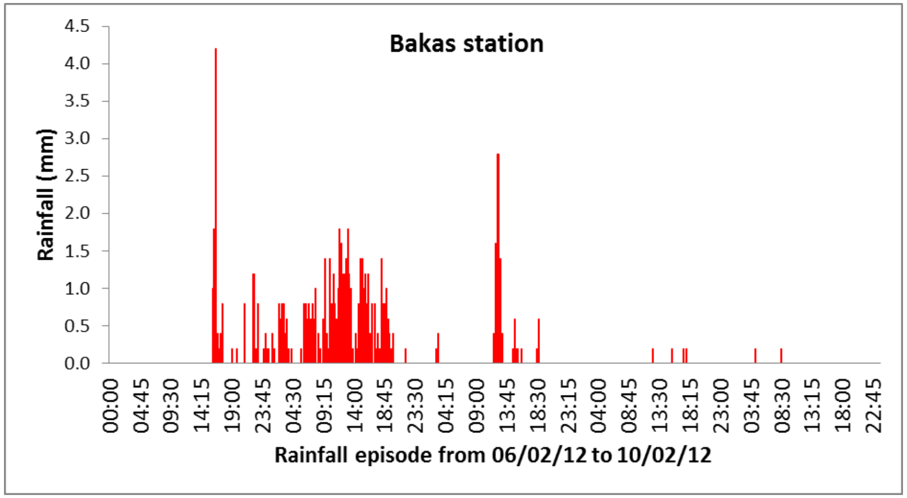


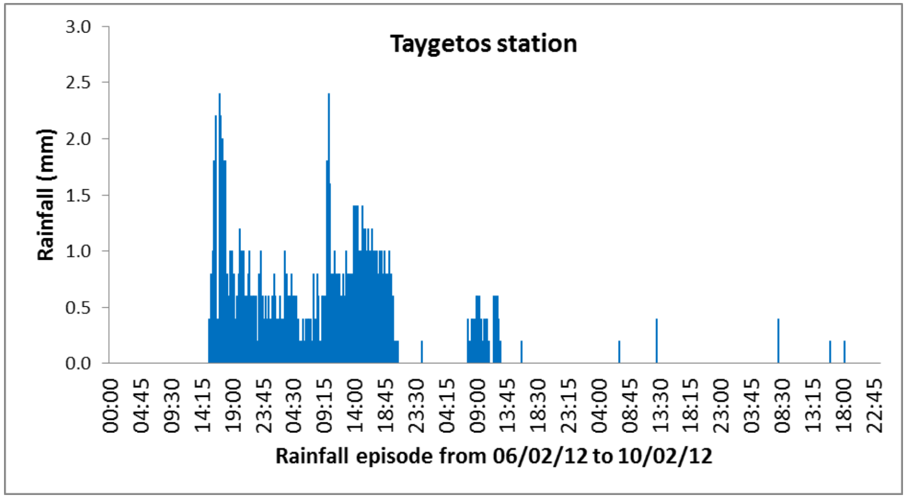
Results of enhanced model – Event A

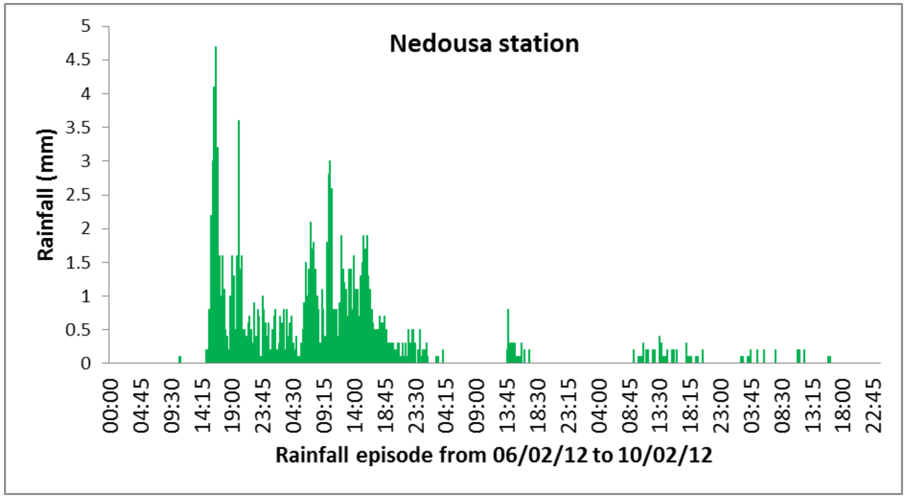
Isochrones of Event A, enhanced model



Event B 6/2/12 - 10/2/12



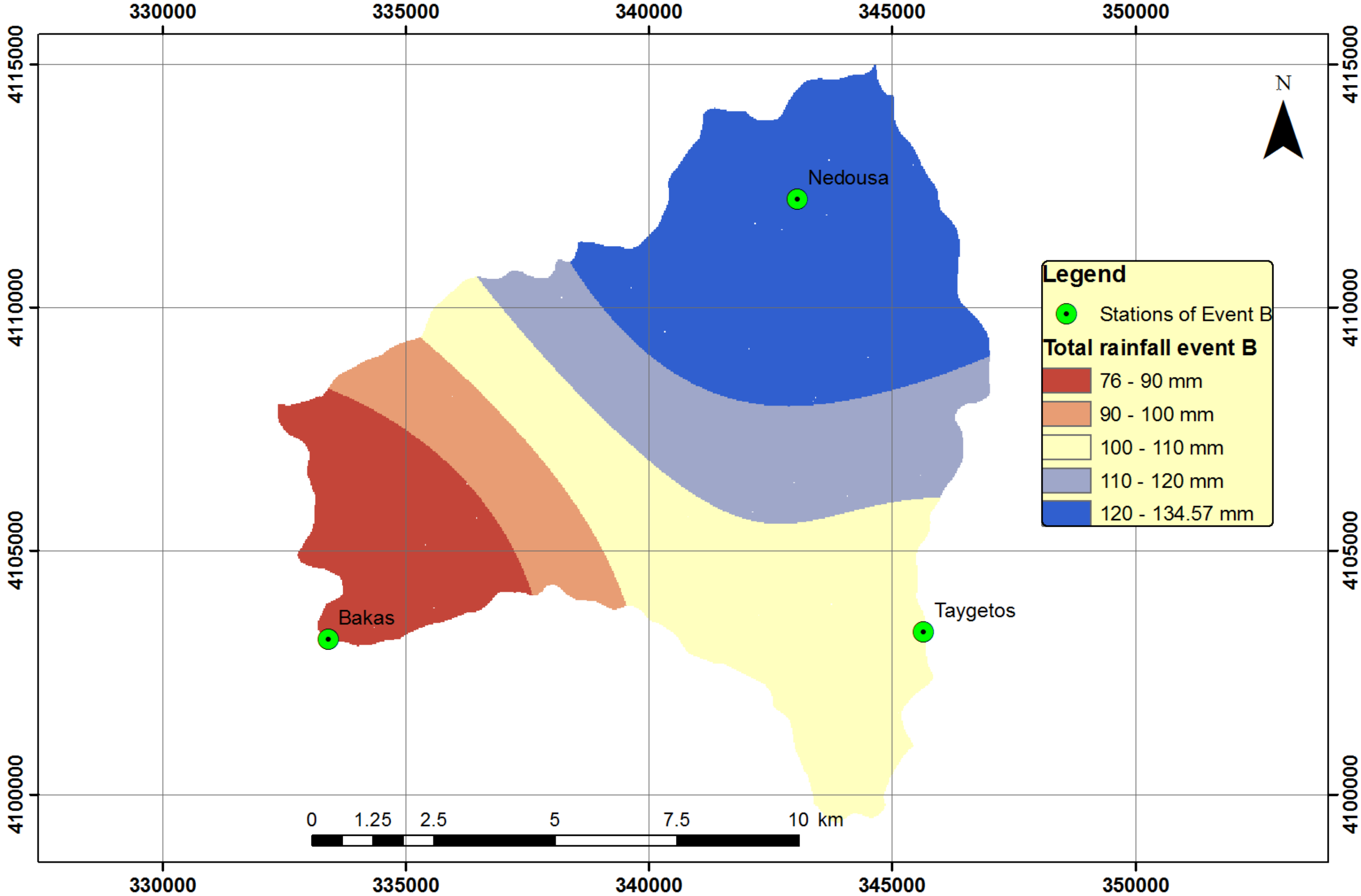




2nd rainfall event for each operational station in the region of Nedontas

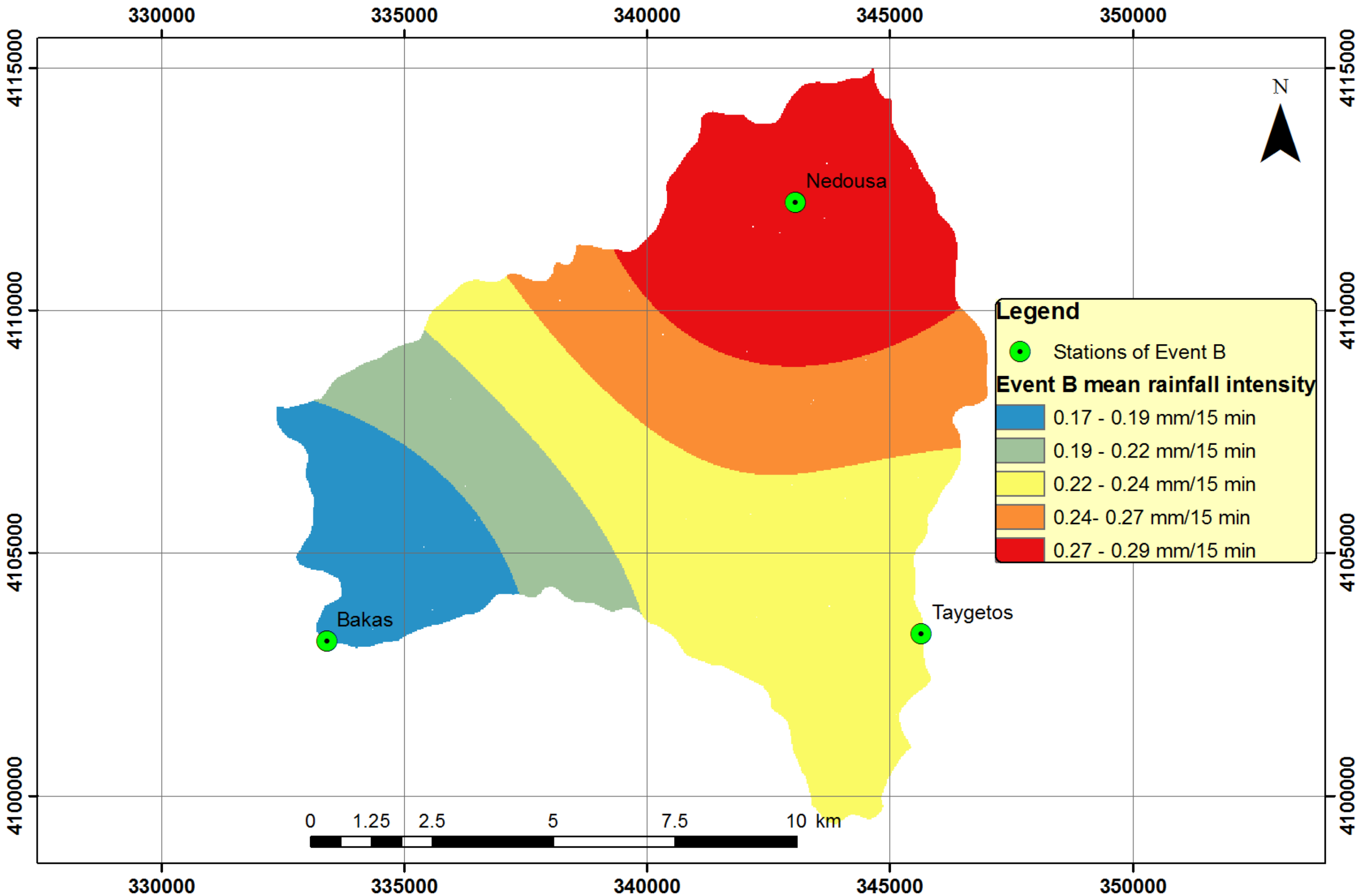
Spatial interpolation of rainfall – Event B

Total rainfall in mm of Event B

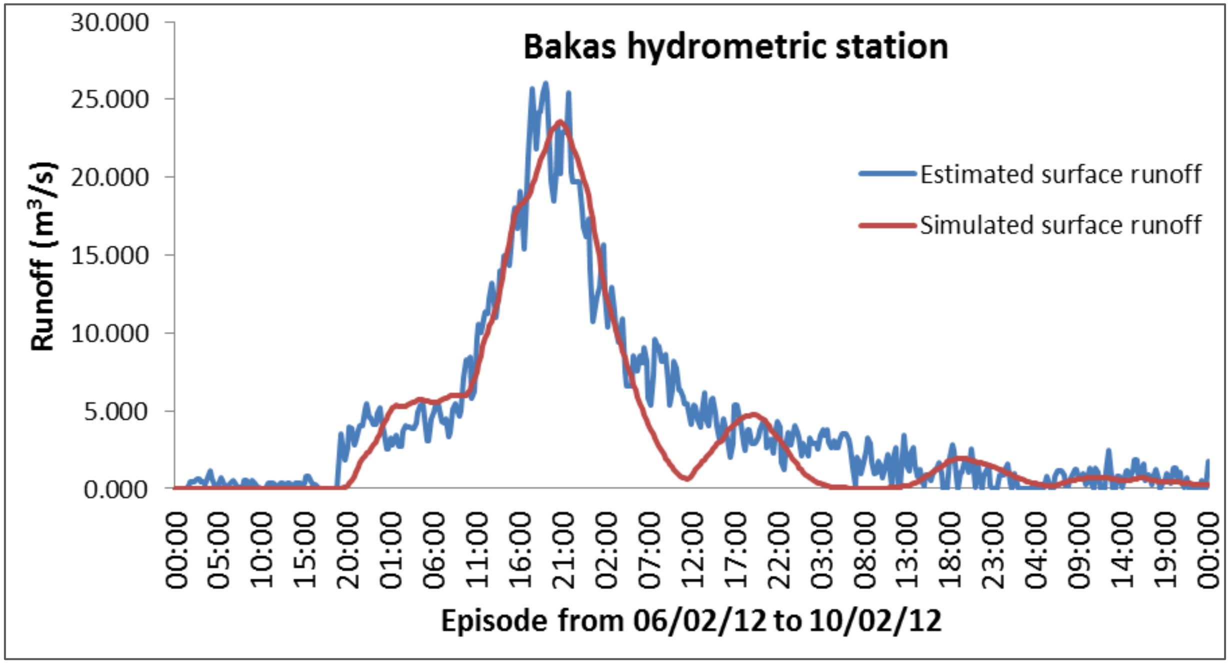


Spatial interpolation of rainfall – Event B

Mean intensity of rainfall, Event B



Results of surface model – Event B



Parameter	Value
λ	0.011
AMC	0.233

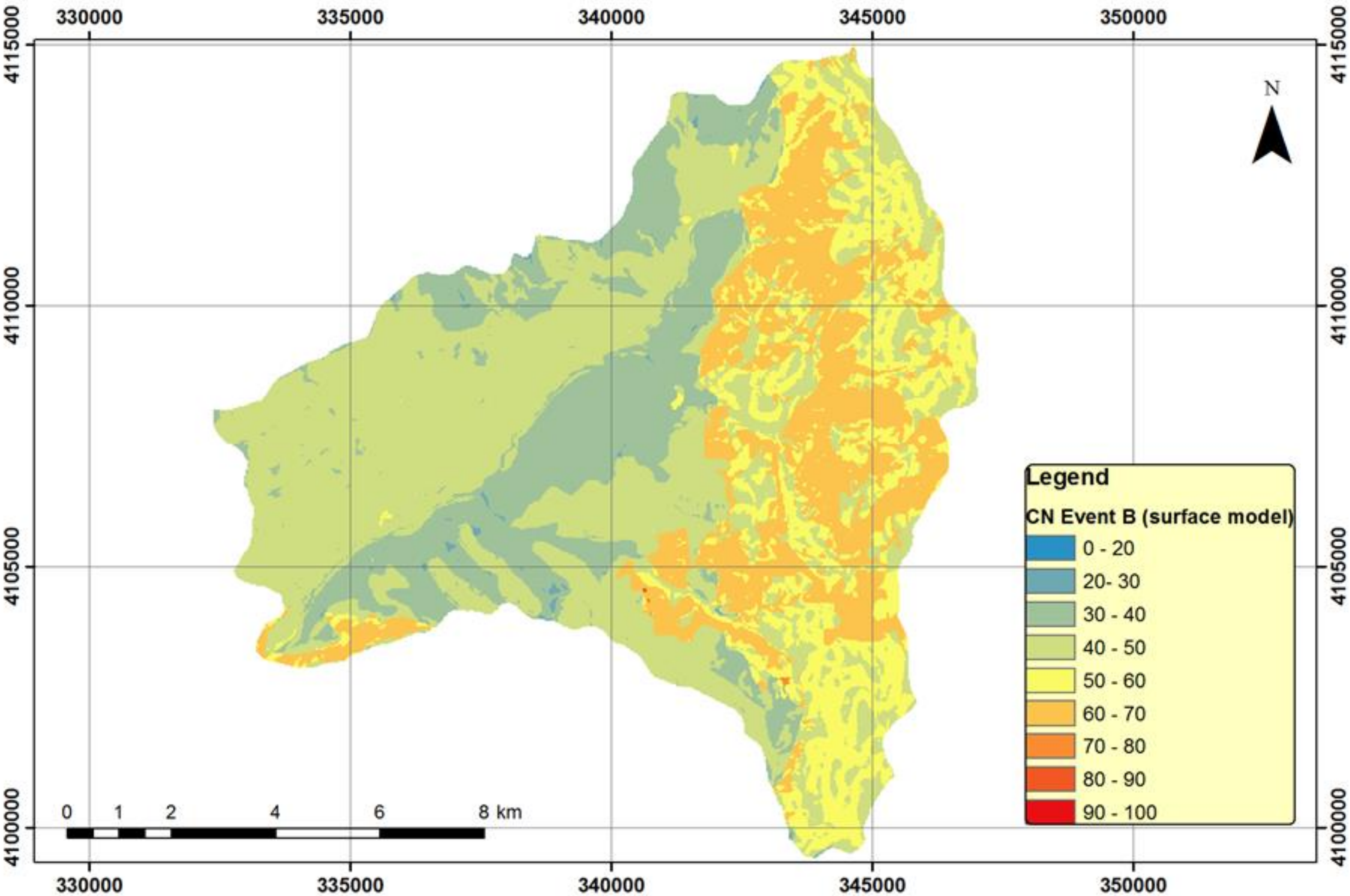
Model parameters after optimization

- 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%
$PEPF$	+7.60%
ΔT_{PF}	-120 min

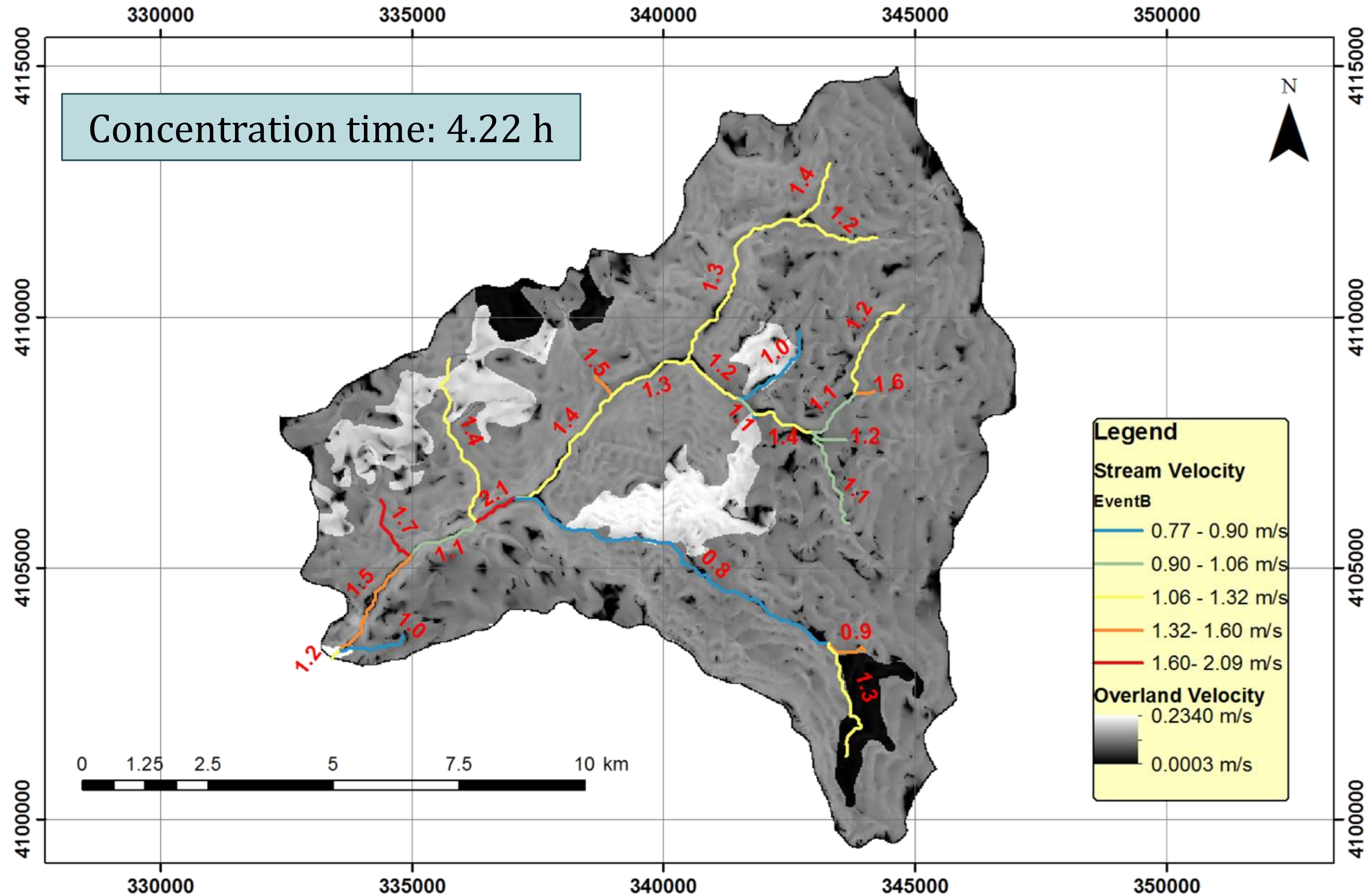
Results of surface model – Event B

Adjusted CN values for Event B



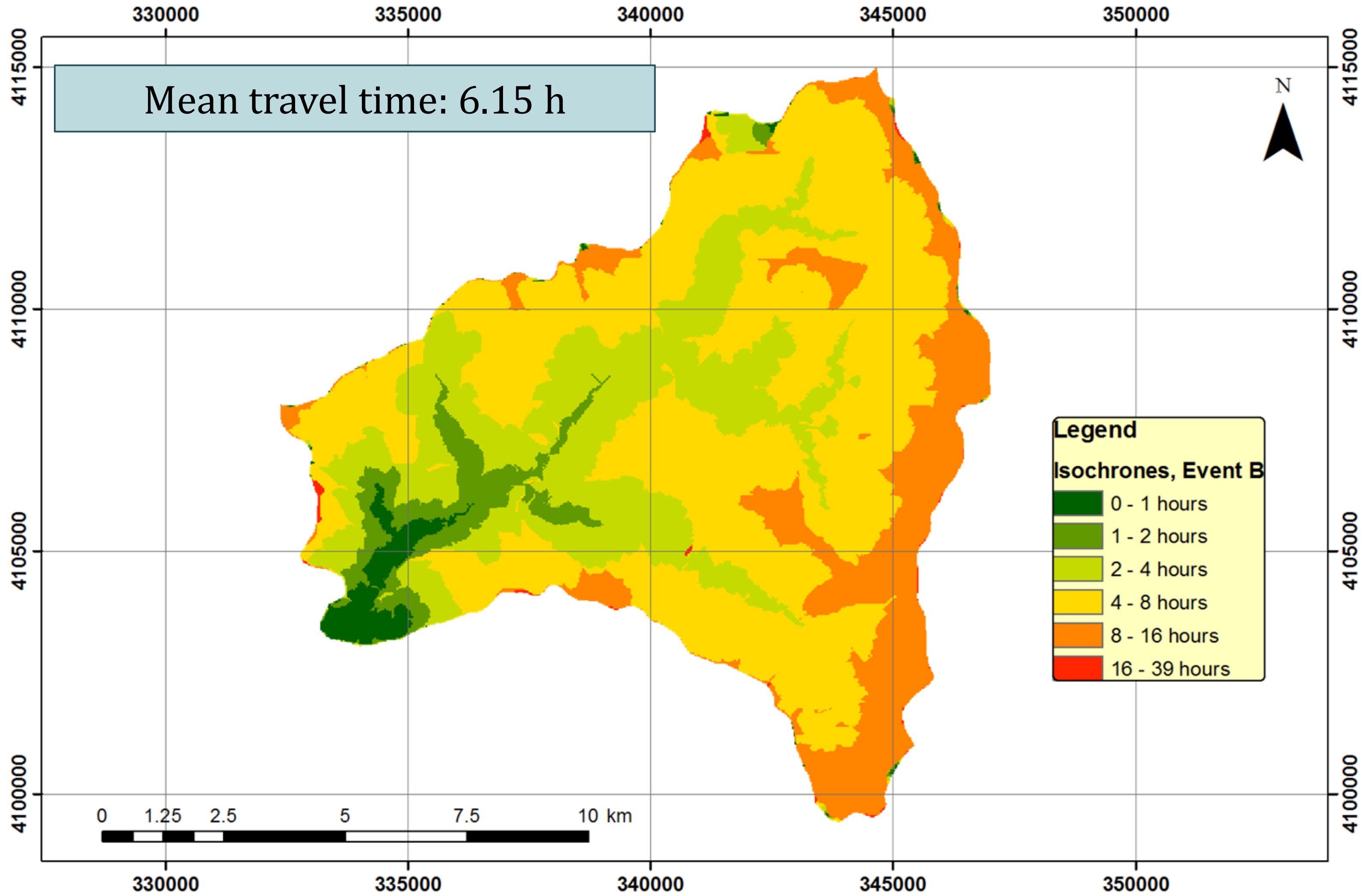
Results of surface model – Event B

Overland and channel velocities of Event B

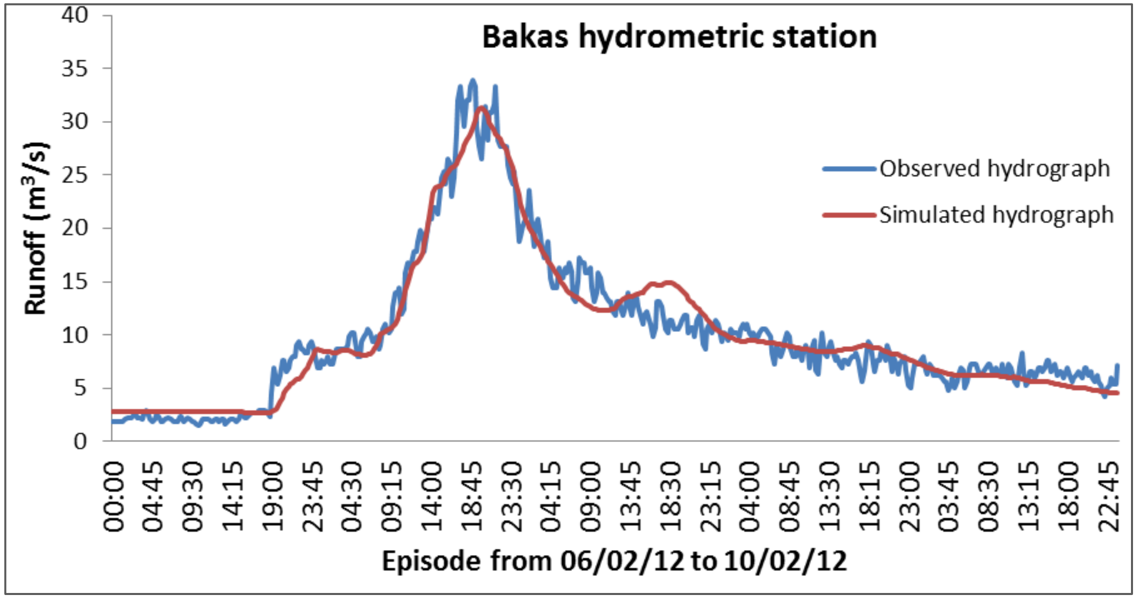


Results of surface model – Event B

Isochrones of Event B



Results of enhanced model – Event B



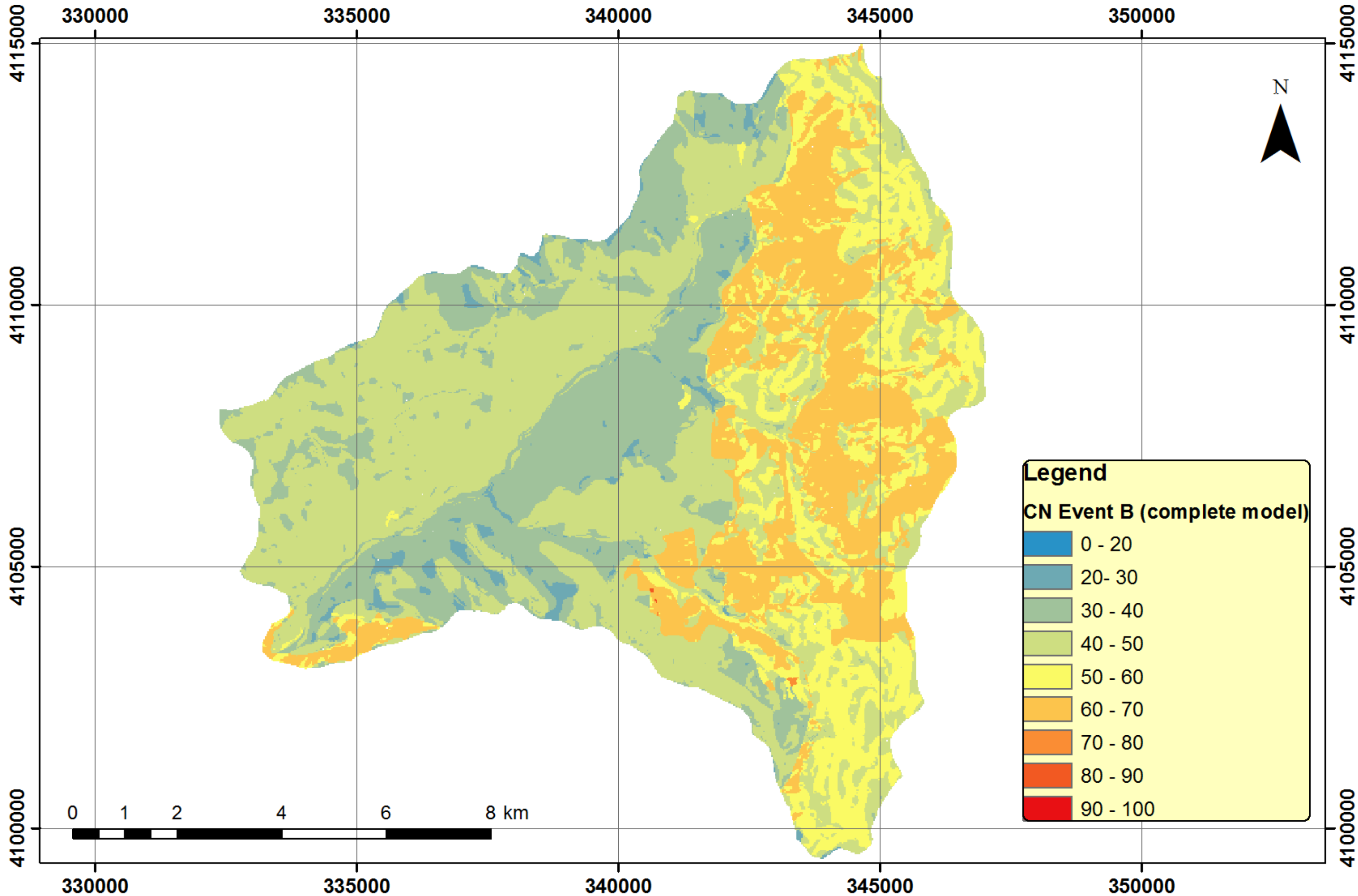
Parameter	Value
λ	0.0005
AMC	0.209
κ	0.0012
μ	0.0038
W_0	16.48 mm
δ	15.5 hours

- 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	0.955
PEV	-15.4%
$PEPF$	+3.0%
ΔT_{PF}	+1 hour

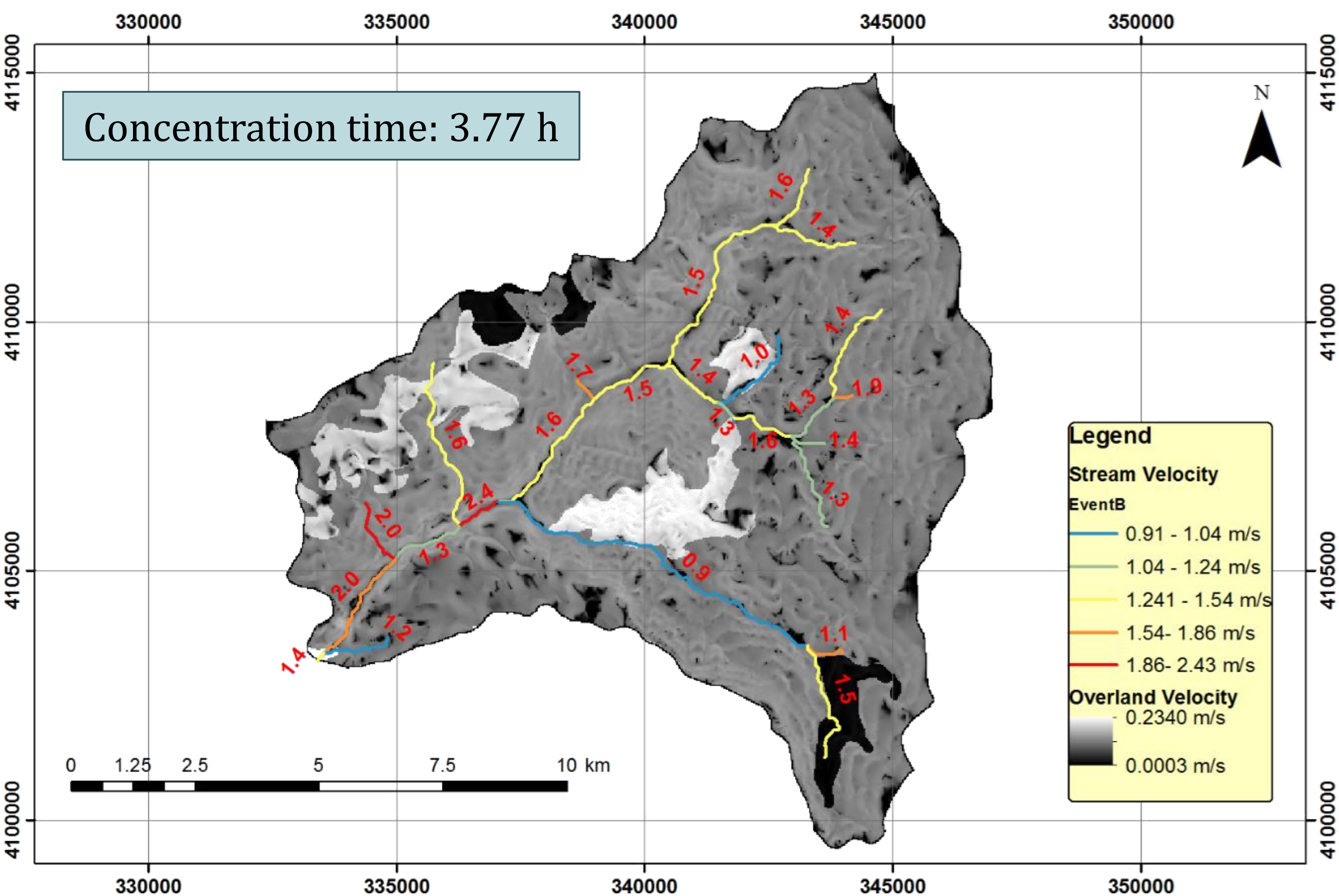
Results of enhanced model – Event B

Adjusted CN values for Event B



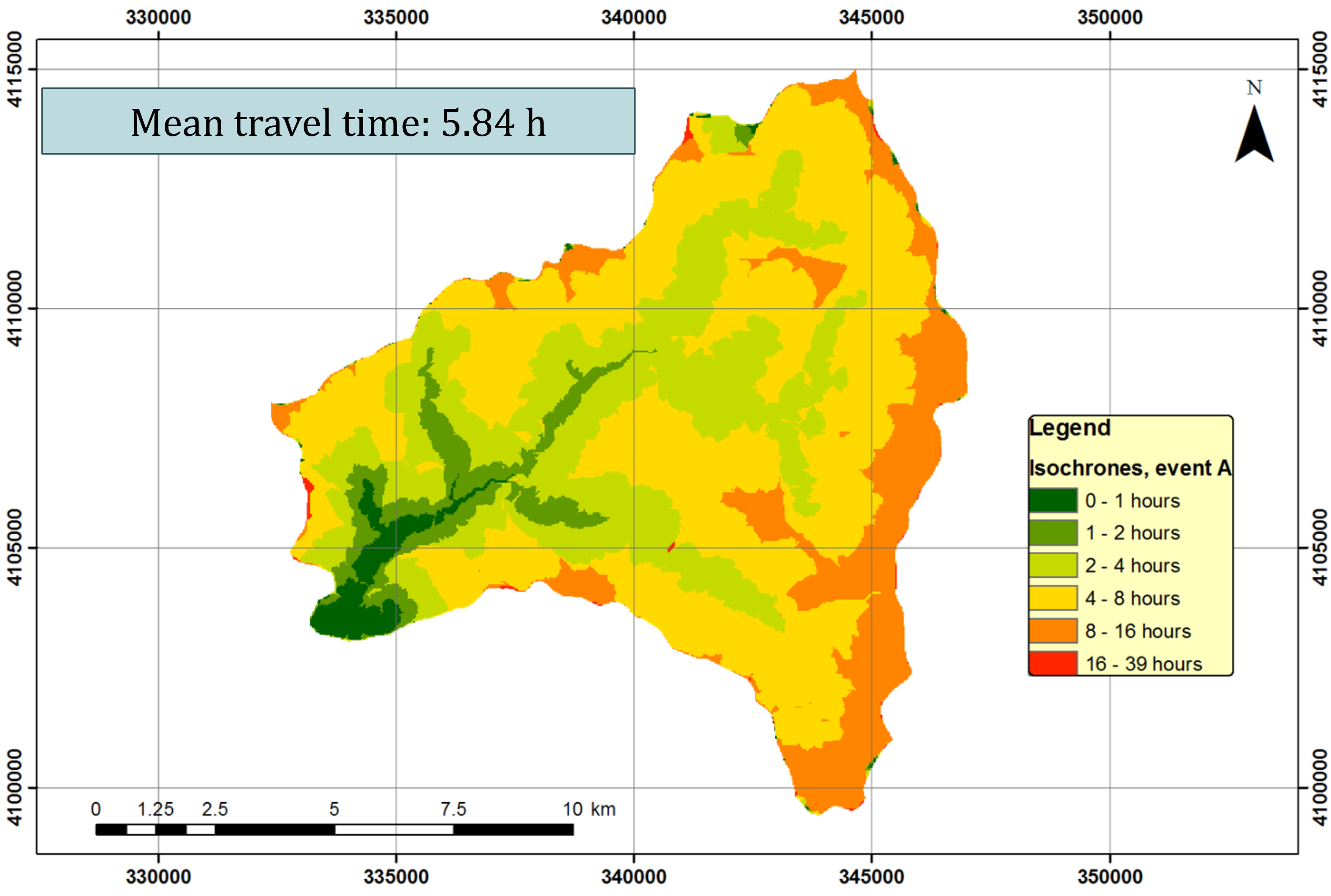
Results of enhanced model – Event B

Overland and channel velocities of Event B



Results of enhanced model – Event B

Isochrones of Event B, enhanced model



Conclusions

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

- A **GIS- based approach** for extracting distributed maps 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 of velocity results with hydraulic models.
- 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.

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