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Hydromorphic Impact of Matera's Urban Area

Ruggero Ermini [1,*], Carmen Fattore [2] and Amir Aubed Zoubi [3]

1 Department of European and Mediterranean Cultures, Università degli Studi della Basilicata, DICEM, 75100 Matera, Italy
2 DICEM (Dipartimento delle Culture Europee e del Mediterraneo), Università degli Studi della Basilicata, SI, 85100 Potenza, Italy; carmen.fattore@unibas.it
3 Industrial Ecology, Faculty of Technology, Policy and Management, Delft University of Technology, 2628 CD Delft, The Netherlands; zoubiamir1@gmail.com
* Correspondence: ruggero.ermini@unibas.it; Tel.: +39-3285760976

Abstract: Urban transformations change land use, permeability, and morphology of the areas involved in the evolution process; this, consequently, modifies the impact produced by the precipitation phenomena and increases the risk of flooding or uncontrolled runoff in different areas.The proposed watershed hydrologic approach enables us to consider the morphology of the territory together with the transformations implemented by human activities, and this allows us to evaluate the effects of each area on neighboring areas, emphasizes the hydrological roles of upper, intermediate, and lower parts, and reveals urban and non-urban connections. This elucidates hydromorphic complexities in urban transformations and assesses climate change adaptability. The suggested methodology has been implemented in the urban district of "Sasso Caveoso" within the city of Matera. This application facilitates a quantitative synthesis of the contextual response, allowing for an analysis across various scenarios and offering decision-support tools of practical utility.

Keywords: urban planning; hydromorphic analysis; urban flood resiliency

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1. Introduction

The term 'hydromorphic' aims to evoke the natural process that is compromised by urbanization, thus emphasizing the need to assess the impact of landform transformations even in urban areas. This term is a combination of 'hydro' and 'morphology' to make the reader understand that through the water flow patterns we can understand the morphology. In fact, urban development induces increases in impervious surfaces and related sewer infrastructure, altering the hydrological dynamics (peak, pathways and time of concentration) and enhancing flooding risks [1,2] at different scales [3–5].

Altered urban evolution (inadequate urban planning, infrastructure limitations, population growth, and resource mismanagement) does not take into account the natural water cycle and can obstruct the infiltration processes, resulting in increased runoff or urban flooding [6,7]. This combination of natural phenomena results from global climate change evolution, which produces increases in the intensity and frequency of maximum rainfall [8–13] and the expansion of urban areas, affecting land uses (enlarge impervious surfaces) and reducing runoff lag times [14–17]; moreover, it has a significant downstream impact on the vulnerability and exposure of urbanized areas, which are increasingly subjected to flooding phenomena [18–23]. In urban areas provided with modern drainage infrastructures, stormwaters are carefully considered [3,24,25] because of their potential impacts on citizens' lives and human activities, and the efficiencies of the drainage networks are also analyzed.

Investigating urban storm management allows us to analyze the impact of climate change on runoff characteristics, the consequences of urban flooding risk and water quality deterioration, and the related possible mitigation and adaptation strategies.

Even if drainage systems are essential for intercepting and collecting runoff outside the urbanized region, they cannot guarantee the total safety of the areas served. Sewerage infrastructure, when present and well-sized, can intercept and divert surface runoff but is not capable of providing widespread protection to the entire territory. They act locally only in very limited areas and are subject to malfunctions, especially during intense events (obstructions, saturation, ruptures, etc.). The only interventions that can significantly impact urban runoff are those that act broadly across the territory through the adoption of planning policies that balance the alterations of morphology induced by urbanization with the need to increase urban surface permeability, providing suitable drainage infrastructure. Often, recently transformed areas, even if equipped with modern drainage networks, face issues that cannot be resolved due to their plan-altimetric conformation. This can only be avoided through planning interventions that recognize the structure of the present catchments to understand their role and improve their balance. Only proactive and preventive interventions that adopt widespread solutions that act on the causes of outflows can have a positive impact on overall sustainability. Sustainable Urban Drainage (SUD) policies must be implemented at various stages [26,27] and at a range of spatial scales considering together the complex interactions between air–water–soil–vegetation and urban needs. Despite the widely recognized benefits of Sustainable Urban Drainage (SUD) systems and numerous experimental and numerical investigations conducted, their implementation in urban planning remains limited. This is likely due to strong influences from economic constraints and varying local regulations. To enhance the effectiveness of SUD planning, innovative approaches are needed, providing useful tools to support decision-making processes. Sustainable management [28,29] practices and water-sensitive urban design strategies must be employed to mitigate the impacts of pluvial events in urban areas and foster the development of new urban, biodiverse ecosystems. Numerous studies have delved into various aspects, developing synthetic approaches and comprehensive models. These investigations have focused on identifying risk areas [30], influencing factors [31,32], flood susceptibility prediction [33–36], risk assessment [37,38], and preventive management [39,40]. In most cities, the urban centre, typically corresponding to the historic nucleus [41], is characterized by dense buildings with limited roads and accessibility. This urban core is adjacent to areas of subsequent expansion, where the original natural context has been transformed to establish new settlements, infrastructures, and services.

These transformations often occur in phases that follow one another over time, integrating different moments of planning that alter the morphology of the places and reduce the permeability of the surfaces, without paying particular attention to the interactions resulting from the changed territorial equilibrium between the urbanizations of different eras. Furthermore, in the city of Matera the historical centre represents the most delicate and precious component, but it is also exposed to direct and indirect actions which increase its vulnerability and exposure to the risks induced by climate change.

Urban flooding strongly depends [42,43] on the morphology of the places, their physical characteristics, and the transformations that have been implemented (land uses, infrastructures) [44], as well as on the variability of climatic conditions. Themes related to water are now widely present in the assessments conducted by many international organizations which, working at different scales, have adopted methodologies for calculating synthetic environmental indicators that consider the water resource in all its forms (risk, safeguard, employment) [45–50].To describe the behaviour of urbanized areas, the term Urban Metabolism is often used, coined by Abel Wolman [51] in the mid-sixties in an analogy between the functioning of a territory and that of a living organism—to live, it needs to feed on raw materials, process them through metabolic processes, and subsequently eliminate their waste. The theory of Urban Metabolism returned to the scientific debate in recent decades thanks to the renewed interest of public opinion in environmental issues and has therefore evolved over the years expanding the use of environmental and social indicators, to also include all those infrastructures serving the city that lie beyond its perimeter.

The present paper, inspired by the theory of Urban Metabolism [52], proposes a methodology that analyzes urban contexts through the description by watershed, permitting an understanding of the relationships between the morphology of the territories, their characteristics, and the transformations that have been implemented, together with the effects determined in terms of hydrological response and surface runoff. The watershed and sub-watershed partition identifies independent areas where the rainfall-runoff processes develop, overcoming the urban districts limits and emphasizing the natural interaction between the morphological parts of the catchment (upper, medium, lower) which contribute together to the natural hydromorphic [53] dynamic. We must consider urban areas as part of a watershed to know where the runoff comes from, how it flows and where it goes. Urban planning has to transition from a project-scale approach to a climate adaptive strategy that considers the catchment scale also in urban areas. The methodology employed in the case study of Matera, Italy, with its intricate and complex morphology, allows for the assessment of responses in various scenarios for each area within the urban context, despite its limited geographical extent.

In this sense, the case study considered in this work is particularly representative and describes the evolution of a part of the city of Matera which includes the historical nucleus of Sasso Caveoso and extends up to the top of the natural hill behind it. In this area, profound urban developments have occurred which have led to significant changes in the morphology and physical characteristics of the places which today appear almost entirely urbanized. The sustainability of the transformations carried out can be assessed by describing how the different scenarios react to the natural climatic phenomena. In particular, considering the effects induced by rainfall and the resulting surface runoff on urban efficiency.

The proposed approach does not aim to replace modern design techniques for drainage networks, which should use sophisticated and comprehensive hydrological–hydraulic calculation models capable of integrating every aspect and simulating the presence of different types of structures (interception, diversion, storage, collection, discharge). Instead, it seeks to emphasize that territorial and urban planning processes must take into account the morphological arrangement described by the watersheds. Urban planners could adopt the proposed methodology, which leverages an agile tool (RM-formula) to synthetically assess the hydrological response from various planned or already developed transformation activities. The peak flow evaluated at a specific section of the watershed is a synthetic indicator correlated with the morphology of the catchment itself and is sensitive to any alterations made.

2. Materials and Methods

In natural territories, runoff results from rainfall events (climate conditions) and strictly depends on basin morphology (shape, extension, slope, etc.), the permeability of the soil and the characteristics of the hydrologic pathways that convey the flows towards the basin outlet. Likewise, in urban areas, runoff flows rely on the morphology of the urban spaces (buildings, streets, squares, green areas, etc.) and on the layers' permeability (pervious, impervious, green, land uses). Therefore, by examining the urban runoff, it is possible to understand how efficient the urban layouts are and where storm flows or flooded zones could occur worsening the local risk conditions.

The hydromorphic complexities related to the transformation processes that involve urban and territorial areas should be analyzed at different moments of the urban evolution, in order to understand the effects of changes introduced over time or relating to future planning hypotheses. The urban context could be analyzed by describing the watershed composition of the whole area [1], where the original natural landscapes are substituted with the patterns generated by urban development, altering the calculations for surface runoff in various conditions and enabling the measurement of the impacts of any alterations. The physical transformations of a natural watershed made by the urbanization processes could modify the shape or the permeability (areal changes), revise the flow pathways inside the catchment (linear changes), or locally intercept or divert runoff flows (punctual changes) producing more or less significant effects on the dynamics of runoff flow development according to the extents and the positions of the modifications realized.

The peak flow that characterizes a specific scenario (urban layout, rainfall condition) summarizes in a single parameter the hydrological response of the catchment to the considered precipitation events and can be considered a valid indicator of the urban hydromorphic efficiency related to the analyzed scenario as it is sensitive to any changes affecting the upstream catchment area [53].

2.1. Methodology

The general principles of the hydromorphic analysis propose a hierarchical approach (Figure 1) based on different steps, as follows:

1. Morphological analysis of the urban area and urban watershed assessment, both conducted by considering the Digital Terrain Model (DTM) of a zone large enough to include all the peculiarities of the area of interest, characterized by a resolution capable of describing the urban morphology; hereafter, the official DTM (resolution 5 m × 5 m) provided by Regione Basilicata is used. While a higher-resolution DTM could potentially enhance the precision of the physical analysis presented below, it would not substantially alter the overall hydrological response of the catchment.
2. Physical analysis of all the watersheds and evaluation by GIS software (Q-GIS 3.4.13) of the descriptive parameters (area, perimeter, length, elevation, slope, land uses) also by considering the pan-European land cover and land use inventory CORINE Land Cover maps.
3. Hydrological analysis of the maximum rainfall data to evaluate the Depth–Duration–Frequency (DDF)curve and the Intensity–Duration–Frequency (IDF)curve that predict the rainfall events for different frequencies (return period), and for a given location.
4. Hydrological evaluation of the expected runoff at the outlet point of each catchment.

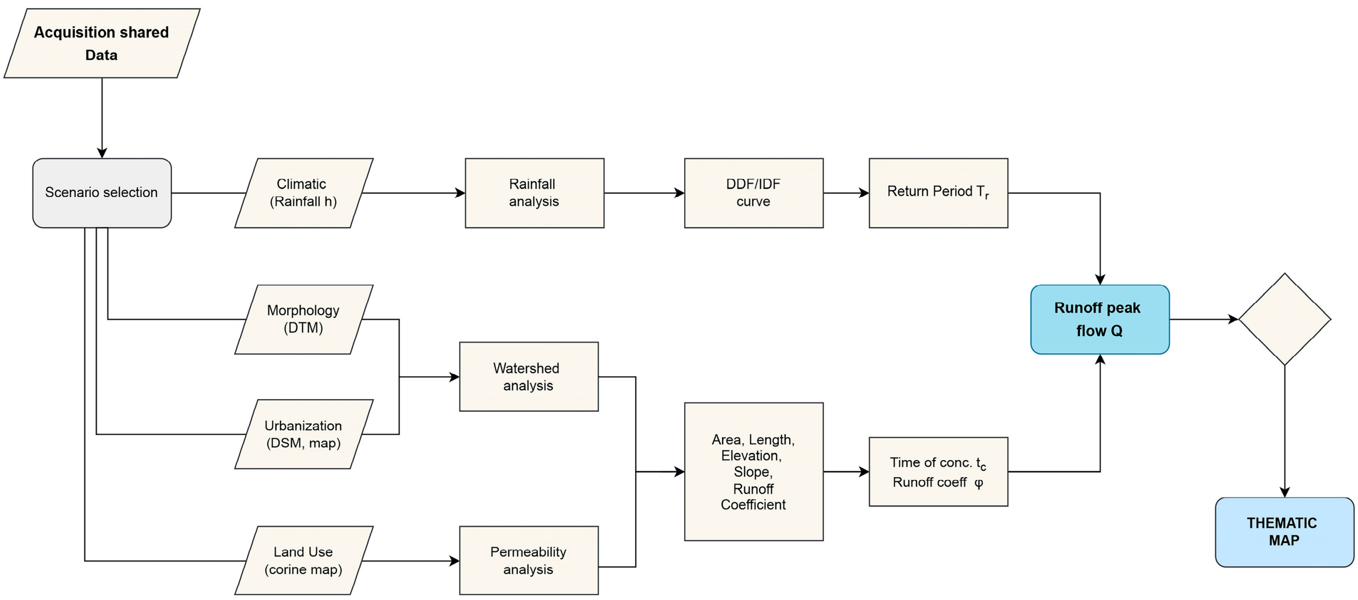


Figure 1. Flowchart of hydromorphic analysis.

Various scenarios, whether physical or climatic, are applied to assess system reactions, reflecting the morphological adaptability of the urban area to address specific situations (Figure 1).

The urbanized area of Matera was already investigated [53], extending up to the most peripheral portions, to evaluate a homogeneous index (Hydraulic Invariance) to facilitate a comparative analysis of various geographical sections and create vulnerability maps of the entire city. Extending the same methodology, in the present work we prove the ability of the proposed method to also reveal the effects of local transformations that affect limited parts of a single area, allowing us to confirm the advantages of this approach. In particular, the identification of the natural interactions between different areas or districts, the evaluation of the effects of the urban transformations acted by the urban evolution and the measurement of the corresponding impacts in terms of peak surface runoff. The approach can support urban planning activities in defining the contribution that each area can make to pursue the sustainability required by the 2030 agenda (Sustainable Development Goals, Goal 11: Smart Cities and Communities, Goal 13: Climate Action). The proposed hydromorphic methodology was applied to the Sasso Caveoso district, an area of high historical and tourist value where recurring critical conditions affected the inhabitants and any activity present in the area by flooding and surface runoff phenomena.

2.1.1. Morphological Analysis

The morphological analysis is conducted by processing the DTM of the area to be examined usingthe Geographic Resources Analysis Support System (GRASS) tools (hydrologic analysis modules r.watershed and r.water.outlet) [54], which allows the recognition of all the catchments and the respective hydrographic networks, evaluating also the physical characteristic parameters (area, perimeter, average slope, slope of the main path, minimum and maximum elevation, etc.) necessary to develop the rainfall-runoff analysis. The process is performed by the open-source software GRASS 7.2.0 and Q-GIS 3.4.13 [55].

The permeability parameters of each catchment can be evaluated according to the land use maps, associating to any homogeneous area the proper runoff coefficient φ_i usually considered (Table 1) in hydrological studies [56].

Table 1. Runoff coefficients φ for different types of drainage area.

Area Type	φ_i
Concrete or Asphalt pavement	0.8–0.9
Commercial and Industrial	0.7–0.9
Gravel Roadways and Shoulders	0.5–0.7
Residential—Urban	0.6–0.8
Residential—Suburban	0.4–0.6
Undeveloped	0.1–0.3
Berms	0.1–0.3
Agricultural	0.1–0.4

The global runoff coefficient φ (Equation (1)) of the single catchment can therefore be obtained by operating an area-weighted average of the φ_i related to the different homogeneous elementary areas (A_i):

$$\varphi = \Sigma(\varphi_i \times A_i)/A_{tot} \quad (1)$$

where:

- φ_i are the runoff coefficient of each homogeneous area;
- A_i are the homogeneous areas;
- A_{tot} is the global area of the watershed.

The critical conditions of a specific area, related to flooded conditions due to pluvial events, can be expressed through the peak flow evaluated at the closure section of the watershed that includes the area itself. The time scale of the rainfall-runoff transformation theory [56] states that peak flow occurs for rainfall having durations equals to the time of concentration t_c (time taken by the precipitation particle falling at the hydraulically farthest point to reach the outlet point) that can be estimated (Equation (2)) on the basis of the geometric parameters evaluated from the GIS analysis by the Kirpich formula.

$$t_c = 0.000325 \times L^{0.77} \times s^{-0.385} \quad (2)$$

where:

- t_c (hours) is the time of concentration;
- L (m) is the length of the mainstream path;
- s (dimensionless) is the average slope of terrain conveying the overland flow.

2.1.2. Hydrological Analysis

The hydrological analysis involves two steps:

- The rainfall analysis, which considers the recorded rainfall data and applies the usual statistical methods for rainfall analysis [57] to estimate the DDF curve (Equation (3)) and the IDF curve (Equation (4)) for different return period T_r

$$\text{DDF curve} \quad h(t) = a \times t^n \quad (3)$$

$$\text{IDF curve} \quad i(t) = a \times t^{n-1} \quad (4)$$

  where:

  - h (mm) is the rainfall depth;
  - i (mm/hour) is the rainfall intensity;
  - t (hours) is the rainfall duration;
  - "a" and "n" are the curve parameters and are related to the return period T_r that characterize the scenario in which the analysis is intended to be carried out.

- The runoff analysis that models the rainfall-runoff process adopting the well-known and widely used Rational Method [56,57] in order to evaluate the peak flow Q (Equation (5)) at the catchment outlet:

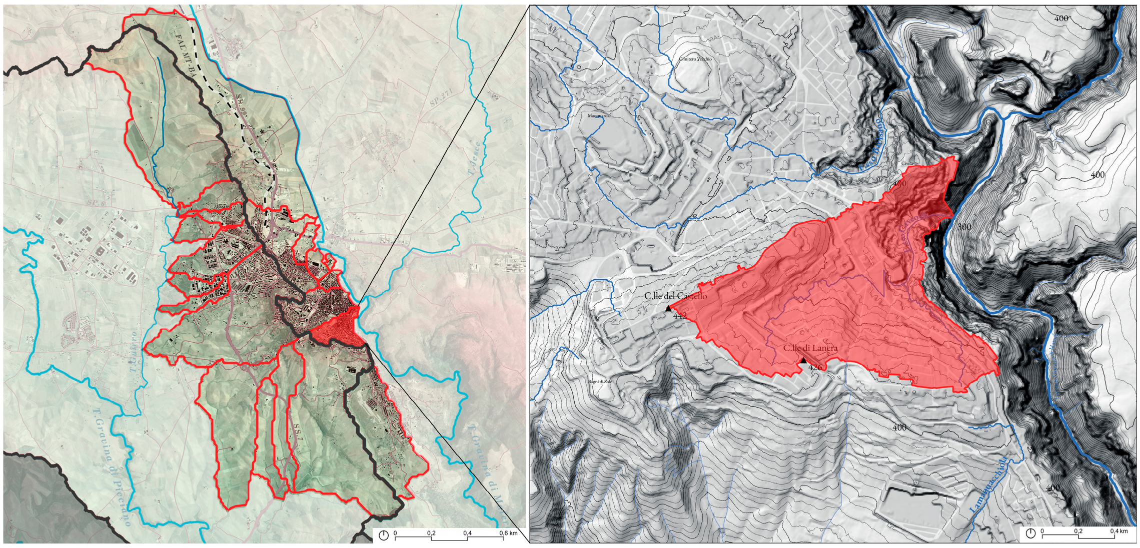
$$Q = \varphi \times i_{tc} \times A \quad (5)$$

  where Q, at the watershed outlet, is strictly related to the physical condition of the catchment (the runoff coefficient φ), to the climatic scenario (the intensity of precipitation i related to the time of concentration t_c), to the shape of the catchment(the surface A), and to the hydrological response of catchment (the time of concentration t_c).

Equation (5) expresses the combined effect of the actions that modify the shape, dimensions, or physical characteristics of the catchment (φ, t_c, i_{tc}, A) through a quantitative indicator that represents the runoff in the catchment outlet for various criticality level T_r of the rainfall events considered.

3. Results

To fully explain how the proposed hydromorphic methodology can provide useful insights into understanding the effects of morphological changes introduced through urbanization projects, a case study related to one of the historic districts of the city of Matera named "Sasso Caveoso" was investigated (Figure 2). The analyzed situation, although referring to a specific urban area, is highly representative of many situations in Italy where urban development has undergone evolutions and expansions over time, inevitably impacting the morphology of catchments and, consequently, the dynamics of surface runoff that measure their effects. For these above-mentioned reasons, the example of Matera could help to disseminate the simple but not yet widespread concepts, namely the relevance of the watershed-based schematization in urban areas.



(**a**) (**b**)

Figure 2. Matera: (**a**) map of the watersheds indentified in the urban area (red line) and location of the Sasso Caveoso watershed (red hatch), (**b**) map of the Sasso Caveoso watershed overlapped to the DTM map in grayscale shaded relief.

3.1. The Case Study

The Sasso Caveoso district is one of the two oldest historic areas of the city, it extends from the lower edge of S. Pietro Caveoso square, includes part of the Tramontano Castle Hill, and reaches the top of the hill in the Lanera district.

The city of Matera has changed its urban structure, transforming and evolving to its current configuration, which responds to the growing needs for urban development, new services and modern infrastructure. Three particular moments in the urban development of the city can be considered: the first settlements of the Sassi, the expansions of the historic centre, and the contemporary city with the creation of the external districts. In the last 70 years, Matera has almost doubled its inhabitants (38,000 in 1954, 60,000 in 2017) and increased its urban extension almost tenfold (80 Ha in 1954, 680 Ha in 2017).

The city's varied morphological and urban planning elements, exhibiting spatial and temporal variability, facilitate the application of hydromorphic analysis. This context serves as a testing ground for the proposed methodology, offering valuable insights for reflection. The districts that have undergone the most important transformations are those of the historic centre and, in particular, the Sassi Barisano and Caveoso, which originally developed around the two natural streams named Grabiglioni, adopting houses organized in overlapping layers. In the Sassi, the waters of different origins were accumulated in cisterns dug into the rock and connected to the roofs and impermeable surfaces of the courtyards or streets [58–60]. From the roofs of the houses, the outflows were conveyed into tanks of approximately 5–15 m^3, single or connected to guarantee the integrated accumulation of resources and the reduction of waste to a minimum. The Grabiglioni naturally conveyed surface runoff and was used to discharge domestic sewer waste. The first expansion of the Sassi involved the surrounding areas (the Piano) where buildings of great value were built (palaces, churches, and public buildings). Then, in the 1900s, the abnormal demographic increase inthe population within the Sassi, forced the evolution of the Sassi towards the upper parts and the two Grabiglioni Barisano and Caveoso were covered to transform them into sewer collectors and the access roads to the Sassi were built on them. Nowadays, the Sassi have become modern residential and touristic districts; they have efficient water distribution system and combined sewerage infrastructures that guarantee water resources and ensure safe sewers, but do not determine an equally efficient protection of the territory from surface runoff phenomena resulting from rainfall, especially in the most exposed urban areas, located downstream in the historic districts.

The Sasso Caveoso catchment, over time, (Figure 3) has undergone wide morphological and land use changes.

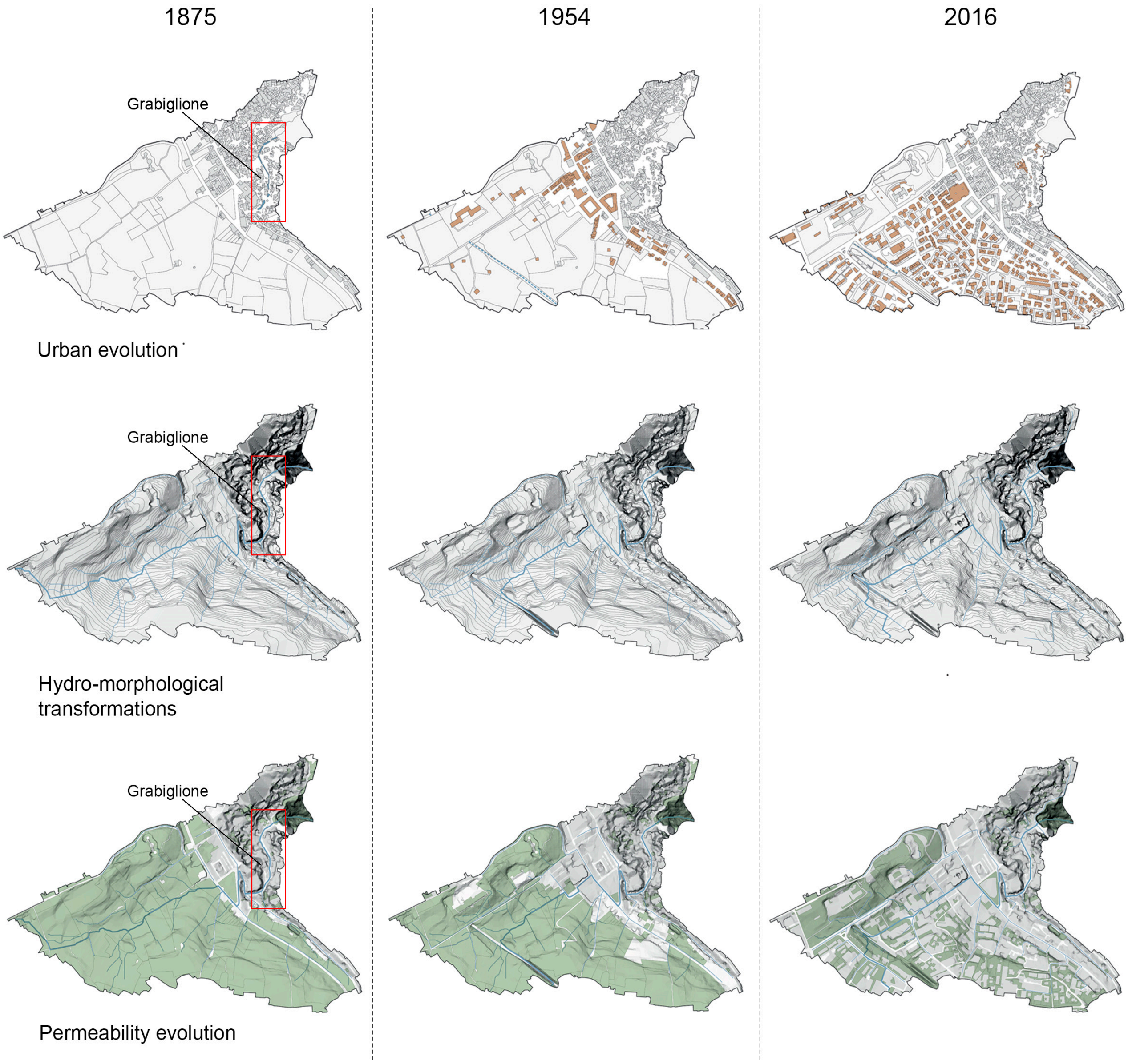


Figure 3. Sasso Caveoso watershed in the 1875, 1954 and 2016 scenarios: Urban evolution (in gray the Sasso Caveoso district, in brown the new urbanizations), morphological transformation (main runoff pathways—blue line), permeability changes (impervious area in gray, pervious in green).

In 1875, the old district stood only on the catchment downstream, while the remaining part was left unspoiled; the natural hydrographic network that crossed the entire catchment, reached the urbanized area, assumed an engraved shape protected by wall edges and the stream acquired the name Grabiglione.

In 1954, the urban area expanded towards the upper closest flat areas, the Grabiglione stream was entirely covered, creating an underground sewer overlapped by a road, and a railway was built in the upper part of the catchment, intercepting and diverting the natural runoff.

In 2016, the expansion of the urbanized area continued, transforming almost the entire upper catchment area, except for a few green spaces.

The catchment kept intact its global extension, but has modified the shape, size, and slope of the main flow path network and above all has changed the overall runoff coefficients φ, consequently having an impact on all the parameters previously cited that affect the hydrologic response of the watershed and, particularly, the outlet peak runoff.

3.2. Hydromorphic Approach

By applying the methodology described, the DTM map of the city of Matera was examined through the Q-GIS 3.4.13/GRASS7.2.0 software [54,55], allowing us to identify 21 independent urban catchments (Figure 2a) including the Sasso Caveoso watershed (Figure 2b), whose urban changes over the last 140 years have been meticulously described and analyzed using the proposed hydromorphic approach.

The Sasso Caveoso watershed kept intact its global extension (A = 0.66 km^2), but the urban evolution has modified land uses of the upstream portion of the catchment, producing larger impervious areas and an increase in the corresponding overall runoff coefficients φ. The global runoff coefficient φof the catchment can be obtained (Equation (1)) by using Table 1 coefficients considering a schematic approach in which only two categories: pervious and impervious areas are evaluated. The first includes urbanized areas and roads ($φ_i$ = 0.8), while the second refers to undeveloped or agricultural areas ($φ_i$ = 0.2).

For the case study considered the permeable surfaces coincide with green spaces all of the same type and therefore can be schematised with a single value of φassumed equal to the average value of the green areas. The impervious surfaces coincide with roofs and roads which, despite having different types, have the same hydrological characteristics. A more detailed description of the characteristics of different surfaces would improve the description of local phenomena, but at the global scale adopted by the present approach it would not provide advantages. In any case, through Formula (5), permeability categories of any size can be considered. Furthermore, by analyzing intense precipitation phenomena in urban areas which have short durations, often less than an hour, the permeability classes used in the calculations are sufficient to represent the most critical conditions. We are considering a greater number of permeability classes in other ongoing studies that use distributed hydrological models and allow the evaluation of the hydraulic conditions in each elementary cell.

From the hydromorphic point of view, the urban transformations that occurred entail an increase in global runoff coefficients φ (Table 2).

Table 2. Watershed area types and corresponding global runoff coefficient φ for different scenarios.

Year	Type		Surface km^2	%	A_i km^2	A_i %	$φ_i$	φ
1875	urban	imp	131,850	19.98	179,256	27.16	0.8	0.36
	road		47,406	7.18				
	green	per	480,744	72.84	480,744	72.84	0.2	
1954	urban	imp	196,230	29.73	272,580	41.3	0.8	0.45
	road		76,350	11.57				
	green	per	387,420	58.7	387,420	58.7	0.2	
2016	urban	imp	311,928	47.26	468,600	71	0.8	063
	road		156,672	23.74				
	green	per	191,400	19	191,400	19	0.2	

Assuming A = 0.66 km^2.

As shown in Figure 3 and evaluated through the GIS, urban evolution has produced also poor changes in the watershed length and average slope that condition the time of concentrations t_c. In fact, in the period considered the watershed length has reduced passing from 1446 m in 1875 to 1360 m in 1954–2016, and the slope has decreased from 0.028 to 0.025. Consequently, the estimated t_c moves from 0.349 to 0.348 h. In general, urban transformations lead to more significant reductions in time of concentration but in our case the watershed considered is small, has undergone only little topographic changes and t_c can be assumed constant and equal to 0.35 h.

In cases where significant reductions in t_c occurred, higher rainfall intensities i_{tc} would result from the IDF curve (Equation (4)) and, consequently, the maximum peak runoff Q (Equation (5))would tend to increase considerably.

The rainfall analysis was developed by considering the annual maximum precipitation from 1924 to 2022 (Table 3) of hourly durations recorded in Matera by the Civil Protection Agency of the Basilicata Region (www.protezionecivilebasilicata.it accessed on 01 January 2024).

Table 3. Matera maximum annual hourly rainfall (mm).

Year	Duration (Hour)					Year	Duration (Hour)				
	1	3	6	12	24		1	3	6	12	24
2022	23.8	27	28.8	28.8	28.8	**1969**	35.6	42.8	42.8	47.4	51.6
2021	32	32	32.2	35	44.6	**1968**	28	32.6	33.6	33.8	48.8
2020	18	30.6	56.2	96	107.8	**1967**	31.8	31.8	31.8	31.8	31.8
2019	36.2	51.2	60.2	68.4	71.8	**1966**	15	22.8	24.8	40.4	56.2
2018	33	39.2	39.2	39.2	45.6	**1965**	42	45	45	45.4	55.6
2015	18.4	22.8	23.6	26.4	37.2	**1964**	20.4	23.6	26.4	45.2	48
2014	29.6	29.8	30.2	31.2	33.2	**1963**	70	72.6	72.8	72.8	83.6
2013	29.8	44.2	70	111	129.6	**1962**	21.6	22	22	31.2	37.6
2012	25.6	26.2	26.6	36.6	37	**1961**	30	36.6	36.8	36.8	36.8
2011	23.2	34.4	35.4	35.4	35.8	**1960**	24	34.2	38.2	47	53.6
2010	34	48.6	59.8	63.4	63.6	**1959**	33	77	91.6	104	174
2009	47.6	51	55.4	55.4	78	**1958**	33.4	43	46.2	67.4	76
2008	17.2	20.8	30.8	39.4	40.6	**1957**	33	55	90	94.8	101
2007	23	50	56.8	71.6	86.2	**1956**	34	60	67.8	67.8	67.8
2006	28.2	36	37	37	50.2	**1955**	21	23	29.6	44.2	49.6
2005	18.6	23	26.4	34.8	41	**1954**	45.8	45.8	45.8	45.8	65.2
2004	16.8	19.6	33.2	40.4	47	**1953**	35.8	42.2	43	43.6	47.2
2003	15	29	35.4	47	53.6	**1951**	34	43	56	67.4	72.2
2002	16.4	25	40	48.2	50.6	**1950**	18	28.6	29.8	29.8	32.4
2001	27.8	29.8	45.6	48.2	48.6	**1949**	20.4	36.8	60.8	70	74
2000	16.6	18.6	22.8	32.6	51.2	**1948**	31	39.4	45	47	47.4
1999	33.2	34.6	34.6	34.6	37.2	**1947**	15.8	31	39	40.6	41
1998	20.6	31.6	27.4	27.4	41.8	**1946**	17.2	17.6	20.2	30.6	45
1997	21	25.8	32.2	42	48.2	**1945**	19.8	21	21.4	22	32.6
1996	36.8	46.4	48.2	48.4	48.4	**1944**	42	46.8	46.8	46.8	47
1995	31.8	37.2	60	63.6	63.8	**1943**	16.6	21	30	38.2	39.8
1994	19.2	26.8	27.8	35.4	47.4	**1942**	14.4	23.2	36.2	52.4	61.2
1993	18	35	36.2	36.4	37.6	**1941**	33	41.2	45.5	62	63.2
1992	38.8	39.6	39.6	39.6	39.8	**1940**	19.8	38	44	48	62.8
1991	35.4	40.2	40.2	40.2	40.2	**1939**	34	37.8	37.8	39.4	46.6
1988	20.6	29.2	39.2	42.8	51	**1938**	17	25.5	30	49.3	65
1971	20.4	24.2	29	29.2	29.2	**1937**	11	13.6	13.7	13.7	13.7
1970	36	39.6	47.4	47.6	47.8						

In particular, it was noted (Table 3) that the city of Matera is often affected by short but intense precipitation, with values of maximum 1 h precipitation depths exceeding 30 mm, although with low return periods (T_r < 5 years). In such situations, severe criticalities are observed with widespread flooding and significant surface runoff (Figure 4) in multiple areas of the city, especially in the Sasso Caveoso.


(**a**) (**b**) (**c**)

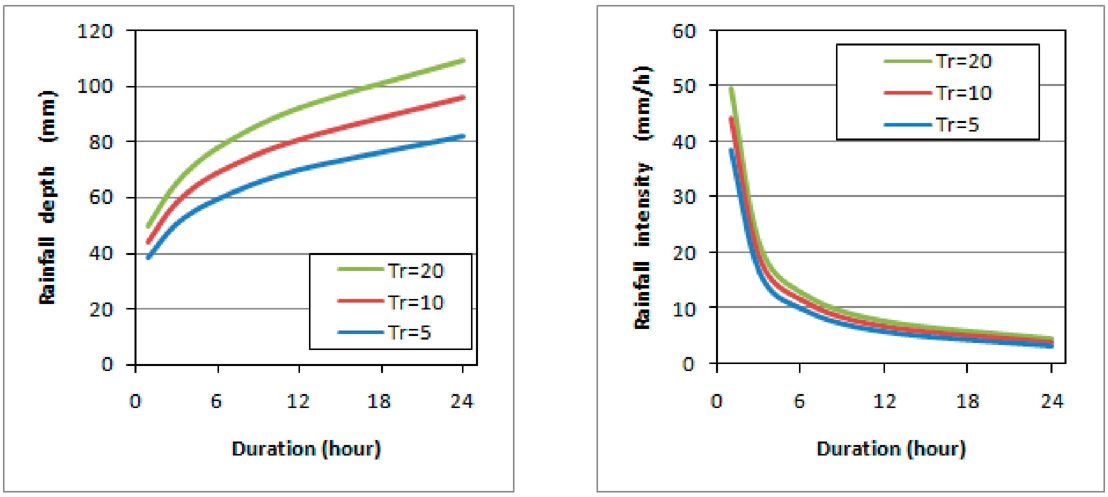
Figure 4. Sasso Caveoso district during intense rainfall event (2019): (**a**) S. Pietro Caveoso square, (**b**,**c**) the old path of the Grabiglione actually Bozzi street.

The analysis of the maximum annual hourly precipitation, adopting the Gumbel distribution and estimating the relevant parameters, allowed us to evaluate the return periods of each observed event, also deducing the DDF and IDF curves for different T_r (Table 4).

Table 4. DDF and IDF parameters for different scenarios T_r.

T_r	a	n	DDF	IDF
5	38.54	0.24	$h = 38.54\ t^{0.24}$	$i = 38.54\ t^{-0.76}$
10	44.20	0.24	$h = 44.20\ t^{0.24}$	$i = 44.20\ t^{-0.76}$
20	49.63	0.25	$h = 49.63\ t^{0.25}$	$i = 49.63\ t^{-0.75}$

Each DDF and IDF curve (Figure 5) expresses a proper climatic condition that could be considered to describe a specific scenario.



(**a**) (**b**)

Figure 5. (**a**) DDF curve and (**b**) IDF curve, for T_r equals 5, 10, 20 years.

Considering the climate scenario T_r = 5 years the hydromorphic analysis was therefore conducted concerning the evaluated DDF and IDF (Equation (6)).

$$\text{DDF}: \ h(t) = 38.54t^{0.24} \qquad \text{IDF}: \ i(t) = 38.54 \times t^{-0.76} \tag{6}$$

Referring to this condition the peak flows that reflect the combined effects of the transformation that affected the Sasso Caveoso watershed can be evaluated for each time step obtaining the hydrologic response Q_{max} values (Equation (5)) reported in Table 5.

Table 5. Runoff peak flows Q_{max} for different scenarios.

Year	Surface Type and %		Φ	t_c (hours)	$i(t_c)$ (mm/h)	Q_{max} (m^3/s)
1875	Impervious Pervious	27.16 72.84	0.36	0.35	85.7	5.7
1954	Impervious Pervious	41.3 58.7	0.45	0.35	85.7	7.0
2016	Impervious Pervious	71 29	0.63	0.35	85.7	9.8

Even if the time of concentration did not vary, because the occurred transformations have not influenced this parameter, the peak flow rate has increased by approximately 40% in the last 60 years and is even 70% higher than that of 1875.

The hydromorphic response of the catchment has worsened significantly over time, especially due to the expansion of urbanized upstream areas which have reduced the permeability of the soil and its capacity to intercept rainfall. At the same time, road and railway works were also carried out which diverted the main flows and covered the stream bed (Grabiglione). The set of urban transformations has altered the hydrological response of the catchment, and this is well expressed by the Q_{max} parameter, evaluated at the outlet watershed point.

The same methodology can be applied to different situations by simply considering the corresponding DDF or IDF curve for the chosen scenario. This allows for the analysis of the Sasso Caveoso catchment concerning any observed precipitation or an event with a given T_r.

Photographic recordings (Figure 4) captured during the 2019 event that correspond to the scenario T_r=5 years allow us to verify the consistency between the evaluated peak flow and the really observed phenomena. In consequences of the described hydromorphic alterations critical situations occur in the Sasso Caveoso district: tumultuous flows along the main roads, widespread flooding of courtyards and lower floors, and the flooding of Piazza San Pietro Caveoso (a major tourist attraction point) located at the downstream end of the catchment, where there are various commercial and tourist venues.

4. Discussion and Conclusions

It is clear that cities and territorial transformations have a strong impact on the rainfall-runoff processes dynamic, on the infiltration capacity guaranteed by permeable areas and that the runoff affects the livability and safety of natural and non-natural spaces. Additionally, the conformation of urban areas can be affected by the different exposures that characterize the variability of rainfall observed in different parts of the city [61–66]. Ultimately, the materials used, the infrastructure present, or the technical choices adopted, can also influence the dynamics of the involved processes.

There is a particularly strong need to develop methodologies capable of carrying out assessments on the efficiency conditions of the different alternative hypotheses to be evaluated, in order to be able to support sustainable planning processes [67].

Several initiatives adopt sustainable urban planning policies known as Water-Sensitive Urban Design (WSUD) and Sustainable Urban Drainage (SUD). WSUD were introduced in the Water-Sensitive Urban Design Guidelines (WSUDG) developed in Australia in order to integrate stormwater management into the planning and design of urban areas [68].

Sustainable Urban Drainage promotes a new approach to the management of rainwater in an urban environment, which appeared in the 1987 "Our Common Future" report [69] (or "Brundtland Report", named after the president of the World Commission on Environment and Development of the United Nations, Gro Harlem Brundtland) in which the critical points and global environmental problems and the need to start a community strategy were noted—the concept of "sustainable development " in its meaning of economic growth and development but also of social order.

To contribute to the sustainable development of the territory and estimate the impacts produced by urban transformations, a methodology named hydromorphic analysis is proposed. It is clear that the hydromorphic analysis reveals the profound physical relationships existing between the historic district and the upstream expansion part, which must be considered in their morphological unity and not as separate administrative bodies. This methodology allows assessment of the impacts of urban layout on hydrological dynamics, to detect the role of any different transformation and to compare different climate conditions or project plans.

In particular, the analysis, once the return period of the reference rainfall event is established, allows for comparing different urban situations within the same area, associating with each of them a synthetic assessment of the peak flow in the closing section of the watershed to which the area belongs. The considered urban situations may represent, as in the examined case study, different scenarios from the past or planned situations not yet implemented. In all cases, the comparison allows the evaluation of the urban solution that determines the least hydromorphic impact, which corresponds to the lowest peak runoff. Furthermore, by varying the considered T_r, the strength of the event used in the analysis may change.

The current evaluations are based on the maximum annual hourly rainfall, under a predetermined critical condition (T_r), aiming at analysing the hydrological responses of the considered watershed with the urbanistical landscape evolution. In further investigation, hydrological analyses will be conducted on the entire sample of precipitation to more accurately characterize the statistical distribution of each event, allowing for estimating the characteristics of future events with which to conduct other simulations.

The evaluation of global indicators of the watershed responses is carried out by adopting open source Q-GIS 3.4.13 software and widely diffused hydrologic formulations that can support urban planning activities in pursuing the sustainability target suggested by the 2030 Agenda (Sustainable Development Goals 11-Smart Cities and Communities and 13-Climate Action) and facilitate the utilization of stormwater Best Management Practices (BMPs) and Best Planning Practice (BPP) including engineering, architecture and ecology aspects in order to account for site-specific characteristics and develop different range scales (local and regional) integration.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the privacy rules of the Municipality of Matera (the processing is part of the planning tools not yet approved).

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