UNIVERSITÀ
DEGLI STUDI
DI BRESCIA

REVISITING THE DESIGN FLOOD ESTIMATION PRACTICES UNDER THE DYNAMIC UNIT HYDROGRAPH APPROACH

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THESIS IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF LAUREA MAGISTRALE (MASTER OF SCIENCE) IN CIVIL AND ENVIRONMENTAL ENGINEERING

1. Premise and Objective of the study

- **Unit hydrograph** (UH): common tool to represent the processes of surface runoff routing.
- UH shape: mainly determined by the **peak and base time**, associated with the basin's response time and significantly influenced by **precipitation** which varies.
- UH cannot be considered a characteristic basin property, but a **dynamic** element.
- **Empirical dynamic synthetic UH:** shape is adapted to excess rainfall intensity, with parameters expressed as functions of the varying time of concentration.
- Model tested against observed events from basins in **Italy**, **Greece** and **Cyprus**.
- **Regional formulas** are provided explaining the variability of the two parameters (base and peak time) across basins with different characteristics.

2. Literature review

1. *tc-tlag* formulas

Italian basins:

Empirical: Ventura (1905); Pasini (1914); Giandotti (1934):
Physically-based: Viparelli (1961, 1963)
Varying *tlag*: Bocchiola et al. (2003)

GIS-based approach (physically-based, varying *tc*): Michailidi et al. (2018)

Comprehensive review: Gericke and Smithers (2014), Michailidi et al. (2018)

2. Integration of varying *tc* formulas in hydrological modelling

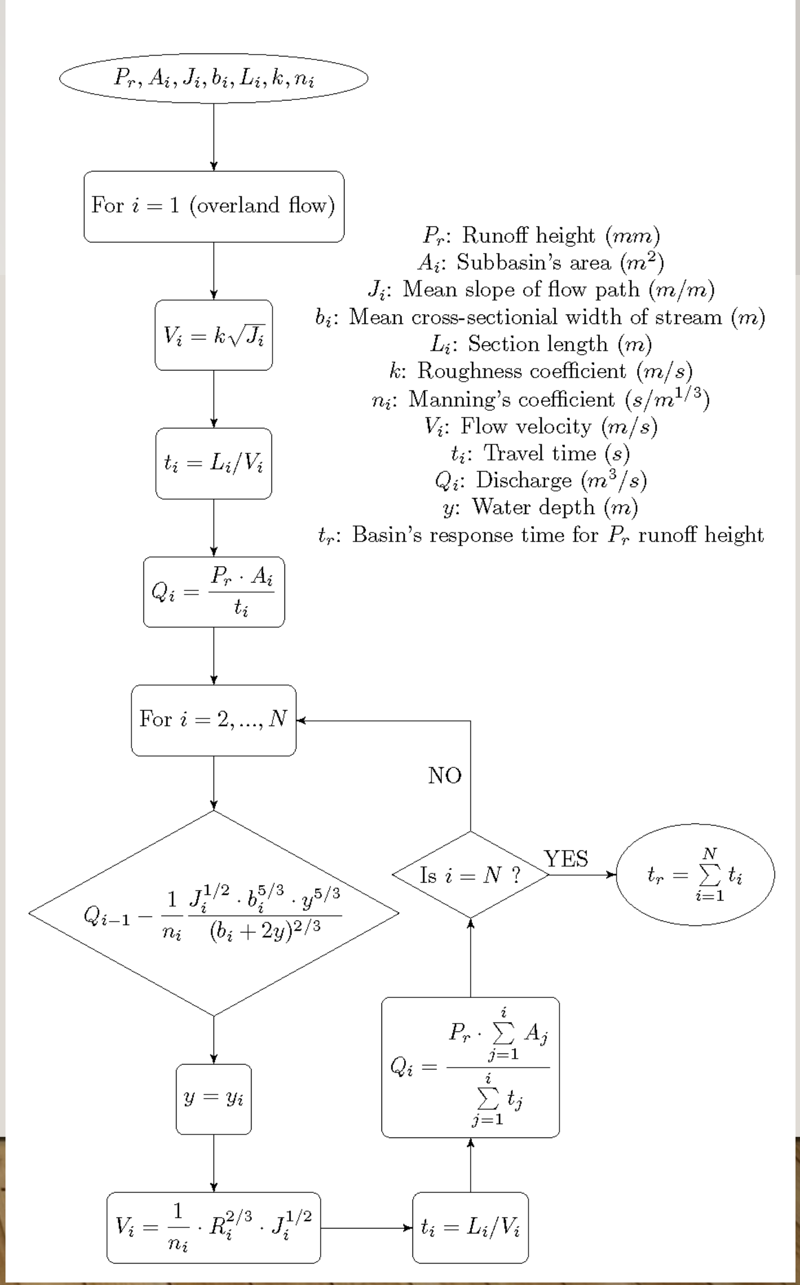
Varying tc (or tlag) in a UH: Reed et al. (1975); Rodríguez-Iturbe et al. (1982)

Pixel-based model: Cho et al. (2018); Risva (2018)

Varying *tc* in an empirical SUH: Michailidi (2018)

3. Methodology: The varying time of concentration (I)

- Improve the existing GIS-based approach for associating basin's response time to runoff of Michailidi et al. (2018);
- Kinematic approach, along the main stream, discretized into a small number of segments according to a user-specified flow accumulation threshold; junctions assigned to major confluences of the main stream with secondary ones; additional junctions, in cases of significant changes of the channel characteristics.
- Flow evolves from upstream to downstream, following key assumptions of the rational method., i.e. a constant runoff depth, Pe, is assigned, uniformly distributed over sub-basins.
- For given channel geometry, travel time along the channel is computed→ response time is sum of upstream travel times.



P_r: Runoff height (mm)
A_i: Subbasin's area (m^2)
J_i: Mean slope of flow path (m/m)
b_i: Mean cross-sectional width of stream (m)
L_i: Section length (m)
k: Roughness coefficient (m/s)
n_i: Manning's coefficient ($s/m^{1/3}$)
V_i: Flow velocity (m/s)
t_i: Travel time (s)
Q_i: Discharge (m^3/s)
y: Water depth (m)
t_r: Basin's response time for P_r runoff height

3. Methodology: The varying time of concentration (II)

Original approach: Michailidi et al. (2018)

- Upstream sub-basin produces only overland flow and its response is a function of slope, length and roughness → $\boldsymbol{t_0} = \frac{\boldsymbol{L_0}}{\boldsymbol{V_0}} = \frac{\boldsymbol{L_0}}{\boldsymbol{k\sqrt{S_0}}}$

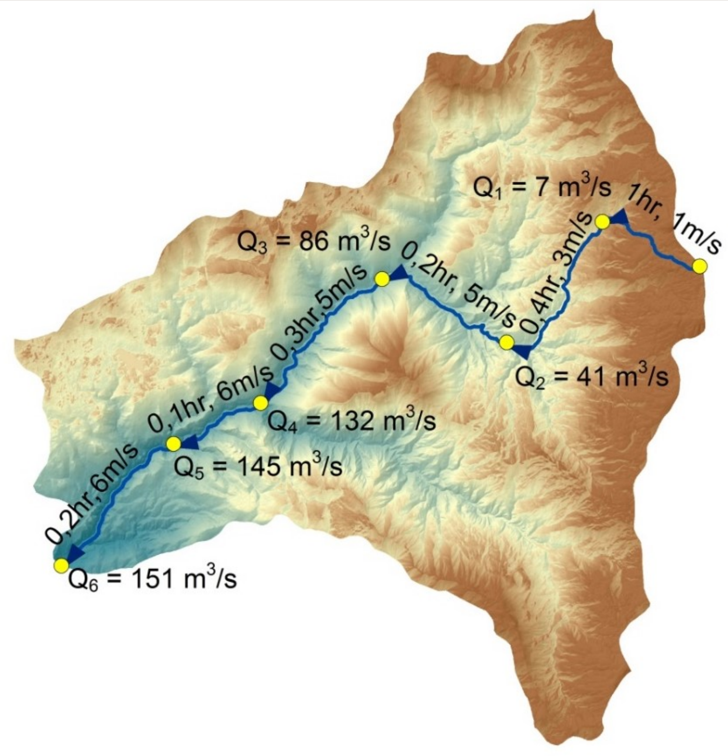


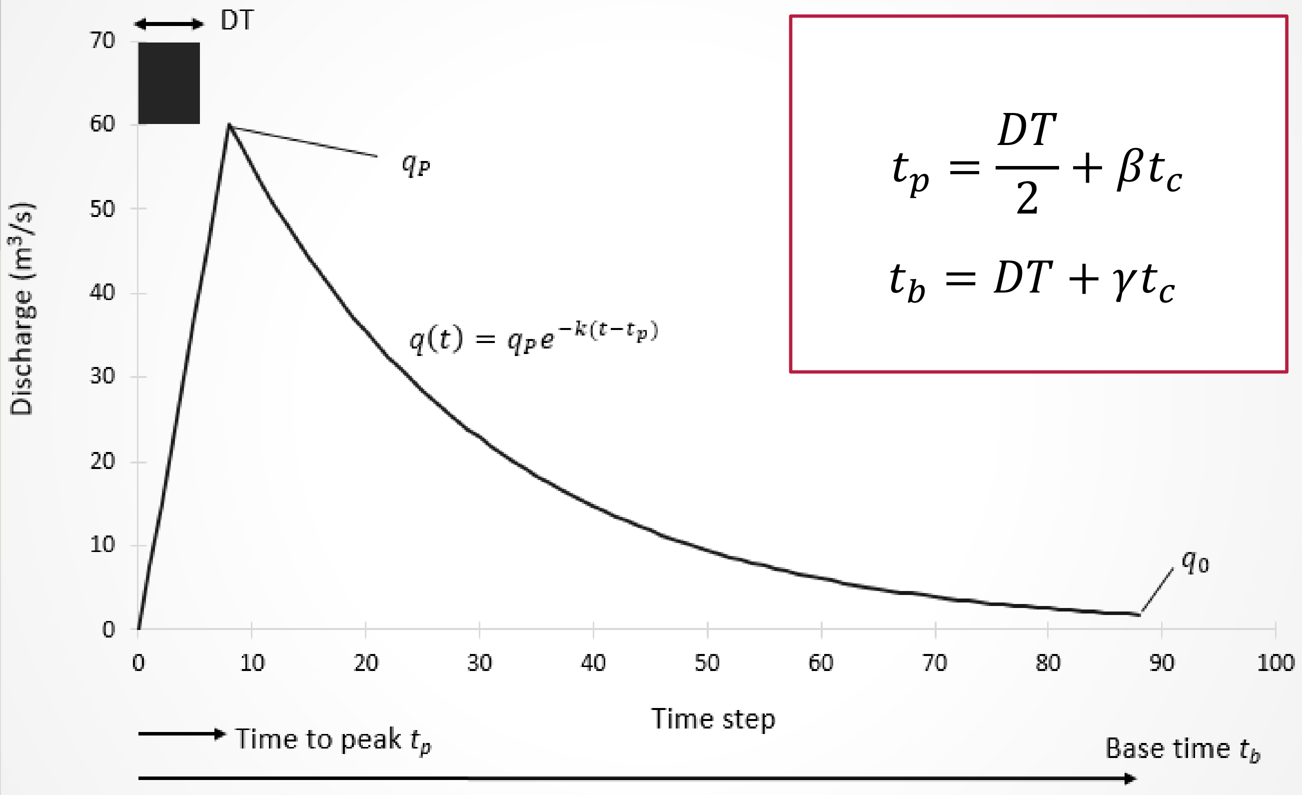
Figure 1: Model results along Nedontas river for P = 10 mm

Improved version

- Upstream sub-basin produces only overland flow and its response is a function of length *L*, slope *S*, roughness *n* and excess rainfall intensity i_e (Chow et al., 1988) → $t = L^{0.6} n^{0.6} / (i_e{}^{0.4} S^{0.3})$

Re-calculations for different runoff depths → new tc vs. i_e relationships and new regional formulas.

3. Methodology: The dynamic synthetic unit hydrograph



$$t_p = \frac{DT}{2} + \beta t_c$$

$$t_b = DT + \gamma t_c$$

Figure 2: The developed dynamic SUH.

- First introduced by Michailidi (2018)
- Base and peak time: functions of *tc*, estimated from the regional formulas of *tc*.
- Parametrised empirical SUH, taking into account the geomorphological basin diversities and the effect of excess rainfall intensity in each time step in a dynamic manner, thus, creating a sort of *dynamic synthetic unit hydrograph.*
- Parameters *β* and *γ* calibrated for each basin.

4. Application: Data Collection

- The study basins are small-to-medium size and mostly mountainous, located in Greece, Italy and Cyprus. The selection of the study basins was carried out based on the following criteria:
- Non-urbanised basin, unaffected by technical interventions at least at the largest percentage of the total cover area.
- Absence of a reservoir controlled by a dam upstream of the hydrometric station;
- Availability of both discharge or stage and rainfall data in a fine temporal scale (≤1 h) in the same time period.

4. Application: Study basins

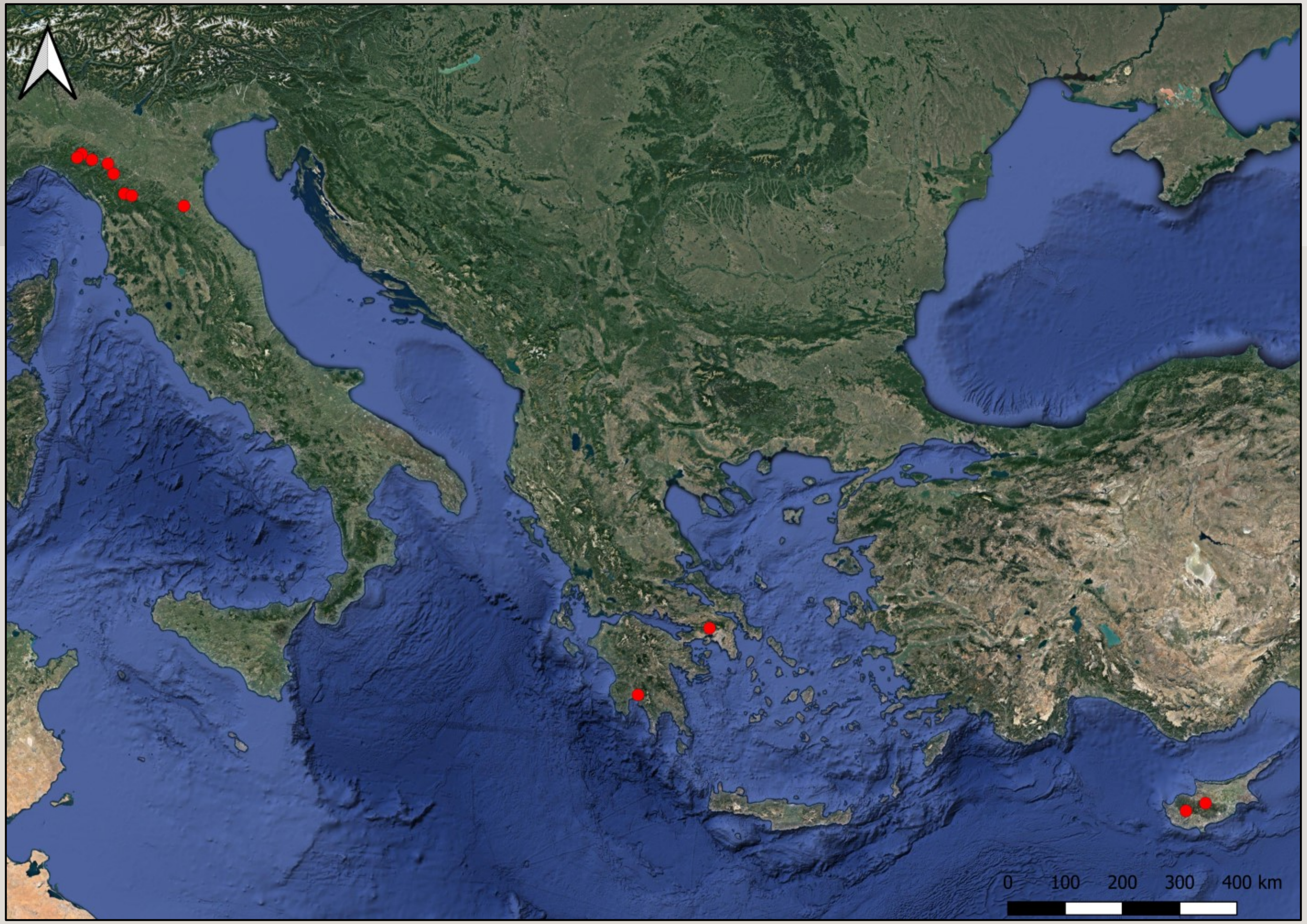


Figure 3: Location of the study basins (in red).

River basin (outlet)	Country	A (km²)	L (km)	J (%)	Δz (m)
Sarantapotamos (Gyra Stefanis)	GR	143.7	32.1	3.8	369
Nedontas (Kalamata)	GR	114.8	21.6	7.5	819
Baganza (Marzolara)	IT	125.5	32.7	3.7	538
Scoltenna (Pievepelago)	IT	129.7	14.9	11.7	583
Ceno (Ponte Lamberti)	IT	328.7	38.2	3.8	517
Nure (Ferriere)	IT	48.3	12.1	7.9	489
Leo (Fanano)	IT	36.9	10.6	18.7	752
Montone (Castrocaro)	IT	235.7	47.4	4.2	455
Enza (Vetto)	IT	293.5	31.5	5.5	551
Nure (Farini)	IT	200.6	24.4	5.0	513
Xeros (Lazarides)	CY	67.5	12.9	12.4	436
Peristerona (Panagia Bridge)	CY	77.8	23.6	8.4	466

4. Application: Calibration framework

- NRCS-CN method for calculation of hydrological losses and excess rainfall; abstraction ratio, λ, considered equal to 0.05 (low infiltration and mountainous basins).
- Global multi-criteria optimisation framework of parameters β (time-to-peak parameter) and γ (base time parameter) on 160 events from 10 basins.
- Objective: reduce the error between the simulated and observed: discharge values, peaks, start and end of event runoff.
- $$F(\beta,\gamma) = \sum_{i=1}^{j}\left(10\sum_{t=1}^{n}\frac{|q_{obs,i,t}-q_{sim,i,t}|}{q_{obs,i,t}} + 3000\frac{|q_{p,obs,i}-q_{p,sim,i}|}{q_{p,obs,i}} + 1000\frac{|t_{start,obs,i}-t_{start,sim,i}|}{t_{start,obs,i}} + 1000\frac{|t_{peak,obs,i}-t_{peak,sim,i}|}{t_{peak,obs,i}}\right)$$
- The Evolutionary Annealing-Simplex (EAS) optimisation algorithm was used, originally developed by Efstratiadis (2008) and written in MATLAB, available freely in https://www.itia.ntua.gr/en/softinfo/29/.

5. Results: The varying time of concentration (I)

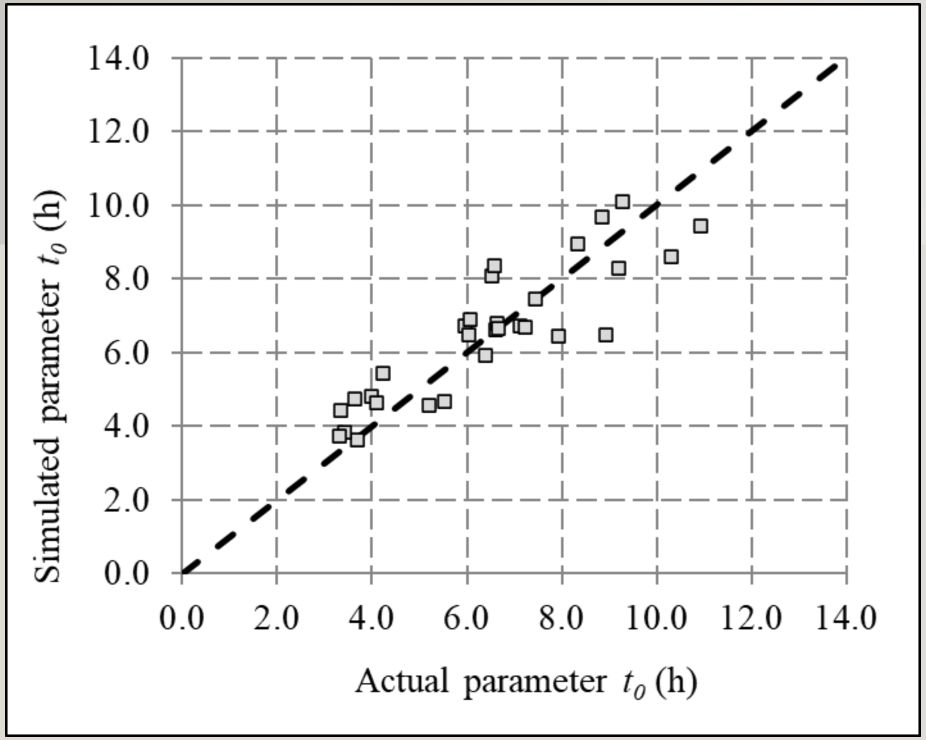
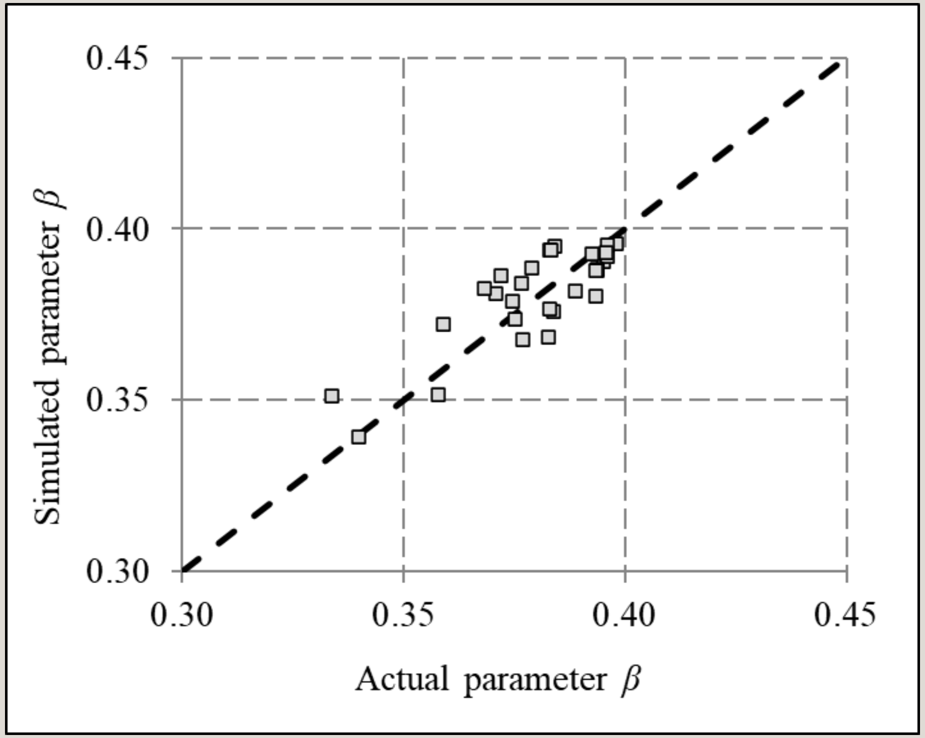


Figure 4: Comparison of actual (i.e. estimated through the GIS procedure) and simulated (by the corresponding regional formulas) parameters t_0 (top) and β (right).

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

$$t_0 = 30.0\, n L^{0.164} b^{0.058} J^{-0.358}$$

$$\beta = 0.40 - 0.03 A^{0.304} L^{0.548} b^{-1.543}$$



5. Results: The varying time of concentration (II)

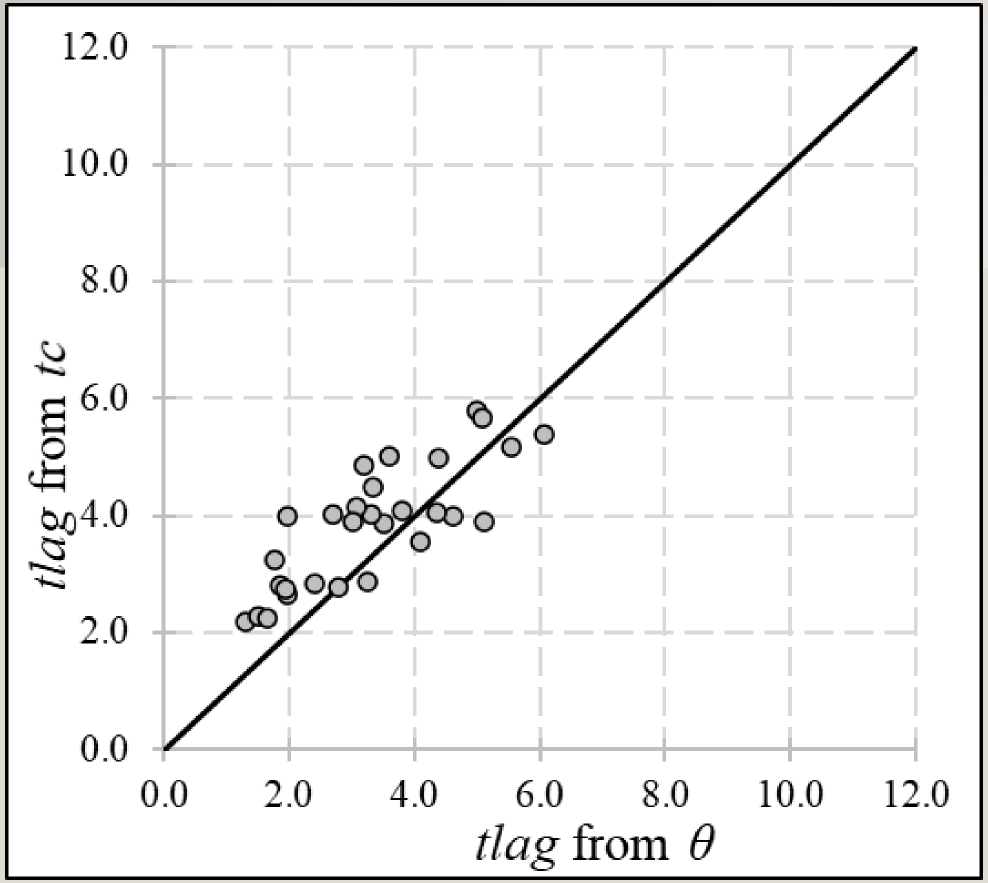


Figure 5: Comparison between tlag, calculated from the tc and from θ.

- t_c highly correlated with the ϑ parameter of the reduction curve introduced (Bacchi et al.,1992).
- Reduction curves represent the speed of the growing and recession phase of the flood event; ϑ is the scale of fluctuation, or else the integral of the autocorrelation function of the discharge process and can be interpreted as a characteristic response time of the basin (Ranzi et al., 2006), measuring a rate of decrease of the autocorrelation function (Franchini and Galeati, 2000).
- Impermeable Apennine basins: $\theta = 12.694 L^{0.64} / \Delta z^{0.5}$ (Ranzi et al., 2006) (θ in in h, L main stream length (km), Δz is the difference between mean and outlet elevation (m)).
- θ=m tlag (Franchini and Galeati, 2000), $1.6 \leq m \leq 2$, depending on the order of the Autoregressive Gaussian process used to describe discharge (for order 4, m=2).
- tlag = 0.6 tc (NRCS, 2004)

5. Results: Calibration (I)

- Remarkably high model fitness, considering its parsimony (2 parameters) and its computational and conceptual simplicity; NSE>0.65 for more than 70 % of the events even under very complex rainfall patterns;

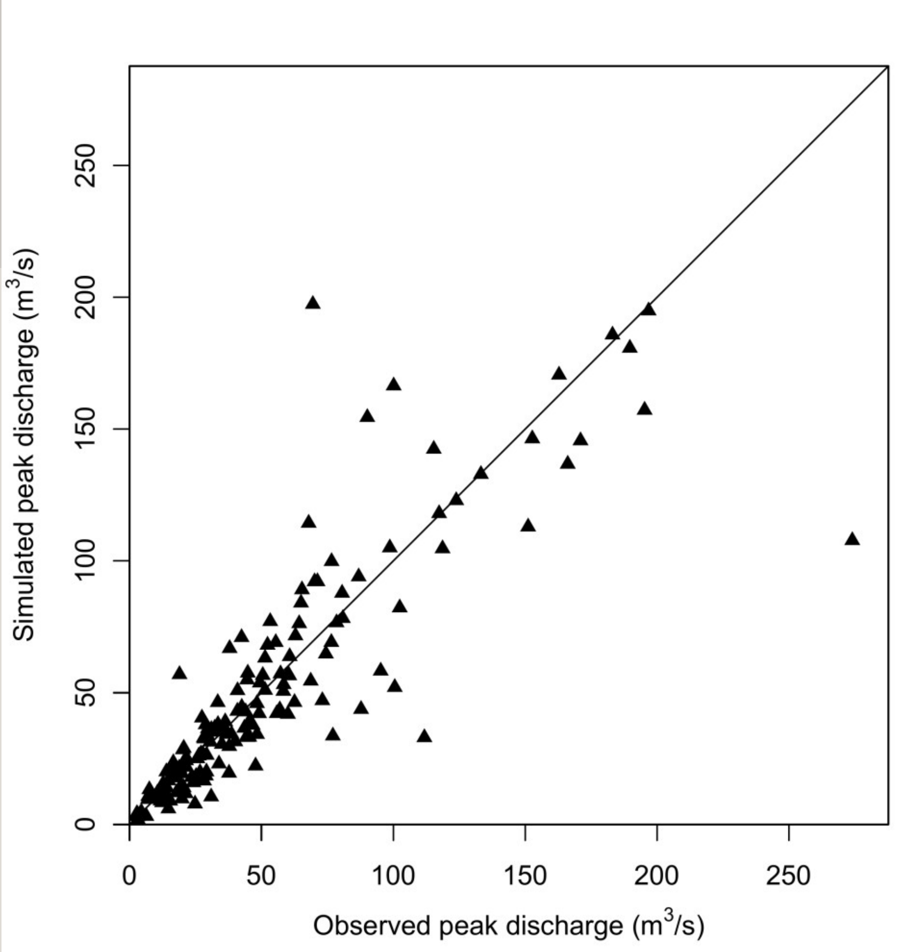


Figure 6: The observed and simulated peaks for the 160 flood events.

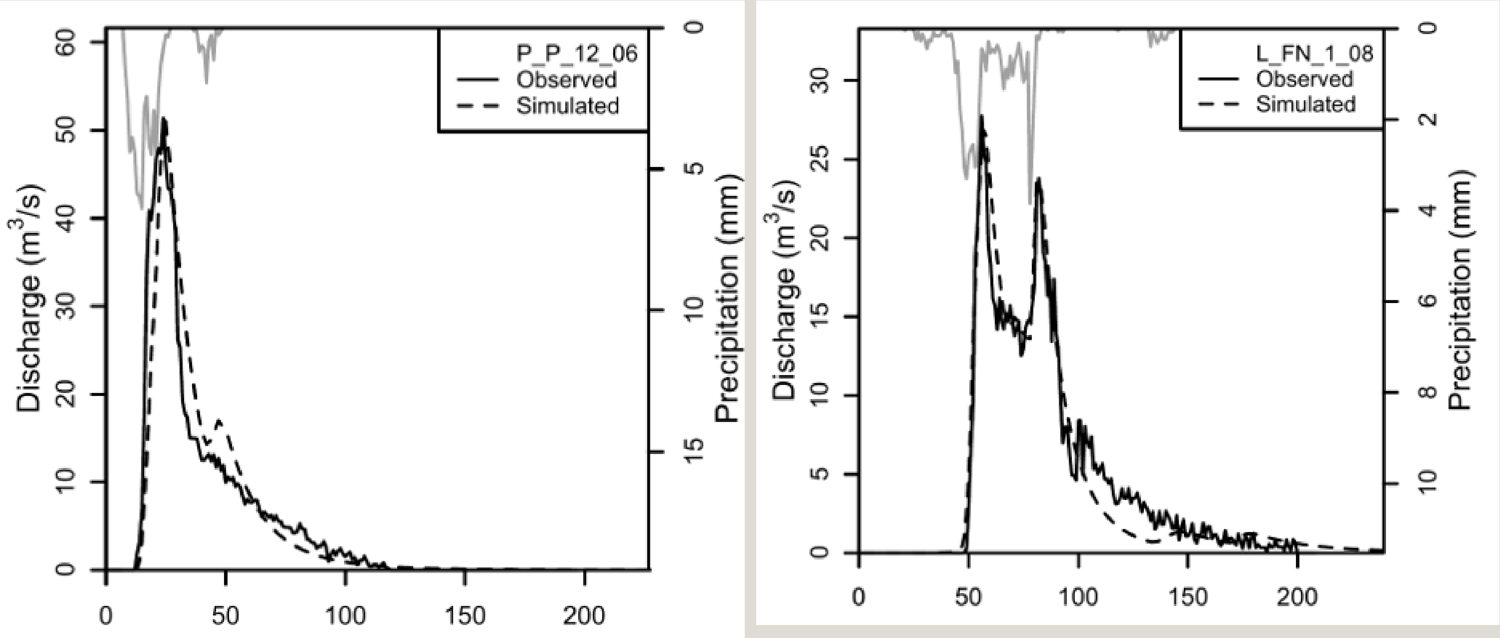
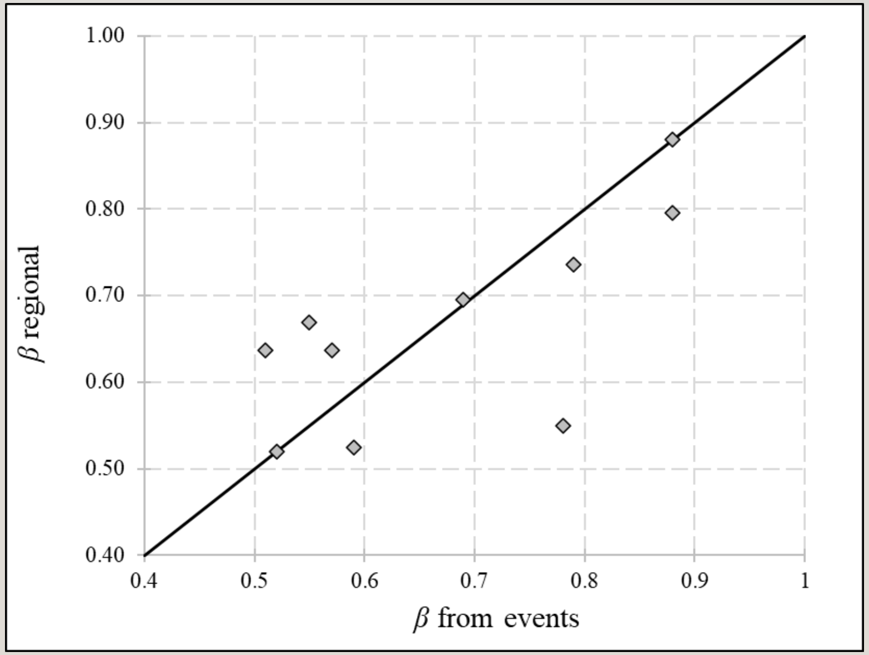


Figure 7: Examples of observed and simulated flood events.

5. Results: Calibration (II)

$$\gamma = 74.1JL/\sqrt{A}$$



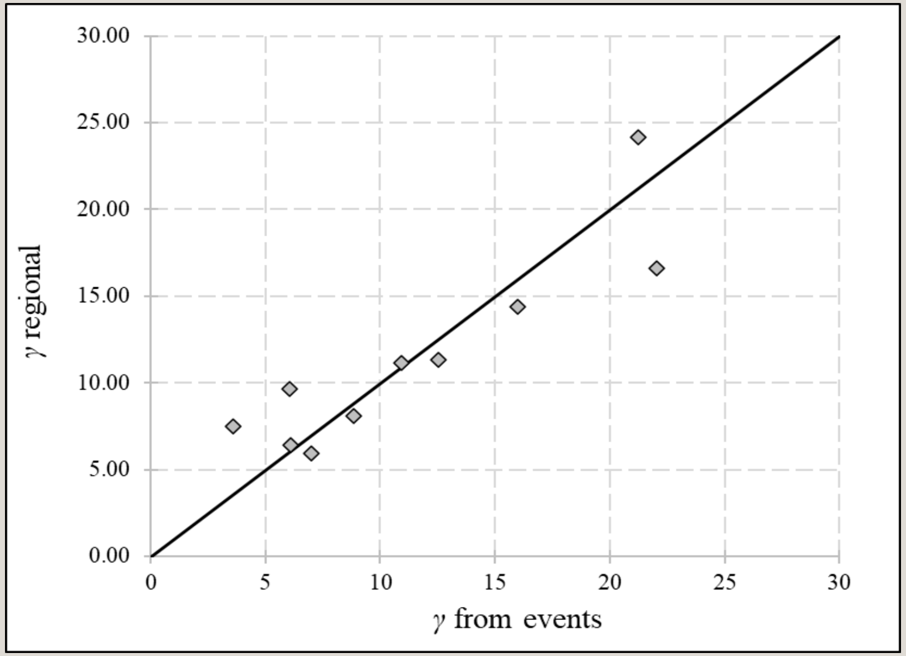


Figure 8: Predictive capacity of the regional relationship for γ (bottom) and β (top).

$$\beta = (JL)^{0.43} b^{-0.22}$$

River basin (outlet)	β	γ	Mean NSE
Sarantapotamos (Gyra Stefanis)	0.57	3.61	0.57
Nedontas (Kalamata)	0.55	10.91	0.62
Baganza (Marzolara)	0.59	8.84	0.56
Scoltenna (Pievepelago)	0.51	12.55	0.40
Ceno (Ponte Lamberti)	0.78	6.98	0.73
Leo (Fanano)	0.88	21.26	0.79
Montone (Castrocaro)	0.69	6.06	0.80
Nure (Farini)	0.52	6.12	0.81
Xeros (Lazarides)	0.79	16.01	0.69
Peristerona (Panagia Bridge)	0.88	22.03	0.77

* where A (km^2) is the basin's size, J (m/m), the mean main stream slope, L (km) the main stream length, b (m) is the mean main stream width

5. Results: Validation (I)

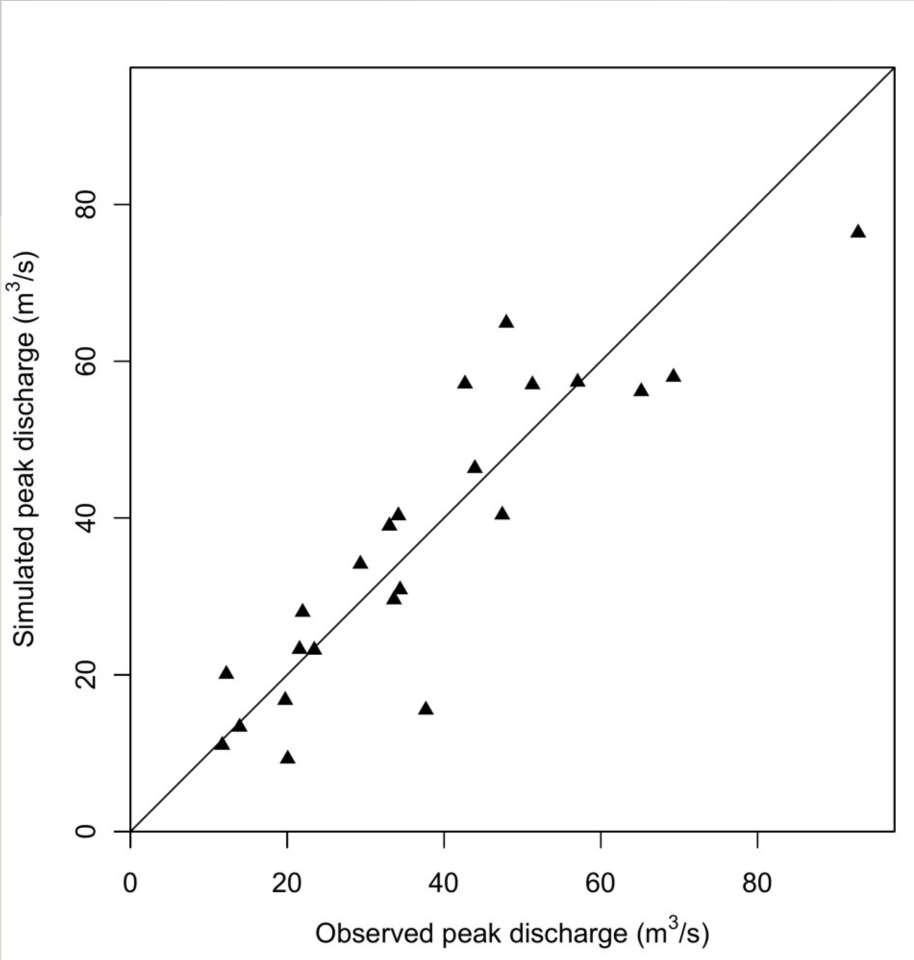


Figure 9: The observed and simulated peaks for the Ferriere flood events.

- Model and regional relationships validated in 23 events (subbasin of Nure, with outlet at Ferriere hydrometric station).
- Simulated events approximate with precision the observed ones, in terms of peak, time-to-peak, attenuation and overall hydrograph form.
- In more than 70 % of the events, NSE>0.80, reaching 0.94; average value 0.81.

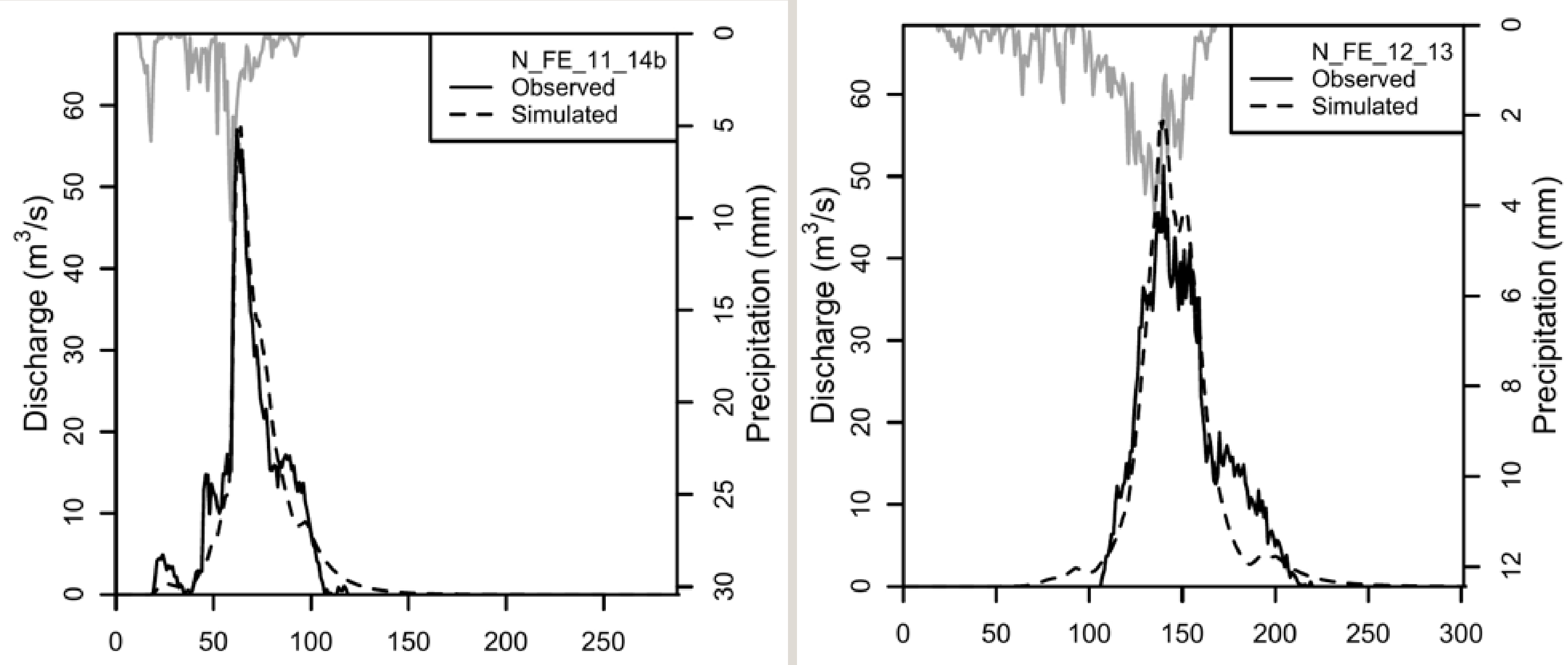


Figure 10: Examples of observed and simulated Ferriere flood events.

5. Results: Validation (II)

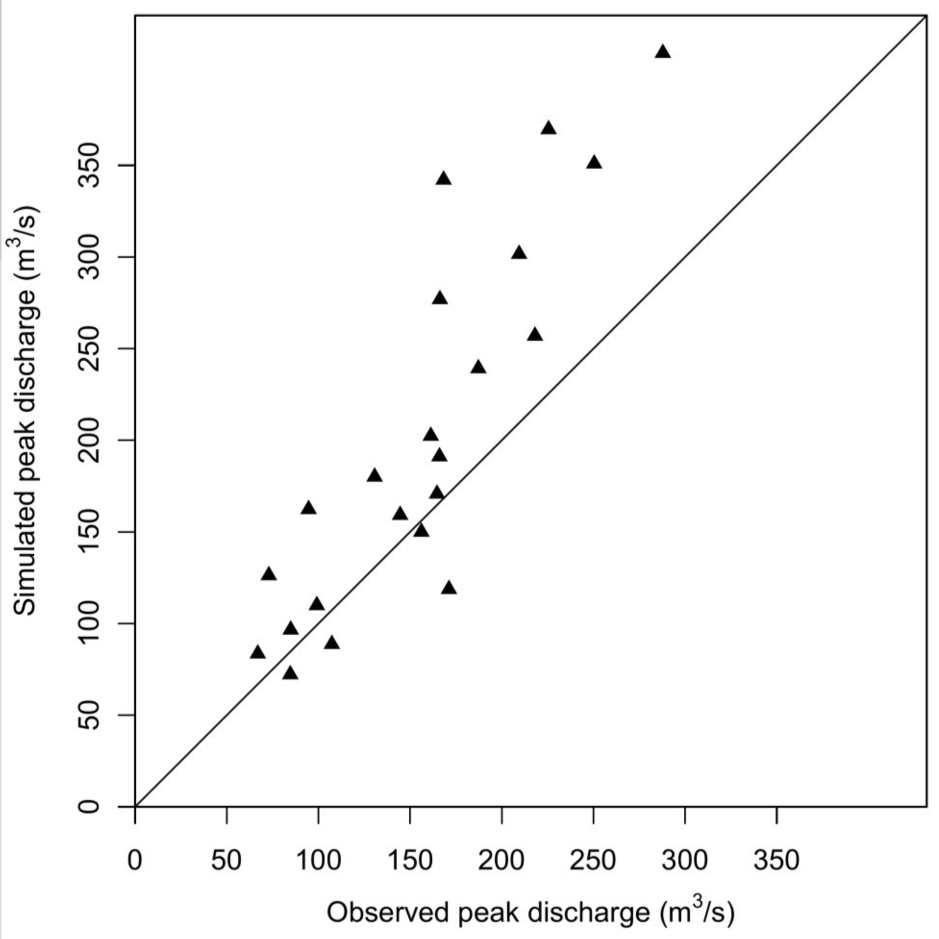


Figure 11: The observed and simulated peaks for the Vetto flood events.

- Model and regional relationships validated in 22 events of a sub-basin of Enza with outlet at the Vetto hydrometric station (294 km^2).
- In more than 60 % of the events, NSE>0.77, reaching 0.93; average value 0.68, despite the bigger dimension of the basin, proving the model's impressive fitness.

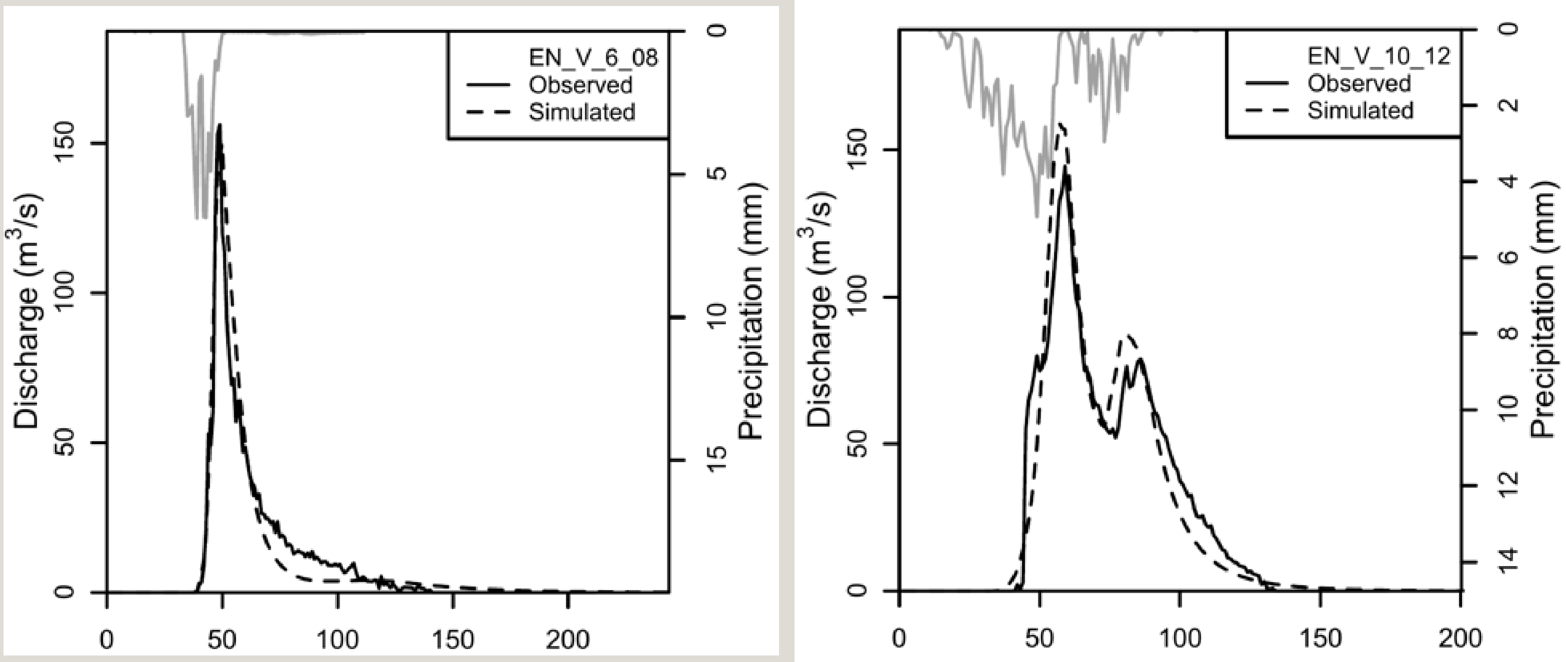
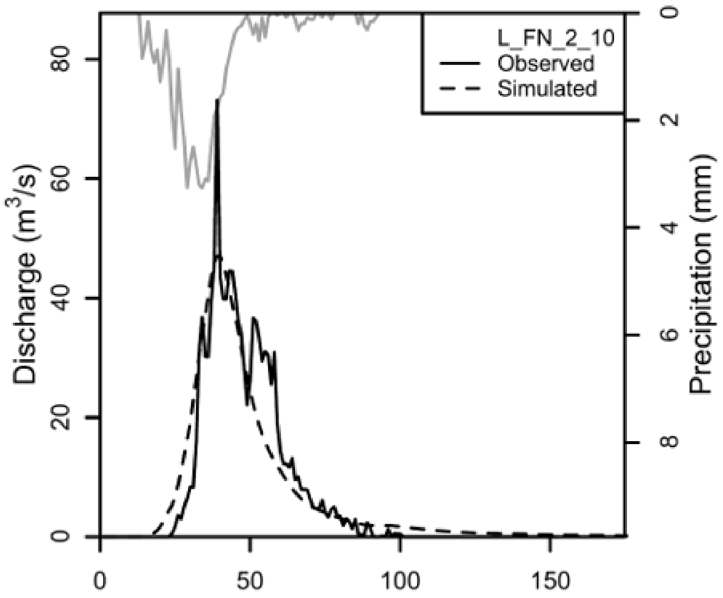


Figure 12: Examples of observed and simulated Vetto flood events.

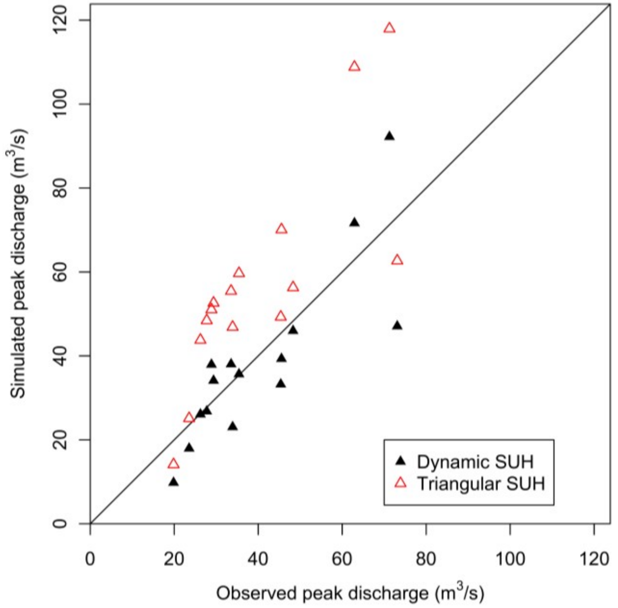
6. Discussion

- **Peak over/underestimations**



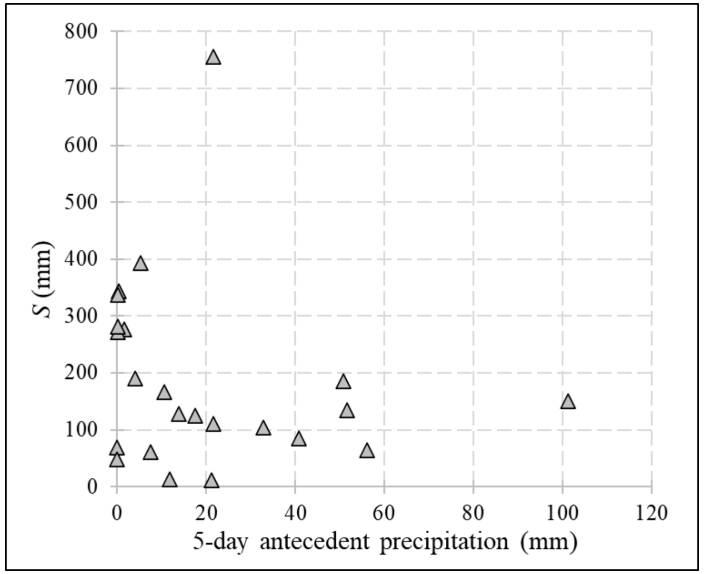
- Mechanisms of infiltration/runoff generation complex: NRCS-CN cannot fully capture them; change in soil moisture before and during an event can be decisive in runoff production.
- Some observed peaks can appear higher than actual values: result of a rating curve extrapolation way beyond measurements.

- **Performance of conventional methods**



- Emprical SUHs' present in the literature do not take into consideration the varying tc and form of SUH can be unrealistic.
- Overestimation of peaks.

- **Problems with the CN**



- NRCS-CN highly sensitive to CN parameter, which is highly variable and uncertain.
- AMC conditions cannot always explain variability in CN, which can also depend on rainfall intensity, duration, total rainfall, cover density, temperature, days to consider for antecedent precipitation.

7. Conclusions and Further research

- Simple and parsimonious *dynamic* SUH, whose shape resembles better the observed hydrographs, and integrates the variable *tc* and regional relationships showed remarkable fit, allowing flood estimation under almost any data scarcity and/or lack of resources.
- More robust implementation of the model in larger ungauged basins: discretization in smaller sub-basins and application in each sub-basin, possibly coupling it with an appropriate routing scheme.
- Proposed model should depart from its deterministic implementation and it should be applied in a more stochastic context. Antecedent precipitation- proxy of soil moisture content- can have a huge effect on maximum potential retention, and thus CN. Since antecedent precipitation is a stochastic variable, the CN parameter should be considered as stochastic. This could entail the development of a relationship that would eventually assign a CN value, for a particular antecedent precipitation based on a probabilistic distribution.

8. Bibliography (I)

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Thank you for your time!