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GIS Terrain Analysis for Hydrologic Applications

Width-Function based Instantaneous Unit Hydrograph rainfall runoff model: relationship between Width Function, hillslope flow velocities and concentration times

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1. Abstract

The Width Function (WF), the frequency of channel links/contributing area at the same hydrologic distance (i.e. the distance measured along the downhill flow path) to the outlet, is an important hydrogeomorphic property of river basins. The rescaled WF, obtained by weighting the flow distances with the corresponding flow velocity, provides the residency time distribution that is commonly used for representing the geomorphic IUH namely the WF Instantaneous Unit Hydrograph (distribution IUH) or WFIUH for the prediction of the hydrologic response in ungauged basins.

The determination of the flow velocities is usually performed lumping the complex dynamics of the heterogenous hydrologic processes of river basins into two main categories: the channelized flow of river channels and the diffusive divergent flow of hillslopes. Nevertheless, the understanding, measuring and preliminary estimation of these variables represents an issue within the WFIUH framework.

This work aims to investigate the possibility of implementing the fully spatial distribution of flow velocities throughout the basin, estimated as a function of local terrain properties (e.g. slope, land use etc) and constraining the flow velocity sample to represent the lag time of river basins.

2. Aim

Aim is to investigate the impact of considering the heterogeneous properties of hillslope runoff dynamics on the hydrologic response represented with the WFIUH approach with particular regard to the time of concentration, time to peak, total duration, peak discharge and volume distribution (Petroselli et al., 2007).

Hydrograph observations are compared to simulation results when using i) constant flow velocities for channel and hillslopes; ii) a spatially variable velocity field calibrated using the lag time information.

4. The Maidment et al. (1996) formula

v = cell velocity
A = upstream drainage area
S = cell steepest slope
b, c = coefficients = 0.5
$[S^b A^c]$ = watershed average value of slope-area term
V_{mean} = average value of the velocity in all cells in the watershed

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

3. Methodology

The following methodology was applied to 6 case studies:

1) Artificial depressions and flat areas are removed from the DEM using PEM4PIT model with automatic parameter estimation (Grimaldi et al., 2007; Nardi et al., in press; Santini et al., in review); 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.

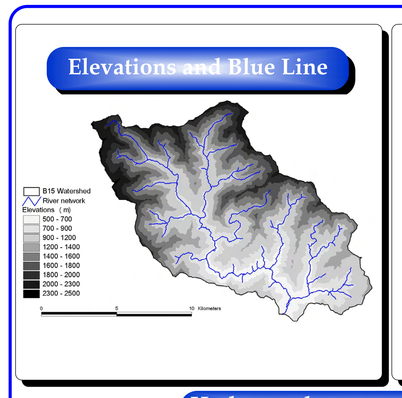
3) Determination of basin Lag Time from observed data (Bocchiola et al., 2003): Lag time is assumed as the time difference between the net hydrograph and the net rainfall centroids (Chow et al., 1988); net hydrograph was obtained with the fixed base method while net rainfall was obtained with the SCS-CN method using a Curve Number that leads to the equivalency between net rainfall volume and direct runoff volume (USDA, 1986; Chow et al., 1988).

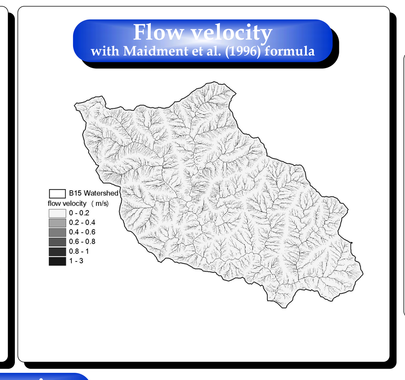
4) Rescaling of WFs are determined weighting the WF with the corresponding flow velocities in the following cases:
   a) - velocity that varies cell by cell: implementation of Maidment et al. formula (Maidment et al., 1996); V_{mean} was iteratively incremented until the WF-rescaled mean (WFIUH centroid) was equal to previously determined basin Lag Time (Chow et al., 1988); a maximum and minimum limit of respectively 0.01 m/s and 3 m/s is set in order to avoid unrealistic estimation of flow velocities.
   b) - constant flow velocity for channels (2 m/s) and hillslopes (0.05 m/s)
   c) - constant flow velocity for channels (1 m/s) and hillslopes (0.05 m/s).
   d) - constant flow velocity for channels (2 m/s) and hillslopes (0.02 m/s).
   e) - constant flow velocity for channels (1 m/s) and hillslopes (0.02 m/s).
   Channel and hillslope velocities of b), c), d), e) were selected according to Botter & Rinaldo (2003).

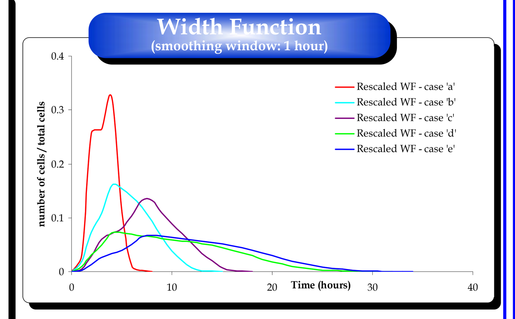
5) Rainfall-runoff modelling using the WFIUH approach using the rescaled WF in the five approaches of a) to e) and the net rainfall.

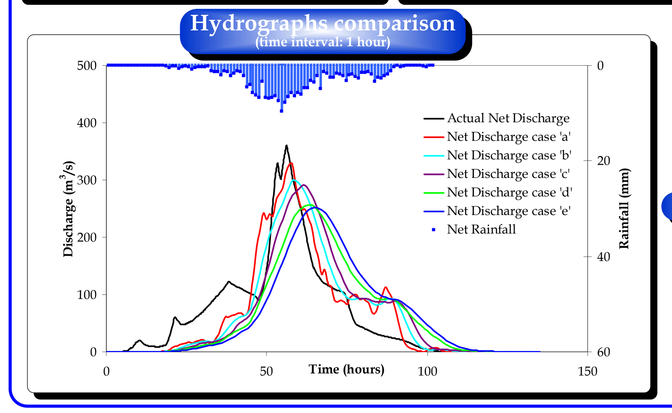
6) Comparison results of 5) with actual net hydrographs.

CASE STUDY 1







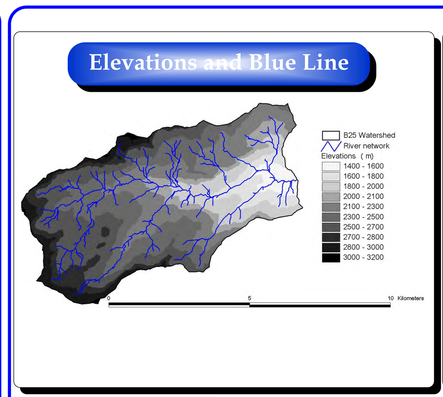


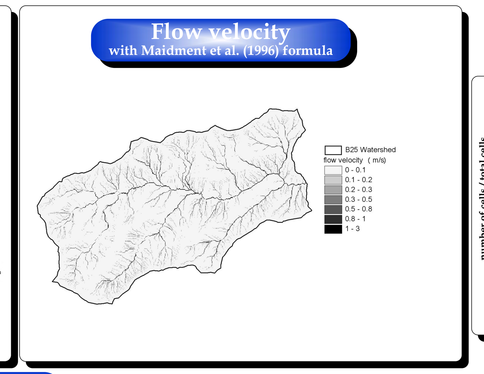
Basin	Mastallone
Outlet	Ponte Folle
Code	B15
Cellsize (m)	20
Precision	integer
Area (Km^2)	149
PEM4PIT Parameters (β, D, θ)	0.01, 160, 0.5
Observed Lag Time (hours)	2.81

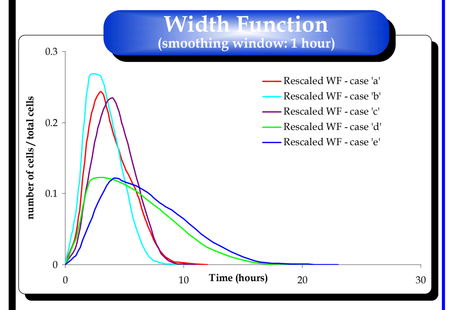
Summary

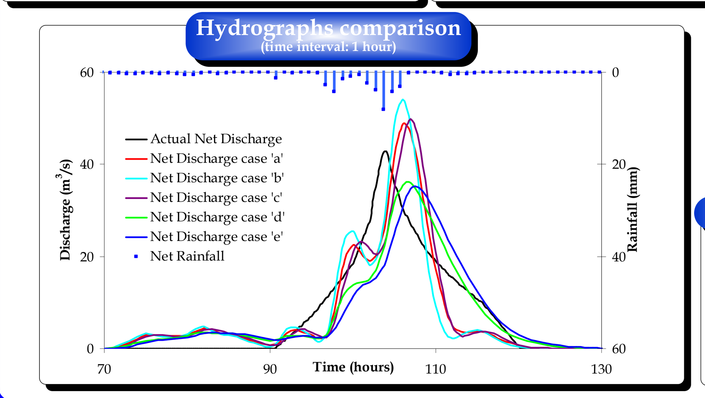
	WF max (hours)	WF peak time (hours)	WF centroid (hours)	Max Discharge (m^3/s)	Max Discharge Observed (m^3/s)
Case 'a': Maidment et al. Formula: Vmean: 0.19 m/s	7.08	3.58	2.81	327.52	360.61
Case 'b': channel velocity: 2 m/s, hillslope velocity: 0.05 m/s	14.33	3.75	4.92	298.63	
Case 'c': channel velocity: 1 m/s, hillslope velocity: 0.05 m/s	17.83	7.00	7.17	290.19	
Case 'd': channel velocity: 2 m/s, hillslope velocity: 0.02 m/s	31.33	3.75	9.08	256.35	
Case 'e': channel velocity: 1 m/s, hillslope velocity: 0.02 m/s	34.00	7.00	11.25	251.42	

CASE STUDY 2







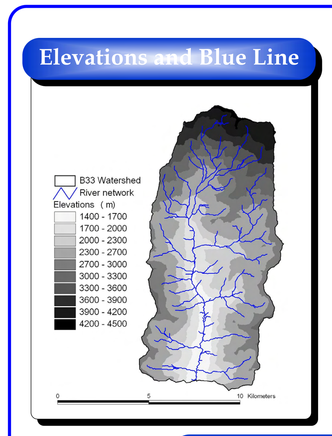


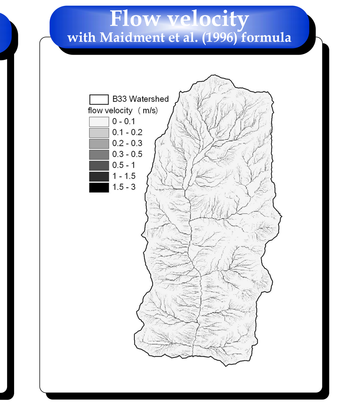
Basin	Ayasse - Dora Baltea
Outlet	Champorcher
Code	B25
Cellsize (m)	20
Precision	integer
Area (Km^2)	42
PEM4PIT Parameters (β, D, θ)	0.01, 188, 0.5
Observed Lag Time (hours)	3.60

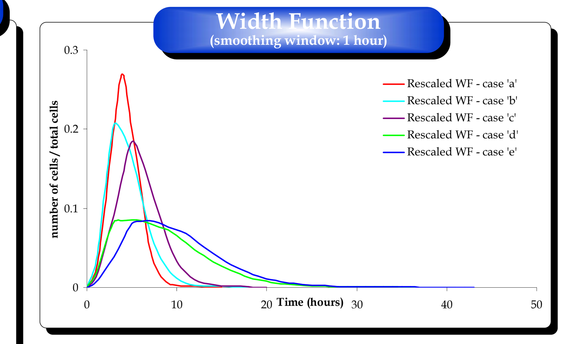
Summary

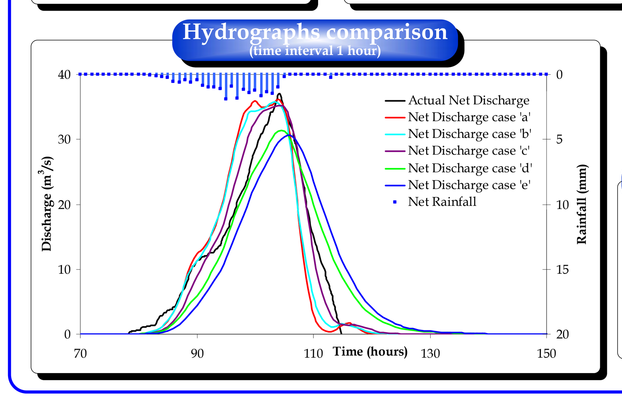
	WF max (hours)	WF peak time (hours)	WF centroid (hours)	Max Discharge (m^3/s)	Max Discharge Observed (m^3/s)
Case 'a': Maidment et al. Formula: Vmean: 0.09 m/s	11.92	2.58	3.60	48.75	42.84
Case 'b': channel velocity: 2 m/s, hillslope velocity: 0.05 m/s	9.25	1.66	2.50	54.08	
Case 'c': channel velocity: 1 m/s, hillslope velocity: 0.05 m/s	10.50	3.16	3.58	49.86	
Case 'd': channel velocity: 2 m/s, hillslope velocity: 0.02 m/s	21.33	1.75	4.92	36.07	
Case 'e': channel velocity: 1 m/s, hillslope velocity: 0.02 m/s	22.50	3.75	5.83	34.85	

CASE STUDY 3







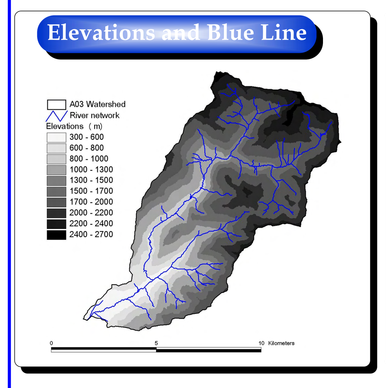


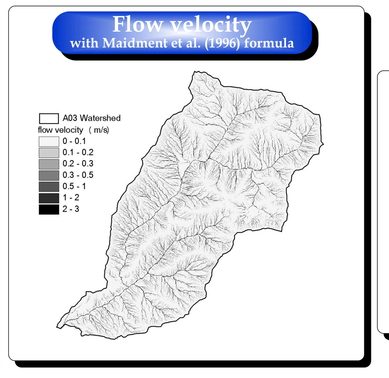
Basin	Lys
Outlet	Gressoney St. Jean
Code	B33
Cellsize (m)	20
Precision	integer
Area (Km^2)	92
PEM4PIT Parameters (β, D, θ)	0.01, 176, 0.5
Observed Lag Time (hours)	3.96

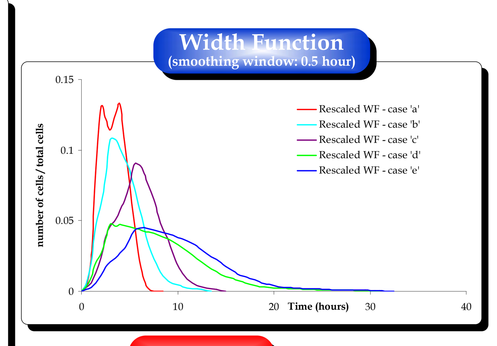
Summary

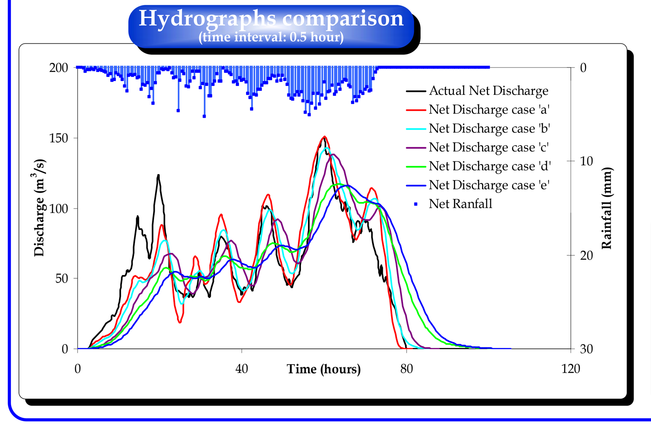
	WF max (hours)	WF peak time (hours)	WF centroid (hours)	Max Discharge (m^3/s)	Max Discharge Observed (m^3/s)
Case 'a': Maidment et al. Formula: Vmean: 0.11 m/s	14.16	3.33	3.96	36.14	37.01
Case 'b': channel velocity: 2 m/s, hillslope velocity: 0.05 m/s	17.58	2.66	3.75	35.72	
Case 'c': channel velocity: 1 m/s, hillslope velocity: 0.05 m/s	19.91	4.50	5.08	35.17	
Case 'd': channel velocity: 2 m/s, hillslope velocity: 0.02 m/s	40.58	4.00	7.16	31.29	
Case 'e': channel velocity: 1 m/s, hillslope velocity: 0.02 m/s	42.83	6.75	8.58	30.59	

CASE STUDY 4







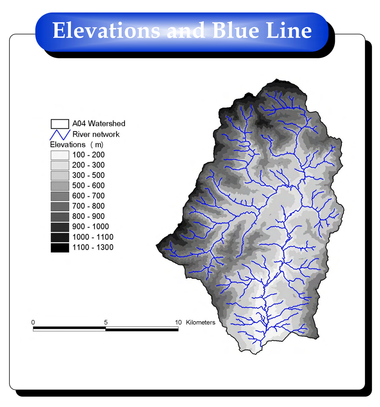


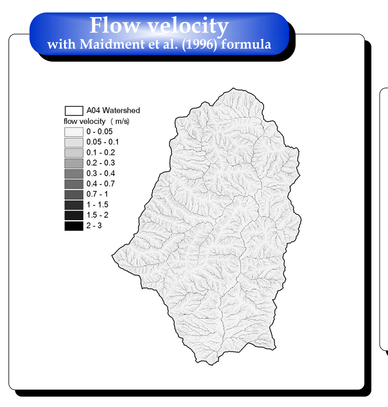
Basin	Isorno
Outlet	Pontetto
Code	A03
Cellsize (m)	20
Precision	integer
Area (Km^2)	71
PEM4PIT Parameters (β, D, θ)	0.01, 165, 0.5
Observed Lag Time (hours)	3.3

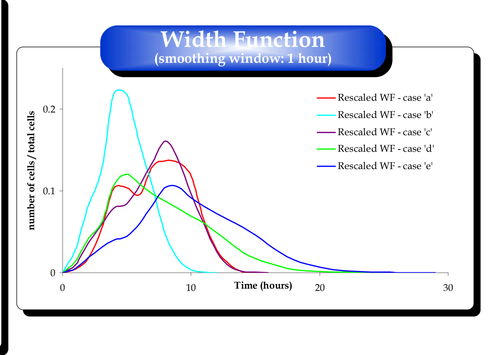
Summary

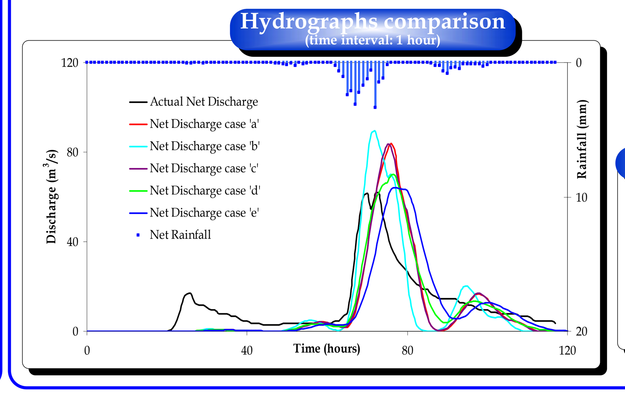
	WF max (hours)	WF peak time (hours)	WF centroid (hours)	Max Discharge (m^3/s)	Max Discharge Observed (m^3/s)
Case 'a': Maidment et al. Formula: Vmean: 0.14 m/s	8.33	3.58	3.30	150.80	149.29
Case 'b': channel velocity: 2 m/s, hillslope velocity: 0.05 m/s	13.25	3.00	3.83	142.64	
Case 'c': channel velocity: 1 m/s, hillslope velocity: 0.05 m/s	14.75	5.50	5.75	138.12	
Case 'd': channel velocity: 2 m/s, hillslope velocity: 0.02 m/s	31.00	3.67	7.00	117.24	
Case 'e': channel velocity: 1 m/s, hillslope velocity: 0.02 m/s	32.41	6.42	8.75	116.01	

CASE STUDY 5







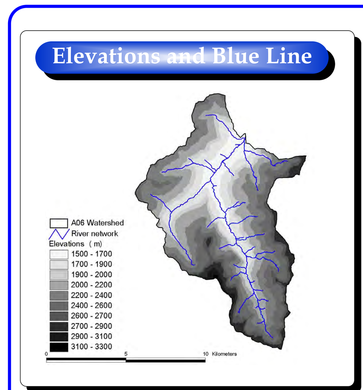


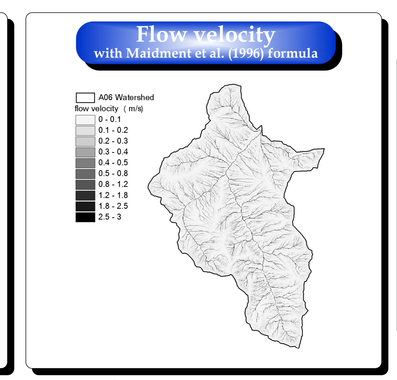
Basin	Bisenzio
Outlet	Gamberame
Code	A04
Cellsize (m)	20
Precision	integer
Area (Km^2)	150
PEM4PIT Parameters (β, D, θ)	0.01, 186, 0.5
Observed Lag Time (hours)	7.08

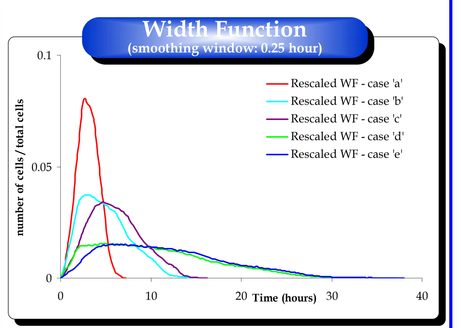
Summary

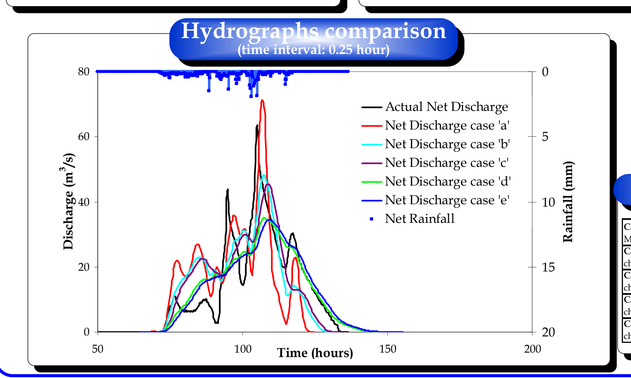
	WF max (hours)	WF peak time (hours)	WF centroid (hours)	Max Discharge (m^3/s)	Max Discharge Observed (m^3/s)
Case 'a': Maidment et al. Formula: Vmean: 0.07 m/s	15.83	6.83	7.08	83.92	61.66
Case 'b': channel velocity: 2 m/s, hillslope velocity: 0.05 m/s	11.91	3.91	4.25	89.16	
Case 'c': channel velocity: 1 m/s, hillslope velocity: 0.05 m/s	15.33	7.58	7.00	83.39	
Case 'd': channel velocity: 2 m/s, hillslope velocity: 0.02 m/s	24.66	3.91	6.50	69.89	
Case 'e': channel velocity: 1 m/s, hillslope velocity: 0.02 m/s	28.08	7.83	9.16	64.11	

CASE STUDY 6









Basin	Chisone
Outlet	Soucheres
Code	A06
Cellsize (m)	20
Precision	integer
Area (Km^2)	86
PEM4PIT Parameters (β, D, θ)	0.01, 182, 0.5
Observed Lag Time (hours)	3.12

Summary

	WF max (hours)	WF peak time (hours)	WF centroid (hours)	Max Discharge (m^3/s)	Max Discharge Observed (m^3/s)
Case 'a': Maidment et al. Formula: Vmean: 0.15 m/s	7.16	2.66	3.12	71.39	63.44
Case 'b': channel velocity: 2 m/s, hillslope velocity: 0.05 m/s	15.33	2.66	4.58	48.23	
Case 'c': channel velocity: 1 m/s, hillslope velocity: 0.05 m/s	16.16	4.66	5.75	45.46	
Case 'd': channel velocity: 2 m/s, hillslope velocity: 0.02 m/s	37.00	4.50	9.50	35.02	
Case 'e': channel velocity: 1 m/s, hillslope velocity: 0.02 m/s	37.91	5.75	10.66	34.39	

Conclusions

The issue of *the a priori* estimation of runoff velocities, solved by automatically calibrating the spatially distributed flow velocity field to reproduce the estimated lag time information, provided new insights for the implementation of the WFIUH scheme for the hydrologic prediction in ungauged river basins.

Results show a good agreement of simulated against observed hydrographs with particular regard to the shape, the peak and the timing (duration and time to peak) of the hydrologic response.

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