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

Konstantina Risva(1), Dionysios Nikolopoulos(1), Andreas Efstratiadis(1),
(1) School of Civil Engineering, National Technical University of Athens, Greece
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

Flood hydrograph

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Calculation of the effective rainfall

\[
h_e = \begin{cases} 
0 & h \leq h_{a0} \\
\frac{(h - h_{a0})^2}{h - h_{a0} + S} & h > h_{a0}
\end{cases} \quad h_{a0} = \lambda S
\]

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

Natural Resources Conservation Service Curve Number (NRCS-CN)

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Shortcomings of NRCS-CN method

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

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Hydrologic soil group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Cultivated areas</td>
<td>62-72</td>
</tr>
<tr>
<td>Pasture areas</td>
<td>30-68</td>
</tr>
<tr>
<td>Forests</td>
<td>25-45</td>
</tr>
</tbody>
</table>

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
Revised method for the CN assessment

\[ CN = 10 + 9 \times i_{\text{PERM}} + 6 \times i_{\text{VEG}} + 3 \times i_{\text{SLOPE}} \]

\( i_{\text{PERM}} \rightarrow \) Permeability (soil, geology)
\( i_{\text{VEG}} \rightarrow \) Land use/cover (vegetation)
\( i_{\text{SLOPE}} \rightarrow \) 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).

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Adaptation to antecedent conditions

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

\[
CN_I = \frac{4.2CN_{II}}{10 - 0.058CN_{II}}
\]

\[
CN_{III} = \frac{23CN_{II}}{10 + 0.13CN_{II}}
\]
For any antecedent soil moisture conditions (AMC):

\[
CN_{AMC} = \begin{cases} 
CN_{II} - \frac{CN_{II} - CN_I}{0.4} \times (0.5 - AMC_{coef}), & AMC_{coef} < 0.5 \\
CN_{III} + \frac{CN_{III} - CN_{II}}{0.4} \times (AMC_{coef} - 0.5), & AMC_{coef} \geq 0.5 
\end{cases}
\]

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 $\lambda$ according to SCS: 0.20
Standard values in small catchments with steep slopes: $\leq 0.05$

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

\[ h_{a0} = 0.20 S, h_e = \ldots \]

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

$\lambda, AMC$: Common parameters for the entire basin
$h_e, S, CN$: Spatially – varying parameters at a cell level

Efstratiadis et al., 2014

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Isochronous method

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

The outlet runoff at each step:

\[ Q_n = i_n A_1 + i_{n-1} A_2 + \ldots + i_1 A_n \]

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

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Calculation of overland velocity

Sheet-flow equation:

\[ V_o = k J^{1/2} \]

\( J \): Slope (%)
\( k \): Roughness coefficient

Correction formula of steep slope:

\[ J' = 0.05247 + 0.06363 J - 0.182 e^{-62.38 J} \]

\textit{Categories of land cover and proposed k values (adapted from McCuen, 1998)}

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

\textit{Grimaldi et al., 2012}

\textit{Risva et al., Development of a distributed hydrological software application employing novel velocity \textendash based techniques}
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

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Estimation of channel velocities

\[ V_i = \frac{1}{n_i} R_i^{2/3} J_i^{1/2} \]

Lumped parameter for the entire basin

\[ R_i^{2/3} = c \]

\[ t_u = \frac{L_u}{V_u} = \frac{L_u}{k_u J_u^{1/2}} \]

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

\[ c = (t_c - t_u) \left( \frac{n_1 L_1}{j_1^{1/2}} + \frac{n_2 L_2}{j_2^{1/2}} + \cdots + \frac{n_N L_N}{j_N^{1/2}} \right) \]

\( Varying \) time of concentration \( t_c \)

Differs by episode

\[ t_c = t_0 i_e^{-\beta} \]

Michailidi et al. (2018)

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Enhanced model version

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

\[
W_t = W_{t-1} + I_t - Y_t - G_t
\]

\[
K = W_0 + S_0
\]

\[
S_t = K - W_{t-1}
\]

\[
Y_t = \kappa W_t
\]

\[
G_t = \mu W_t
\]

\[
Q_t = \varphi X_t
\]

\[
X_t = X_{t-1} + H_{et} - Q_t
\]

\[
R_t = Y_{t-\delta} + Q_{t-\tau}
\]
Software implementation

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Study area– Nedontas river basin

- Water Department of Western Peloponnese. Nedontas passed through the city of Kalamata.
- Area: 119.3 km²
- $H_{\text{min}}$: 93 m
- $H_{\text{max}}$: 1715 m

Manning values of the stream segments

DEM of the study area

- Major tributaries: Nedousa, Alagonia, Karveliotis
- Estimation of Manning coefficients macroscopically by means of satellite imagery interpretation
- $t_0 = 3.1, \beta = 0.193$
Study area – Nedontas river basin

- Steep slopes, mean value 49%
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

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Spatial interpolation of rainfall – Event A

Total rainfall in mm of Event A

Legend
- Stations of Event A
- Total rainfall Event A
- 172 - 200 mm
- 200 - 220 mm
- 220 - 240 mm
- 240 - 260 mm
- 260 - 280 mm

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Spatial interpolation of rainfall – Event A

Mean intensity of rainfall, Event A

Legend
Stations of Event A

Event A mean rainfall intensity
- 0.44 - 0.53 mm/15 min
- 0.53 - 0.59 mm/15 min
- 0.59 - 0.63 mm/15 min
- 0.63 - 0.67 mm/15 min
- 0.67 - 0.72 mm/15 min

Nisaki
Poliani
Nedousa
Alagonia
Karveli
Taygetos
Results of surface model– Event A

- Nash – Sutcliffe Efficiency Metric
  \[ PEV = 100 \left( \frac{V_0 - V_M}{V_0} \right) \]

- \( PERF = 100 \left( \frac{Q_0(PEAK) - Q_M(PEAK)}{Q_0(PEAK)} \right) \)

- \( \Delta T_{PF} = T_{peak_{obs}} - T_{peak_{sim}} \)

---

**Model parameters after optimization**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda )</td>
<td>0.050</td>
</tr>
<tr>
<td>( AMC )</td>
<td>0.005</td>
</tr>
</tbody>
</table>

**Results of surface model**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NSE )</td>
<td>0.704</td>
</tr>
<tr>
<td>( PEV )</td>
<td>-21.4%</td>
</tr>
<tr>
<td>( PEPF )</td>
<td>-5.57%</td>
</tr>
<tr>
<td>( \Delta T_{PF} )</td>
<td>+120 min</td>
</tr>
</tbody>
</table>
Results of surface only model– Event A

Adjusted CN values for Event A

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Results of surface model– Event A

Overland and channel velocities of Event A

Concentration time: 3.69 h
Results of surface model - Event A

Isochrones of Event A

Mean travel time: 5.70 h
Results of enhanced model – Event A

Nash – Sutcliffe Efficiency Metric

\[ PEV = 100 \left( \frac{V_0 - V_M}{V_0} \right) \]

\[ PERF = 100 \left( \frac{Q_0(PEAK) - Q_M(PEAK)}{Q_0(PEAK)} \right) \]

\[ \Delta T_{PF} = T_{peak_{obs}} - T_{peak_{sim}} \]

Parameter | Value
---|---
\( \lambda \) | 0.245
\( AMC \) | 0.034
\( \kappa \) | 0.00078
\( \mu \) | 0.0061
\( W_0 \) | 16.50 mm
\( \delta \) | 9.25 hours

Metric | Value
---|---
\( NSE \) | 0.865
\( PEV \) | -15.4%
\( PEPF \) | +3.0%
\( \Delta T_{PF} \) | +1 hour
Results of enhanced model - Event A

*Adjusted CN values for Event A*

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Results of enhanced model – Event A

Overland and channel velocities of Event A

Concentration time: 3.59
Results of enhanced model – Event A

Isochrones of Event A, enhanced model

Mean travel time: 5.34 h
**Event B 6/2/12 - 10/2/12**

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

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Spatial interpolation of rainfall – Event B

Total rainfall in mm of Event B

Legend
- Stations of Event B
- Total rainfall event B
- 76 - 90 mm
- 90 - 100 mm
- 100 - 110 mm
- 110 - 120 mm
- 120 - 134.57 mm

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Spatial interpolation of rainfall – Event B

Mean intensity of rainfall, Event B

Legend:
- Stations of Event B
- Event B mean rainfall intensity
  - 0.17 - 0.19 mm/15 min
  - 0.19 - 0.22 mm/15 min
  - 0.22 - 0.24 mm/15 min
  - 0.24 - 0.27 mm/15 min
  - 0.27 - 0.29 mm/15 min

Stations:
- Bakas
- Nedousa
- Taygetos

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Results of surface model – Event B

- Nash – Sutcliffe Efficiency Metric
  \[ PEV = 100 \left( \frac{V_0 - V_M}{V_0} \right) \]

- \( \text{PERF} = 100 \left( \frac{Q_0(\text{PEAK}) - Q_M(\text{PEAK})}{Q_0(\text{PEAK})} \right) \)

- \( \Delta T_{PF} = T_{\text{peak}_{obs}} - T_{\text{peak}_{sim}} \)

Parameter | Value
--- | ---
\( \lambda \) | 0.011
\( AMC \) | 0.233

Model parameters after optimization

Metric | Value
--- | ---
\( NSE \) | 0.901
\( PEV \) | 9.62%
\( PEPF \) | +7.60%
\( \Delta T_{PF} \) | -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

Concentration time: 4.22 h
Results of surface model – Event B

Isochrones of Event B

Mean travel time: 6.15 h
Results of enhanced model – Event B

- Nash – Sutcliffe Efficiency Metric
- \[ PEV = 100 \left( \frac{V_0 - V_M}{V_0} \right) \]
- \[ PERF = 100 \left( \frac{Q_0(PEAK) - Q_M(PEAK)}{Q_0(PEAK)} \right) \]
- \[ \Delta T_{PF} = T_{peak_{obs}} - T_{peak_{sim}} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda )</td>
<td>0.0005</td>
</tr>
<tr>
<td>( AMC )</td>
<td>0.209</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>0.0012</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.0038</td>
</tr>
<tr>
<td>( W_0 )</td>
<td>16.48 mm</td>
</tr>
<tr>
<td>( \delta )</td>
<td>15.5 hours</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NSE )</td>
<td>0.955</td>
</tr>
<tr>
<td>( PEV )</td>
<td>-15.4%</td>
</tr>
<tr>
<td>( PEPF )</td>
<td>+3.0%</td>
</tr>
<tr>
<td>( \Delta T_{PF} )</td>
<td>+1 hour</td>
</tr>
</tbody>
</table>
Results of enhanced model – Event B

*Adjusted CN values for Event B*

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Results of enhanced model – Event B

Overland and channel velocities of Event B

Concentration time: 3.77 h
Results of enhanced model – Event B

Isochrones of Event B, enhanced model

Mean travel time: 5.84 h
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.
References


