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On the impact of urbanization on flood hydrology of small ungauged basins: the case study of the Tiber river tributary network within the city of Rome

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Abstract

The small ungauged basins of the highly urbanized area of the city of Rome are often the subject of critical flood conditions for the significant human-made transformations. In this work the EBA4SUB framework, implementing the hydrogeomorphic width function instantaneous unit hydrograph rainfall run-off model, and using digital elevation model, land use and synthetic precipitation as main input information, is applied for evaluating extreme hydrologic forcing conditions at the basic scale. The goal is to understand the rationale behind the observed increasing frequency of local urban inundations that are also observed in the uplands. Results present the impact of urbanization expressed by both the run-off coefficient, the artificial drainage, impacted by paved surfaces and a dramatic number of river–road intersections (i.e. culverts), and the upstream to downstream non-natural scaling behaviour of hydrologic parameters and in particular the peak discharge per unit drainage area.

Introduction

The increasing frequency and unusual spatial distribution of local inundation events in the urban area of Rome, happening always more often in the uphill of the small tributaries of the Tiber river basin, is certainly related to the impact of urbanization. In the last decades, urban development processes in the area of Rome have completely transformed the majority of the flood plains (Nardi *et al*., 2013; Manfreda *et al*., 2014). It is easy to observe, using aerial photos or land use layers, the impact of river–road intersections along major channels in the downstream regions towards the confluence with the major Tiber and Aniene river systems (Figure 1). In the upstream domain, while it is not easy to identify the ephemeral channels, the human development is still evident with a significant presence of culverts, bridges and urban paved areas and artificial drainage features (Aronica and Lanza, 2005). While in the past, uphills have not produced significant fluvial hazard conditions, the increasing and continuing unregulated and poorly engineered development of urbanization outside the fluvial corridors is now posing a serious flood hazard management issue. This is particularly challenging for small ungauged basins for both the lack of flow observations that avoid the proper understanding and preventing of the hydrologic system behaviour and for the impossibility of adopting forecasting and alerting systems given the small spatial scale and fast dynamics characterizing the precipitation and run-off mechanisms.

For small ungauged basins, flood hazard mapping and urban planning represent the most effective risk management actions with specific regard to the preliminary identification of the most critical areas along the river network. Nevertheless, the analysis of inundation prone areas in this highly urbanized context cannot follow the same procedure of medium to large river basins where the scale of hydrologic and hydraulic features and processes governing the flood wave propagation along the valley are dominant as respect to the urban feature/process scale. For those uplands, flood events are usually strictly related to local urban conditions as in the case of the inefficiency of flow control and drainage structures (e.g. bridges, culverts) that are very often not able to convey intense precipitation driven flows.

The impact of urbanization on flood hydrology has been the subject of several and diverse research works. Hollis (1975) investigated the relation between impervious area development and recurrence interval of run-off extending the work by Leopold (1968) that originally demonstrated the

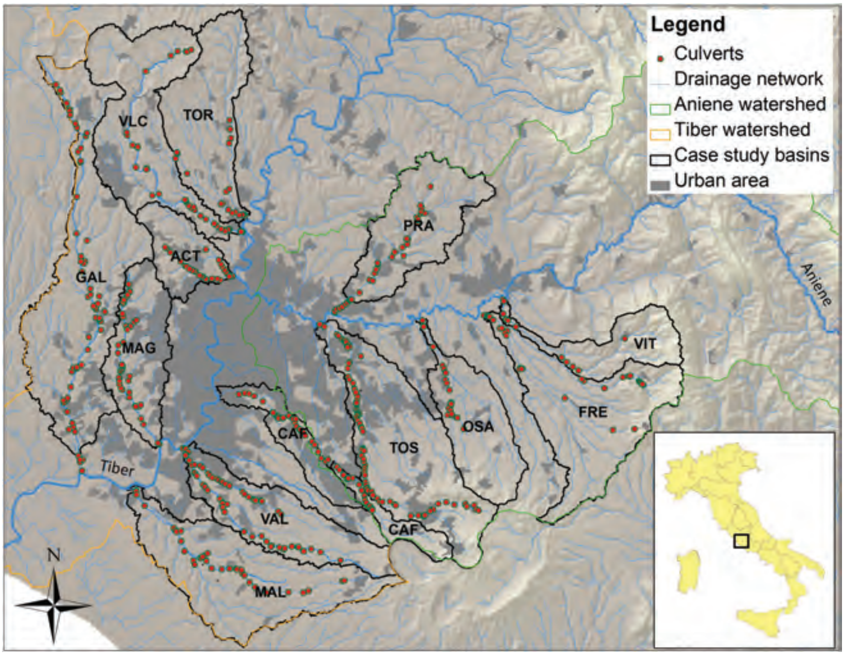

Figure 1 The case study of the 13 small ungauged tributary basins of the Tiber-Aniene system with the simulated river network and the culverts within the urbanized area of the city of Rome.

change of the main hydrologic parameters (flood flow peaks, volume and related statistics of extreme value occurrence) as a function of urbanization. Hundecha and Bárdossy (2004) analysed the catchment peak flows of subcatchments of the Rhine basin (Germany) as related to land use changes. Chang (2007) worked on the spatial and temporal scale of climatic and physiographic conditions impacting the hydrology of urban areas in the Pacific Northwest of the United States discussing scale-dependent modifications of stream flow regimes. Climate and hydrologic change dynamics have been also deeply investigated (e.g. Reynard *et al.*, 2001; Shuster *et al.*, 2005; Franczyk and Chang, 2009; Aronica *et al.*, 2012; Fiseha *et al.*, 2014) focusing on the increasing observed frequency and magnitude of flood events in urban areas (Persoons *et al.*, 2002; Diakakis, 2013; Radojevic *et al.*, 2013; Hall *et al.*, 2014). Land change science is recognized to be a pivotal theme for a better understanding of extreme events towards resilient urban planning (Turner *et al.*, 2007). Nevertheless, there is still a significant need of a simple yet accurate model for understanding, thus predicting, flood hazard in small ungauged basins for any node of the river network with specific regard to the uphills and the river–road intersections. The investigative framework of this research is based on the evaluation of the interdependent play among river basin geomorphologic, morphometric and hydrologic processes and features (e.g. Ivanov *et al.*, 2004; Martina and Entekhabi, 2006; Noto *et al.*, 2008) with specific regard to the application of the width function (WF) geomorphic approach (Marani *et al.*, 1994; Rodriguez-Iturbe *et al.*, 1994; Rodríguez-Iturbe and Rinaldo, 1997) also considering varying geomorphoclimatic (Graf, 1977; Rodriguez-Iturbe and Valdes, 1979; Rodriguez-Iturbe *et al.*, 1982; Naden, 1992; Di Lazzaro and Volpi, 2011; Volpi *et al.*, 2013) and urban settings (Veitzer and Gupta, 2001; Smith *et al.*, 2002; Ogden *et al.*, 2011) for providing flood risk managers and decision makers an accurate informative framework to develop safe river basin and urban area development and management plans (e.g. Cunha *et al.*, 2011; Faulkner *et al.*, 2012; Pedersen *et al.*, 2012; Ciervo *et al.*, 2014; Emanuelsson *et al.*, 2014).

In this work, the design flood hazard scenario for the Tiber tributary rivers is investigated by estimating synthetic peak flows as a function of the hydrologic and geomorphic parameters for different locations pertaining to basin outlets and sub-basins within the highly urbanized area of Rome city. Discharge values for predefined locations along the river network for different return periods are estimated using the WF instantaneous unit hydrograph (WFIUH) rainfall-runoff modeling approach (Grimaldi *et al.*, 2012a). The main input information are the synthetic design precipitation of the Italian VAPI model (GNDCI-CNR, 2000), digital topographic and land use spatial layers available at accurate resolution for the region. Results present the dramatic conditions of this vulnerable territorial setting where the average interdistance between two (usually inefficient) culverts or bridges is 0.3 km (to maximum 1 km) and where the exponential impact of paved surfaces proceeding downstream produce significant peak discharges.

The manuscript is organized as follows. First the available data and selected methods are described. Then, the selected case study of the 13 small ungauged basins of the Tiber river tributary network within the city limits of Rome are presented with specific regard to a description of recent inundation events. Flood hydrology and morphometric data are inserted in the results sections before the final discussion and conclusion sections.

Data and methods: the hydrogeomorphic rainfall run-off WFIUH model (EBA4SUB)

Flood peak discharge are estimated by, first, identifying the simulated river network implementing standard terrain analysis hydrologic routines (Jenson and Domingue, 1988) using digital elevation model (DEM) and a predefined area threshold for identifying the stream network source nodes (Tarboton *et al.*, 1991; Nardi *et al.*, 2008). For each predefined return time, the design rainfall hyetograph is derived with the VAPI regionalization model for calculating the precipitation intensity (GNDCI-CNR, 2000). Rainfall event duration is defined as the river basin time of concentration. Then, for predefined nodes along the river network, the DEM-based WFIUH model is applied for transforming the rectangular synthetic rainfall hyetograph into a flood hydrograph. The applied model corresponds to the EBA4SUB procedure (Grimaldi *et al.*, 2010, 2012b,c, 2013a,b,c; Grimaldi and Petroselli, 2014) with minor variations corresponding to a different net rainfall and time of concentration calculation algorithms. Hydrologic losses are evaluated using the standard SCS-CN model associating curve number (CN) to classified land use information. The time of concentration is calculated using a physically based estimation of the time needed by the surface flow to route along the longest flow path. Channel and hill slope flow velocities are estimated as a function of local slope and land use properties. CN values are analogously calibrated if rainfall and flow series are available or derived from literature values. The run-off coefficient is estimated as the ratio between the volume of the flood hydrograph (i.e. volume of the SCS-CN net rainfall) and the input gross rainfall.

The implemented procedure, depicted in the flow diagram of Figure 2, is optimized for small ungauged basins making a parsimonious use of largely available digital data, in particular the DEM and the land use. Specifically, digital terrain and land use information are gathered from the 1:5000 scale Regional Technical Numerical geodatabase (CTRN) of the Lazio Region, including 5 m floating point precision DEM and digital terrain model, providing respectively the raster data of the topography and land use. In addition, the CTRN geodatabase includes the vector layers of the digitized urban and natural features (e.g. buildings, rivers, etc.) and infrastructures (e.g. railways, roads, highways, etc.). Aerial ortophotos and technical maps are also available for the entire region. River–road intersections for identifying flow obstructions (culverts) are mapped by image interpretation and validated with on-site field surveying activities.

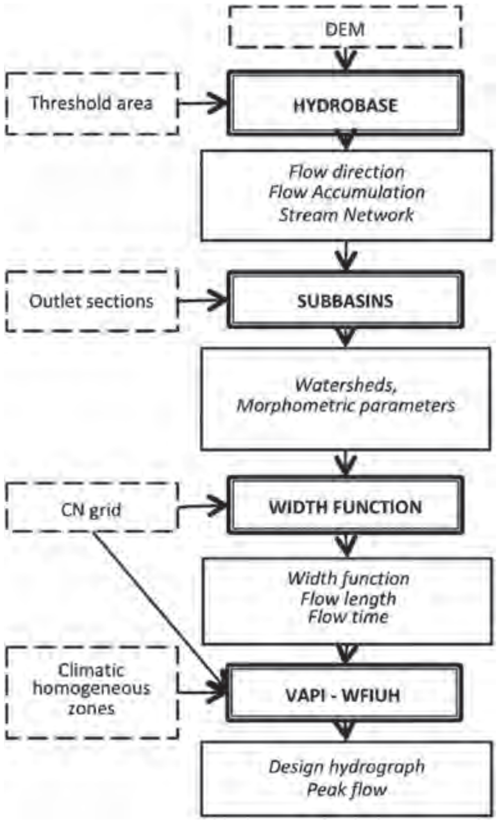

Figure 2 Flow diagram of the flood peak discharge estimation procedure implementing the parsimonious synthetic rainfall-run-off width function instantaneous unit hydrograph (WFIUH) model optimized for the hydrogeomorphic characterization of small ungauged basins using standard digital elevation model (DEM)-based terrain analysis algorithms for stream network identification (HYDROBASE) (boxes legend: dashed, bold and regular boxes indicate respectively input, model and output features of the model).

Case study: the city of Rome minor river network

The case study is characterized by 13 small basins tributaries of the Tiber-Aniene river system within the city of Rome administrative limits: the Vittorino, Freghizia, Osa, Tor Sapienza and Pratolungo (tributaries of the Aniene river); the Caffarella Vallerano, Malafede, Torraccia, Valchetta, Acqua Traversa, Magliana and Galeria (tributaries of the Tiber river). Basin sizes vary from approximately 25 to 153 km^2 and elevations range approximately from 1 to

Table 1 Morphometric properties and design rainfall for 200 years return time of the selected basins

Basin	Code	Area [km^2]	Main channel length [km]	Elevation [m a.s.l.]			ΔH [m]	Total rainfall height (200 years) [mm]	Rainfall intensity (200 years) [mm/h]
				Min	Max	Mean			
AcquaTraversa	ACT	31.3	9.9	19.0	168.6	88.04	149.6	196.8	37.9
Caffarella	CAF	23.3	15.2	13.7	172.8	69.8	159.0	184.8	28.6
Freghizia	FRE	85.4	23.7	38.4	790.7	296.9	752.2	141.3	17.9
Galeria	GAL	152.4	38.6	6.4	336.6	96.0	330.1	241.0	22.9
Magliana	MAG	54.2	16.2	9.0	147.2	67.7	138.1	202.9	31.7
Malafede	MAL	104.3	24.9	6.6	275.6	85.0	268.9	222.1	26.9
Osa	OSA	73.9	24.7	27.8	771.4	233.9	743.5	163.2	21.0
Pratolungo	PRA	67.4	16.9	20.7	406.2	98.2	385.6	190.1	31.4
San Vittorino	SAV	77.7	19.4	17.5	385.8	157.5	368.6	167.1	22.8
Torraccia	TOR	116.1	31.1	19.3	955.6	237.7	936.4	186.8	20.0
Tor Sapienza	TOS	58.1	19.8	42.1	1217.2	542.4	1175.0	184.0	28.3
Valchetta	VLC	99.6	26.4	23.8	436.3	184.3	412.5	187.7	24.4
Vallerano	VAL	84.1	26.5	10.0	947.2	151.8	937.2	212.9	20.5

1200 m a.s.l. The full summary of morphometric properties is inserted in Table 1 that also includes the design cumulated synthetic rainfall for the 200 years return time, the rainfall intensity and the main channel length, while in Figure 1 the map of the watershed boundaries, river network and culverts is represented.

The selected basins lack of flow observations, except for the Galeria River, where a flow gauge is installed in the proximity of the confluence with the Tiber River. A limited number of observed flood events (five in total) are available for the Galeria basin. A calibration procedure of the WFIUH model for the Galeria River (not represented here for brevity) is implemented for estimating channel and hill slope surface flow velocities and the CN values. Calibration parameters are, then, used for the other 12 basins. The validation of this procedure is not fully achieved for the limited observed data, but simulations demonstrate to represent accurately the hydrologic response to intense rainfall for observed events with specific regard to the estimation of the time of concentration, the run-off coefficient, and the main geometric properties of the flood hydrograph (i.e. volume, base time and peak).

The city of Rome urban area has been the subject of frequent floods in the last few years with most of the inundation cases observed in the uphills with very low contributing areas (even less than 10 km^2). Causes are very difficult to understand (Molinari *et al.*, 2014), given the lack of spatially distributed measurements of rainfall, soil moisture and flow quantities that avoid a direct and accurate interpretation of the inundation process. However, the geopositioning of the inundated areas provide an important clue of the phenomenon especially if interpreted in conjunction with the hydrogeomorphic framework of the implemented WFIUH rainfall run-off model that provides hydrologic spatial layers of the flow routing processes in relation with the culvert/bridge critical node position. Three events are selected: the January 2014 event for the Magliana and Galeria basins, and the September 2014 event for the Caffarella basin. In the Magliana basin, Boccea street was inundated just upstream of a culvert draining a small secondary tributary (0.24 km^2 drainage area) draining towards the main Magliana tributary (at a location draining approximately 10 km^2 of the entire basin). A total cumulated rainfall of 186.2 mm during the 15 h event with a precipitation intensity of approximately 12 mm/h was recorded. In the Galeria basin for the same event, the collapse of the culvert of an artificial minor tributary (0.9 km^2) draining towards the Galeria River (at a location draining approximately 108 km^2 of the entire basin) was reported with significant damages and traffic interruption for Malagrotta street. The Caffarella River, for a different event in September 2014, caused the inundation of the Appia Antica street. The main causes of the Appia inundation were a critical outlet, positioned at a location draining approximately 25 km^2, and the very intense rainfall (15 mm in less than an hour for a 20 mm/h precipitation intensity) that impacted a highly urbanized area. The three selected events are described in Figure 3 that shows the simulated stream network, the culvert positioning as well as the flow path and time spatial layers produced by the hydrogeomorphic model for characterizing the surface hydrologic dynamics of the domain of interest. A summary of the main hydrologic information of the selected inundation events is inserted in Table 2.

Flood hydrology: results

Results of simulated peak flows for 200 years recurrence interval are summarized in Table 3, that also includes the time of concentration, the spatially averaged CN, the run-off coefficient and the net cumulated rainfall. Peak flow absolute values vary significantly for the selected outlet locations of

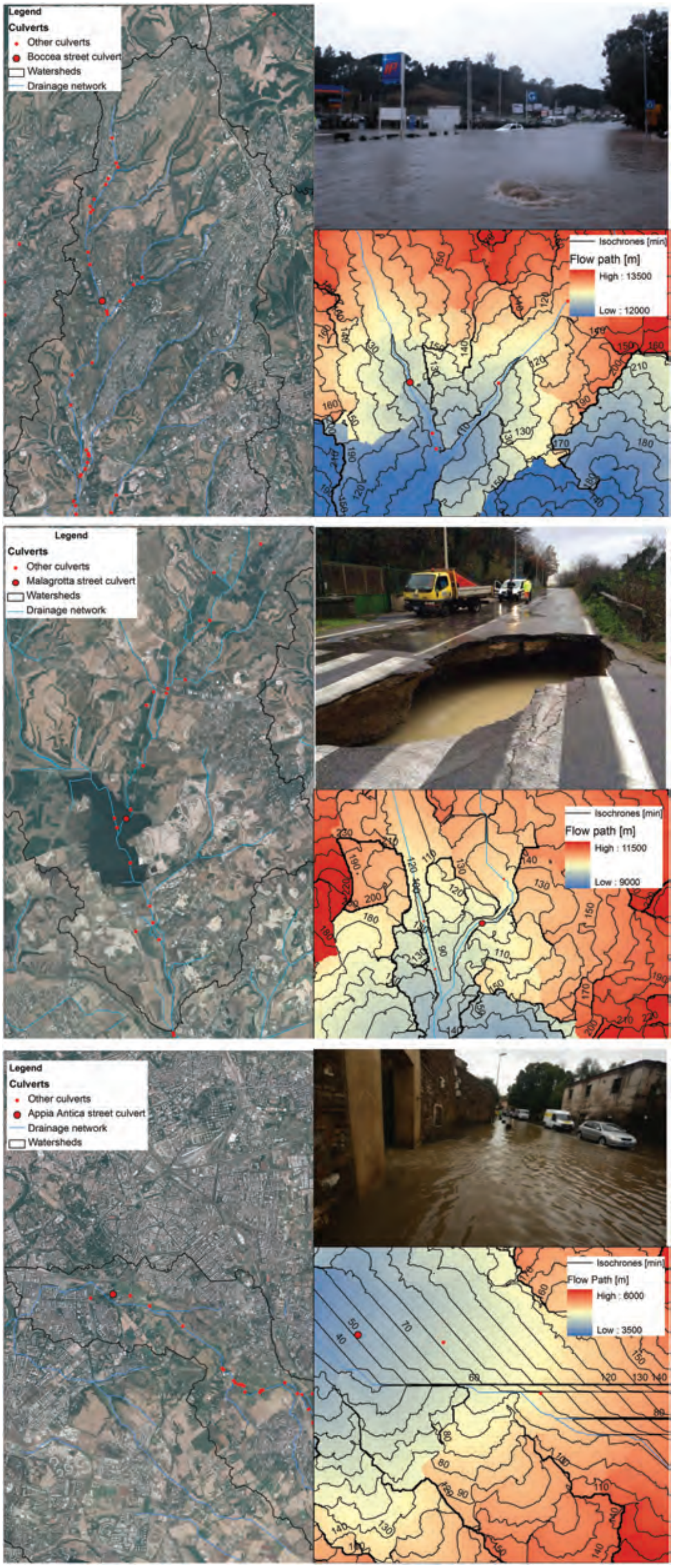

Figure 3 2014 flood events on the Magliana (upper plot), Galeria (middle plot) and Caffarella (lower plot) basins.

Table 2 Summary of hydrologic forcing of the 2014 events for the Galeria, Caffarella and Magliana basins and contributing areas at both the critical culverts and at the main tributary channel

Basin	Culvert	Cumulated rainfall [mm]	Rainfall duration [h]	Rainfall intensity [mmsdsddsds/h]	Contributing area culvert [km^2]	Contributing area [km^2]
GAL	Malagrotta Street	180.2	15.0	12.0	0.9	108.0
CAF	Appia Antica street	15.0	0.7	20.0	25.4	25.4
MAG	Boccea street	186.2	15.0	12.4	0.2	9.6

GAL, Galeria; CAF, Caffarella; MAG, Magliana.

Table 3 Summary of results of the hydrologic model application for estimating peak flows also including the time of concentration, the spatially averaged curve number, the run-off coefficient and the net cumulated rainfall

Code	Time of concentration [h]	Mean CN	Urbanized area [%]	Difference of percentage of urbanized area between downstream and upstream nodes	Run-off coefficient (200 years)	Net Rainfall height (200 years) [mm]	Peak flows [m^3/s]	Peak flows [m/s/km^2]
ACT	5.2	53.8	32.3	6.5	0.33	64.6	150.5	4.8
CAF	6.5	57.3	39.4	9.7	0.36	65.93	96.5	4.1
FRE	7.1	45.7	6.4	–3.4	0.14	19.9	87.8	1.0
GAL	10.4	52.8	19.2	18.2	0.38	90.8	519.4	3.4
MAG	6.4	58.9	41.0	5.3	0.41	82.8	265.2	4.9
MAL	8.2	49.2	10.5	–16.6	0.30	67.5	368.2	3.5
OSA	7.8	45.5	11.1	0.4	0.19	30.3	127.3	1.7
PRA	6.0	48.1	10.6	10.6	0.24	45.7	209.9	3.1
SAV	7.3	49.7	7.9	5.3	0.23	38.7	185.0	2.3
TOR	9.3	52.2	31.4	14.3	0.30	56.2	283.0	2.4
TOS	6.5	46.2	12.2	–9.9	0.21	39.4	149.9	2.5
VLC	7.7	50.3	12.2	12.2	0.28	52.1	271.7	2.7
VAL	10.4	54.7	29.2	21.1	0.37	78.6	269.4	3.2

CN, curve number; CAF, Caffarella; FRE, Freghizia; GAL, Galeria; MAG, Magliana; MAL, Malafede; OSA, Osa; PRA, Pratolungo; SAV, San Vittorino; TOR, Torracia; TOS, Tor Sapienza; VLC, Valchetta; VAL, Vallerano.

the 13 basins from approximately 80 m^3/s to more than 450 m^3/s, while related unit peak flow (i.e. maximum discharge divided by the related drainage area), vary from a minimum of approximately 1 m^3/s/km^2 to almost 6 m^3/s/km^2. The scaling of the geomorphic and hydrologic modeling results is represented for the four selected basins, the Galeria, Magliana, Caffarella and Tor Sapienza in Figure 4. For each basin, three subplots are represented: the unit discharge q_s (m^3/s/km^2) and the urbanized area (%) (top), the averaged CN and the culvert density (number of culverts per km) (middle), and the rainfall intensity i (mm/h) and the mean basin slope, all plotted from upstream to downstream as a function of the normalized contributing area (node drainage area by total catchment area). The curves are derived from the linear interpolation of selected internal outlet nodes for each basin. In particular, eight internal nodes for the Galeria and Tor Sapienza, five for the Magliana, four for the Caffarella are selected, and related modeling parameters and output variables are calculated. A graphic summary of hydrologic modelling results for the 54 nodes is inserted in Figures 5 and 6 with the q_s plotted respectively as a function of the urbanization (% urban area) and the normalized drainage area.

Results describe the impact of the intense urbanization on the flood hydrology of the tributary basins providing interesting insights for understanding the hydrogeomorphic conditions that characterized the recent flood events that have been observed in the low contributing areas along the minor channels at critical river–road intersections (Figure 3). The run-off production in the uphill is significant with high slopes and rainfall intensity that corresponds to high discharges due to the presence of dense urbanization (impermeable surfaces increasing the water volumes and paved roads with artificial drainage channels increasing the run-off propagation celerity also concentrating the flow sharpening hydrograph peaks). The morphometric and hydrologic analysis represented in Figure 4 motivates the important effect of culverts that are the main cause of the recent inundation and road collapse events. The analysis, at the basin scale, proceeding towards the confluence with the main rivers (Figures 4–6) shows the increase of the hydrologic forcing for the effect of the run-off coefficient that, on the low portion of the basins in the flat downstream areas, is correlated to the presence of fully developed floodplains and hill slopes as investigated by means of the evaluation of the unit peak discharge parameters.

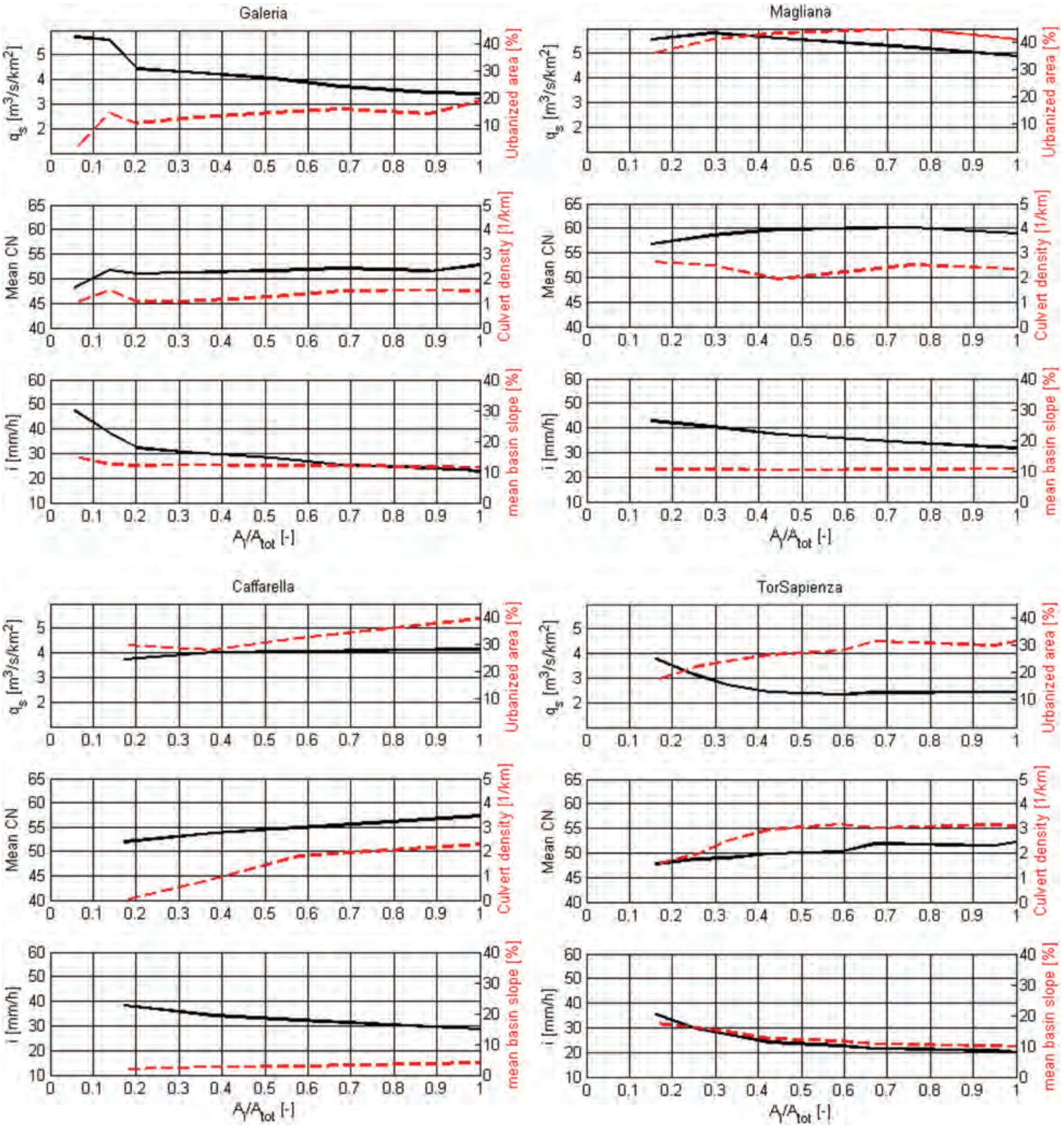

Figure 4 The morphometric, climatic and hydrologic modeling results of the Galeria, Magliana, Caffarella and Tor Sapienza basin as respect the urbanization parameters represented by the averaged curve number (CN) values, the per cent of urbanized area, and the culvert density. Black line and red dashed lines are linked respectively to left and right vertical axis.

Discussion and conclusions

This work investigates on the use of a DEM-based parsimonious hydrogeomorphic model in small ungauged basins and more specifically on the application of the WFIUH for the estimation of flood hydrologic variables for each node of the river network from uphills to the confluence with major river systems. The spatial distribution of peak discharges as a function of climatic, land and morphometric conditions is characterized providing an accurate information framework for a preliminary identification and understanding of inundation prone areas.

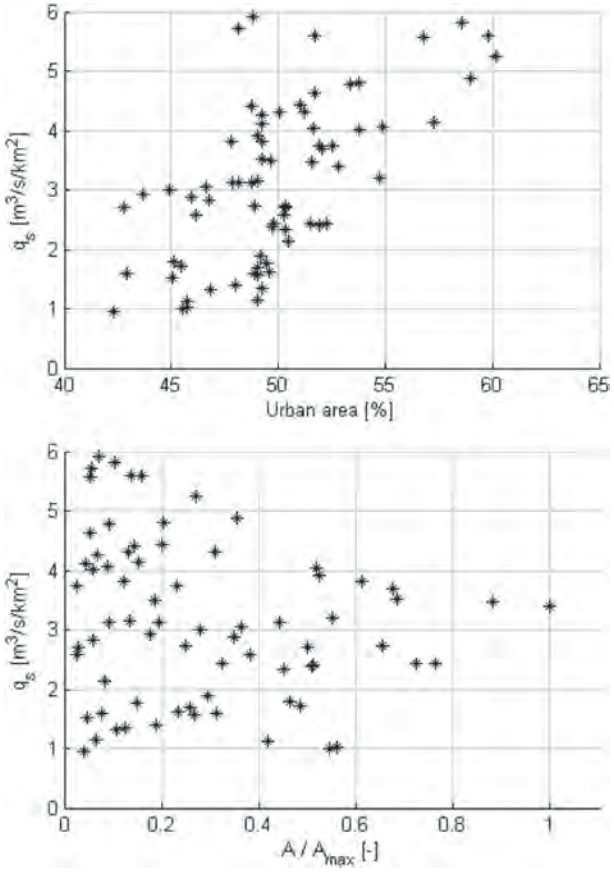

Figure 5 Unit discharge q_s as respect the urban area (%) and the normalized contributing area for the 54 nodes of the outlets of the 13 basins and for the further 41 internal nodes distributed on the entire case study domain.

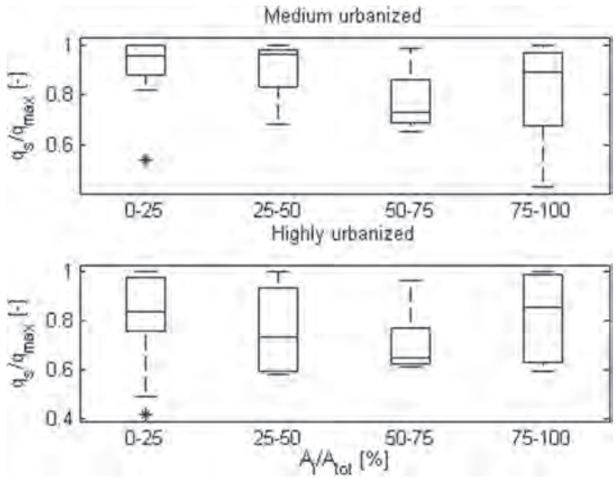

Figure 6 Box plots of the normalized unit discharge for the 13 basins across the spatial scale (contributing area) categorized using the difference of percentage of urbanization from upstream to downstream (less than 10% and between 10% and 30%, respectively, in the upper and lower subplots).

The case study of the highly urbanized area of the city of Rome is selected considering 13 tributaries of the Tiber and Aniene basins. Recent floods are considered highlighting the impact of the dramatic frequency of river–road intersections, often equipped with inefficient culverts, that significantly condition the safe and efficient routing of the run-off downstream. The implemented modeling framework, once identified the critical culvert nodes, is able to evaluate for each location, by means of the WF approach, the flow intensity and dynamics that is not only the potential magnitude (peak) but also the travel distance and time with a physically based interpretation of the river basin morphology in hydrologic terms. In this way, a spatially distributed flood hazard informative framework is developed at the entire basin scale from the hill slopes to the valleys taking advantage of largely available digital data. The presented approach seems to be the most accurate and efficient way to preliminary understand the actual potential flood hazard of the minor river basins that are often lacking of detailed flood modeling studies for economic and technical restraints.

Moreover, the proposed GIS-based hydrogeomorphic framework, considering the varying spatially distributed information of precipitation and land use, is able to mimic the impact of the climatic and hydrologic change. Results show the impact of urban transformation in both the downstream and upstream areas of the tributaries that, while significantly developing the floodplain with paved surfaces and artificial drainage features, produce an increasing of the hydrologic forcing. In particular, unit peak discharges are calculated that do not decrease downstream, as naturally expected (Figures 5 and 6). In addition, the usefulness of the presented framework shall be also considered while evaluating its potential not only for preliminary identifying the most critical culvert nodes that are often the main cause of local urban inundation phenomena but also the capability of estimating the design peak flow for efficient engineering design of new artificial drainage systems for safe urban development.

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