Adaptation of the concept of varying time of concentration within flood modelling: Theoretical and empirical investigations across the Mediterranean

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E. Michailidi[1], S. Antoniadi[2], A. Koukouvinos[2], B. Bacchi[1], and A. Efstratiadis[2]

(1) University of Brescia, DICATAM, Brescia, Italy; (2) Department of Water Resources & Environmental Engineering, National Technical University of Athens, Greece

Contact info: e.michailidi@unibs.it

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1. Abstract

The time of concentration, t_c, is a key hydrological concept and often is an essential parameter of rainfall-runoff modelling, which has been traditionally tackled as a characteristic property of the river basin. However, both theoretical proof and empirical evidence imply that t_c is a **hydraulic quantity that depends on flow**, and thus it should be **considered as variable and not as constant parameter**. Using a kinematic method approach, easily implemented in GIS environment, we first illustrate that **the relationship between t_c and the effective rainfall produced over the catchment is well-approximated by a power-type law**, the exponent of which is associated with the **slope of the longest flow path** of the river basin. Next, we take advantage of this relationship to adapt the concept of varying time of concentration within flood modelling, and particularly the well-known **SCS-CN approach**. In this context, the initial abstraction ratio is also considered varying, while the propagation of the effective rainfall is employed through a **parametric unit hydrograph**, the shape of which is dynamically adjusted according to the runoff produced during the flood event. The above framework is tested in a number of Mediterranean river basins in Greece, Italy and Cyprus, ensuring faithful representation of most of the observed flood events. Based on the outcomes of this extended analysis, we provide guidance for employing this methodology for **flood design studies in ungauged basins**.

2. The time of concentration *enigma*

- **Mainstream (one out of many) definition:** Longest travel time of surface runoff to the basin outlet, where 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).

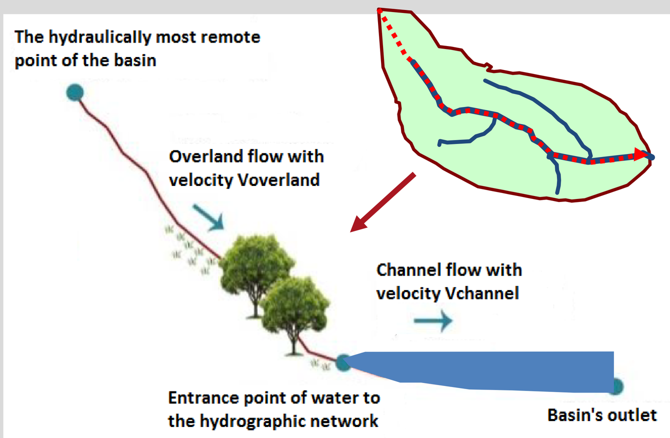

Fig. 1: The time of concentration rationale

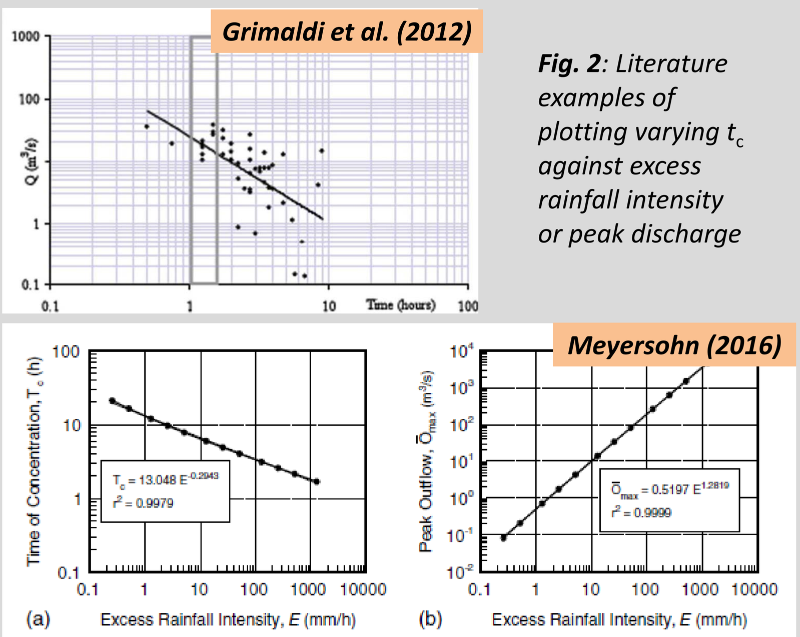

Fig. 2: Literature examples of plotting varying t_c against excess rainfall intensity or peak discharge

- Recently, several 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).
- The shocking conclusion is that t_c may change up to an order of magnitude **during and between flood events**, which affects key hydrological design components, such as the **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

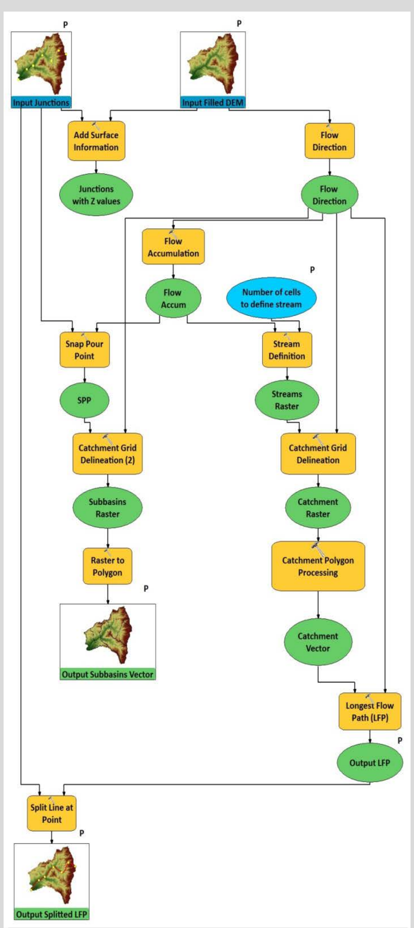

Fig. 3: ArcGIS model for river segment delineation and spatial calculations in Model Builder

- **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.

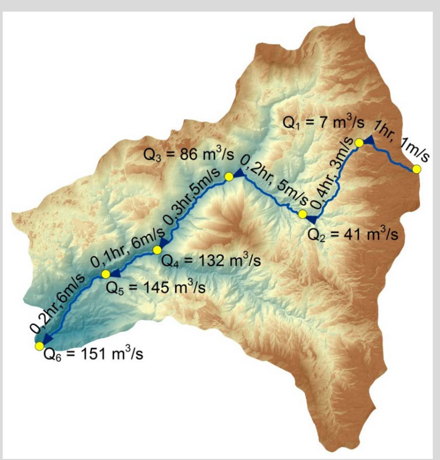

Fig. 4: Model results along Nedontas river for P = 10 mm

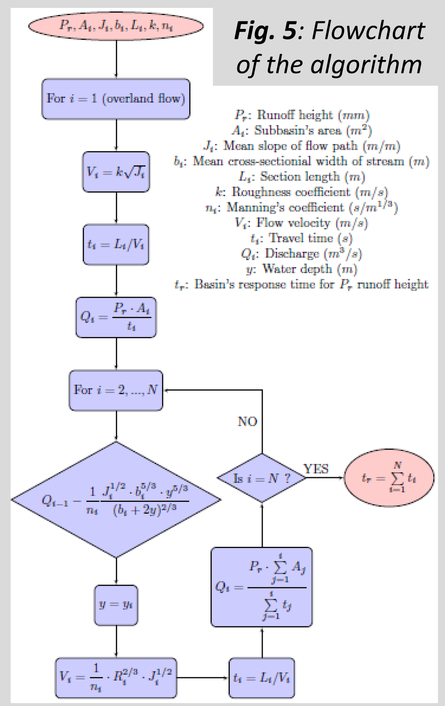

Fig. 5: Flowchart of the algorithm

- The upstream sub-basin produces only **overland flow** and its response is a function of slope.
- 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

- The method was tested at **24 small to medium-sized Mediterranean basins from Italy, Greece and Cyprus** (Table 1).
- For each basin, the following **geomorphological characteristics** were calculated:
  - Drainage area, *A* (km²)
  - Main stream length, *L* (km)
  - Average main stream slope, *J* (%)
  - "Reference" time of concentration, t_c (h), estimated through the Giandotti formula
- For each stream segment we assumed a **rectangular cross-section**, 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 (e.g., 0.02 for concrete, 0.03 for earth channels).
- For the upstream overland flow we assigned a **roughness coefficient *k*** using the CORINE land cover maps and the suggested values by Haan *et al.* (1994).

***Table 1**: Study basins and their geomorphological characteristics*

River basin (outlet)	A (km²)	L (km)	J (%)	Δz (m)	$t_{Giandotti}$ (h)
Rafina	123	30	3.1	226	7.4
Sarantapotamos (Gyra Stefanis)	144	32	3.8	369	6.3
Xerias	112	34	4.5	466	5.4
Nedontas (Baka)	115	22	7.4	819	3.3
Baganza (Marzolara)	125	33	3.8	538	5.1
Scoltenna (Pievepelago)	130	15	11.9	583	3.5
Ceno (Ponte Lamberti)	329	38	3.9	517	7.0
Nure (Ferriere)	48	12	7.9	489	2.6
Tresinaro (Ca' De' Caroli)	139	35	3.2	310	7.0
Rossenna (Rossenna)	183	30	6.5	454	5.9
Leo (Fanano)	37	11	18.9	752	1.8
Mesohora (Mesohora dam)	639	41	9.0	700	7.7
Lavino (Lavino di Sopra)	83	26	4.5	241	6.0
Montone (Castrocaro)	236	47	4.2	455	7.8
Tassobbio (Compiano)	98	21	3.4	271	5.4
Enza (Vetto)	294	32	5.6	551	6.2
Nure (Farini)	201	24	5.0	513	5.1
Mella (Tavernole)	130	20	8.8	751	3.5
Mella (Gardone)	183	28	7.1	751	4.3
Aggitis (Simvoli)	1854	59	3.2	381	16.7
Pamisos (Arios)	564	47	4.4	332	11.3
Upper Peneus (Kalabaka)	529	39	5.5	748	6.9
Upper Oglio (Ponte di Legno)	122	18	11.8	1078	2.7
Xeros (Lazarides)	68	13	12.4	436	3.1
Peristerona (Gefyri Panagias)	78	24	8.4	466	4.1

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

- At each basin, we ran the algorithm for six fixed values of runoff depth, i.e. *P* = 1, 5, 10, 25, 50 and 100 mm, and estimated the corresponding response times, t_c (h), and runoff intensities, *i* (mm/h), by dividing *P* with t_c.
- At each basin we fitted a power-type regression model of the form $t_c = t_0\, i^{-\beta}$, which yielded almost perfect regression ($R^2 \approx 1$) (Fig. 6).
- Next, we computed the **correlations** between the multipliers, t_0, and exponents, *β*, against the basins' geomorphological characteristics (or simple combinations of them), in an attempt to provide **linear regression** estimators of the two parameters (Table 2).
- Multiplier t_0 was significantly correlated (R^2 = 0.86) with the main stream length to slope ratio (Fig. 7), and secondarily with the basin area.
- Exponent *β* was quite satisfactorily correlated with the main stream slope (Fig. 8).

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

	A	L	J	k	Mean b	L/J
t_0	0.50	0.81	-0.82	-0.40	0.29	0.91
β	0.22	0.61	0.65	0.30	-0.49	0.62

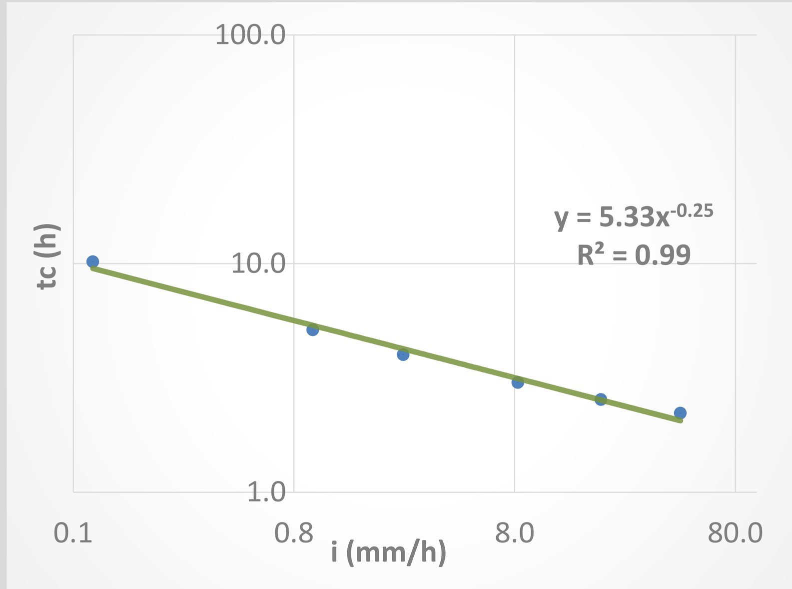

Fig. 6: Typical time of concentration-intensity relation

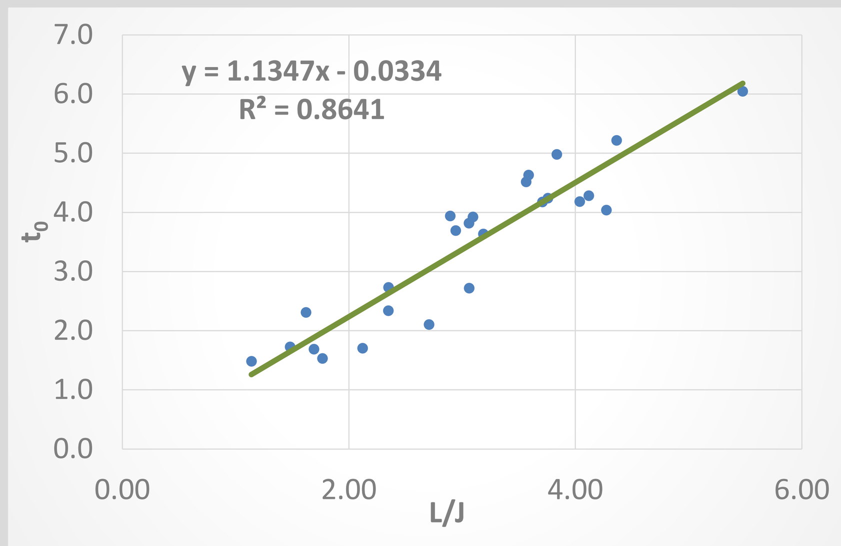

Fig. 7: Multiplier t_0 as a function of the main stream length to slope ratio

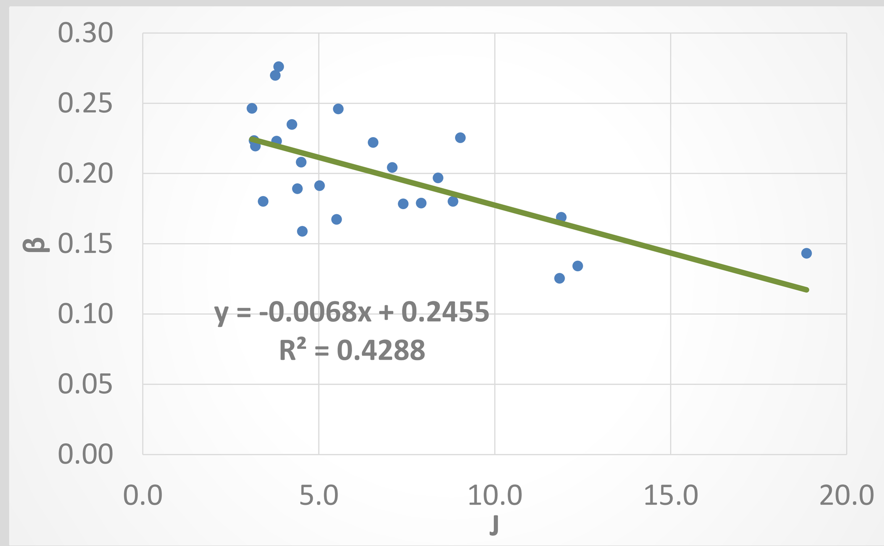

Fig. 8: Exponent β as a function of the main stream slope

6. Towards establishing a regional formula for varying t_c

- After testing various parameterizations, we concluded that the time of concentration 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** (%).

$$t_c = \frac{L^{0.522}}{J^{0.374}}\, i^{-0.294 * J^{-0.135}}$$

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

- The unit hydrograph approach allows implementing the concept of varying t_c within flood modelling.
- A **linear rising limb** and an **exponential recession limb** were considered, in order to account for the typical shape observed in real-world flood hydrographs (Fig. 1).
- The time to peak and the base time were parametrized as $t_p = b * t_c + d_t/2$ and $t_b = c * t_c + d_t/2$, where d_t is the unit rainfall duration.

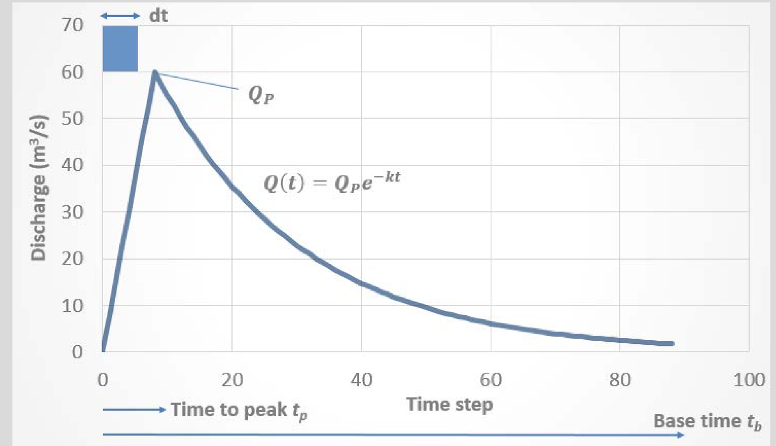

Fig. 9: Modified SUH

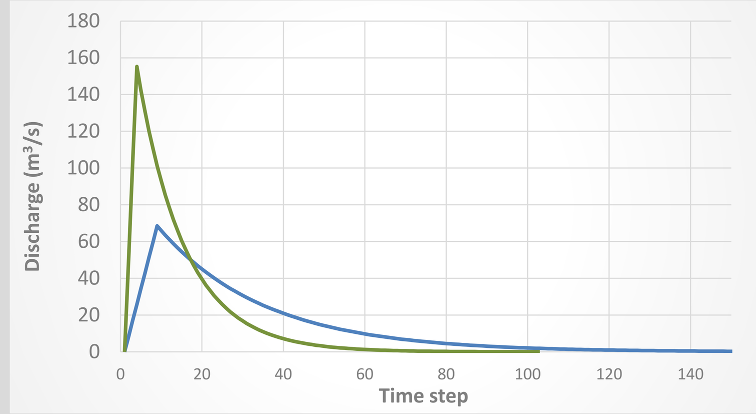

Fig. 10: Example of varying SUH against runoff intensities.

- t_c was considered varying **at each time step of every event** and was estimated from the power-law function, after estimating the 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.
- It is seen that the dynamically adjusted hydrographs can change dramatically in different events of the same basin (Fig. 10).

8. Model validation

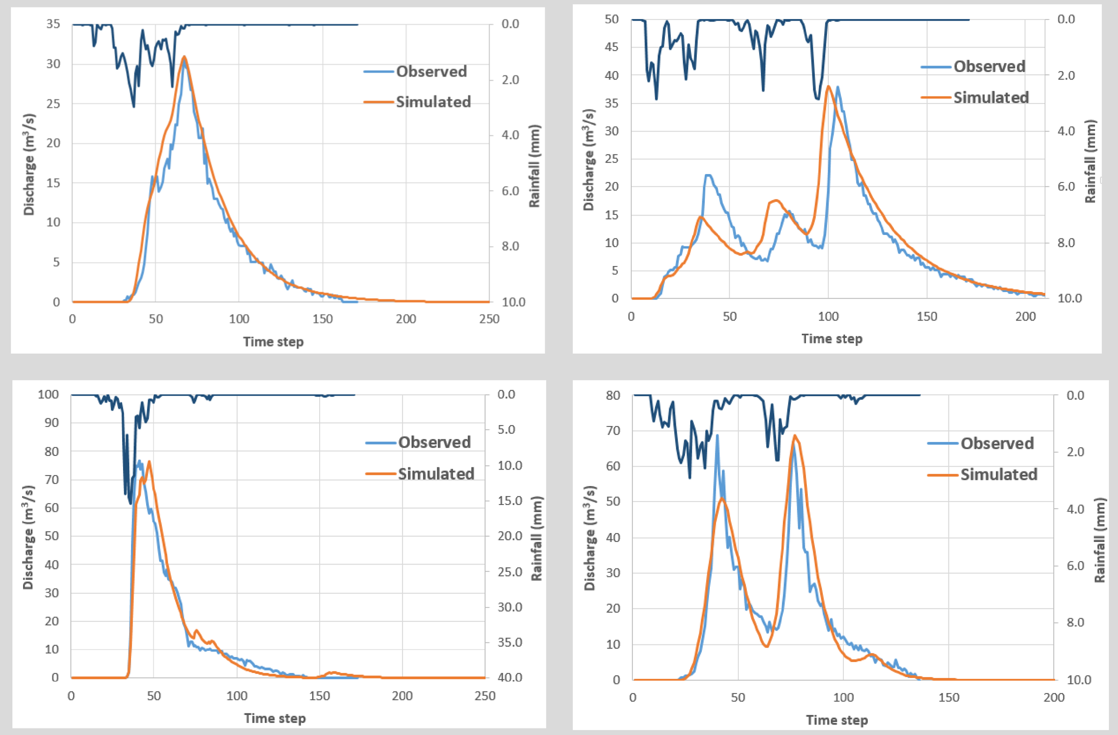

Fig. 11: Observed and simulated hydrographs from various basins

- Calibration of **initial loss, time to peak and base time parameters** in 70 events of various basins by considering a **varying t_c within the same event** depending on the **effective rainfall intensity of each time step.**
- For most of events we ensured a **great fit** of the observed events even when complex rainfall patterns were present (Fig. 11).

9. Conclusions

- Recent advances in literature argue that t_c depends not only on the hydraulic characteristics of the basin but also on runoff intensity.
- A relation that associates the length and mean slope of the main stream as well as runoff intensity with t_c is developed and it is found to approximate the hydraulically calculated t_c of each runoff depth of every basin satisfactorily.
- A Synthetic Unit Hydrograph was developed with an exponential recession limb and a parametrized time to peak, base time and initial losses SCS-CN parameter.
- A very good fit of the majority of the simulated against the observed events was achieved when implementing the varying t_c approach within the calibrated SUH.
- The varying t_c concept will provide much more reliable results in hydrological design and flood risk management studies.

10. References

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