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VELOCITY-BASED APPROACH FOR ESTABLISHING A VARYING TIME OF CONCENTRATION: A STUDY IN THREE MEDITERRANEAN COUNTRIES

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1. Abstract

The time of concentration, tc, has a crucial role in hydrological design, as an essential input of rainfall-runoff modelling. In common practices it is considered as a characteristic property of the watershed, even though theoretical proof and empirical evidence imply that it is a **function of flow**, and thus varies within the same basin. Here, we implement a **velocity-based approach**, partially integrated in a GIS environment and show that the relation between tc and runoff intensity for a basin is approximated almost perfectly by a **power-law** function. The coefficient of this relation depends on the length and mean slope of the main stream and the exponent shows a small variability within the study basins. Next, we propose a **regional formula** for the estimation of tc that is a **function of runoff intensity**, as well as key geomorphological characteristics of the basin, calibrated and validated in a number of Mediterranean river basins in Greece, Italy and Cyprus. Lastly, we propose its adaptation in flood modelling, in the **SCS-CN** method, using a parametrised Synthetic Unit Hydrograph (SUH) whose shape is **dynamically adjusted** according to the runoff produced during the flood event. The proposed methodology is tested in a number of observed flood events with very satisfying results in the majority of the cases.

2. The time of concentration *enigma*

- **Definition:** Longest travel time of surface runoff to the outlet; surface runoff initially appears as **overland flow** and next as **channel flow** (Fig. 1).
- Usually estimated through empirical approaches, on the basis of **geomorphological characteristics** (e.g., catchment area, channel slope/length), thus t_c is considered as constant (Efstratiadis *et al.*, 2014).
- Early attempts to associate t_c to **rainfall intensity** are attributed to Izzard (1946).

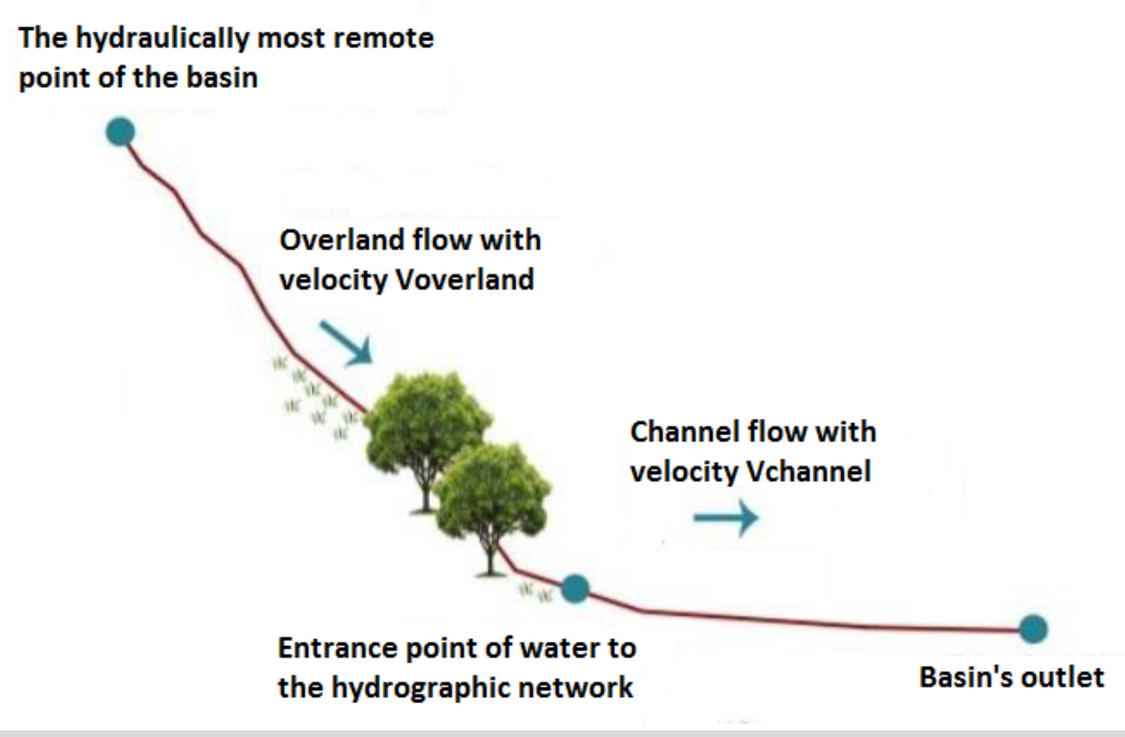

Fig. 1: The time of concentration rationale

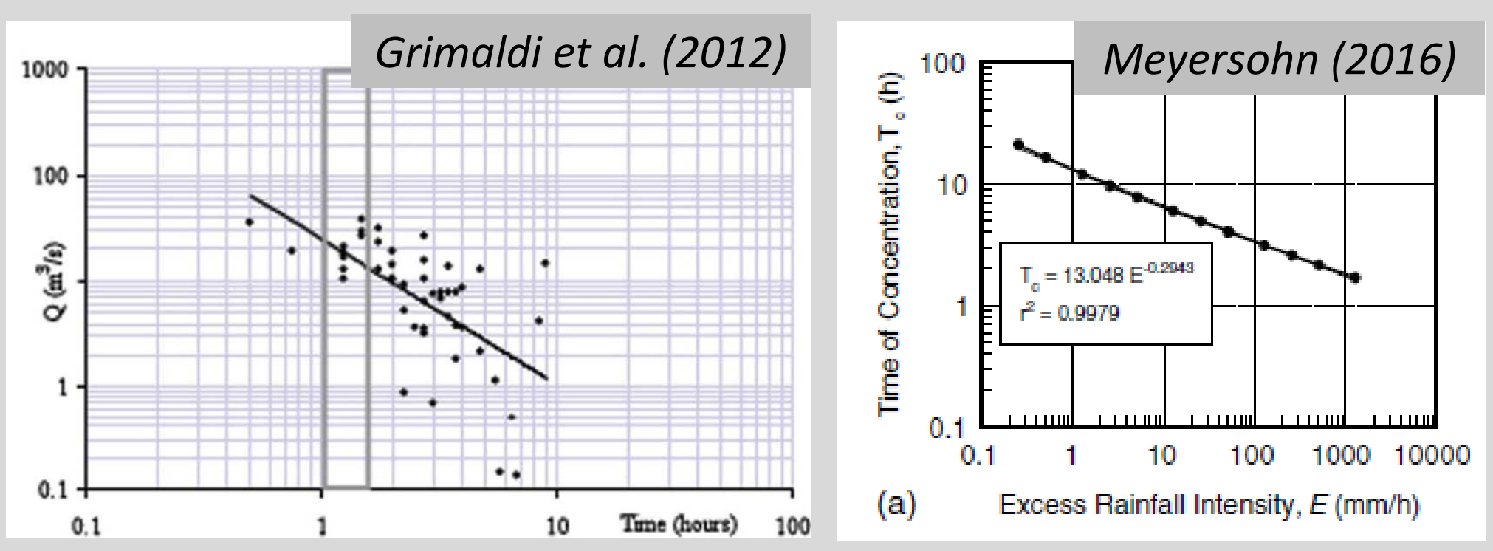

Fig. 2: Literature examples of plotting varying t_c against excess rainfall intensity or peak discharge

- Researchers revisited the concept of varying t_c, providing experimental (e.g. Grimaldi *et al.*, 2012) or theoretical formulas (e.g., Meyersohn, 2016) for estimating t_c as a **negative power function of flow** (Fig. 2).
- t_c may change up to an order of magnitude during and between flood events, affecting key hydrological design components (e.g. unit hydrograph).
- Treating t_c as variable rather than constant implies a radical change to the philosophy of everyday flood engineering.

3. GIS-based hybrid approach for associating basin's response time to runoff

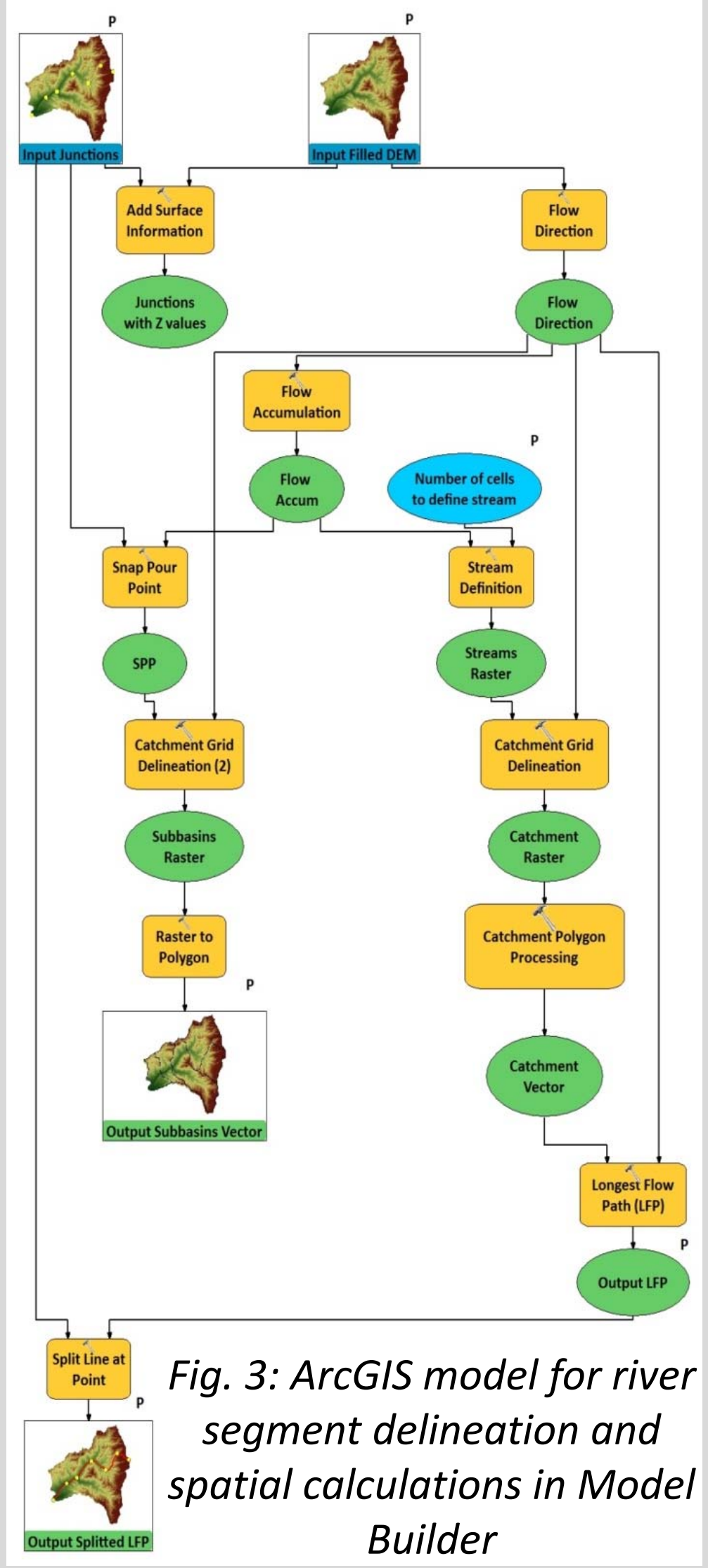

Fig. 3: ArcGIS model for river segment delineation and spatial calculations in Model Builder

- **Kinematic approach**, employed along the main stream of the basin, discretized into a relatively small number of segments according to a user-specified flow accumulation threshold (Fig. 3).
- Flow evolves from upstream to downstream following key assumptions of the **rational method**., i.e. a constant runoff depth, *P*, is assigned, uniformly distributed over sub-basins.

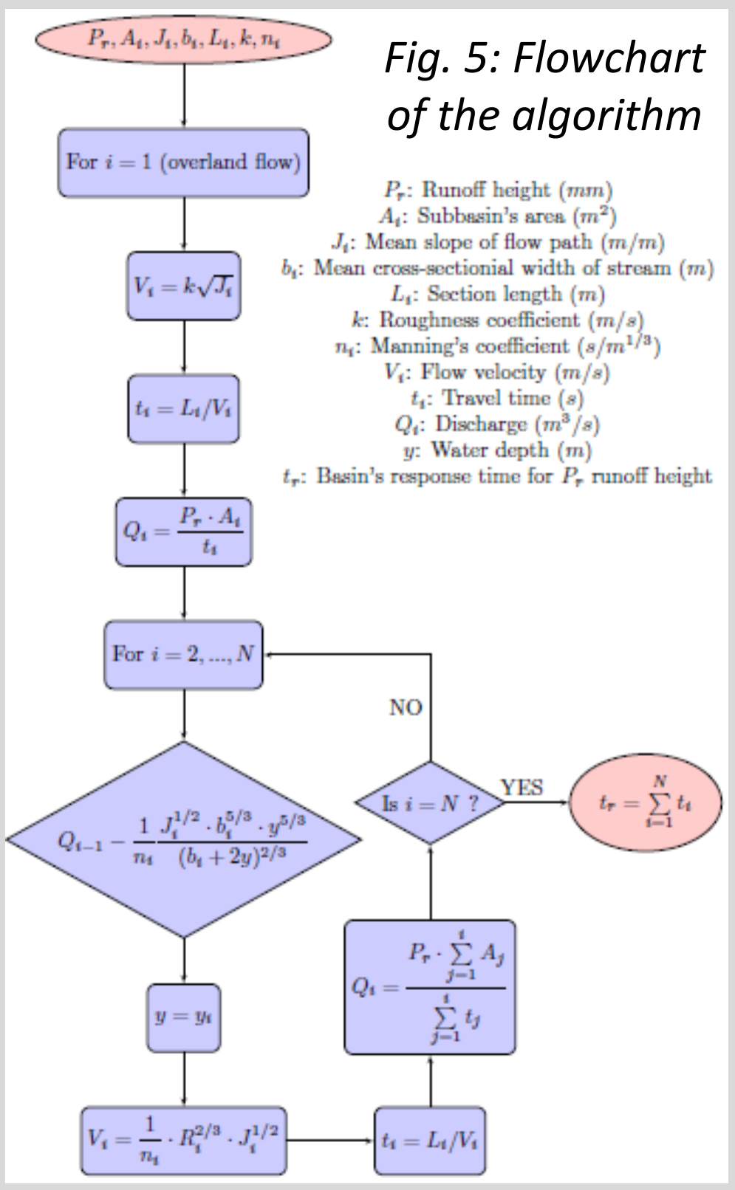

Fig. 5: Flowchart of the algorithm

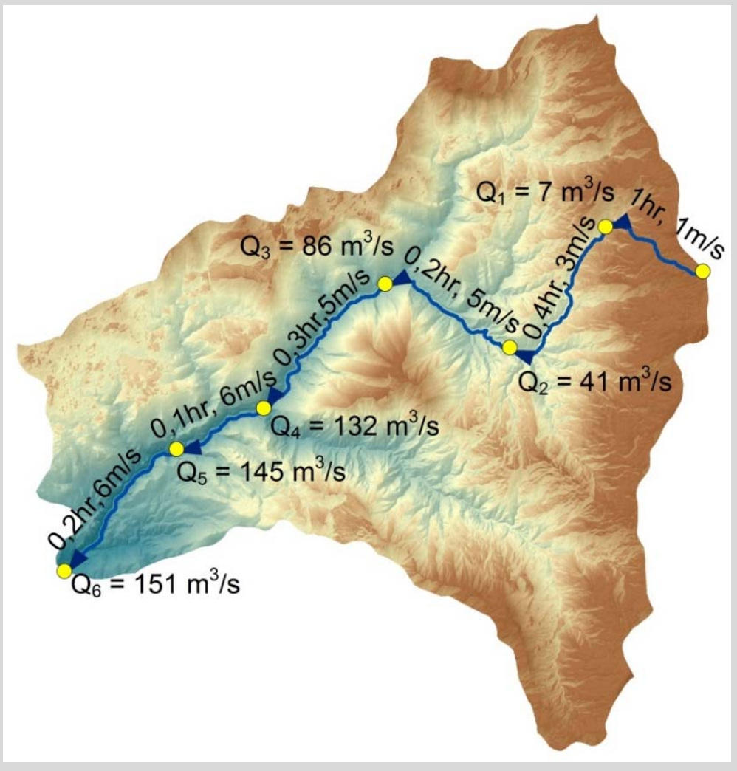

Fig. 4: Model results along Nedontas river for P = 10 mm

- For given channel geometry, we compute the **travel time** along the channel, thus the response time so far is the sum of all upstream travel times.
- By repeating calculations for different runoff depths, we can establish a t_c vs. *P* relation.

4. Study basins and input data

- **24 small to medium-sized Mediterranean basins from Italy, Greece and Cyprus** (Table 1).
- For each basin, the drainage area, *A* (km^2), main stream length, *L* (km) and slope, *J* (%).
- For each stream segment a **rectangular cross-section** was assumed, estimating its **width *b*** from **satellite imagery/topographic relief maps**.
- **Manning's coefficient *n*** of each segment was assigned by accounting for the bed material
- For the upstream overland flow a **roughness coefficient *k*** was assigned using the CORINE land cover maps and the suggested values by Haan *et al.* (1994).

Table 1: Geomorphological characteristics of study basins

Basin (outlet)	A (km²)	L (km)	J (%)
Rafina	123	30	3.1
Sara/potamos	144	32	3.8
Xerias	112	34	4.5
Nedontas	115	22	7.4
Baganza	125	33	3.8
Scoltenna	130	15	11.9
Ceno	329	38	3.9
Nure	48	12	7.9
Tresinaro	139	35	3.2
Rossenna	183	30	6.5
Leo	37	11	18.9
Mesohora	639	41	9.0
Lavino	83	26	4.5
Montone	236	47	4.2
Tassobbio	98	21	3.4
Enza	294	32	5.6
Nure	201	24	5.0
Mella (1)	130	20	8.8
Mella (2)	183	28	7.1
Aggitis	1854	59	3.2
Pamisos	564	47	4.4
Upper Peneus	529	39	5.5
Upper Oglio	122	18	11.8
Xeros	68	13	12.4
Peristerona	78	24	8.4
Titarisios	1813	94	3.0
Enipeas	1113	128	1.7
Sperxeios	1404	79	2.4
Peneus (1)	1373	78	3.1
Peneus (2)	1071	78	3.2

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Haan, C. T., Barfield, B. J., and Hays, J. C. (1994). Design Hydrology and Sedimentology for Small Catchments, Academic Press, N. Y..

Izzard, C. F., & Hicks, W. I. (1947). Hydraulics of runoff from developed surfaces, In Highway Research Board Proceedings (Vol. 26).

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5. Investigation of response time vs. runoff intensity relation across basins

- At each basin, we ran the algorithm for six runoff depths (1, 5, 10, 25, 50 and 100 mm), and estimated the corresponding response times, t_c (h), and runoff intensities, *i* (mm/h).
- At each basin a power-type regression model of the form $t_c = t_0\, i^{-\beta}$ was fit, yielding perfect regression (Fig. 6).
- We computed the correlations between the multipliers, t_0, and exponents, *β*, against the basins' geomorphological characteristics, to provide **linear regression** estimators of the two parameters (Table 2).
- Coefficient t_0 was significantly correlated (R^2 = 0.85) with L/J; exponent *β* was mildly satisfactorily correlated with J (Fig. 7).

Table 2: Correlations between power function parameters and key geomorphological characteristics of basins

	A	L	J	k	Mean b	L/J
t_0	0.70	0.89	-0.78	-0.49	0.08	0.85
β	0.21	0.29	0.60	-0.30	-0.51	0.22

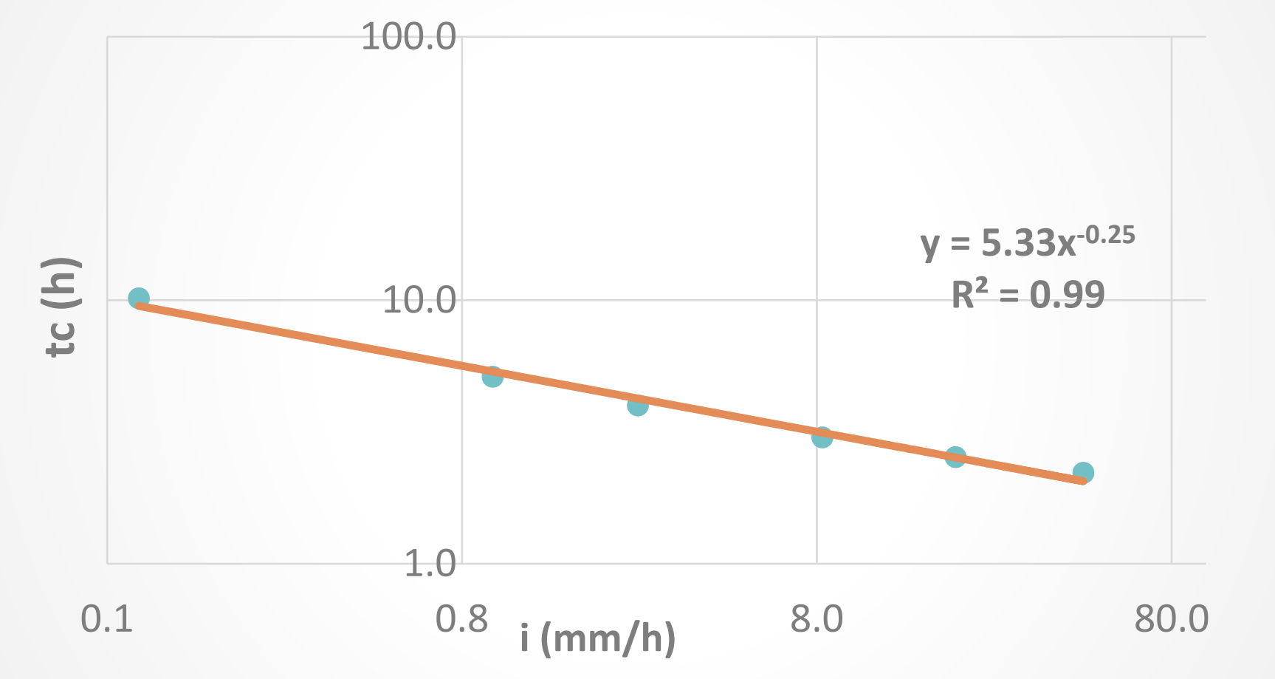


Fig. 6: Typical time of concentration-intensity relation

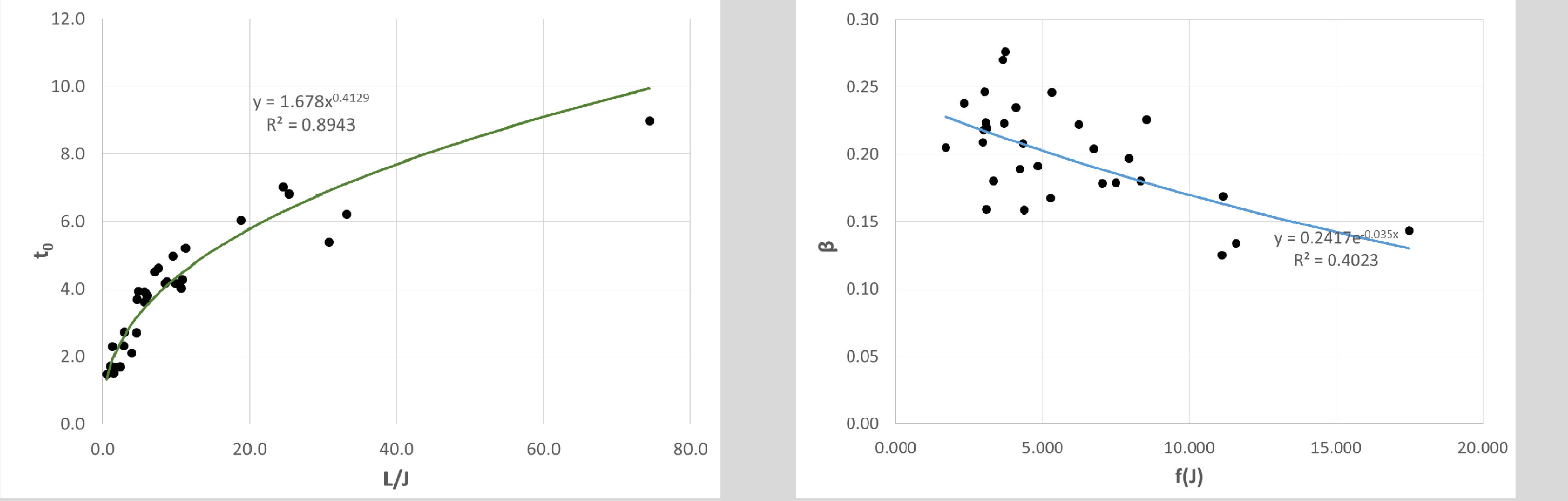


Fig. 7: left: Coefficient t_0 as a function of L/J; right: exponent β as a function of J

6. Towards establishing a regional formula for varying t_c

- t_c can be expressed by a **generalized power-type model**, whose parameters t_0 and *β* are expressed as functions of each basin's characteristics, i.e. $t_0 = L^{a_1} J^{a_2}$ and $\beta = \beta_0\, J^{-\beta_1}$.
- The proposed regional formula contains four global parameters, i.e. a_1, a_2, β_0 and β_1, that have been calibrated by fitting the model to the already derived time of concentration-intensity relations.
- Conclusively, the **time of concentration** for given **runoff intensity** can be estimated as a function of two key geomorphological characteristics, i.e. the **main stream length** (km) and **slope** (%).

$$t_c = \frac{L^{0.509}}{J^{0.300}}\, i^{-0.286 * J^{-0.226}}$$

7. «Tinkering» the Synthetic Unit Hydrograph and the SCS-CN method

- The UH allows implementing the concept of varying t_c within flood modelling.
- A **linear rising limb** and an **exponential recession limb**; parametrized time to peak and base time $t_p = b * t_c + d_t/2$ and $t_b = c * t_c + d_t/2$, where d_t is the unit rainfall duration (Fig. 8).
- t_c was considered varying **at each time step of every event**, estimated from the power-law function, for each individual runoff intensities of the event.
- The **initial losses parameter** of the SCS-CN method (% of max. retention capacity) was also considered varying across events.
- The dynamically adjusted hydrographs can change dramatically in different events of the same basin (Fig. 9).

Fig. 8: Modified SUH

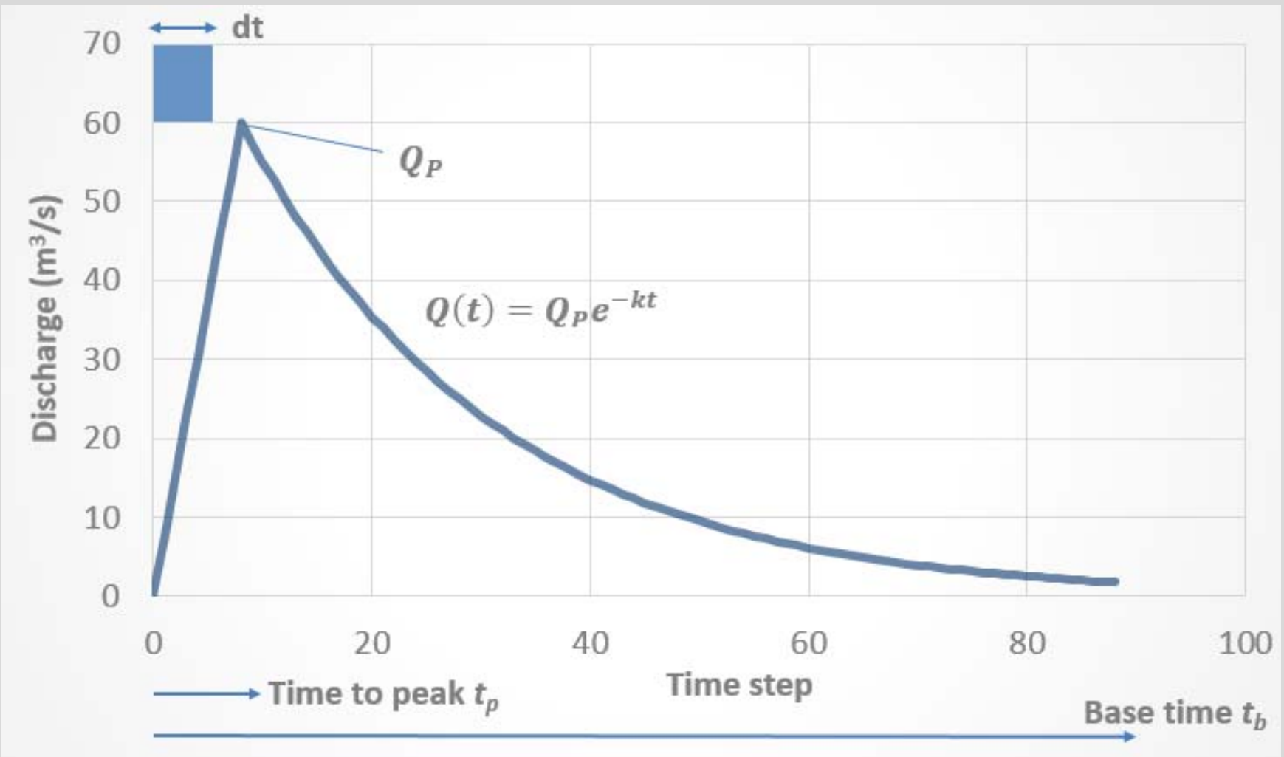
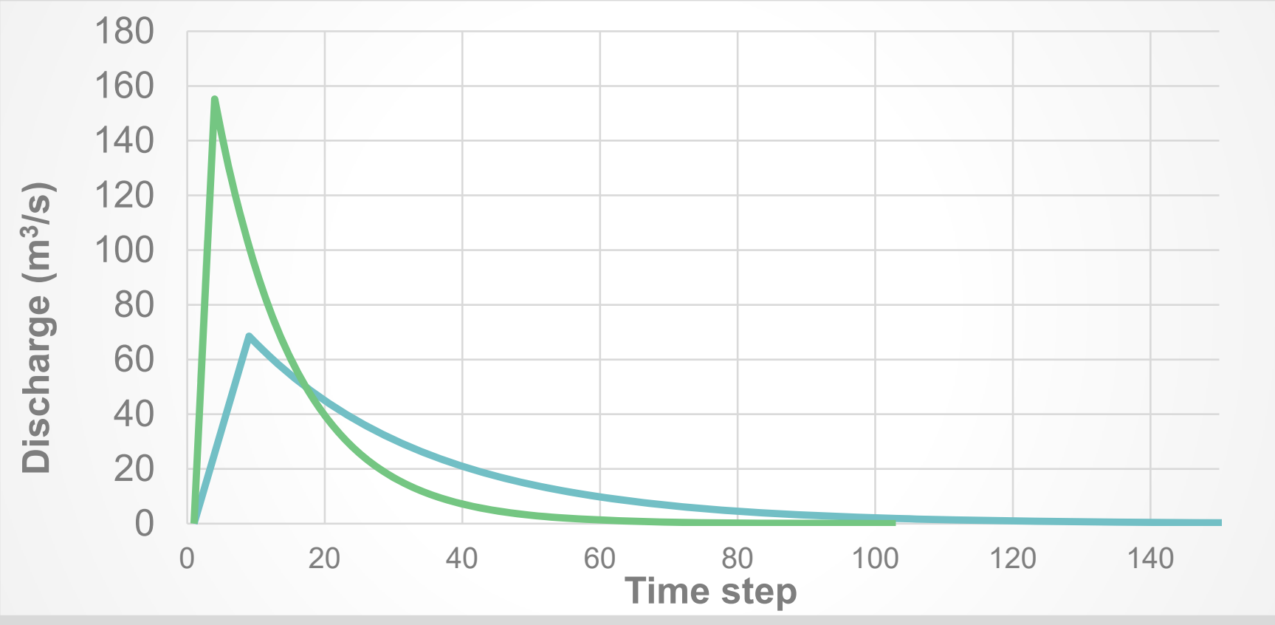


Fig. 9: Example of varying SUH against runoff intensities.



8. Model validation

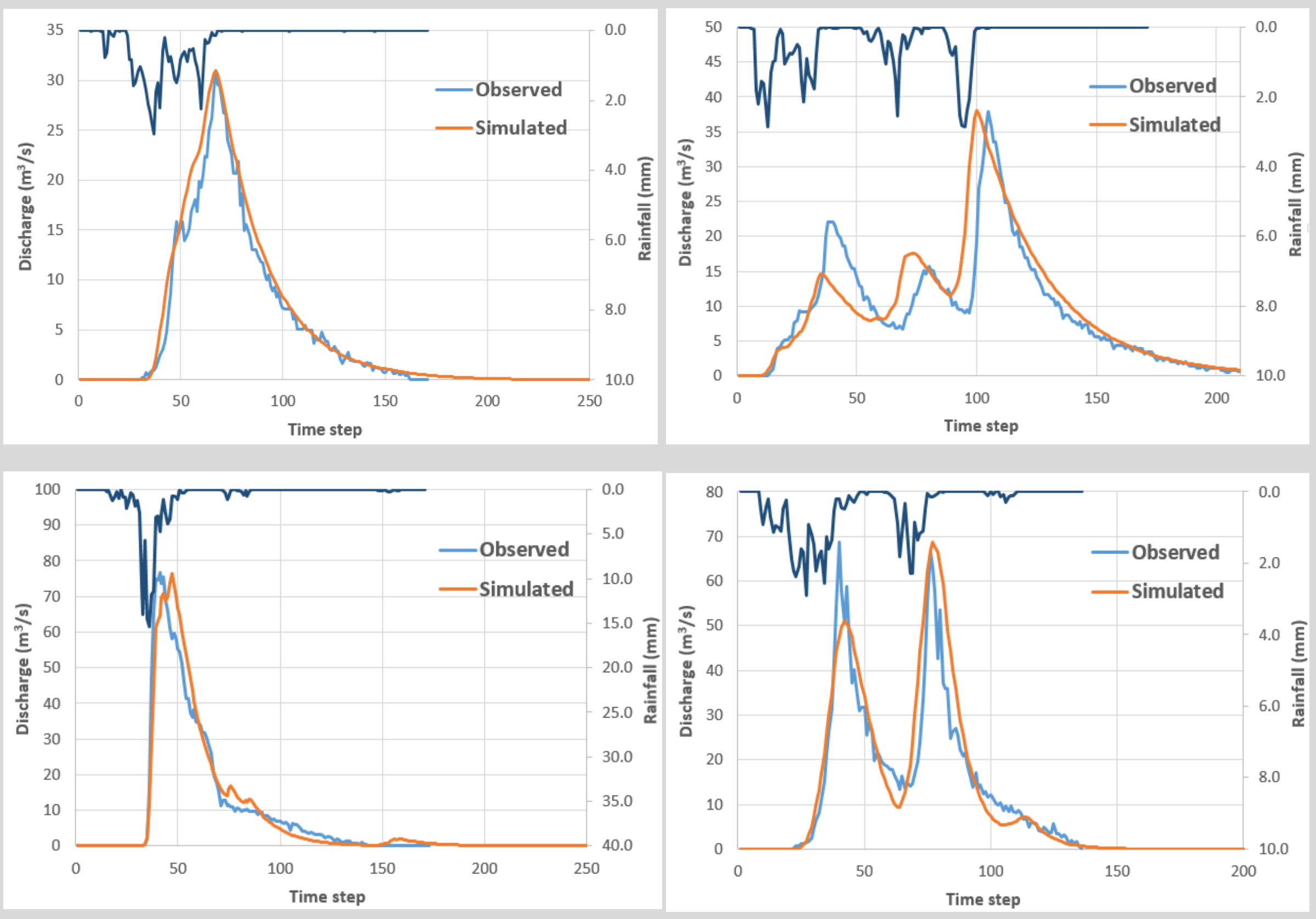


Fig. 10: Observed and simulated hydrographs from various basins

- Calibration of **initial loss, time to peak and base time parameters** in 70 events of various basins, considering **varying t_c within the event** depending on the **effective rainfall intensity of each time step.**
- **Great fit** on the majority of the observed events even when complex rainfall patterns were present (Fig. 10).

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