INVESTIGATION OF THE TIME-RESPONSE VARIABILITY OF RIVER BASINS - EXTENDED ABSTRACT

Introduction

A primary design variable in hydrology is the peak discharge, Q_P, defined as the maximum flow rate passing from a particular cross-section during a design storm event. Peak discharge can be estimated by rainfall-runoff models, such as the rational method and the unit hydrograph approach. Several time parameters are associated with flood modelling, which have direct impacts on the estimation of peak discharge. Commonly used time parameters are the time of concentration, t_c, the lag time, t_L, as well as the time to peak, t_p, and base time, t_b, of the unit hydrograph. These are used to quantify how fast runoff traverses the watershed and the delay between rainfall and runoff. The time of concentration is the most widely-studied, and is typically used for estimating the rest of time parameters.

In the literature are provided various definitions for the time of concentration concept, both computational and theoretical. According the most common one, t_c is defined as "the travel time required for a rain drop to flow from the hydraulically most remote point of a basin to its outlet". Theoretically, given a uniformly distributed effective rainfall over the basin, t_c refers to the time interval after the start of rainfall for which the entire basin contributes to runoff generation, thus maximizing the flow rate at the outlet. When both rainfall and runoff observations are available, and after excluding hydrological losses and baseflow, the time of concentration can be determined as the time difference from the end of rainfall excess to the end of direct runoff. Nevertheless, restricted field data for graphical estimations lead to empirically-established methods for computing t_c on the basis of geomorphological data, such as the Giandotti's formula. Although these regional formulas are widely accepted in applied hydrology, they have inherent limitations, since they have been generally derived through regression analysis fitted to local field observations. An alternative approach, which was proposed by Natural Resources Conservation Service (NRCS), in 1986, is founded on a more natural basis and is known as the velocity method. This distributed approach considers three flow regimes along the longest flow path, i.e. sheet flow, shallow concentrated flow and open-channel flow.

Due to discrepancies among definitions and estimation procedures, t_c remains one of the most ambiguous concepts in hydrology. Even the simplest approaches, employing regional formulas, are affected by several uncertainties, such as geometrical hypotheses, automatic extraction of the drainage network, as well as DEM resolution and pre-processing. However, the most important misconception is the treatment of t_c as a constant property of the basin. In fact, the time of concentration is not constant, but varies inversely with discharge, and thus the rainfall intensity. The variability of t_c is absolutely crucial, since it strongly affects the reliability of hydrological design and the safety of associated hydraulic structures. The aim of this master thesis is to quantify the variability of the travel time across the longest flow path (LFP) of a river basin against the effective rainfall produced over the catchment. The methodology is based on the kinematic approach employed within typical design of urban sewer networks, which employs a semi-distributed schematization of the hydrological system and takes advantage of the rational method for the estimation of design peak discharge of each network element. The input data are derived through digital elevation model processing on geographic information systems. Finally, a sensitivity analysis is applied to investigate how the methodology is affected by various input parameters and DEM resolution.

Data

The analysis is implemented in four mesoscale rural basins. ***Table 1*** shows their main characteristics, as well as the time of concentration values that are calculated through two of the most popular regional formulas, i.e. Giandotti and Kirpich. It is remarked that the two formulas provide estimations that differ up to 100%.

Table 1. *Main characteristics of the four selected basins.*

	Nedontas	Sarantapotamos	Rafina	Xerias
Location	Messenia	Western Attica	Eastern Attica	Magnesia
Area (km^2)	114.8	143.7	123.3	111.5
Min elevation (m)	47.7	118.5	0.0	0.0
Max elevation (m)	1666.0	1353.8	902.6	1573.3
Mean elevation (m)	866.4	495.0	225.6	465.8
Longest flow path (km)	21.6	32.1	29.6	34.0
Mean slope of LFP (%)	7.5	4.0	3.0	4.4
Time of concentration, Giandotti formula (h)	3.3	6.3	7.4	5.4
Time of concentration, Kirpich formula (h)	1.9	3.4	3.5	3.3

Methodology

The proposed methodology adopts a semi-distributed spatial scale, following the rationale of urban stormwater design. After determining the longest flow path of the basin, two flow types are taken into consideration i.e. overland flow and channel flow. Essentially, along the maximum flow route are defined junctions and river segments with specific morphometric and hydraulic characteristics (upstream drainage area, length, mean slope, roughness). Initially we determine the overland velocity (m/s) of the most upstream sub-basin, by employing the empirical formula:

$$V_{overland} = k \cdot \sqrt{J} \tag{1}$$

where k is a roughness coefficient that is mainly related to the soil cover (m/s), and J is the mean slope of the watercourse (m/m).

By proceeding from upstream to downstream, we calculate the input peak discharge, Q_{r}, through the rational formula, considering a temporally and spatially uniform surface runoff depth (effective rainfall) P_{r} over the upstream drainage area, which duration is at least equal to the travel time of the upstream network, i.e.:

$$Q_r = \frac{\mathrm{P_r} \cdot \sum_{i=1}^{N} A_i}{\sum_{i=1}^{N} t_i} \quad (2)$$

where A_i (m^2) is the area of each individual upstream sub-basin i, and t_i (m/s) is the associated travel time, which is given by:

$$t_r = \sum_{i=1}^{N} \frac{L_i}{V_i} \quad (3)$$

where L_i is the length of each upstream river segment i (m) and V_i (m/s) is the corresponding channel velocity (m/s). The latter is calculated through the Manning's formula, thus considering uniform flow conditions, i.e.:

$$V_{channel} = \frac{1}{n} R^{2/3} \cdot J^{1/2} \quad (4)$$

where n is the Manning's roughness coefficient, R is the hydraulic radius (m), and J is the mean longitudinal slope of the river segment (m/m). For given input discharge, Q (m^3/s), the hydraulic radius is estimated by assuming a rectangular cross section, and solving the Manning's formula for the unknown flow depth, i.e.:

$$Q - \frac{1}{n} \frac{J^{1/2} \cdot b^{5/3} \cdot y^{5/3}}{(b + 2 \cdot y)^{2/3}} = 0 \quad (5)$$

where b is the width of the cross section (m), y is the depth of the cross section (m).

In the above procedure, most inputs are extracted via distributed spatial analysis, while some parameters, such as the roughness coefficients k and n, are user-specified. In particular, the schematization of the hydrological system is derived from a structured topology in GIS environment, which is composed of junctions, flow segments and surface elements (basins). Regarding the hydraulic characteristics, the length and slope are extracted through the DEM, while the section width is either estimated by field measurements or, in the absence of such data, from the DEM's topography or other sources (e.g., satellite maps).

Results

For given runoff depth, P_r, the proposed methodology calculates the travel time, t_r, as well as the resulting peak discharge, Q_r, at the basin outlet. In ***Figure 1*** are shown the scatter diagrams of travel time against runoff depth, at the four studied basins. In all cases, the two variables, i.e. travel time and runoff depth, are highly correlated, and they are well-approximated by power relationship of the form $t_\mathrm{r} = a\, P_\mathrm{r}^{-b}$, where a, $b > 0$. Additionally, an asymptotic behavior is apparent, which means that for extreme hydrological events, the travel time converges to a minimum value.

Interesting conclusions are also obtained by plotting the time of concentration values that are estimated by the two empirical formulas, i.e. Giandotti and Kirpich. In three out of four basins (Nedontas, Rafina, Xerias), the Giandotti's value corresponds to a runoff height of about 2 mm, while the Kirpich's value corresponds to a runoff height of about 20 mm, i.e. one orfer of magnitude higher. In Sarantapotamos basin, the flow regime of which is strongly affected by topographic peculiarities, the Giandotti's time corresponds to a much higher value, while the Kirpich's time is outlier.

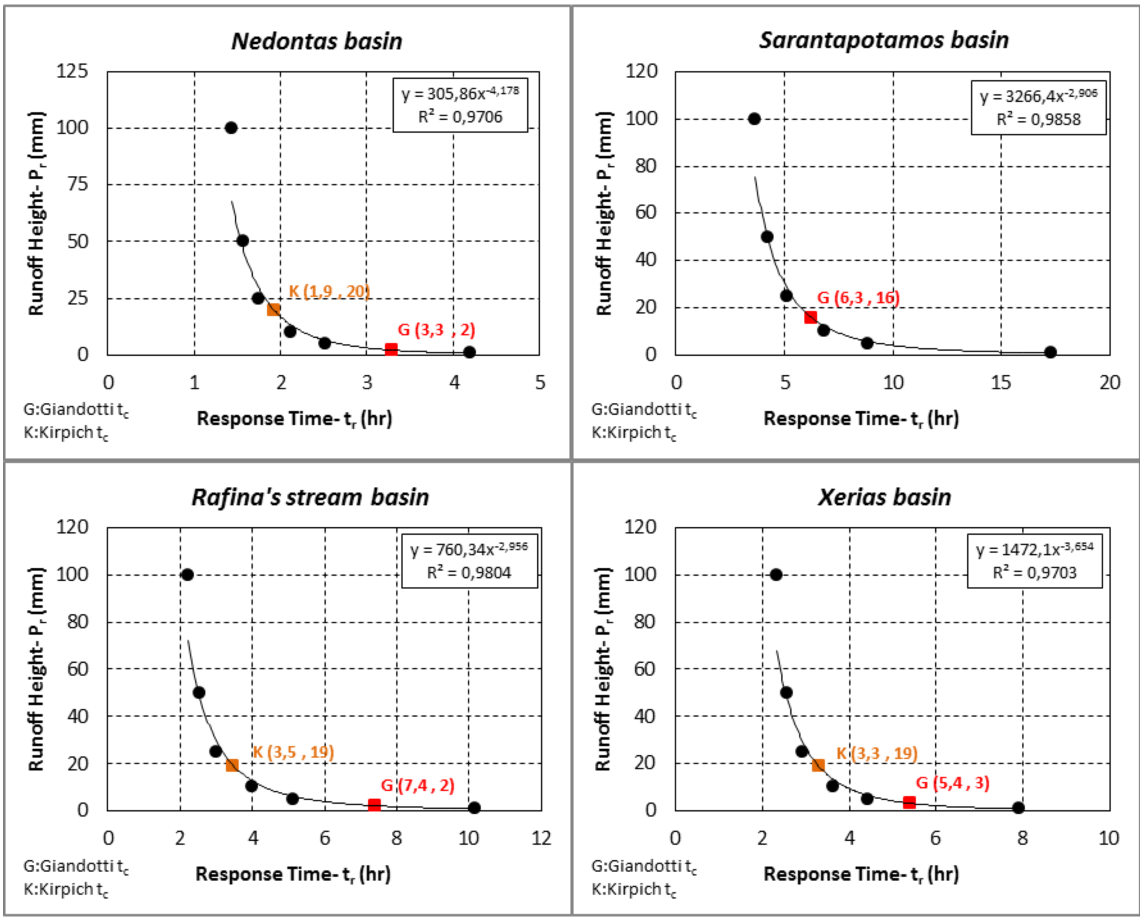

Figure 1. *Scatter plots of travel time against runoff depth, in selected basins.*

The variability of the travel time across the four basins is also demonstrated by means of box plots (***Figure 2***). It is shown that this variability is larger in cases of basins containing areas with flat topography, due to the storage effects and flow attenuations (routing). This also explains why the deviations between the Giandotti's and Kirpich's formula are smaller in the river basin of Nedontas, which is characterized by steep slopes and rapid response, and are larger in the river basin of Rafina stream, which extends over a much more smooth terrain. We remind that the the Giandotti's formula provides much higher t_c values than the Kirpich's formula, since the two methods use different indices to account the relief effects. Actually, their differences are more significant in basins characterized by heterogeneous slopes.

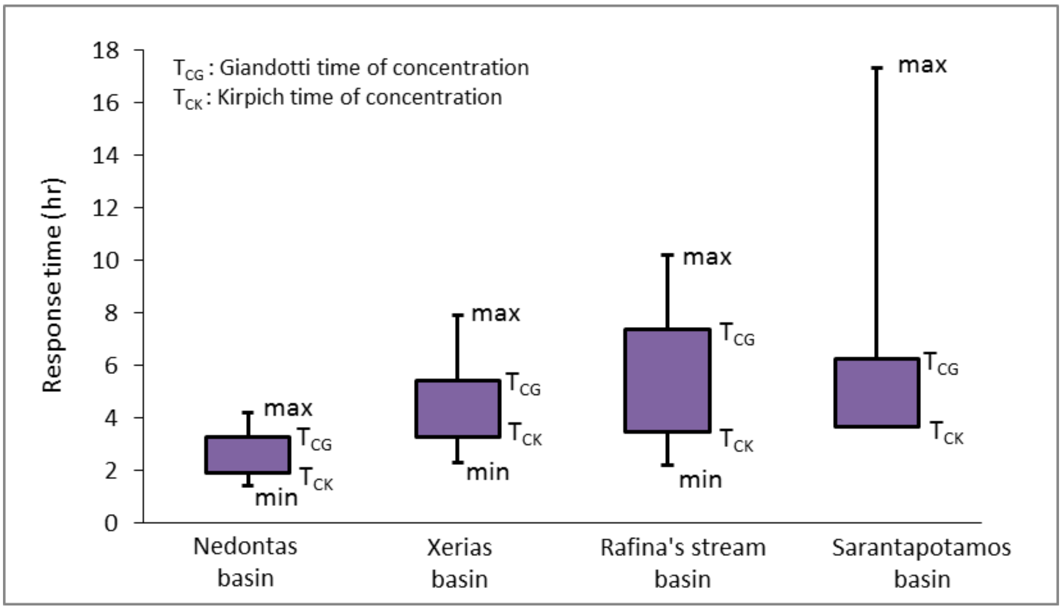

Figure 2. *Box plots for all estimated timing values for the four selected watersheds.*

It is also worth mentioning is that coefficients *a* and *b* of the runoff-time relationship are well-correlated with two major geomorphometric characteristics of the four basins. (***Figures 3 and 4***). In particular, the exponent *b* is linear function of the average slope of the longest flow path, and the coefficient *a* is also function of length. This conclusion is very important and may be the basis for establishing empirical formulas of general applicability.

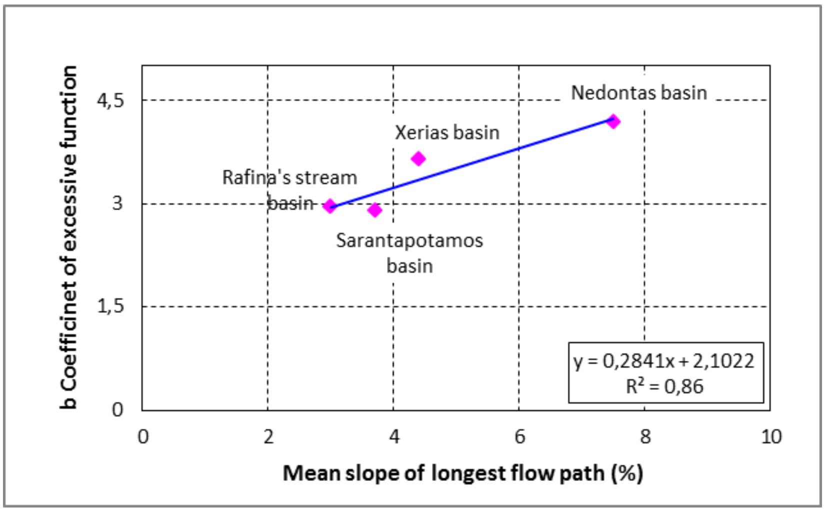

Figure 3. *Scatter plot of exponent b against the average slope of the longest flow path.*

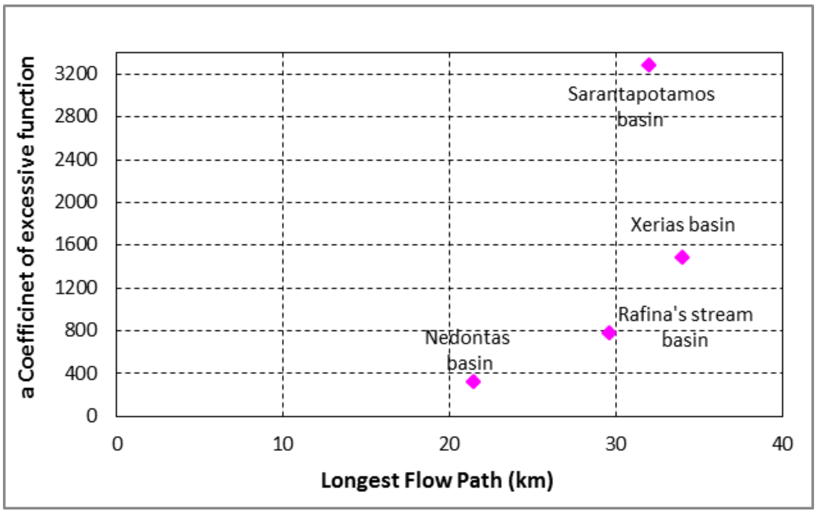

Figure 4. *Scatter plot of coefficient a against the longest flow path length.*

Sensitivity analysis

In order to quantify the effects of parameter uncertainty to travel time estimations, we employed a scenario-based sensitivity analysis, by changing by ±20% the following inputs:

- surface roughness coefficient, *k*;
- Manning's roughness coefficient, *n*; and
- width of rectangular section, *b*.

The selection of these parameters is considered crucial, due to uncertainty induced from measurement errors, lack of field information and inadequate knowledge of associated hydrological mechanisms.

From the sensitivity analysis it is concluded that in all basins, the range of uncertainty reduces as the runoff depth increases. Specifically, the section width is a parameter with low sensitivity, which is becomes negligible for high runoff depths. In the other hand, the most sensitive parameter is the surface roughness coefficient.

Effects of DEM resolution

In order to give a well-established answer for this inquire, DEMs resolutions of 25 m, 50 m and 100 m have been compared against a reference DEM of 5 m analysis. The analysis was conducted for the Nedontas river basin, which has steep morphology and significant surface water potential. The three DEMs were created using a bilinear resampling starting from the original resolution of 5 m. Results reveal that:

- The drainage area tends to be overestimated by about 1% at 100 m resolution and 0.2% at 25 m and 50 m. However, these differences are extremely low, providing rather minor changes in the estimated area, which is mainly realized due to errors of the interpolation method.
- The ability of DEM for meandering streams is gradually limited, leading to a reduction of the flow length as the resolution making coarser. The LFP length

exhibits the largest uncertainty in comparison to other geomorphological characteristics. The maximum difference is up to 6%, for 100 m resolution.

- The time of concentration of the Kirpich's formula shows larger deviations from the Giandotti's. This is justified by the sensitivity of the length parameter of the Kirpich's equation.
- As the resolution decreases, the representation of topography by a DEM tends to become smoother. The average slope of the watershed is underestimated, while the average slope of the maximum flow path is kept relatively constant. Quantitative, it is not obvious, how likely is the change of watercourse slope, as both the elevations and the flow length decrease, in coarser models.
- As shown in ***Figure 5***, at the resolution becomes coarser, the travel time is underestimated, led to increased estimates of peak discharge. Yet, similarly to model parameters discussed before, it is observed that the effect of spatial resolution becomes smaller, as the runoff depth increases. Hence, the effect of DEM resolution is attenuated when considering low frequency flood events.

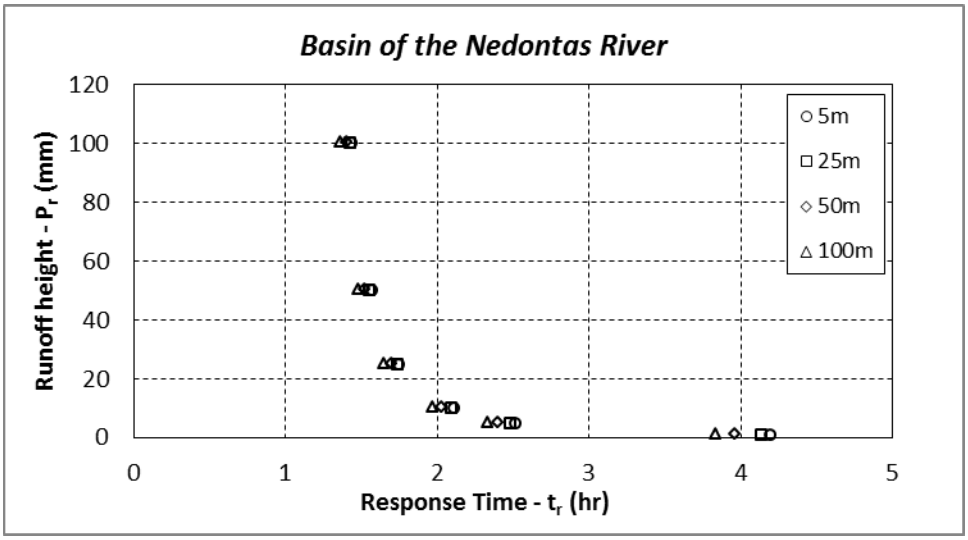

Figure 5. *Response time as function of runoff depth for different DEM resolutions in the river basin of Nedontas.*

Conclusions

The developed methodology allows handling the travel time across the longest flow path, which is one of the commonly used definitions for the time of concentration, as a varying parameter, which depends on the effective rainfall (runoff depth) generated over the basin. This provides a novel, physically-consistent approach for all temporal parameters that are associated with t_c, which will radically change significant aspects of hydrological modelling.

The accuracy of results may be enhanced via proper selection of the channel source point and the identification of the flow regime separation, which is crucial point of the methodology. Further improvement may be ensured by accounting for routing effects in low-slope channels, for which the use of the Manning's formula is not valid. Field measurements can also improve several hydraulic assumptions, including section geometry, roughness coefficient, etc. The longest flow path discretization should be also examined, either in coarser parts, or cell by cell, for the effect on time estimation. Finally, technological progression of GIS tools, for the automatic extraction of the drainage network and DEM pre-processing may be increased quality of DEM data.

Anyway, the sensitivity analysis showed the influence of parameter uncertainty is attenuated, as runoff increases. Particularly, the sensitivity of travel time against the width parameter is rather minor, even for small runoff values. Moreover, although the travel time is slightly affected by the DEM resolution, this effect is not statistically important.

Apparently, the current sample (four basins) is not sufficient for extracting safe statistical conclusions, e.g. by means of establishing regional formulas that account for. However, this study triggers further research on the treatment of the response time of the basin as a varying parameter, which depends on runoff. For this purpose, it is essential to apply the methodology on a sufficient sample of basins, which different geomorphological characteristics.

Key words*: time of concentration; travel time; runoff depth; longest flow path (LFP); rational method; Digital Elevation Model (DEM).*