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HW. 5 Prediction in ungauged basins - a benchmark report
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Tuscia University
GEMINI Department - Water Engineering Section
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# Flow time estimation in ungauged basins

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## 1. Abstract

The aim of this work is to focalize the attention on the design flood estimation on small ungauged river basin of limited extension (<150 Km$^2$).
In this contest we refer to the Width Function Based Instantaneous Unit Hydrograph (WFIUH) model, which optimizes, through the DEM, the distributed morphological basin information. The Width Function (WF) is defined as the distance-area function or the probability measure obtained by dividing the number of cells at given hydrologic distance from the outlet by the total number of basin cells (the distance is measured along the flow path and normalized by the maximum distance from the divide to the outlet). WF is easily obtained using common flow direction algorithms on elevation data, but in order to obtain the basin travel time distribution (IUH, or FT, Flow Time) two parameters have to be assigned: the channel and hillslope velocities ($V_c$, $V_h$). Indeed these two values, rescaling the WF expressed in terms of length, provide the travel time of each cell of the basin.
The WFIUH model is not largely applied since these two velocity values have to be calibrated while this IUH approach should be adopted on small and almost ungauged basin. Further improvements can be obtained considering the spatial variability of hillslope velocities with the aim to reduce the number of parameter and to better determine the basin IUH. Overland flow velocities are recognized to vary with slope length, flow depth, land use and other geomorphic hillslope characteristics. Several approaches for the variability velocity field estimation applied for FT definition can be found in literature, for instance starting from classic Manning's law and making assumptions on the hydraulic ratio, or linking hillslope velocity with power laws or local geomorphic properties such as slope or contributing area.
Although several studies have already focused on the relationships between WF, channel flow velocity and hillslope flow velocity, in literature it was not deeply investigated the spatial variability of overland flow velocity and how this variability affects the basin hydrologic response. So, after a brief review of the main methods, aim of this work will be:
A) to highlight if it is useful and what are differences in using a fully spatial distributed hillslope flow velocity field to rescale the FL, as respect to the standard approach which considers constant hillslope and river network velocity values.
B) to evaluate approaches useful for the flow velocity estimation in term of the capability to reproduce appropriate values and in term of the number and type of parameter introduced.

## 2. Methodology

1) Artificial depressions and flat areas are removed from DEMs resumed in Table 1 using PEM4PIT model with automatic parameter estimation (Grimaldi et al., 2007; Nardi et al., 2008; Santini et al., in press); flow directions and contributing areas are characterized using the D8-LTD method (Orlandini et al., 2003) with dampening factor = 1; stream network is extracted using the automated drop analysis combined with the curvature based method (Tarboton et al., 1991; Tarboton and Ames, 2001). Slope is extracted according to maximum downhill criterion.

2) Determination of the Width Function is based on the estimation of hydrologic distances measured along the D8-LTD based steepest slope path for the river network and using the D-∞ method (Tarboton, 1997; Bogaart & Troch, 2006) for the hillslopes.

3) In order to estimate the flow velocity for each cell of the basin, the following methods are considered (see Table 2 and Table 3 for details):

case 1a) In the hillslopes: Darcy – Weisbach formula; flow depth 'y' = 0.002 m; in the channels: channel velocity set to 2 m/s.
case 1b) In the hillslopes: Darcy – Weisbach formula; flow depth 'y' = 0.005 m; in the channels: channel velocity set to 2 m/s.
case 1c) In the hillslopes: Darcy – Weisbach formula; flow depth 'y' = 0.010 m; in the channels: channel velocity set to 2 m/s.
case 2a) In the hillslopes: Manning formula; flow depth 'y' = 0.002 m; in the channels: channel velocity set to 2 m/s.
case 2b) In the hillslopes: Manning formula; flow depth 'y' = 0.005 m; in the channels: channel velocity set to 2 m/s.
case 2c) In the hillslopes: Manning formula; flow depth 'y' = 0.010 m; in the channels: channel velocity set to 2 m/s.
case 3) In the hillslopes: SCS formula; in the channels: channel velocity set to 2 m/s.
case 4a) For hillslope and channel cells: Maidment et al. (1996) formula; mean basin velocity 'Vmean' = 0.05 m/s.
case 4b) For hillslope and channel cells: Maidment et al. (1996) formula; mean basin velocity 'Vmean' = 0.10 m/s.
case 4c) For hillslope and channel cells: Maidment et al. (1996) formula; mean basin velocity 'Vmean' = 0.15 m/s.

In order to avoid unrealistic low velocities due to particular combinations of slope and drainage areas, thresholds for velocities are fixed. Literature review allowed setting both lowest and highest threshold limits assuming valid the range from 0.02 to 2 m/s, so velocity values lower or higher than these thresholds are changed respectively to 0.02 or 2 m/s.

4) Rescaling of WFs are determined weighting the WF with the corresponding flow velocities in the following cases:

hv var.) - velocity that varies cell by cell according the previous cases from '1a' to '4c'.
hv const.) - constant flow velocity for channels (set to 2 m/s) and constant flow velocity for hillslopes, equal to the average of the heterogeneous velocity values defined in the case 'hv var.'

5) Comparison of the WF with the aims:

A) to highlight the differences in using a fully spatial distributed hillslope flow velocity field to rescale the FL, as respect to the standard approach which considers constant hillslope and river network velocity values (here only the case 2c is showed for all the DEMs considered)
B) to highlight the differences in the flow velocity estimation schemes (here only one DEM is considered, having applied all the cases from '1a' to '4c').

### Table 1: DEM case studies

| Number | Basin | Area (Km$^2$) | cellsize (m) | zmin (m) | zmax (m) | outlet coordinates x | outlet coordinates y | Projection | Horton order - |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Isorno | 71.00 | 20 | 323 | 2683 | -15542 | 5132440 | UTM33N | 5 |
| 2 | Chisone | 85.08 | 20 | 1512 | 3265 | -134728 | 5016486 | UTM33N | 4 |
| 3 | Lernu | 131.15 | 30 | 3 | 894 | 546199 | 4522635 | UTM32N | 5 |
| 4 | Isalle tributary | 35.15 | 30 | 80 | 840 | 537202 | 4471895 | UTM32N | 4 |
| 5 | Cedrino tributary | 63.60 | 30 | 0 | 827 | 554542 | 4472889 | UTM32N | 5 |
| 6 | Lodè tributary | 49.48 | 30 | 120 | 1015 | 543352 | 4493378 | UTM32N | 4 |
| 7 | Ayasse | 41.60 | 20 | 1434 | 3183 | -75500 | 5078831 | UTM33N | 4 |
| 8 | Lys | 91.50 | 20 | 1410 | 4525 | -57692 | 5096250 | UTM33N | 4 |
| 9 | Nestore | 78.45 | 20 | 233 | 856 | 267738 | 4765213 | UTM33N | 5 |
| 10 | Naja tributary | 51.69 | 20 | 183 | 586 | 288225 | 4736359 | UTM33N | 5 |
| 11 | Rigo | 84.25 | 20 | 73 | 551 | 273355 | 4715745 | UTM33N | 3 |

### Table 2: Surface flow velocity equations

$$v = \frac{8gSy^2}{K\Phi}$$

**Darcy – Weisbach**
**(only for hillslope cells)**

$$v = \frac{y^{\frac{2}{3}}\sqrt{S}}{n}$$

**Manning**
**(only for hillslope cells)**

$$v = a\sqrt{S}$$

**SCS**
**(only for hillslope cells). Note that if S > 0.04 than a term S' is used instead of S:**

$$S' = 0.05247 + 0.06363 \cdot S - 0.182 \cdot e^{-62.38S}$$

$$v = \frac{V_{mean}}{[S^b A^c]_{mean}} S^b A^c$$

**Maidment et al.** (1996)
**(both for hillslope and channels cells)**

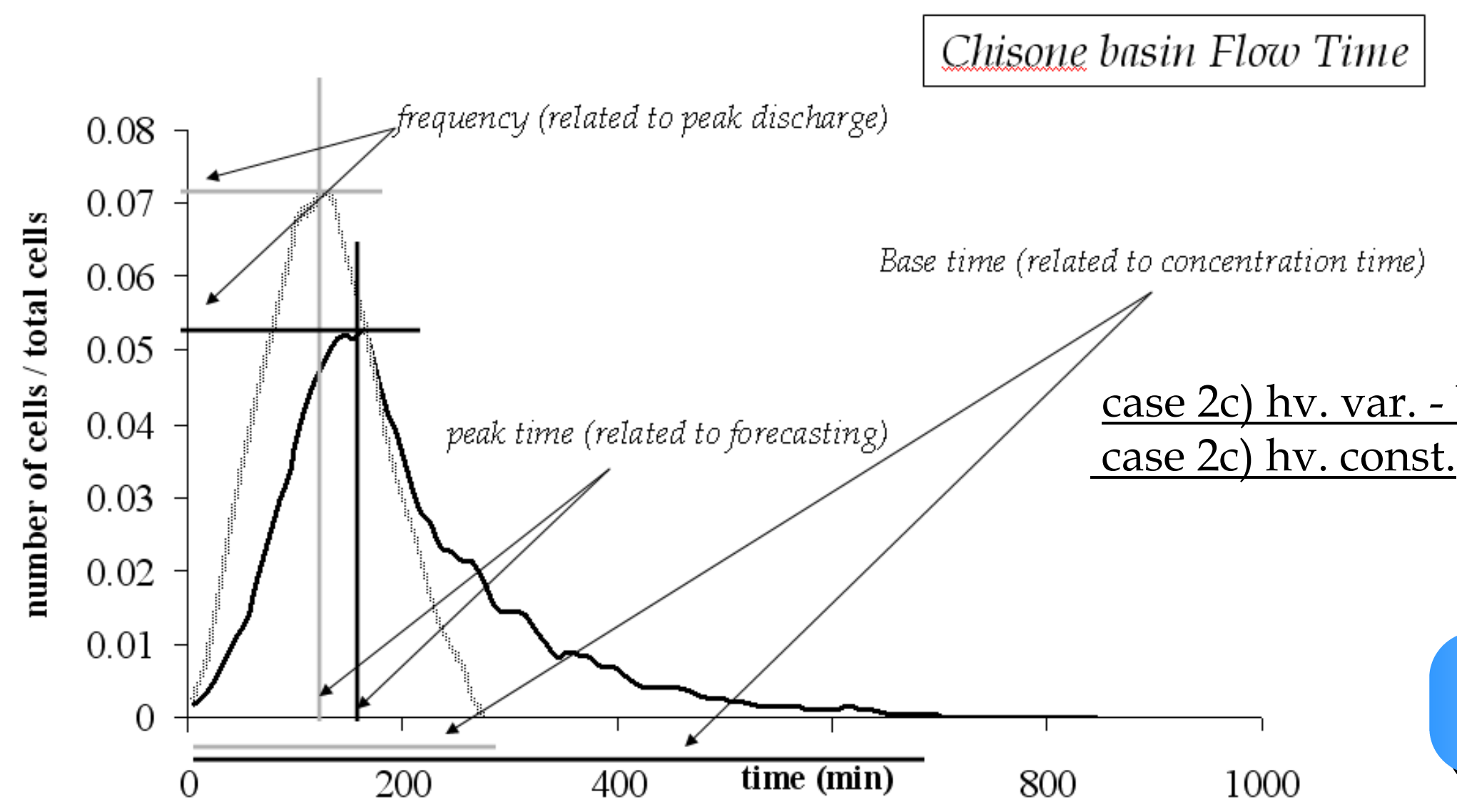
v = velocity (m s$^{-1}$)
g = gravity acceleration (m s$^{-2}$)
S = slope (unitless)
y = overland flow depth (m)
Φ = cinematic viscosity (m$^2$ s$^{-1}$)
K = coefficient related to land use and rainfall intensity (unitless)
n = Manning's roughness coefficient (s m$^{-1/3}$)
a = land use or flow type coefficient (m s$^{-1}$)
$V_{mean}$ = the mean velocity in the whole basin (accounting for both hillslope and channels) (m s$^{-1}$)
A = upstream drainage area (m$^2$)
b, c = calibration coefficients (unitless)

| Formula | Parameters Number | Parameters description | Ancillary Data |
|---|---|---|---|
| a) Darcy-Weisbach | 2 | Flow depth in hillslopes; channel velocity in river network | Land cover |
| b) Manning | 2 | Flow depth in hillslopes; channel velocity in river network | Land cover |
| c) SCS | 1 | Channel velocity in river network | Land cover |
| d) Maidment | 1 | Mean velocity in the whole basin | - |

### Table 3: look-up table between land cover and velocity equation parameters

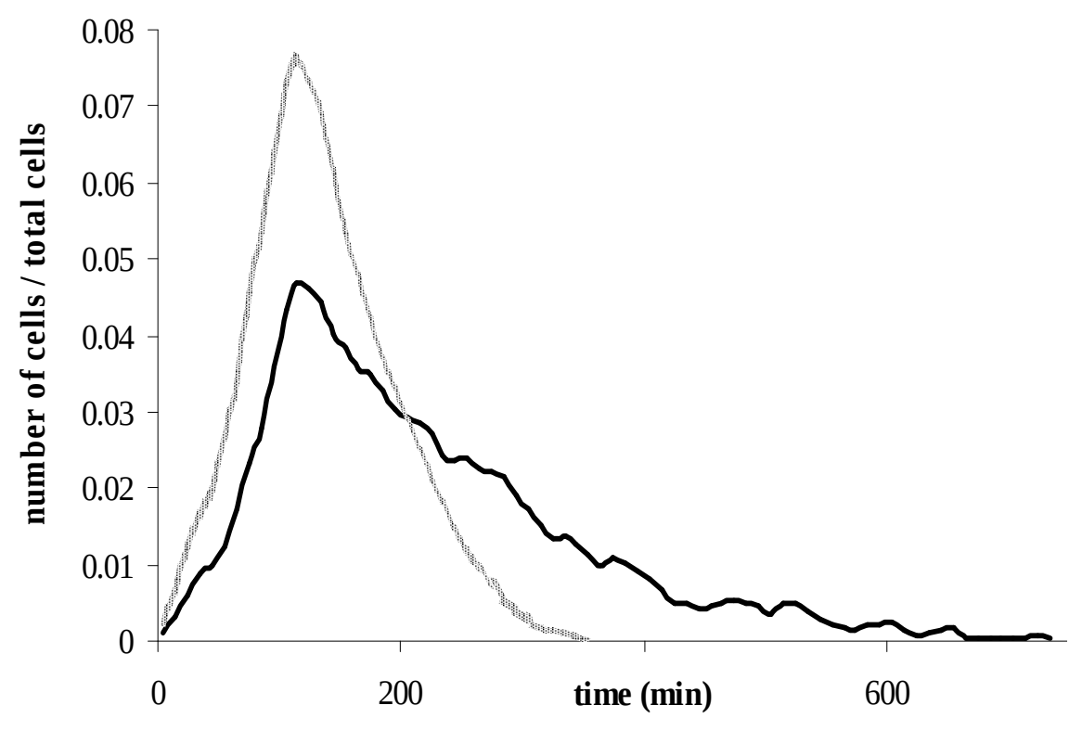
| Corine Code | Nomenclature | 'K' Darcy-Weisbach | 'n' Manning | 'a' SCS |
|---|---|---|---|---|
| 111 | Continuous urban fabric | 1000 | 0.03 | 2.96 |
| 112 | Discontinuous urban fabric | 1000 | 0.05 | 2.96 |
| 121 | Industrial or commercial units | 1000 | 0.03 | 2.96 |
| 124 | Airports | 1000 | 0.05 | 2.96 |
| 131 | Mineral extraction sites | 1000 | 0.05 | 2.96 |
| 133 | Construction sites | 1000 | 0.05 | 2.96 |
| 142 | Sport and leisure facilities | 1000 | 0.03 | 2.96 |
| 211 | Non-irrigated arable land | 4000 | 0.12 | 2.06 |
| 212 | Permanently irrigated land | 4000 | 0.12 | 2.06 |
| 221 | Vineyards | 4000 | 0.15 | 2.06 |
| 222 | Fruit trees and berry plantations | 4000 | 0.15 | 2.06 |
| 223 | Olive groves | 4000 | 0.12 | 2.06 |
| 231 | Pastures | 15000 | 0.25 | 2.59 |
| 241 | Annual crops associated with permanent crops | 15000 | 0.25 | 2.59 |
| 242 | Complex cultivation | 15000 | 0.25 | 2.59 |
| 243 | Land principally occupied by agriculture, with significant areas of natural vegetation | 10000 | 0.15 | 2.59 |
| 244 | Agro-forestry areas | 15000 | 0.3 | 2.59 |
| 311 | Broad-leaved forest | 20000 | 0.6 | 0.73 |
| 312 | Coniferous forest | 20000 | 0.6 | 0.73 |
| 313 | Mixed forest | 20000 | 0.6 | 0.73 |
| 321 | Natural grassland | 15000 | 0.25 | 2.59 |
| 322 | Moors and heathland | 15000 | 0.25 | 2.59 |
| 323 | Sclerophyllous vegetation | 15000 | 0.25 | 2.59 |
| 324 | Transitional woodland shrub | 15000 | 0.25 | 2.59 |
| 331 | Beaches, dunes, and sand plains | 15000 | 0.3 | 2.59 |
| 332 | Bare rock | 2000 | 0.1 | 2.96 |
| 333 | Sparsely vegetated areas | 10000 | 0.13 | 2.59 |
| 334 | Burnt areas | 2000 | 0.1 | 2.96 |

## Results: A) comparison between fully spatial distributed hillslope flow velocity field and constant hillslope and river network velocity values.

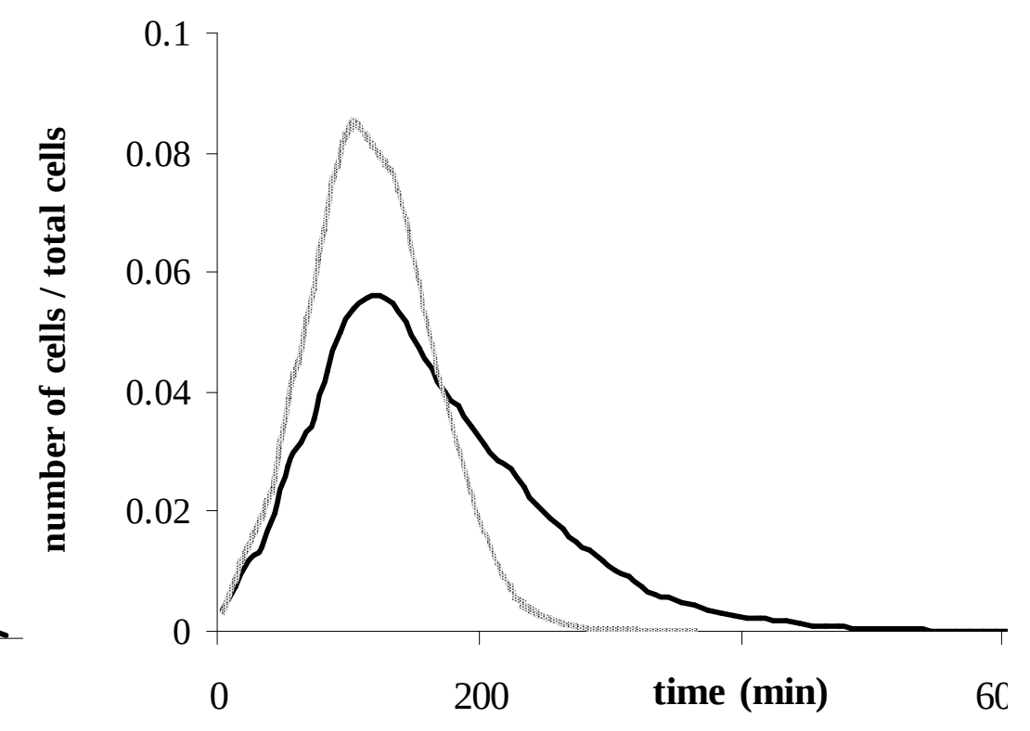


case 2c) hv. var. - black line;
case 2c) hv. const. - gray line

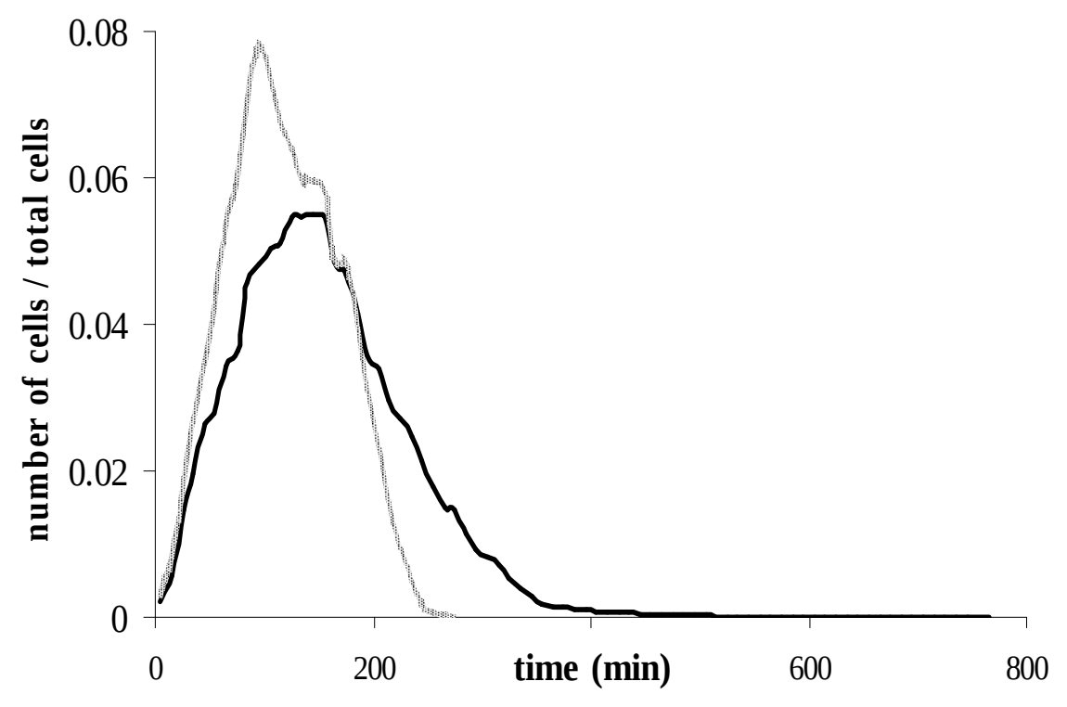
### FT - Width Function



**Lodè tributary Flow Time**



**Nestore Flow Time**



**Naja tributary Flow Time**

### Normalized FT moments and statistics

$$M1 = \frac{<T>Vc}{<L>}$$ (related to mean)

$$M2 = \frac{\mathrm{var}(T)}{<T>^2}$$ (related to variance)

$$M3 = \frac{<(T-<T>)^3>}{\mathrm{var}(T)^{3/2}}$$ (related to skewness)

<L> = mean of travel distances (FL – Flow Length) in the basin
<T> = mean of travel times (FT – Flow Time) in the basin
Vc = channel velocity
(Botter & Rinaldo, 2003)

| Basin | Case | f (-) | $FT_{mode}$ (min) | $FT_{max}$ (min) | M1 (-) | M2 (-) | M3 (-) |
|---|---|---|---|---|---|---|---|
| Isorno | hv var. | 0.062 | 185 | 699 | 1.90 | 0.19 | 1.09 |
| | hv const. | 0.070 | 155 | 329 | 1.45 | 0.15 | 0.02 |
| Chisone | hv var. | 0.053 | 165 | 844 | 2.65 | 0.32 | 1.33 |
| | hv const. | 0.071 | 125 | 280 | 1.70 | 0.18 | 0.18 |
| Lernu | hv var. | 0.039 | 205 | 794 | 1.70 | 0.23 | 0.81 |
| | hv const. | 0.044 | 155 | 512 | 1.42 | 0.20 | 0.37 |
| Isalle tributary | hv var. | 0.083 | 115 | 385 | 2.11 | 0.19 | 0.67 |
| | hv const. | 0.095 | 95 | 285 | 1.79 | 0.18 | 0.42 |
| Cedrino tributary | hv var. | 0.070 | 95 | 597 | 1.97 | 0.33 | 1.47 |
| | hv const. | 0.083 | 95 | 352 | 1.60 | 0.23 | 0.83 |
| Lodè tributary | hv var. | 0.047 | 115 | 725 | 2.94 | 0.34 | 1.11 |
| | hv const. | 0.076 | 115 | 356 | 1.85 | 0.19 | 0.50 |
| Ayasse | hv var. | 0.094 | 95 | 327 | 1.77 | 0.21 | 0.93 |
| | hv const. | 0.098 | 95 | 183 | 1.35 | 0.17 | 0.04 |
| Lys | hv var. | 0.091 | 145 | 503 | 1.67 | 0.17 | 0.93 |
| | hv const. | 0.079 | 115 | 289 | 1.26 | 0.18 | 0.19 |
| Nestore | hv var. | 0.056 | 125 | 655 | 2.09 | 0.28 | 0.96 |
| | hv const. | 0.085 | 105 | 361 | 1.51 | 0.16 | 0.30 |
| Naja tributary | hv var. | 0.055 | 145 | 768 | 1.82 | 0.26 | 0.93 |
| | hv const. | 0.078 | 95 | 279 | 1.39 | 0.18 | 0.14 |
| Rigo | hv var. | 0.017 | 165 | 2855 | 6.44 | 0.67 | 1.08 |
| | hv const. | 0.031 | 165 | 957 | 2.74 | 0.36 | 0.76 |

**case 2c)**

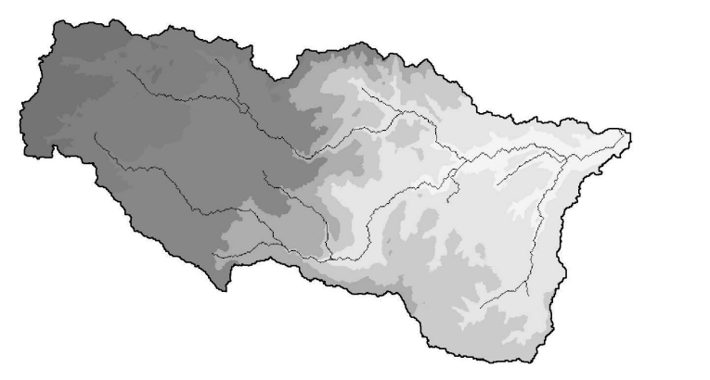
In all case studies the assumption of heterogeneous flow condition leads to a more spread IUH response, with larger durations ($FT_{max}$) and lower peaks (f), while differences in terms of time to peak ($FT_{mode}$) are smaller.

### Relationships between contributing areas and flow velocities

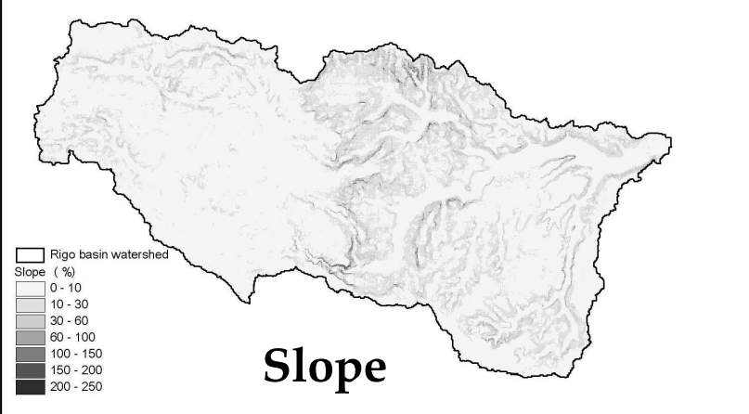
A simple explanation concerning the larger duration in the variable velocity field is provided. Here only the mean contributing area for those hillslope cells with velocity lower or greater to a specific values are considered. **Results suggest that the highest velocities belong to cells with lowest contributing areas and vice versa**. When the velocity variability is not random but is anti correlated to the contributing areas the travel time is longer than the constant velocity case.

| Basin | 1/2 Mean Velocity Hillslope Cells<br>Mean Velocity (m/s) | 1/2 Mean Velocity Hillslope Cells<br>Mean Contributing Area (m$^2$) | Mean Velocity Hillslope Cells<br>Mean Velocity (m/s) | Mean Velocity Hillslope Cells<br>Mean Contributing Area (m$^2$) | 3 Mean Velocity Hillslope Cells<br>Mean Velocity (m/s) | 3 Mean Velocity Hillslope Cells<br>Mean Contributing Area (m$^2$) |
|---|---|---|---|---|---|---|
| Isorno | 0.073 | 11375 | 0.147 | 7846 | 0.439 | 2250 |
| Chisone | 0.097 | 16823 | 0.194 | 11696 | 0.581 | 2808 |
| Lernu | 0.042 | 10196 | 0.083 | 7794 | 0.249 | 5899 |
| Isalle tributary | 0.043 | 12042 | 0.087 | 7005 | 0.260 | 5019 |
| Cedrino tributary | 0.046 | 9857 | 0.093 | 6995 | 0.278 | 4438 |
| Lodè tributary | 0.053 | 20132 | 0.107 | 11449 | 0.320 | 6203 |
| Ayasse | 0.113 | 8152 | 0.226 | 5794 | 0.679 | 1129 |
| Lys | 0.151 | 11271 | 0.301 | 8706 | 0.904 | 4612 |
| Nestore | 0.039 | 5050 | 0.077 | 3533 | 0.231 | 1787 |
| Naja tributary | 0.049 | 4827 | 0.098 | 3824 | 0.295 | 1030 |
| Rigo | 0.048 | 51993 | 0.097 | 19189 | 0.290 | 1846 |

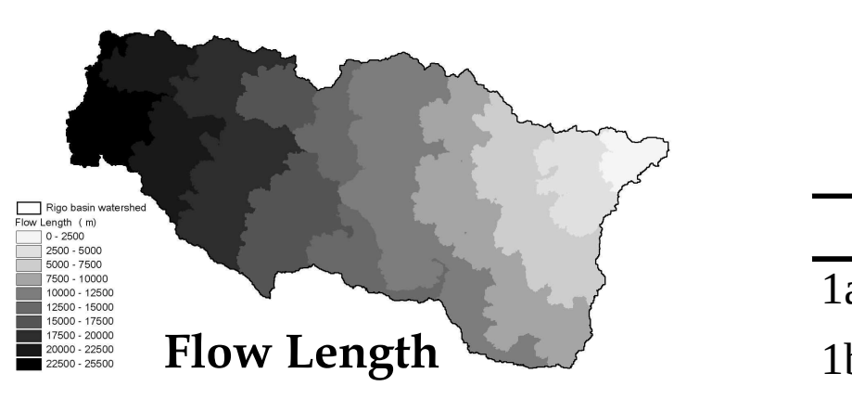
## Results: B) comparison between the flow velocites estimation schemes: the Rigo basin



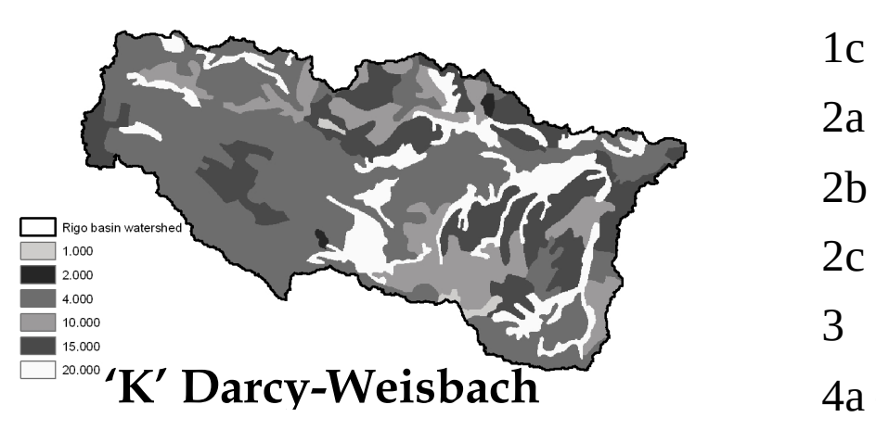
**DEM and river network**



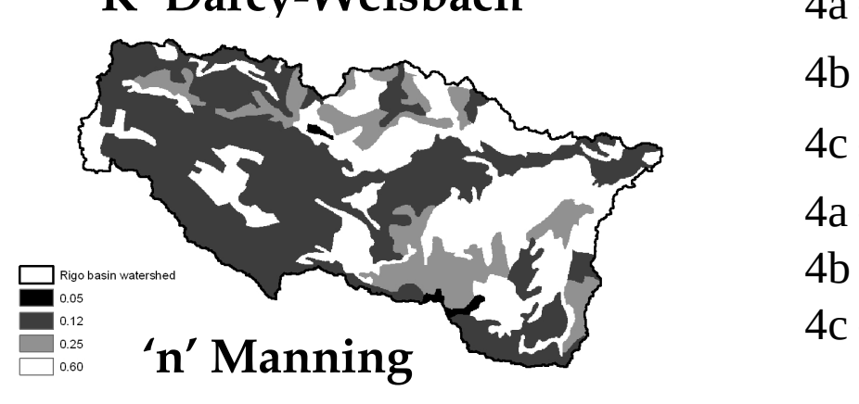
**Slope**



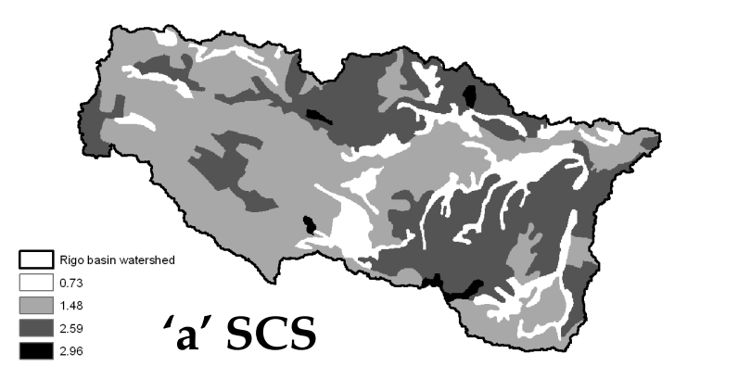
**Flow Length**



**'K' Darcy-Weisbach**



**'n' Manning**



**'a' SCS**

| Case | $V_{min}$ | $V_{max}$ | $V_{mean}$ | $V_{st.dev.}$ |
|---|---|---|---|---|
| 1a | 0.02 | 0.077 | 0.0201 | 0.001 |
| 1b | 0.02 | 0.487 | 0.032 | 0.025 |
| 1c | 0.02 | 1.946 | 0.104 | 0.114 |
| 2a | 0.02 | 0.209 | 0.035 | 0.018 |
| 2b | 0.02 | 0.383 | 0.062 | 0.037 |
| 2c | 0.02 | 0.605 | 0.096 | 0.060 |
| 3 | 0.02 | 1.068 | 0.390 | 0.187 |
| 4a – hillslope | 0.02 | 2.000 | 0.043 | 0.059 |
| 4b – hillslope | 0.02 | 2.000 | 0.080 | 0.119 |
| 4c – hillslope | 0.02 | 2.000 | 0.119 | 0.172 |
| 4a – channel | 0.02 | 2.000 | 0.890 | 0.601 |
| 4b – channel | 0.03 | 2.000 | 1.355 | 0.621 |
| 4c – channel | 0.05 | 2.000 | 1.594 | 0.547 |

**Velocity maps statistics**
**(using thresholds 0.02 m/s for low velocities and 2 m/s for high velocities)**

| Case | $V_{min}$ | $V_{max}$ | $V_{mean}$ | $V_{st.dev.}$ | Low outlier | High outlier |
|---|---|---|---|---|---|---|
| 1a | $1*10^{-7}$ | 0.08 | 0.004 | 0.004 | 205582 (98.6%) | 0 |
| 1b | $7*10^{-7}$ | 0.49 | 0.026 | 0.029 | 120443 (57.7%) | 0 |
| 1c | $3*10^{-6}$ | 1.95 | 0.103 | 0.116 | 29282 (14.1%) | 0 |
| 2a | $6*10^{-5}$ | 0.21 | 0.033 | 0.021 | 61549 (29.5%) | 0 |
| 2b | $1*10^{-4}$ | 0.38 | 0.061 | 0.038 | 27349 (13.1%) | 0 |
| 2c | $2*10^{-4}$ | 0.61 | 0.096 | 0.061 | 14983 (7.2%) | 0 |
| 3 | $2*10^{-3}$ | 1.07 | 0.390 | 0.187 | 285 (0.1%) | 0 |
| 4a – hillslope | $2*10^{-4}$ | 2.03 | 0.039 | 0.060 | 88561 (42.5%) | 1 (0.0005%) |
| 4b – hillslope | $4*10^{-4}$ | 4.05 | 0.079 | 0.120 | 26482 (12.7%) | 36 (0.02%) |
| 4c – hillslope | $6*10^{-4}$ | 6.08 | 0.119 | 0.181 | 4736 (2.3%) | 281 (0.1%) |
| 4a – channel | 0.016 | 7.14 | 0.986 | 0.859 | 1 | 242 (10.8%) |
| 4b – channel | 0.032 | 14.28 | 1.972 | 1.719 | 0 | 785 (35.1%) |
| 4c – channel | 0.048 | 21.42 | 2.958 | 2.579 | 0 | 1201 (53.8%) |

**Velocity maps statistics**
**(without thresholds)**

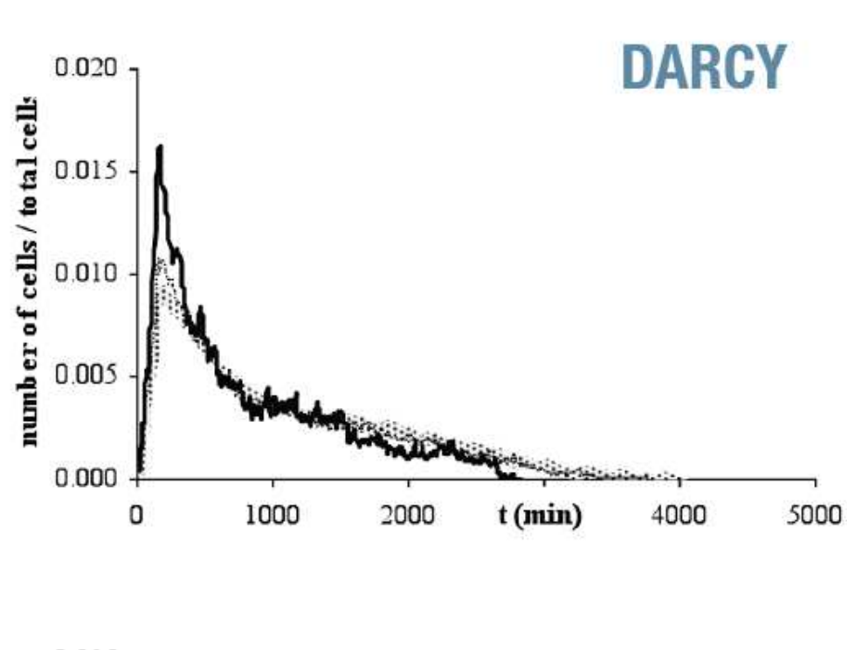
Low and high outlier percentages suggest how many basin cells provide velocity values outside the plausible range.
**Interesting to highlight that for all the cases, except to SCS case (3), such percentages could be significant.**

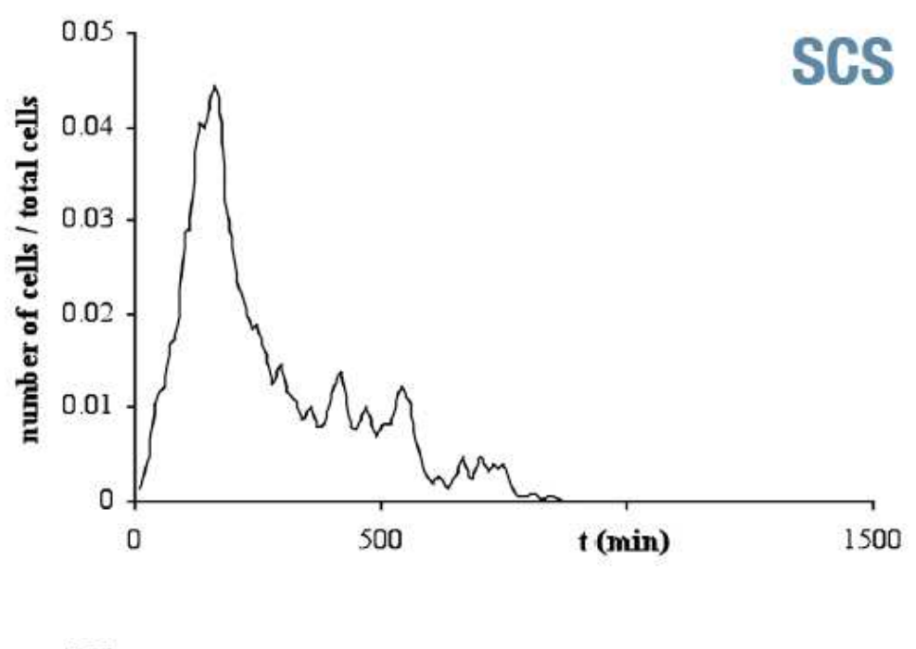
### Flow Time – FT statistics
### (with velocity thresholds)

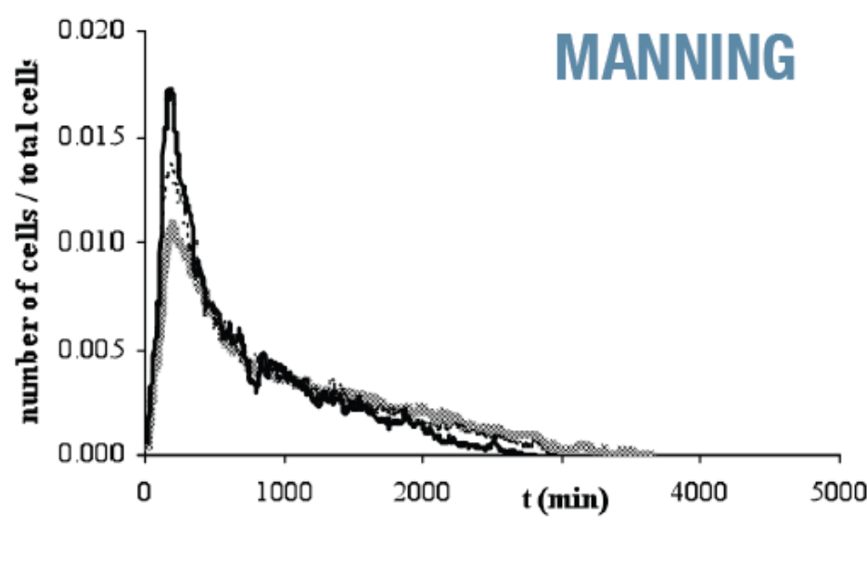
| Case | $FT_{min}$ | $FT_{max}$ | $FT_{mean}$ | $FT_{st.dev.}$ | q25 | q50 | q75 | q90 | $FT_{mode}$ | f |
|---|---|---|---|---|---|---|---|---|---|---|
| 1a | 0 | 4106 | 1070 | 827 | 370 | 837 | 1643 | 2334 | 185 | 0.009 |
| 1b | 0 | 4080 | 1033 | 819 | 336 | 800 | 1584 | 2288 | 165 | 0.010 |
| 1c | 0 | 3474 | 873 | 707 | 272 | 640 | 1308 | 1989 | 145 | 0.015 |
| 2a | 0 | 3606 | 969 | 769 | 325 | 735 | 1484 | 2163 | 185 | 0.011 |
| 2b | 0 | 2992 | 829 | 669 | 269 | 610 | 1255 | 1889 | 165 | 0.013 |
| 2c | 0 | 2855 | 703 | 578 | 235 | 503 | 1041 | 1634 | 165 | 0.017 |
| 3 | 0 | 897 | 265 | 176 | 133 | 204 | 387 | 545 | 155 | 0.044 |
| 4a | 0 | 1251 | 455 | 203 | 309 | 412 | 593 | 765 | 315 | 0.027 |
| 4b | 0 | 720 | 253 | 110 | 172 | 228 | 330 | 423 | 175 | 0.050 |
| 4c | 0 | 518 | 191 | 82 | 132 | 172 | 252 | 317 | 145 | 0.070 |

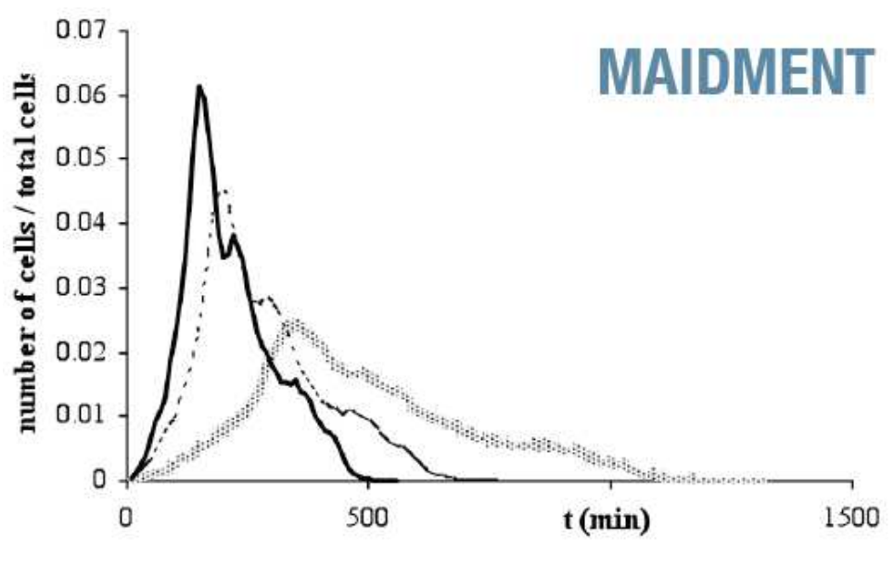
all values are expressed in minutes, except 'f' that is unitless.

$FT_{max}$ is related to concentration time; applying several formulas at basin scale (Giandotti, Kirpich, SCS) an average concentration time of 270 minutes is obtained.

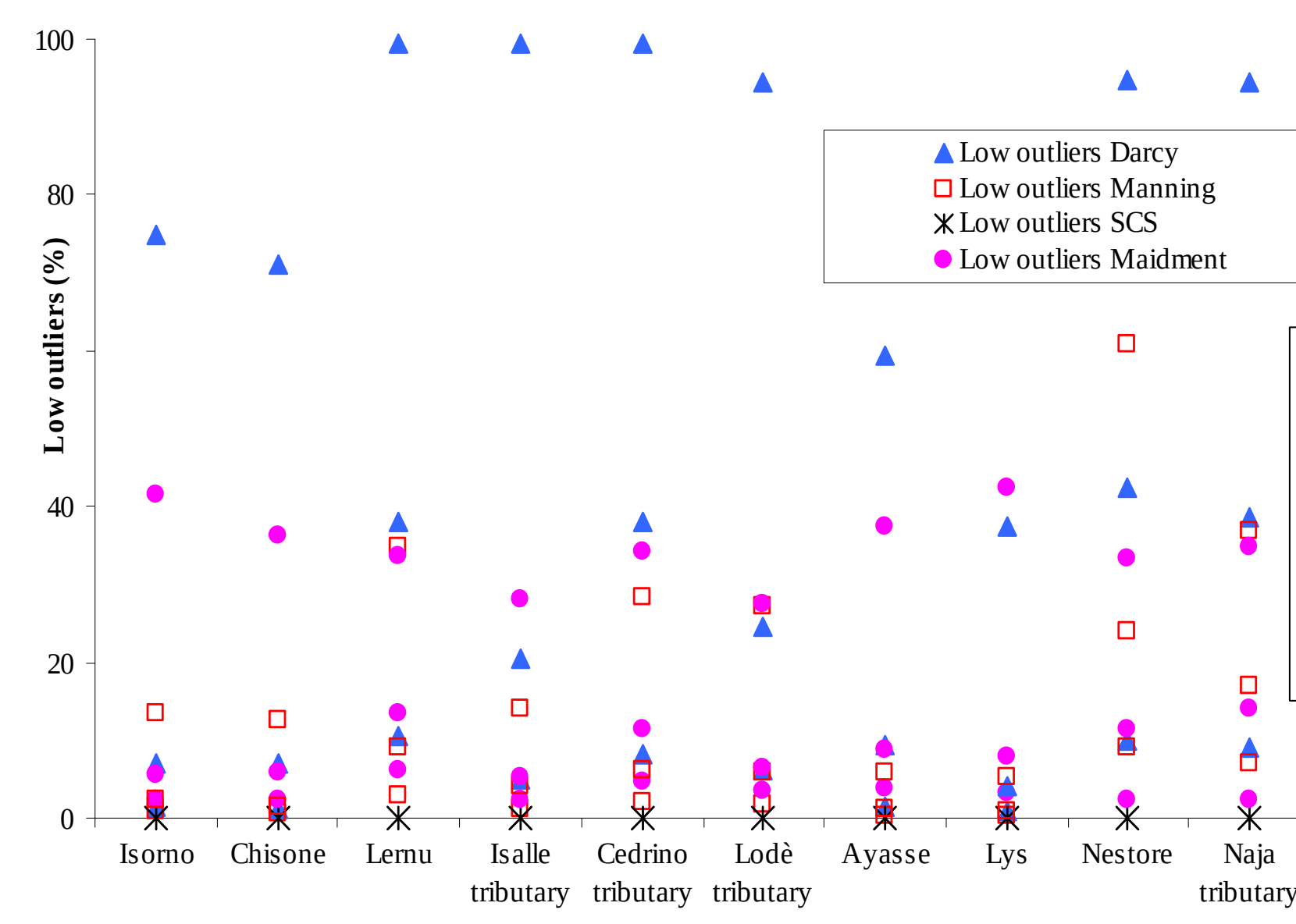




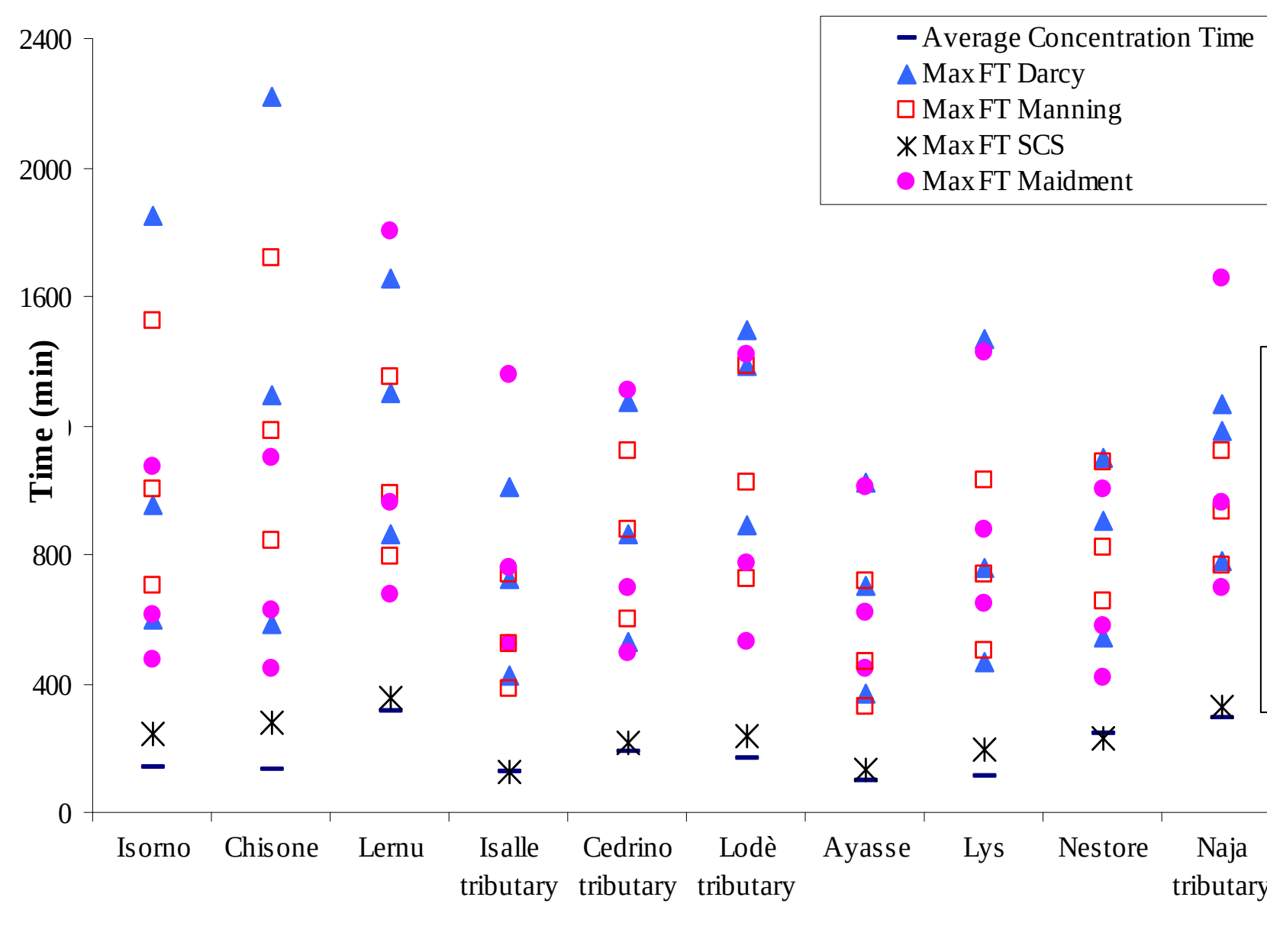




### Generalizing to all the basins:



Low outliers (percentage of basin cells with velocity lower than the threshold of 0.02 m/s) for all the basins and all the velocity schemes considered).



Flow Time maximum for all the basins and all the velocity schemes considered; also concentration time on basin scale is showed.

## Conclusions

It is now recognized the importance in the Width Function estimation procedure in order to improve the rainfall-runoff modeling in ungauged basins, not only for the peak discharge but for the whole hydrograph. The WFIUH application is in fact the way by which we can estimate the whole hydrograph (maintaining all the information available) starting only with the DEM and, maybe, land cover. The main aim is to define the travel time distribution by rescaling the WF through appropriate velocities, going beyond the standard approach consisting in assigning constant channel and hillslope velocity values.
The first analysis is to evaluate the effects of assuming spatially variable velocity instead of constant values all over the basins: several case studies confirmed the necessity to use a more complex cinematic scheme and highlighted a common behavior in differences among the basin travel times: highest velocities are in all case studies identified in cells with low contributing area and vice versa the lowest ones in the high contributing area cells, consequently these latter have a major influence in travel time definition providing slower patterns (this is the reason for the FT base time increasing).
In order to investigate which is the best method to estimate the hillslope velocity, four approaches are considered and they are applied on the case studies using different parameters values. The obtained velocity maps are analyzed: evaluating how realistic are the estimated velocity values comparing the basin travel time estimated both from the FT maps and from classical empirical formulas. The achieved results allow supporting two conclusions: the former is that the best method to define the velocity fields appears the SCS, the latter is that concerning the travel time distribution estimation either SCS's or Maidment's scheme can provide useful results using just one parameter.

## References

Bogaart P. W., Troch P. A. (2006), Curvature distribution within hillslopes and catchments and its effect on the hydrological response, Hydrology and Earth System Sciences (10) 6, 925-936.
Botter G., and Rinaldo A. (2003), Scale effect on geomorphologic and kinematic dispersion, Water Resour. Res., 39, No 10, 1286, doi: 10.1029/2003WR002154.
Grimaldi S., Nardi F., Di Benedetto F., Istanbulluoglu E., Bras R.L. (2006) A physically-based method for removing pits in digital elevation models. Advances in Water Resources, 30(10) October 2007: 2151-2158
Orlandini S., Moretti G., Franchini M., Aldigheri B. and Testa B. (2003), Path-based methods for the determination of non-dispersive drainage directions in grid-based digital elevation models, Water Resources Research 39(6), 1144, DOI: 10.1029/2002WR001639.
Maidment D.R., Olivera F., Calver A., Eatherall A., Fraczek W. (1996), Unit Hydrograph derived from a spatially distributed velocity field, Hydrological Processes, Vol 10, 831-844.
Nardi F., Grimaldi S., Santini M., Petroselli, Ubertini L. (2008), Hydrogeomorphic properties of simulated drainage patterns using DEMs: the flat area issue, Hydrological Science Journal, 53(6), 1176 - 1193
Petroselli A., Santini M., Nardi F., Grimaldi S., Vivoni E. (2007), Investigating the spatial variability of hillslope flow velocities, AGU Fall Meeting 2007.
Santini M., Grimaldi S., Nardi F., Petroselli A., Rulli M.C. (in press), Pre-Processing algorithms and landslide modelling on remotely sensed DEMs, Geomorphology.
Tarboton, D. G., R. L. Bras, and I. Rodriguez-Iturbe (1991), On the extraction of channel networks from digital elevation data, Hydrol. Processes, 5(1), 81- 100.
Tarboton D.G. (1997), A new method for the determination of flow directions and upslope areas in grid digital elevation models, Water Resour. Res., 33, 309- 319.
Tarboton D.G., and Ames D.P. (2001), Advances in the mapping of flow networks from digital elevation data, in World Water and Environmental Resources Congress, Orlando, Florida, May 20-24, ASCE.