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Adaptation for River Floods at Urban Level: Choosing Future Directions with Aware Climate Risk Assessment. A Case Study

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Adaptation for River Floods at Urban Level: Choosing Future Directions with Aware Climate Risk Assessment. A Case Study

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Highlights

What are the main findings?

- The integrated CLIMAAX hazard and exposure workflows enabled the identification of spatial flood risk hotspots and the quantification of potential economic losses and population exposure within the selected pilot (Foglia River basin).
- Climate projections indicate an intensification of extreme river discharges, with flood recurrence increasing by more than 20% for the 5-, 10-, and 50-year return periods.

What are the implications of the main findings?

- The CLIMAAX framework proves to be a transparent and transferable methodology for climate risk assessment in complex Mediterranean urban–coastal basins.
- The results support the integration of climate risk information into regional and municipal planning processes, contributing to the implementation of the Regional Plan for Adaptation to Climate Change (RPACC).

Abstract

Floods are among the most damaging natural hazards, threatening human safety and causing substantial economic losses. Their risk results from the interaction between hazard, exposure, and vulnerability, and has been increasing due to the rising frequency and intensity of extreme hydrometeorological events. This issue is particularly relevant in Mediterranean regions, where floods often affect small, densely populated, and highly urbanised basins. This study applies a comprehensive climate risk assessment to the Foglia River basin (Marche, Italy) using the framework and tools developed within the Horizon Europe CLIMAAX project. Locally developed flood hazard maps were integrated with exposure and vulnerability data, focusing on the city of Pesaro at the river mouth. Risk was quantified in terms of building damage and population exposure for different return periods. To further investigate changes in flood hazard, projected river discharge under climate scenarios was analysed. The results indicate a relative increase in flood recurrence exceeding 20% for the 5-, 10-, and 50-year return periods, suggesting a significant intensification of flood risk. The study provides spatially explicit estimates of potential economic losses and supports the refinement of regional climate adaptation strategies, offering valuable insights for the integration of climate risk considerations into urban and territorial planning.

Keywords: climate change adaptation; river flooding; river discharge; climate risk analysis

1. Introduction

Urban areas are more and more exposed to a wide range of climate-related hazards, including increasingly frequent extreme weather events, heatwaves, and rainfall-driven stresses, as documented in recent studies on the evolution of urban flood hazards under climate change [1]. Among these hazards, the rising frequency and intensity of extreme hydrological events make river flooding an increasingly critical threat for cities intersected by river systems, where changing climatic conditions amplify the likelihood and magnitude of fluvial inundation. The combination of expanding urbanization, vulnerable infrastructure, and shifting hydrological regimes makes it progressively more challenging to guarantee adequate safety levels and protect essential services, also through resilient territorial management. Recent studies highlight how urban flood events are exacerbated by factors such as soil sealing, densification of the built environment, and the presence of critical infrastructure located in hazard-prone zones, producing both direct and indirect impacts on populations, buildings, and essential networks [2,3].

Within this evolving scenario, the need for increasingly accurate and context-sensitive climate risk assessments becomes central to guiding effective adaptation strategies. Contemporary literature emphasizes the importance of integrated risk assessment approaches —those that combine hazard, exposure, and vulnerability —to support urban planning and the prioritization of interventions, especially where infrastructures and exposed elements present high criticality [4,5].

These dynamics acquire particular relevance in Mediterranean regions, where the combination of pronounced climatic variability, increasing temperature and precipitation extremes, and a long history of dense urban settlement amplifies the exposure of cities to flood risk. Several studies show that Mediterranean basins are especially sensitive to shifts in rainfall patterns, including more frequent short-duration, high-intensity events and prolonged dry periods that alter the hydrological response of rivers and their tributaries [6,7]. When such phenomena intersect with highly urbanized floodplains, characterized by extensive soil sealing and limited drainage capacity, the probability of severe fluvial flooding substantially increases.

In this context, climate adaptation cannot rely solely on traditional protective measures—such as levees or local structural defenses—but must increasingly embrace broader strategies aimed at enhancing territorial resilience. This involves rethinking urban development models, integrating adaptive principles into spatial planning, and promoting land-use configurations capable of reducing exposure while improving the capacity of urban systems to absorb, recover, and transform when facing hydrological extremes. Urban planning thus becomes a key lever for adaptation, enabling cities to anticipate future climate conditions, regulate development in hazard-prone zones, and incorporate nature-based solutions that restore hydrological functions and mitigate flood impacts.

A rigorous and spatially explicit climate risk assessment, therefore, plays a foundational role in supporting decision makers in the identification of appropriate adaptation measures. By quantifying the interplay between hazard dynamics, the distribution of exposed assets, and the specific vulnerabilities of urban elements, such assessments allow for more informed prioritization of interventions, tailored to local criticalities and long-term climate projections. Accurate risk characterization not only guides the choice of protective infrastructures but also informs planning instruments, governance processes, and investment strategies that collectively shape a resilient urban transition.

Integrating climate risk analysis into adaptation planning has become an essential requirement for developing effective and forward-looking strategies. Embedding risk information in planning helps ensure that adaptation measures are not only reactive, but structurally integrated into spatial policies, infrastructure design, and sectoral management frameworks —especially in contexts where overlapping climatic pressures exacerbate existing socio-environmental fragilities.

Across Europe, regional and local authorities are increasingly formalizing their own adaptation strategies, recognizing the need for place-based approaches that connect scientific evidence with governance processes. This trend is visible in several Italian regions as well, where adaptation planning has evolved from preliminary climate strategies to more structured and operational documents. Among these, the Regione Marche represents a particularly advanced example: it has adopted a comprehensive Regional Plan for Adaptation to Climate Change (RPACC), approved with Regional Council Act n. 84/2025

The Marche regional adaptation plan reflects a holistic and multisectoral approach, grounded in a detailed assessment of climatic trends, vulnerabilities, and sectoral exposure. The plan analyses the current and projected climate conditions of the territory, identifies key risks —including precipitation variability, drought, hydro-geomorphological instability, and coastal inundation —and translates them into adaptation measures relevant across multiple domains of regional governance.

Moreover, the RPACC is explicitly embedded within the broader Regional Strategy of Sustainable Development, with a multisectoral governance structure reflecting the inherently cross-cutting nature of climate risks, which requires decision-making and alignment between sectoral policies. In this sense, the Marche Region provides an example of how regional authorities can operationalize climate risk assessments within coherent adaptation frameworks, reinforcing resilience while ensuring consistency with long-term sustainable development pathways.

This study aims to analyse how specific risk analysis could be integrated in adaptation planning, supporting the refinement and implementation of adaptation measures. The "River Flooding" workflow of the climate risk assessment toolbox developed within the Horizon Europe CLIMAAX project is applied in a pilot area. The toolbox is designed to make advanced climate risk methodologies more accessible and replicable at local scales. Its river flooding workflow integrates hydrodynamic modelling, territorial indicators, and exposure/vulnerability metrics, following conceptual structures widely recognized in flood-risk studies and aligned with recent innovations in data-driven, flexible, and transparent risk evaluation [8].

The selected pilot area is the mouth of the Foglia River, in the municipality of Pesaro (Marche Region, Italy)—a coastal urban context where settlements, economic activities, and critical infrastructures coexist within a spatial configuration subject to potential fluvial inundation. The morphological conditions of the river mouth, combined with anthropogenic pressures and climate variability, make this area particularly suitable for testing advanced risk assessment methodologies and for exploring long-term adaptation pathways.

The objective of this article is therefore twofold:

1. To present a practical application of the CLIMAAX toolbox to the urban context of Pesaro, identifying its methodological potential and operational limitations;
2. To outline future directions for informed adaptation planning, integrating scientific risk analyses with local decision-making processes, in line with emergent international perspectives on urban governance and sustainable flood-risk management.

This study is situated within a broader European research context where cooperation projects support the development and testing of climate risk assessment methodologies at regional and local scales. In Marche Region, EU-funded initiatives have enabled the integration of climate data, modelling tools and risk indicators across flood risk management and adaptation planning. Projects such as INTERREG projects STREAM, CASCADE, ADRIACLIM, REALIST and Horizon project CLIMAAX have contributed to refining hazard mapping, exposure analysis and scenario-based assessments. Within this cumulative framework, the present application builds on previous project experiences, providing an additional case study on the operational use of advanced risk assessment tools in a Mediterranean urban–coastal context.

2. Materials and Methods

This study applies the CLIMAAX climate risk assessment toolbox, developed under the Horizon Europe programme, to evaluate river-flood risk and adaptation needs in the Foglia River mouth area (Pesaro, Marche Region, Italy). The methodology follows two key workflows of the CLIMAAX river-flooding pipeline:

(1) "Building and Population Exposed", which estimates exposure levels by combining flood extent datasets with socio-economic and built-environment indicators.

(2) "River Discharge", which quantifies flood hazard through hydrological modelling and climate-conditioned discharge simulations;

The combined use of hazard and exposure workflows aligns with well-established concepts of flood-risk analysis, where risk is defined as the intersection of hazard, exposure and vulnerability, as emphasized in recent systematic reviews of flood-risk frameworks [8].

2.1. Building and Population Exposed Workflow: Exposure Assessment

The Building and Population Exposed workflow evaluates the quantity and characteristics of assets and people located in areas identified as flood-prone according to hazard maps.

This workflow requires flood-extent maps derived from hydrodynamic modelling. For the simulation in the pilot area, two set of maps, with different return periods, are used:

- The maps produced by European Commission's Joint Research Centre (JRC) at 3 arc-seconds resolution [9];
- maps of flooding developed available locally for the River Foglia Basin.

These latter have been produced within the Interreg Italy-Croatia project "STREAM" for Marche Region, in collaboration with CIMA Foundation [10]. A bidimensional hydraulic model, TELEMAC-2D, was applied on the Foglia river, to compute hazard maps for various return periods. Buildings, bridge, embankments and perimeter walls have been checked to test permeability and their influence on the dynamic of simulations.

To account for exposure, the following data have been introduced:

- Building data: information on geometry and classification extracted by [11] is used to collect building information, both in terms of geometry and classification.
- Population density: the GHSL data package [12], published by the European Commission's Joint Research Centre, is used for mapping the population estimates, with a resolution of 3 arc seconds and a global coverage. The workflow allows for selecting the population estimate in 5-year intervals between 1975 and 2020, or the population projection of either 2025 or 2030.

The damage to buildings is determined by the flood depth to which they are subjected, establishing a relationship between water depth and damage. Maximum damage values are based on the global flood depth-damage functions according to the methodology explained by [13]. The value assumed are based on the World Bank Consumer Price Index (CPI) for country of interest [14] referred to 2010 (reference year) and to 2024 (latest value). In calculating maximum damage, the first array value is 2010 building reconstruction cost per square meter. The second array value is the 2010 building content replacement value per square meter. The values of CPI used in the simulation are 100 for 2010 and 129.9 for 2024.

Buildings are classified according to the following classes: Residential, Commercial, Industrial, Agriculture, Cultural, and Transportation. To each class, damage values are associated, based on [13]. Cultural, and Transportation as well as unclassified buildings are set to Universal class. Damages are hence estimated based on JRC depth-damage curves.

The workflow includes:

1. Spatial overlay analysis between flood-extent maps and building/population layers.
2. Quantification of exposed assets, including number of buildings, surface area, construction categories, and economic relevance.
3. Population exposure estimates, including number of residents and potential vulnerability factors (e.g., density, location within high-hazard zones).
4. Extraction of exposure metrics for different return periods.

The workflow produces two primary categories of outputs derived from the combination of flood-hazard maps, building datasets, and population distribution data. First, it estimates economic damage to buildings by intersecting modeled inundation depths with building footprints and

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structural characteristics. Damage is computed using depth–damage curves and building-type information, resulting in quantitative assessments of direct economic losses under the specified flood event. Second, the workflow quantifies population exposure and displacement by overlaying flood extent and depth with gridded population datasets. Individuals located within inundated areas are classified as exposed, while displacement is assessed by applying depth thresholds beyond which a habitation is considered temporarily infeasible.

2.2. River Discharge Workflow: Flood Hazard Assessment

The River Discharge workflow is designed to generate hydrological simulations that describe the magnitude and frequency of river flows under different climate conditions. It provides the hazard backbone for the risk assessment.

As input data, the workflow integrates:

- Observed discharge records, for calibration and baseline characterisation.
- Climate model projections (regional or global) to simulate future discharge scenarios.
- Catchment descriptors such as elevation, land cover and soil characteristics, which influence rainfall–runoff processes.

The discharge time series used for the Foglia River mouth are daily simulated flows derived from the E-HYPEcatch hydrological model forced by EURO-CORDEX climate projections. For each climate model chain, continuous discharge time series were extracted for the catchment corresponding to the river mouth and used to derive flow-duration curves, annual maxima series and return period estimates. The use of multiple climate model simulations allows the representation of uncertainty associated with climate projections and hydrological modelling.

The modelling procedure performed by the workflow includes:

1. Hydrological modelling to convert precipitation inputs into river discharge.
2. Bias correction and statistical processing to improve the alignment of simulated flows with observed conditions.
3. Extraction of flood-related indicators such as peak flows, return periods, and projected changes in discharge extremes.

These steps follow the structure of modern hazard-assessment frameworks, which require consistent treatment of climate-induced variability and uncertainty in flood drivers.

The outputs of River Discharge workflow are:

- Time series of present and future discharge;
- Hydraulic boundary conditions for subsequent inundation modelling;
- Scenario based hazard descriptors (e.g., extreme flow increases).

2.3. Integration of Workflows and Case Study Application

The two workflows were executed to characterize risk conditions in the Foglia River mouth, an area where the interplay between fluvial dynamics, coastal processes, and dense urban occupation magnifies flood impacts.

The pilot area extends for an area of about 30 km^2 and covers the last stretch of the Foglia river and part of the city of Pesaro, depicted in **Figure 1**.

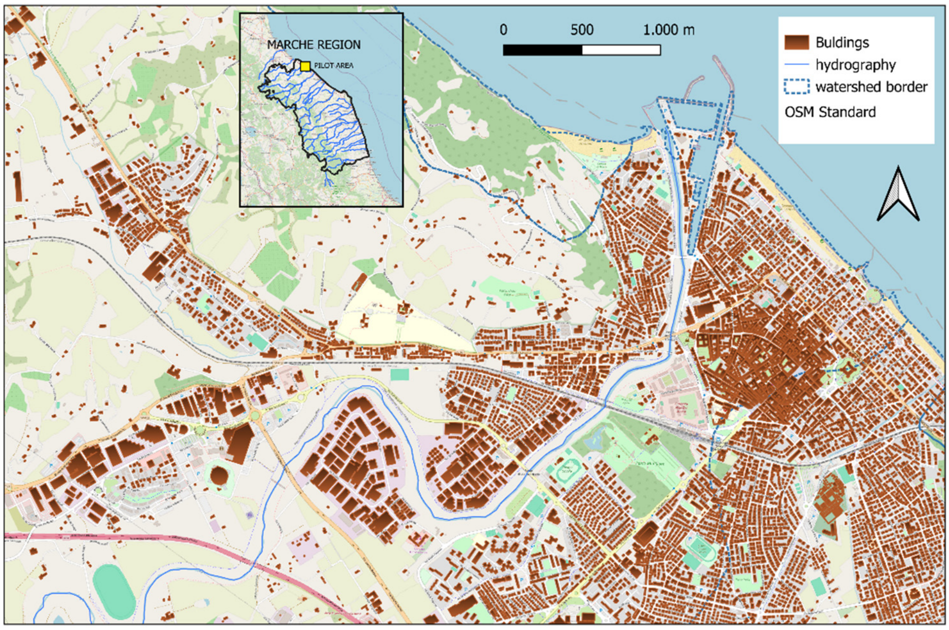

Figure 1. Pilot area outline.

The combined hazard - exposure framework enables:

- identification of hotspots of risk,
- assessment of future vulnerability under climate-change scenarios.

The methodological integration reflects current recommendations in adaptive flood-risk governance, which call for multi-layered approaches addressing both physical and socio-economic dimensions of exposure.

3. Results

3.1. Risk Assessment with Flood Maps

For the current scenarios two sets of maps of flooding have been used for the hazard analysis, as discussed in section 2.1.

The JRC map with return period of 10, 50, 100 and 500 yrs are shown in **Figure 2**.

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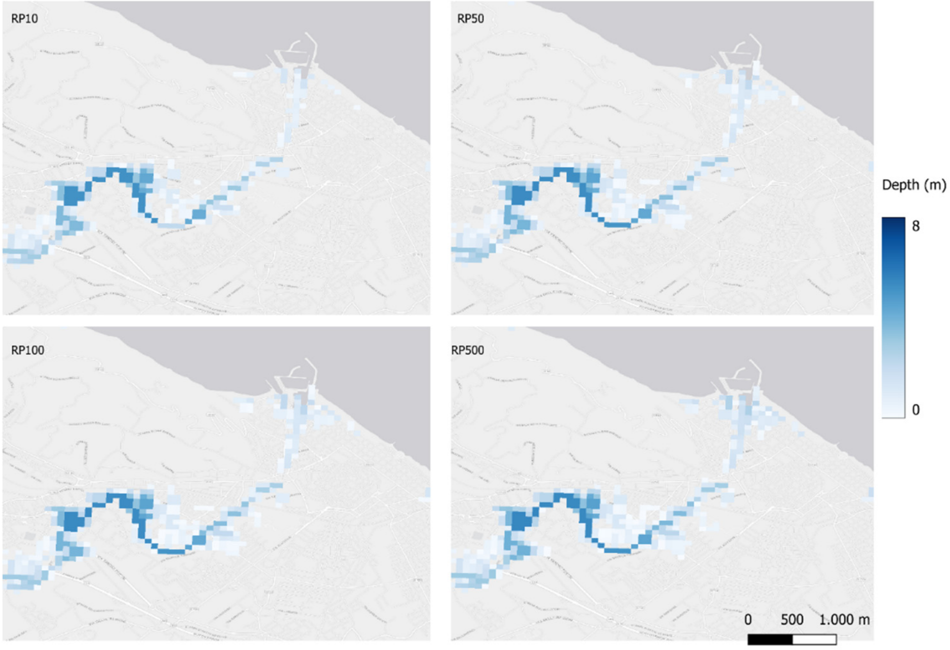


Figure 2. River flood potential for different return periods for the river Foglia pilot, present day-scenario with JRC floods map.

Moreover, local maps for river flooding were integrated in the workflow: the use of these maps overcomes some of the limitations identified for the methodology of the workflow since they present a better resolution and a more accurate distribution of flooded areas. Local maps with return period of 10, 50, 100 and 500 years are shown in **Figure 3**.

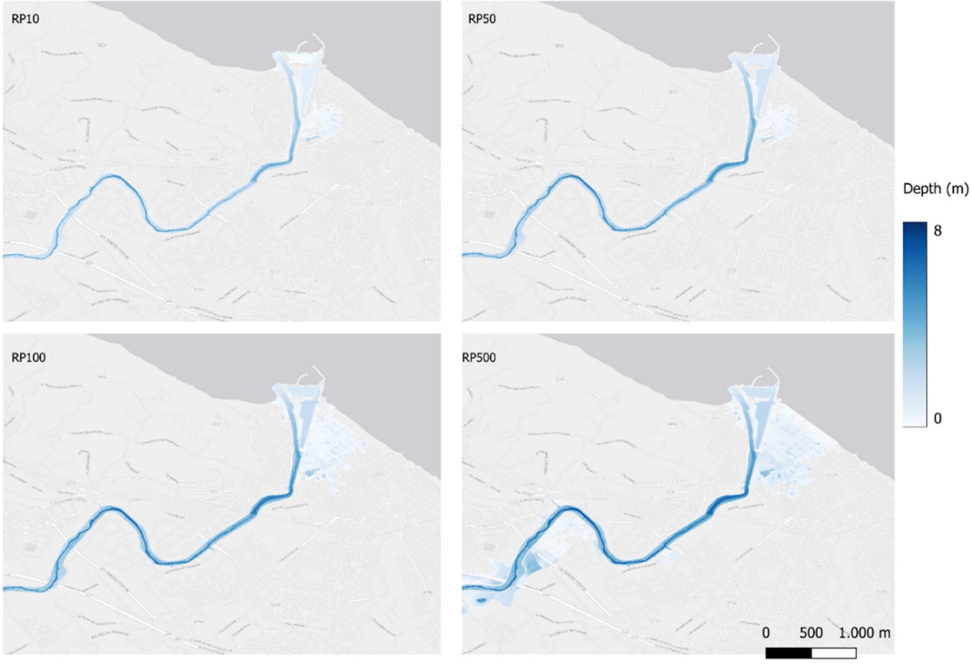


Figure 3. River flood potential for different return periods for the river Foglia pilot, present day-scenario with Cima foundation local floods map.

In the workflow methodology, the estimation of the change in river flood potential due to climate change for future scenarios is performed using the Aqueduct dataset [15], which includes flood maps for a baseline scenario (1980) and future climates. However, Aqueduct has a coarse resolution (30 arc-seconds) for the pilot area (and for central Italy in general) which doesn't allow for a proper risk assessment. For this reason, a further refinement has been applied using the workflow on river discharge (see Section 3.2). Even if this doesn't directly supply maps of flooding for future scenarios, it can help evaluate the increase in frequency of extreme events.

For risk analysis, buildings have been classified based on OSM. Data have been checked with the regional technical map, showing consistency for the examined area. Buldings with unspecified classification or mixed use (i.e., residential and commercial use) have been set to "universal" (**Figure 4**).

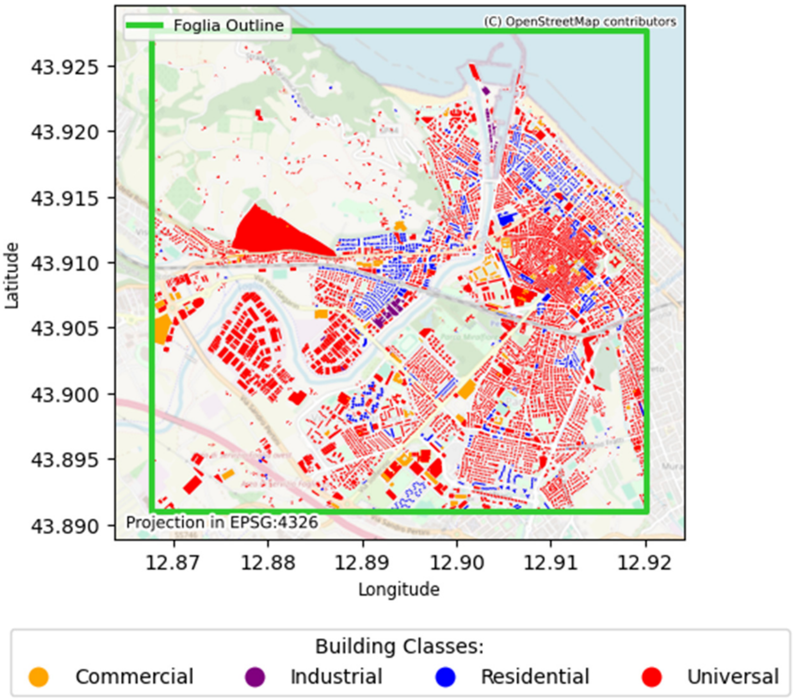


Figure 4. Building classification for the pilot area.

The combination of the flood maps at different return period with building data allows to examine potential risks. Results (**Figure 5**) show a significant increment of buildings interested by flooding with RP=500yr compared with RP=10Yr. In this latter scenario, only buildings that are very close to the river bed are interested by flooding. The analysis on critical infrastructure confirms that the urban planning has placed all the critical infrastructure outside the potentially flooded areas, even with RP=500 yr (**Figure 6**).

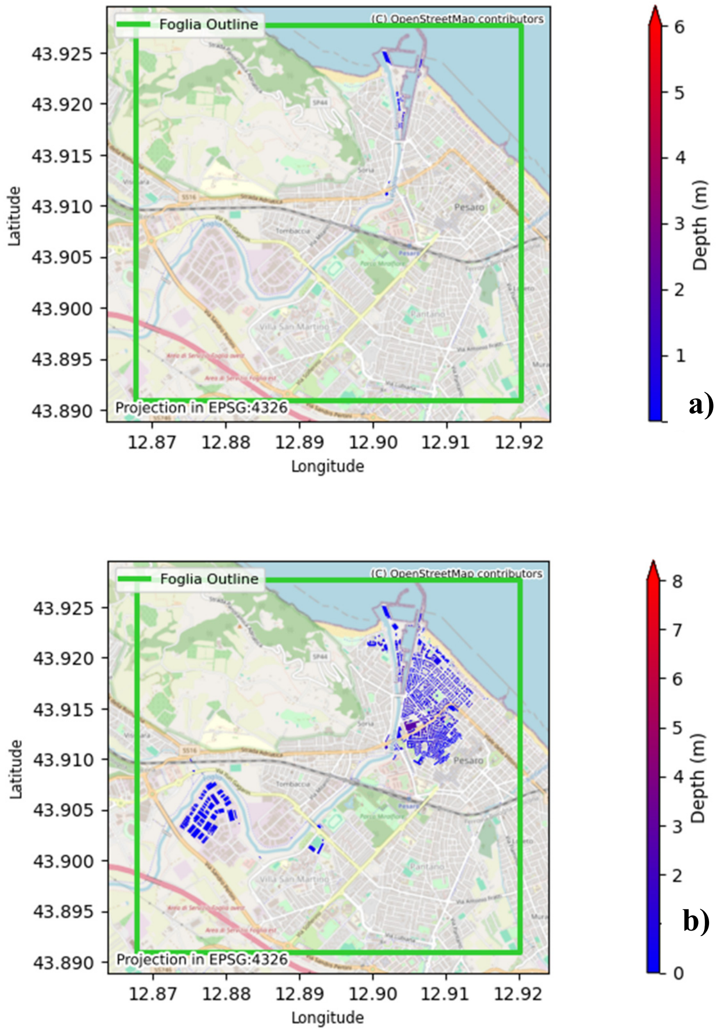


Figure 5. Mean flood depth at building locations derived from flood map with 10 yr (a) and 500 yr (b) return period at the pilot location.

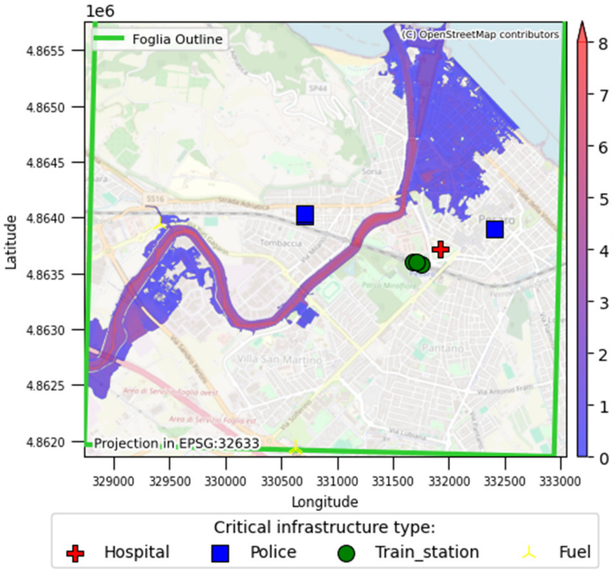


Figure 6. Critical infrastructure exposure to river floods with 500 yr return period.

The quantification of total damage to buildings is shown in Table 1. For comparison the result obtained with the JRC's flood maps are also reported. The coarse resolution of the JRC flood maps and the lack of consideration of barriers and structures for floods protection tend to overestimate the flooded area, resulting in larger damage costs. This confirms the importance of using accurate data for the estimation of the risks.

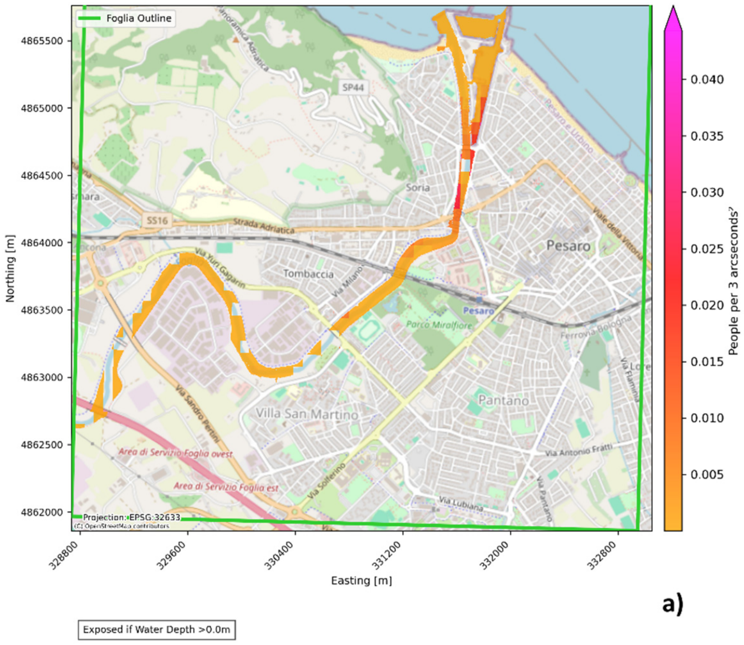
Table 1. Economic damage at buildings for different return period.

Return period	Local floods maps	JRC floods maps
RP=10	1.130.206 €	78.304.069 €
RP=50	13.538.664 €	101.270.392 €
RP=100	35.238.812€	108.070.062 €
RP=500	73.036.964 €	126.273.271€

Risk was assessed in terms of building damage and population exposed. Results show that risk of flood is concentrated in some areas (within the meander and in the river mouth), implying relevant cost in terms of both damage and population exposed even for low return periods.

Damage costs increase with the RP, moving, in the area under analysis, from ~1M€ for events with RP of 10 yr to ~74M€ for events with RP of 500 yr. It is also important to note that the computation of costs refers to buildings and not, for example, to damage to infrastructures (roads, water supply or sewage systems, electric infrastructure, etc.) or costs related to restoration works.

Based on the flood depth maps, the exposed population is determined in respect to different return periods (see **Figure 7** and **Figure 8**). The displaced population is also reported as a subset of the exposed population that experiences flood depths above a given threshold. It is interesting to note that even with low return period (10 yr) there is a consistent number of people exposed (>3000). The displaced population increases with RP (from 150 with RP 10 yr to over 1300 with RP 500 yr).



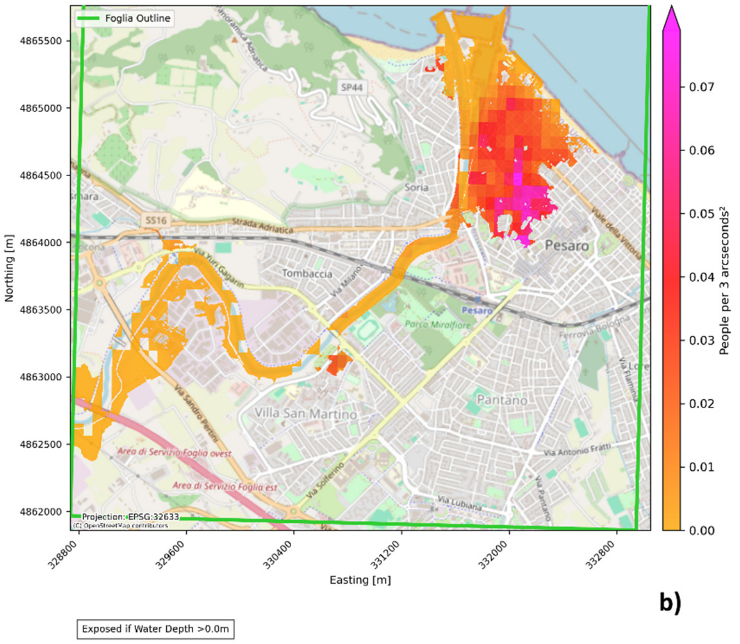
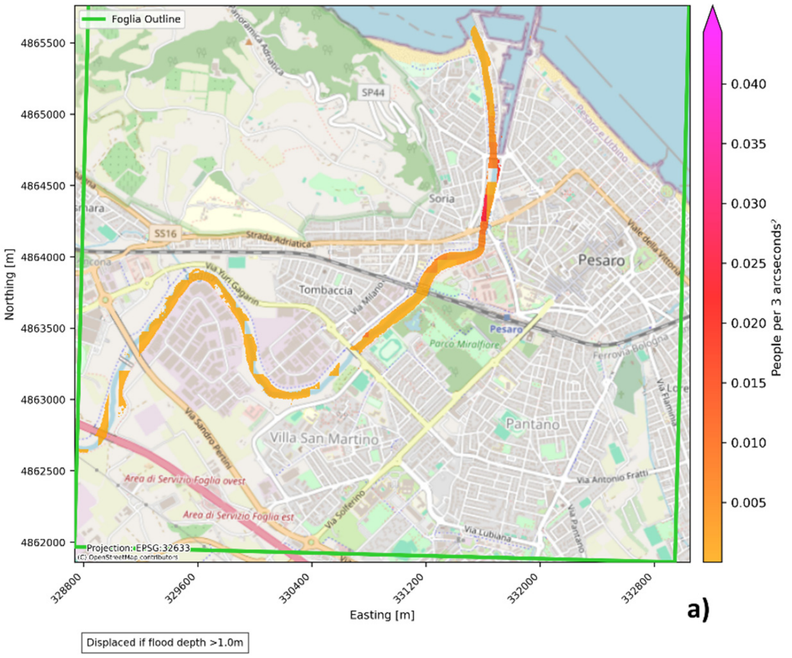


Figure 7. Exposed population for the river flood event with 10 yr (a) and 500 yr (b) return period (population statistics based on estimate for year 2025).



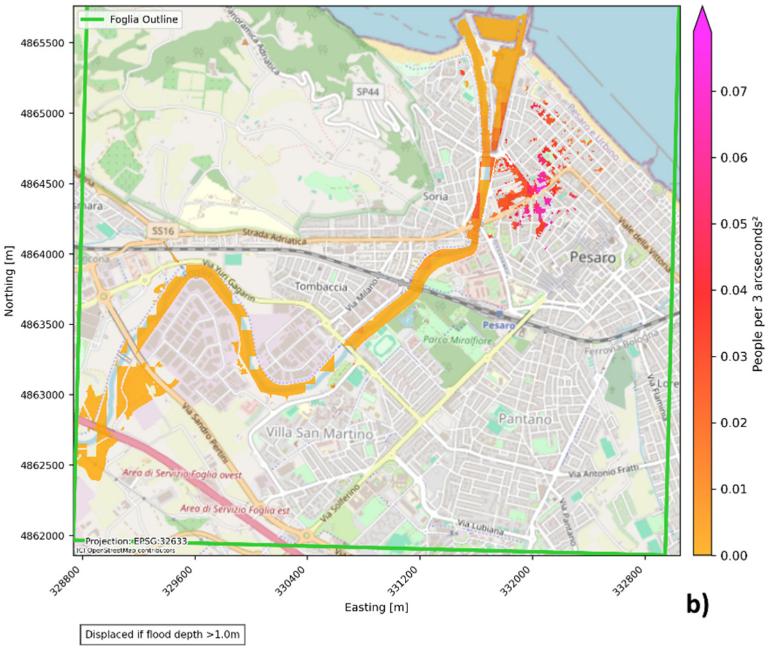


Figure 8. Displaced population for the flood event with 10 yr (left) and 500 yr (right) return period (population statistics based on estimate for year 2025).

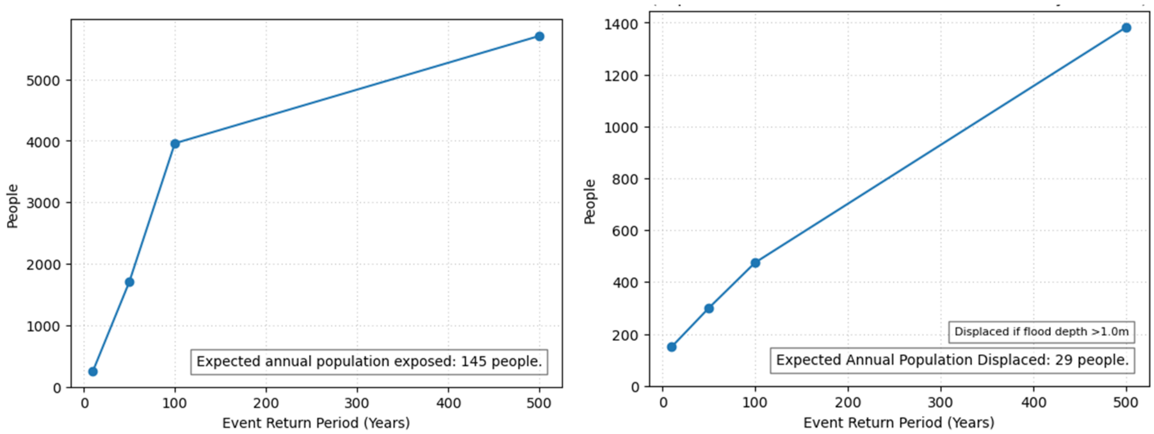


Figure 9. Estimated exposed population and displaced population per flood event return period (population statistics based on estimate for year 2025).

Table 2. Population exposed and population displaced with different return period.

Return period	Population exposed	Population displaced
RP=10	*3365*	*150*
RP=50	*3858*	*299*
RP=100	*3863*	*475*
RP=500	*4196*	*1383*

3.2. Assessment of Future Scenarios with River Discharge Workflow

The river discharge workflow has been applied to support in terms of future scenarios the elaborations performed within the river floods workflow. Investigation of climate change scenarios, in terms of monthly discharge and extreme events seems relevant both to improve Early Warning System and drought long term strategies.

CLIMAXX workflow on river discharge uses the dataset of hydrological climate impact indicators by SMHI that is available via the Copernicus Data Store [16] to assess the projected changes in river discharges due to climate change, modelled using a European-wide hydrological model forced with climate models. Catchment-level data used are from E-HYPEcatch model, with a resolution of the catchment-level data approx. 0.11 degrees (5-10 km).

The following variables are used:

- daily timeseries of river discharges for a historical period to assess the variation in discharge and compare to local observations;
- monthly means of catchment-level river discharges to assess the seasonal changes in river discharges in the historical and future climates;
- extreme river discharges for different return periods and their relative changes for different climate models, climate scenarios and timeframes (early-, mid- and end-century) to assess potential changes in flood hazard.

Relative change of extreme river discharges is analised for 2, 5, 10, 50 year return periods and for the following timelines:

- early century (2011-2040)
- mid-century (2041-2070)
- end-century (2071-2100)

For each time period, climate scenarios RCP4.5 and RCP8.5 (mean values over a 30-year time period) has been considered. Relative increases in flood recurrence for these periods are expressed relative to the reference period (1971-2000).

3.2.1. Validation in Selected Sub-Basins

In order to deepen the hazard analysis on Foglia case study and test the robustness of the results on Marche region territories, the discharge validation work flow has been tested on four different regional basins, where longer flow data series were available.

This supplementary notebook has been built to demonstrate how the modelled discharges dataset can be compared to local observations. This comparison is important to check how well the modelled data corresponds to the observations, in order to assess the accuracy of the modelled values for the specific location.

Historical daily time series (1991-2005) and monthly means of river discharges for 1971-2000 from the hydrological EHYPEcatch model, which are useful for checking longer-term statistics of river discharges in the historical climate, and monthly means of discharges for future periods of 2011-2040, 2041-2070 and 2071-2100 were downloaded and scenarios for 2, 5, 10 and 50 years return period analysed.

Then E-HYPE subbasin related to regional points of interest were identified.

The coordinates of the locations of regional stations were slightly modified to select the most appropriate E-HYPE catchments (**Figure 10**).

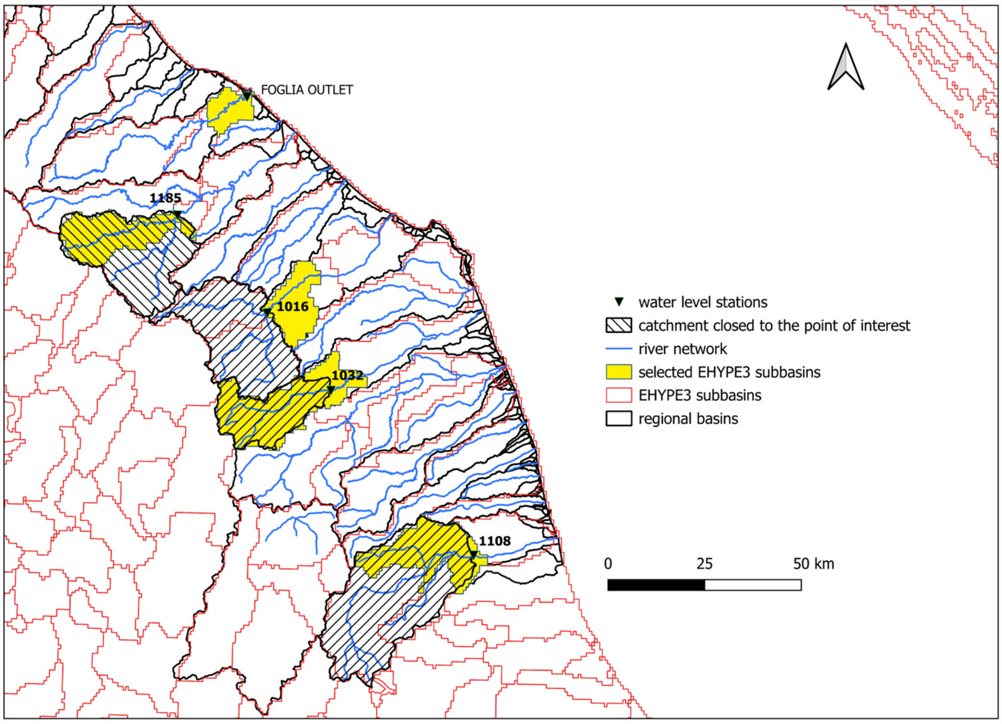


Figure 10. regional water level stations localization and related selected E-HYPE subbasins.

Foglia watershed and regional water level station (WL) outlets (from North to South) were associated to the following E-HYPE ID subbasins:

- Foglia watershed: code ID 9001103;
- Acqualagna WL n. 1185: code ID 9000605;
- Camponocecchio WL n. 1016: code ID 9000602;
- San Severino WL n. 1032: code ID 9000601;
- Brecciarolo WL n. 1108: code ID 9744229.

Local daily discharge time series, estimated by rating curve from water level recorded data, could be freely downloaded through SIRMIP on – line platform [16]

For Acqualagna site, data are available from year 1923 to 1979 and from 2007 to 2025, for Camponocecchio, and Brecciarolo from 2005 to 2025, for San Severino from 2010 to 2025. Validation results on Acqualagna site, the closer station to Foglia outlet also in terms of climatology, seem to be encoraging in order to adopt CLIMAXX discharge work flow methodology also for Foglia case study. The validation plots obtained on these four stations are shown in **Annex A.**

3.2.2. Application to the Foglia Watershed

In the following, the obtained results, executing the CLIMAXX river flood “discharge” work flow, in terms of future scenarios for Foglia basin outlet are reported.

Table 3. Monthly median (and mean) river discharge change (%) for different scenarios and different return periods.

Month	Historical 1971-2000 [m³/s]	RCP4.5			RCP8.5		
		2011-2040	2041-2070	2071-2100	2011-2040	2041-2070	2071-2100

		median % (mean %)	median % (mean %)	median % (mean %)	median % (mean %)	median % (mean %)	median % (mean %)
January	9.68	+15.3	+19.5	+14.3	+12.4	+23.5	+12.2
	(9.98)	(+17.3)	(+16.5)	(+9.7)	(+17.5)	(+29.2)	(+8.7)
February	12.50	+8.9	+11.6	+0.3	−2.7	+19.3	−4.9
	(12.71)	(+15.5)	(+8.7)	(+9.9)	(−5.4)	(+23.0)	(−7.6)
March	9.96	−1.6	−5.0	−11.8	+9.8	+5.0	−19.3
	(10.75)	(+1.4)	(−4.8)	(−5.2)	(+6.0)	(+3.8)	(−21.8)
April	5.97	−5.5	−9.1	−11.3	+19.0	+1.1	−8.0
	(6.45)	(−8.4)	(−8.1)	(−14.0)	(+21.2)	(+6.0)	(−2.5)
May	3.10	+6.2	+0.6	−15.1	+4.6	−11.9	−16.6
	(3.16)	(+2.1)	(+2.5)	(−16.7)	(+5.6)	(−7.9)	(−19.5)
June	2.08	−11.4	+14.1	+11.4	+7.0	+7.3	−6.5
	(2.48)	(+1.8)	(+21.0)	(+19.7)	(+7.2)	(+16.9)	(−0.8)
July	1.24	−10.7	−11.8	−32.0	+5.5	−4.8	−47.0
	(1.24)	(+16.7)	(−5.9)	(−26.0)	(+3.3)	(−0.6)	(−30.4)
August	1.21	+24.6	−7.1	−11.6	+26.5	+57.6	+11.5
	(1.17)	(+21.0)	(−8.9)	(−2.7)	(+40.7)	(+75.2)	(+20.6)
September	3.24	+11.4	+9.9	−3.1	+10.0	−11.2	+9.9
	(3.60)	(+7.8)	(+5.9)	(+40.5)	(+21.6)	(+5.7)	(+27.3)
October	6.76	−9.0	−18.8	+0.9	+8.1	−26.6	+10.2
	(6.68)	(−8.2)	(−23.3)	(+7.8)	(+2.1)	(−11.4)	(+8.5)
November	12.28	+1.8	−2.2	+4.4	+20.1	+29.0	−4.3
	(12.30)	(+1.6)	(+0.1)	(+3.9)	(+18.8)	(+30.7)	(+5.6)
December	12.47	+0.6	+6.0	+10.9	−4.0	+4.2	−3.3
	(13.13)	(+2.4)	(+19.1)	(+11.5)	(+1.2)	(+19.2)	(−2.5)

Note: + indicates increase, − indicates decrease relative to 1971–2000 historical median (mean).

Analyzing the extreme scenarios for different return periods in terms of quantitative discharge [m^3/s] (**Figure 11**) and in terms of relative change in projected extreme values [%] (**Figure 12**), a positive trend is shown both for rcp4.5 and 8.5. Data are provided as the 2, 5, 10 and 50 year return period of annual daily maximum river discharge estimated using a Gumbel distribution. For future periods the indicator is given as a relative change against the reference period (1971-2000).

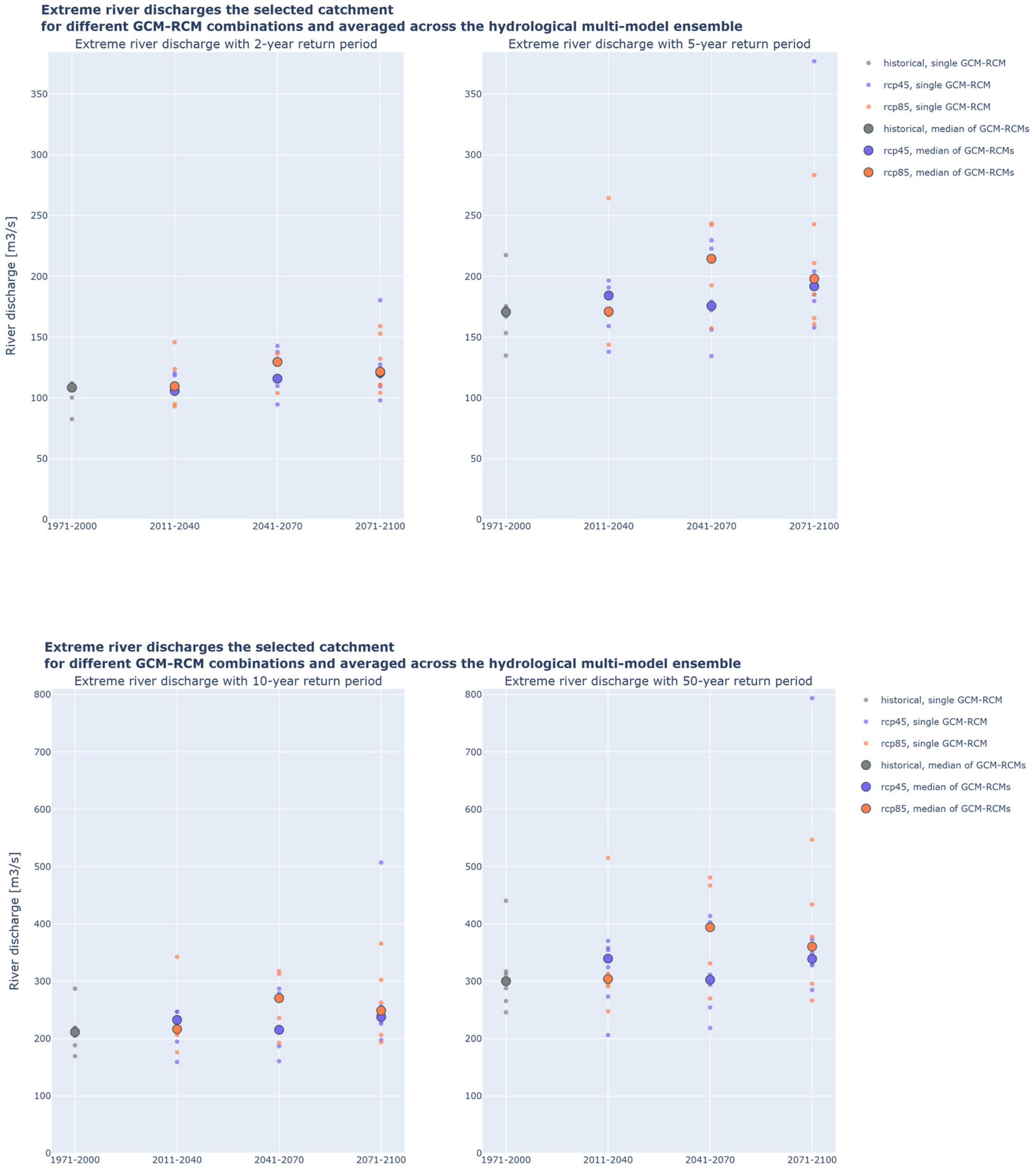


Figure 11. Extreme river discharge (m3s-1) for Foglia basin. Top: 2 years return period (left) and 5 year return period (right); Bottom: 10 years return period (left) and 50 years return period (right).

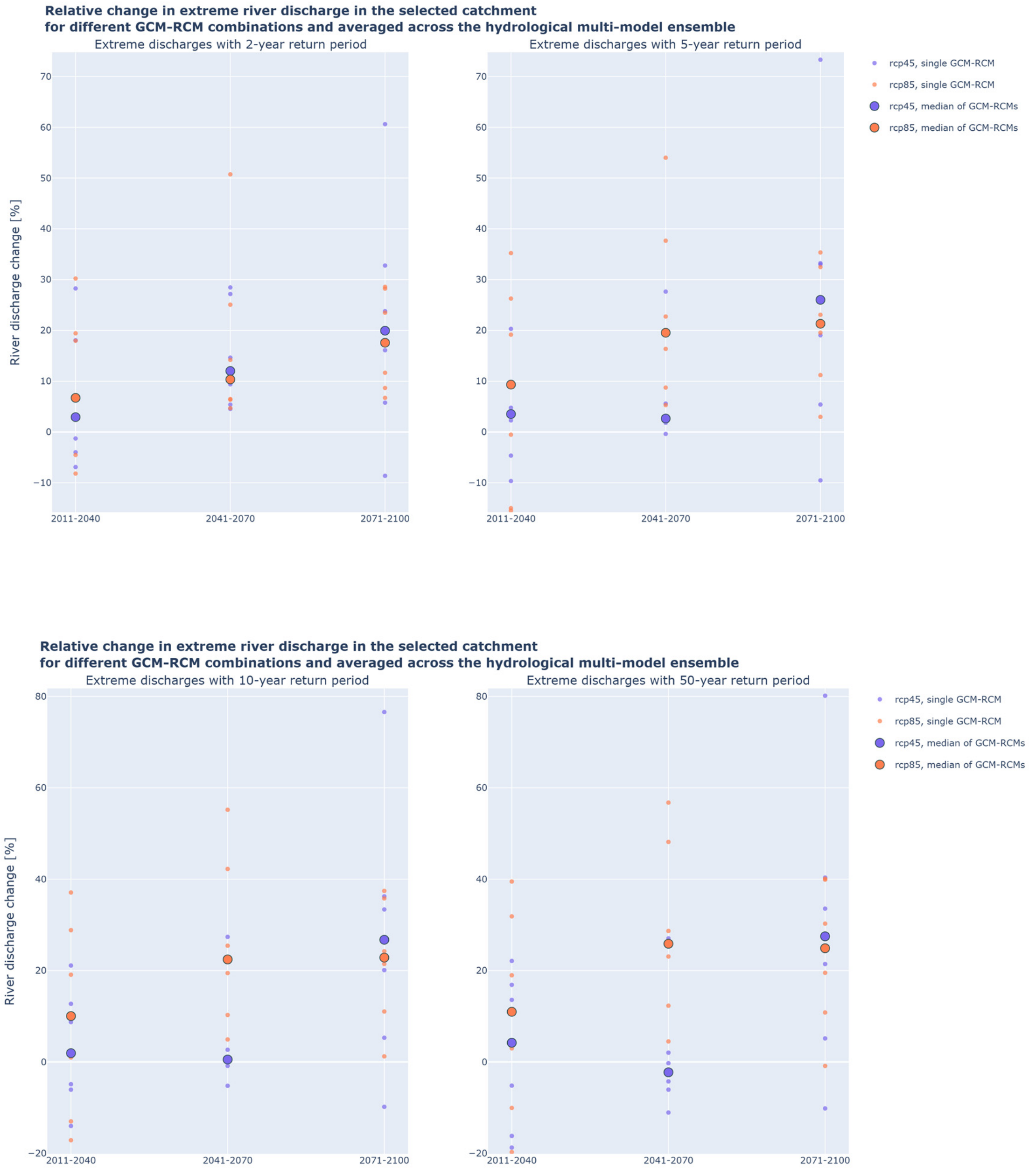


Figure 12. Extreme river discharge (%) for Foglia basin. Top: 2 years return period (left) and 5 year return period (right); Bottom: 10 years return period (left) and 50 years return period (right).

Climate scenarios are similar for 2011-2041 and 2071-2100 periods. A highest increase for rcp 8.5 is shown for 2041-2070, followed by a decrease for 2071-2100 period. Uncertainty seems higher for 2071-2100 period.

Looking over at the monthly results (**Figure 13**), winter months (December, January, February) show a general wetter trend, spring months (March, April May) a drier one, probably due to a lower contribution of snow melting.

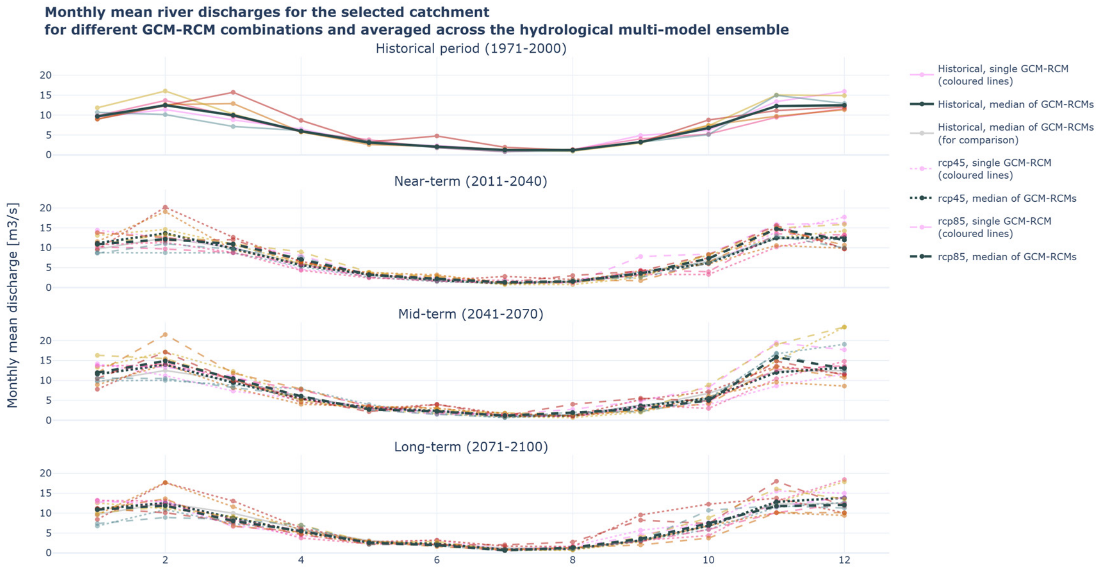


Figure 13. Monthly mean river discharges [m^3/s] – Foglia basin: 12 months simulation for each climate scenario.

Figure 14 allows in order to better understand the future monthly discharge trend and the correlated variability. Highest uncertainty and change in percent are shown for summer months, in particular in August.

Figure 14. Monthly mean river discharges – Foglia outlet: single month analysis in [%] for all scenarios.

A general quite similar trend is shown also for Acqualagna site, which represents the best match of modelling with observation, in the closest analyzed part of the region.

4. Discussion

The application of the CLIMAAX climate risk assessment toolbox to the Foglia River mouth highlights several relevant insights regarding both the methodological robustness of the tool and its potential contribution to regional adaptation planning. Overall, the combined use of hazard- and exposure-oriented workflows provides a coherent framework for identifying risk hotspots in complex urban–coastal contexts, yet the results also underline the importance of locally refined datasets and the need for iterative, context-sensitive assessments.

A first key finding concerns the contrast between high resolution local flood maps and continental-scale JRC products. While JRC maps offer homogeneous coverage and facilitate rapid preliminary assessments, their coarse resolution and lack of representation of small-scale hydraulic controls (bridges, embankments, walls) lead to a marked overestimation of flood extent and, consequently, of economic damage. This discrepancy is evident in the pilot area, where damage estimates for the 10-year event range from ~1.1 M€ (local maps) to over 72 M€ (JRC maps). Such differences confirm that data accuracy remains a fundamental determinant of flood-risk quantification, particularly in highly urbanized settings where drainage structures and micro-topography strongly influence inundation patterns. The implication is clear: high-resolution, site-specific hazard layers should be prioritized whenever possible for urban adaptation planning.

Nevertheless, it must be underlined that the inundation maps used for this case study, were realized inside STREAM project with the aim to produce daily forecast scenarios inside an operative chain, implementing a simplified hydraulic model. An optimal implementation of this analysis would rely on official inundation maps for different return periods, produced by the Italian Central Apennines District Basin Authority (competent authority for the Foglia watershed); however, these maps are not yet available.

It is important to stress that the estimated economic losses represent the cost of inaction, that is, the direct damages that may occur in the absence of additional adaptation measures. These values should therefore be interpreted as an indication of the potential financial burden that municipalities and communities may face if current conditions remain unchanged. At the same time, the quantification of damages must be considered indicative rather than literal, as it serves primarily to clarify the order of magnitude of potential losses. Uncertainties arise both from the climate component—particularly the variability inherent in future discharge projections—and from methodological factors. These include simplifications in the estimation of direct building damages and, especially, the exclusion of several cost categories that typically follow flood events, such as debris removal, restoration of road networks, and repair of water supply, sewage, and drainage infrastructure. Consequently, the figures presented should be interpreted as a conservative approximation of the broader socio economic impacts associated with river flooding in the study area.

The analysis of population shows that, even with conservative hazard estimates, more than 3,000 people are potentially exposed to a 10-year flood event, and displacement grows significantly with return period, surpassing 1,300 individuals for a 500-year scenario. These values demonstrate that Pesaro’s coastal fringe remains structurally vulnerable despite the absence of critical infrastructures in flood-prone zones. The concentration of exposure around the river meanders and at the river mouth suggests that small variations in hazard extent may strongly affect social vulnerability, which further supports the need for accurate local modelling and updated demographic layers.

The integration of the River Discharge workflow provides additional insights, especially concerning long-term climate-driven changes in hydrological extremes. Although the Foglia Basin lacks long continuous discharge records for full validation, the parallel analyses conducted on four regional basins help assess model reliability. Results show that modelled climatology broadly matches observations, particularly in northern basins and when merged long-term datasets are used. Despite some underestimation of monthly discharges in certain seasons, the general agreement supports the applicability of E HYPE-based climate scenarios to the Foglia Basin.

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Future river discharge projections indicate an increase in extreme flow magnitudes across most return periods and climate scenarios, especially toward mid- and late-century horizons. These trends align with broader Mediterranean projections, where intensification of short-duration, high-intensity rainfall events is expected to amplify fluvial flood hazards. Although the River Discharge workflow does not directly produce inundation maps, the derived relative changes in extreme flows offer a meaningful basis for estimating potential variations in flood frequency and severity and for prioritising proactive adaptation measures. Furthermore, monthly mean discharge scenarios show a variation on water resource availability that could suggest a different planning on water exploitation, especially to face drought periods.

5. Conclusions

This study demonstrates the value of the CLIMAAX climate risk assessment toolbox in supporting river flood risk analysis and informing adaptation planning in complex urban–coastal environments such as the Foglia River mouth in Pesaro.

The integrated use of hazard and exposure workflows proved effective in identifying spatial hotspots of risk and quantifying potential economic and social impacts under different return periods. Although the comparison between continental-scale flood maps and locally refined hydraulic simulations highlights the crucial role of high resolution, context-specific data, the broader methodological framework provided by CLIMAAX offers a transparent and replicable basis for climate risk evaluation at the local level.

The analysis also shows that the projected intensification of extreme river discharges under future climate scenarios may exacerbate existing vulnerabilities. Even though the River Discharge workflow does not directly generate future inundation maps, the relative increase in flow extremes provides essential indications for anticipating how flood frequency and severity may evolve throughout the century. When combined with exposure assessments, these insights reinforce the need for proactive, long term adaptation strategies, ranging from land use regulation to infrastructure upgrades and the design of nature based solutions.

Overall, the results highlight the importance of embedding scientific risk assessments into regional and municipal planning processes. Beyond quantifying current and future flood impacts, the pilot application serves as a testing ground to understand which components of climate risk analysis can be effectively integrated into territorial planning instruments, including hazard indicators, exposure metrics and scenario-based assessments. This experimentation also supports the development of operational tools, such as guidelines for climate proofing plans and projects, and standardised procedures for evaluating their climatic consistency. Embedding these elements into planning practice contributes to making risk-informed decisions more systematic, transparent and comparable across administrative levels. This approach is fully coherent with the adaptation measures foreseen by the Regional Plan for Adaptation to Climate Change (RPACC), which explicitly promotes the strengthening of climate risk analysis within spatial planning and sectoral governance.

Beyond the specific results, this study also highlights the strategic role of European cooperation projects in supporting institutional learning and policy innovation for climate adaptation. For regional administrations such as the Marche Region, EU-funded initiatives provide structured opportunities for cross-sectoral collaboration, methodological experimentation, and capacity building across departments dealing with climate change, civil protection, sustainable development and international cooperation.

The insights gained through the pilot therefore contribute not only to the reduction of local flood vulnerability, but also to the institutionalization of climate aware territorial planning across the Marche Region. Modern strategy in flood planning must take into account not only return period "classic" scenarios but also the climate change impact on water resources, economic aspects and the uncertainty linked to the future forecast extreme trend.

Author Contributions: "Conceptualization, F.S. and G.G.; methodology, F.S. and G.G.; software, M.E. and S.R..; validation, F.S., S.R. M.E.. and G.G.; formal analysis, F.S., G.G. M.E. and S.R.; investigation, F.S., G.G. M.E. and S.R.; resources, F.S., G.G. M.E. and S.R.; data curation, F.S., G.G. M.E. and S.R.; writing—original draft preparation, G.G. and F.S.; writing—review and editing, G.G., F.S., PP, N.B., M.E., and S.R; visualization, M.E. and S.R.; project administration PP, N.B., F.S. and G.G.; funding acquisition, PP, NB.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CPI	Consumer Price Index
GHSL	Global Human Settlement Layer
JRC	Joint Research Centre
RPACC	Regional Plan for Adaptation to Climate Change

Appendix A

In the following the validation for the discharge workflow for the four selected sites, namely: Acqualagna, Camponocecchio, San Severino Brecciarolo is shown.

As for Acqualagna two local historical data series were available, one "ante" and one "post" the modelled period, the differences of result using only the recent one and merging of the two data series were investigated.

A better agreement between models and observations is found in the northern basins, in particular merging the two observations datasets at Acqualagna point of interest. In general models simulated a lower monthly discharge, especially from January to September. Flow duration curves data are quite similar to the observed data, in particular for Acqualagna merged observed dataset.

Even if it is evident the limit of the comparison using different period of data and lightly different domains, results provide an agreement in terms of climatology on studied areas.

Some spreading between model results can be seen zooming the flow duration curve in the period 1991-2005.

The obtained results in terms of future scenarios for Acqualagna, Camponocecchio, San Severino and Brecciarolo are also reported.

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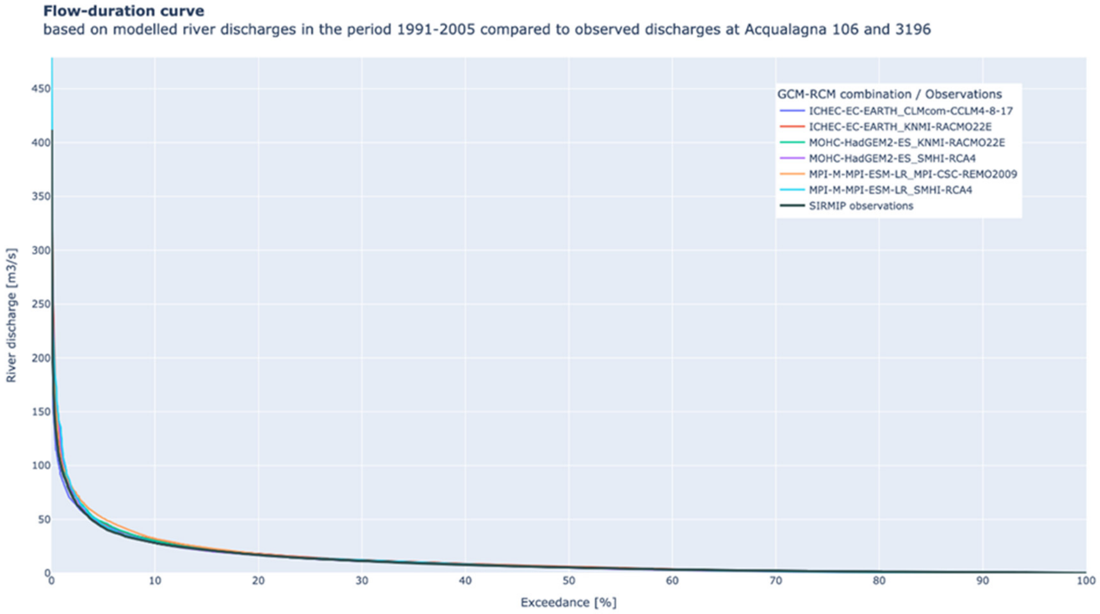


Figure A1. Flow duration curve – Acqualagna observation dataset from 1923 to 1979 and from 2007 to 2025 (merged dataset).

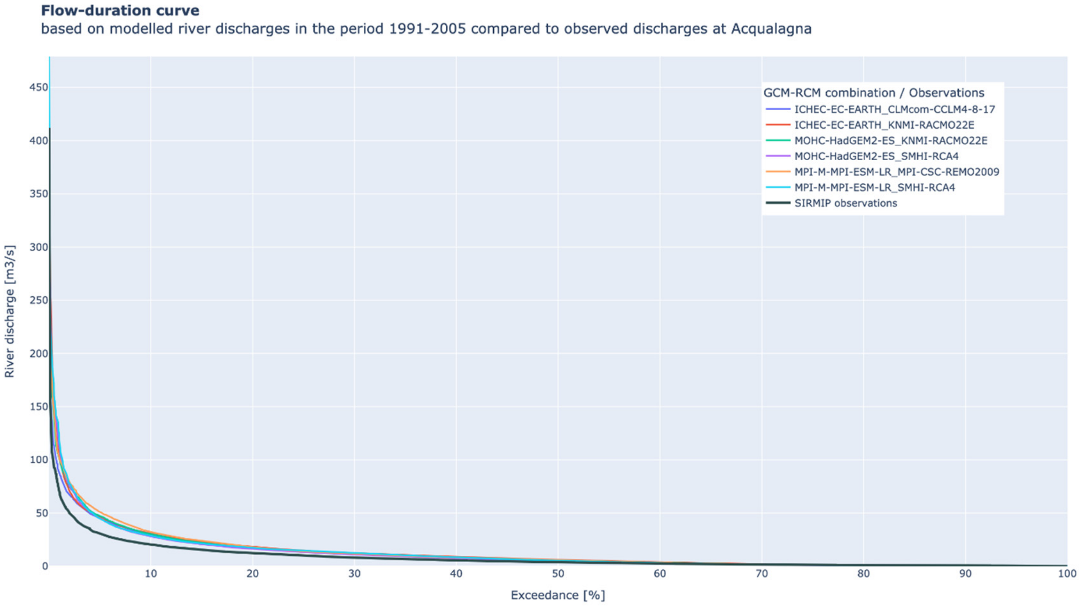


Figure A2. Flow duration curve – Acqualagna observation dataset from 2007 to 2025.

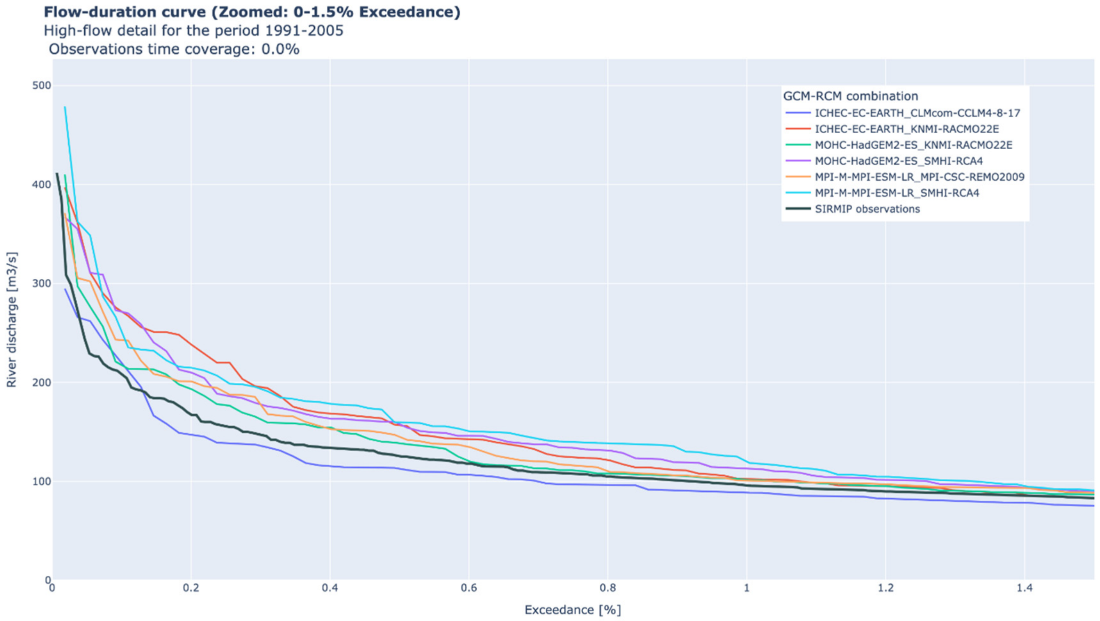


Figure A3. Acqualagna flow duration curve – zoom on uncertainty range and observation (merged dataset).

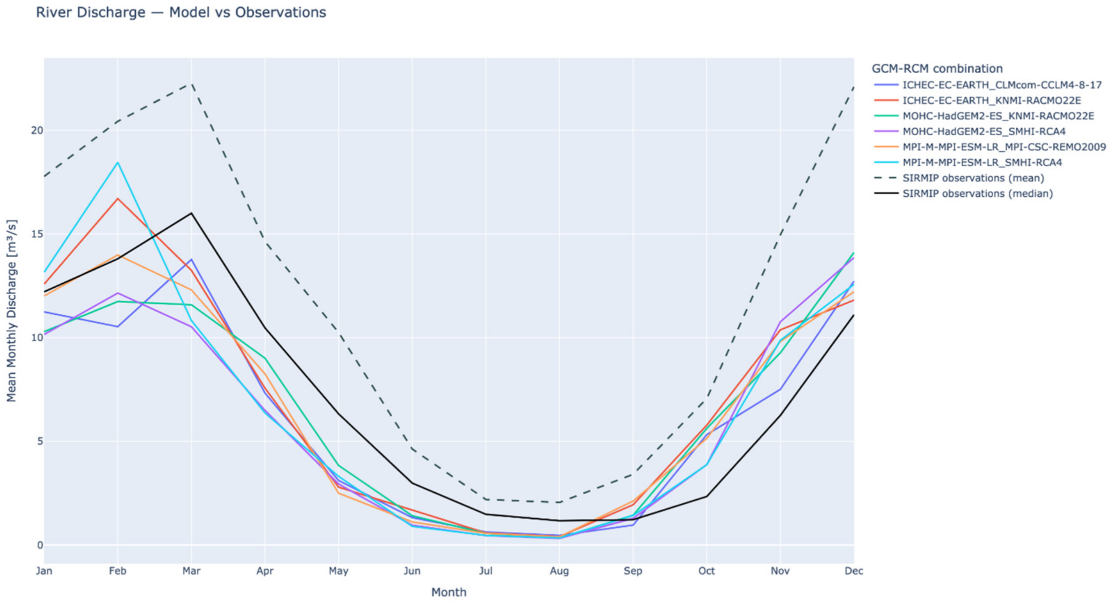


Figure A4. Monthly mean river discharges for Acqualagna (merged dataset).

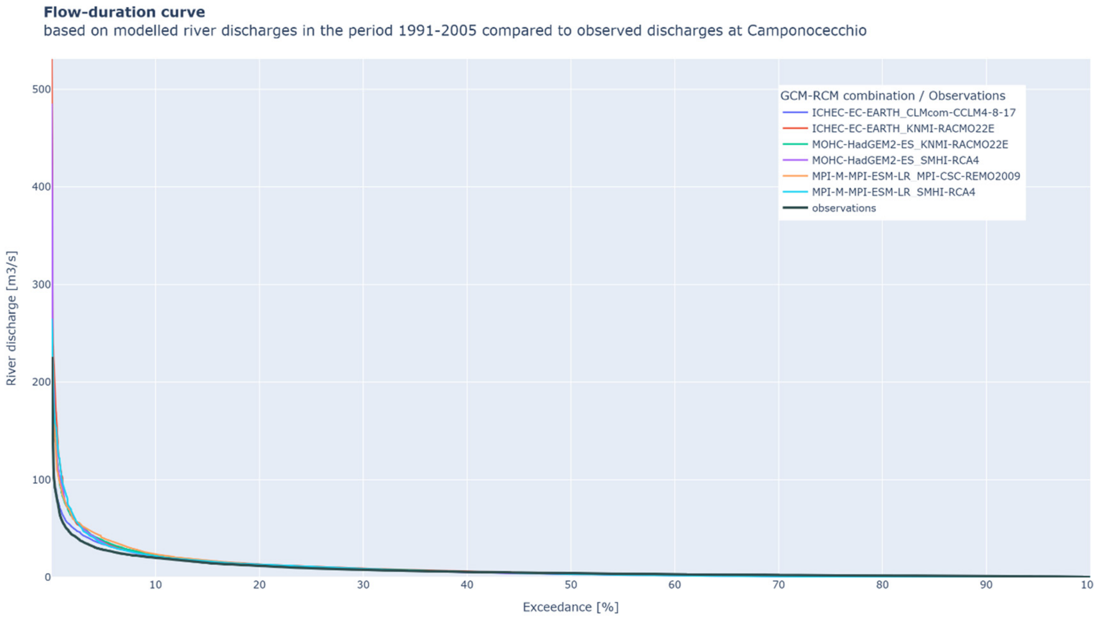


Figure A5. Flow duration curve – Camponocecchio observation data set from 2005 to 2025.

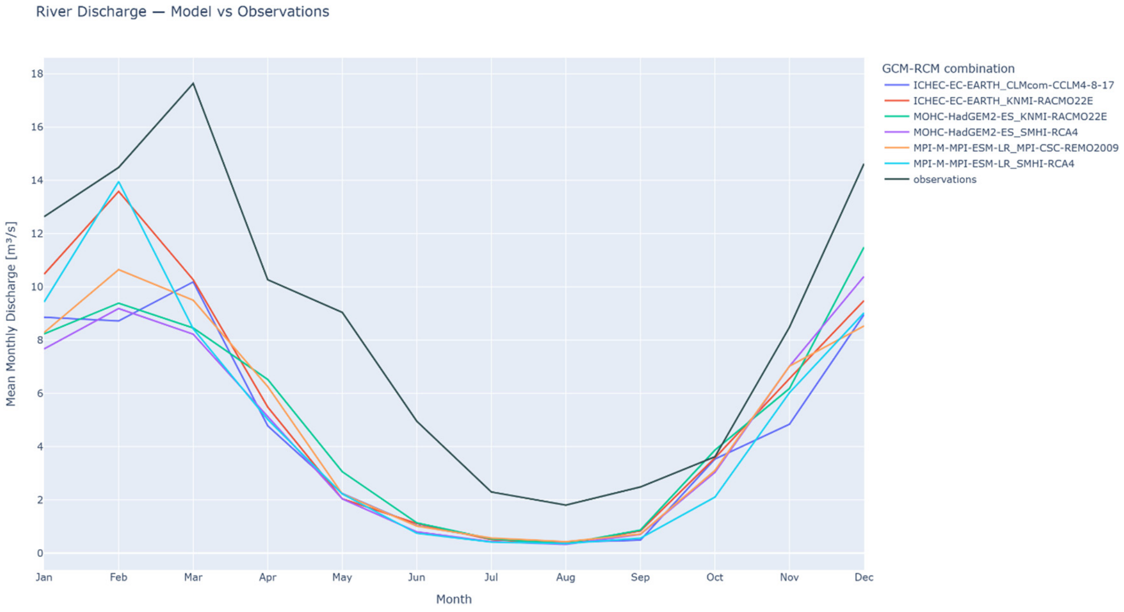


Figure A6. Monthly mean river discharges for Camponocecchio catchment for different GCM-RCM 1991-2005) compared to observations from 2005 to 2025.

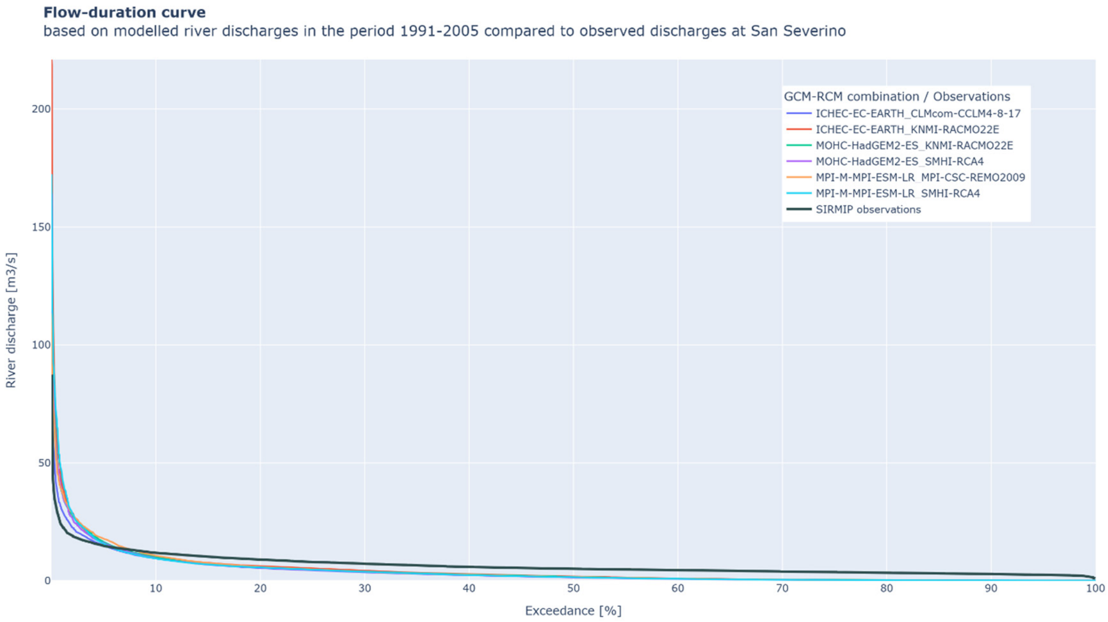


Figure A7. Flow duration curve – San Severino observation dataset from 2010 to 2025.

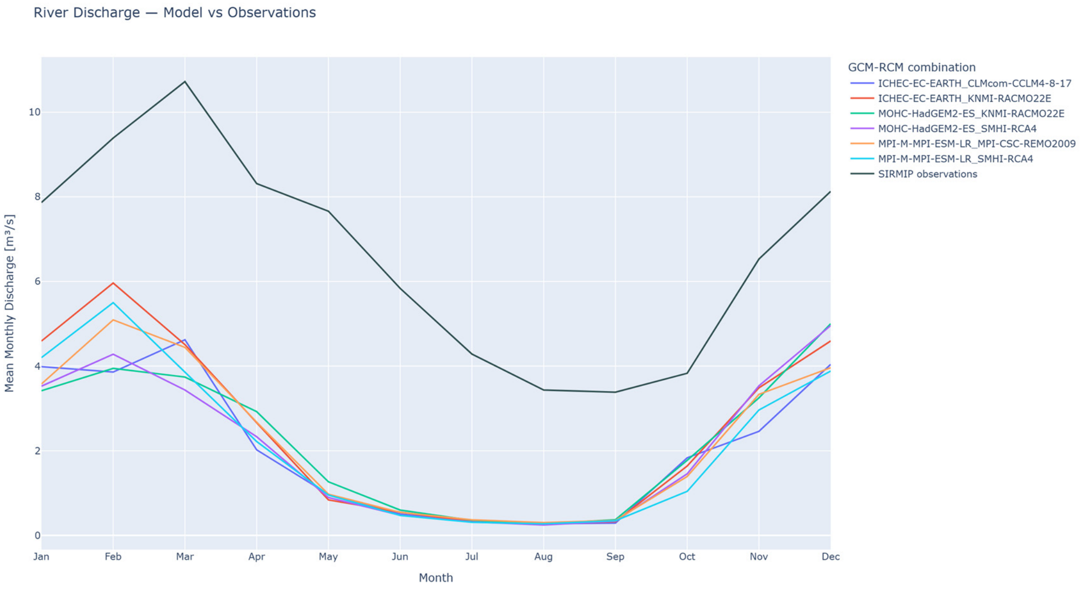


Figure A8. Monthly mean river discharges for San Severino catchment for different GCM-RCM 1991-2005) compared to observations from 2010 to 2025.

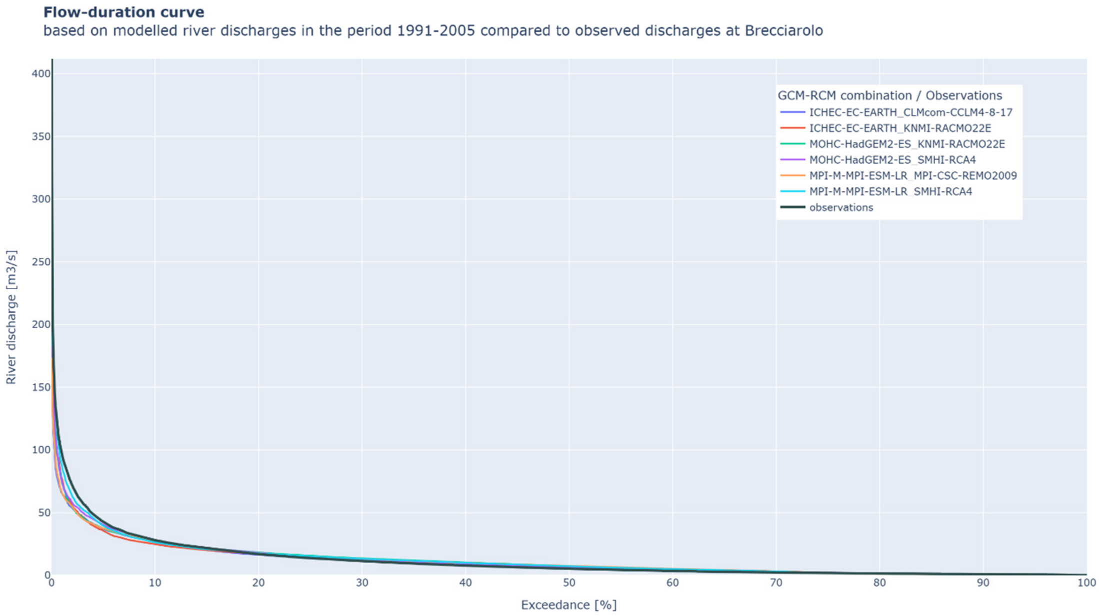


Figure A9. Flow duration curve – Brecciarolo observation data set from 2005 to 2025.

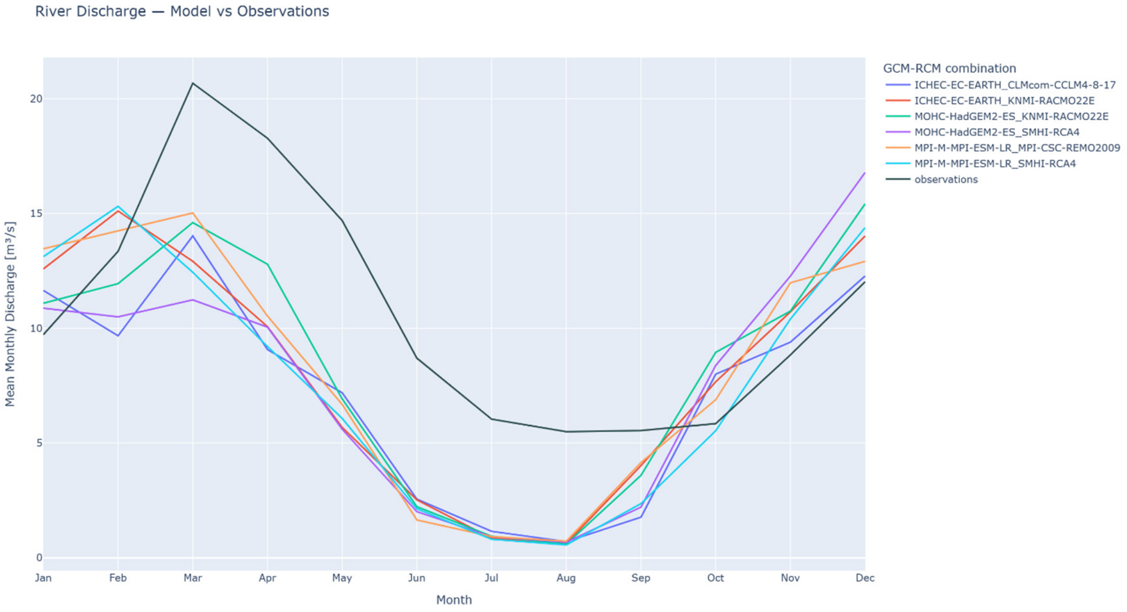


Figure A10. Monthly mean river discharges for Brecciarolo catchment for different GCM-RCM 1991-2005) compared to observations from 2005 to 2025.

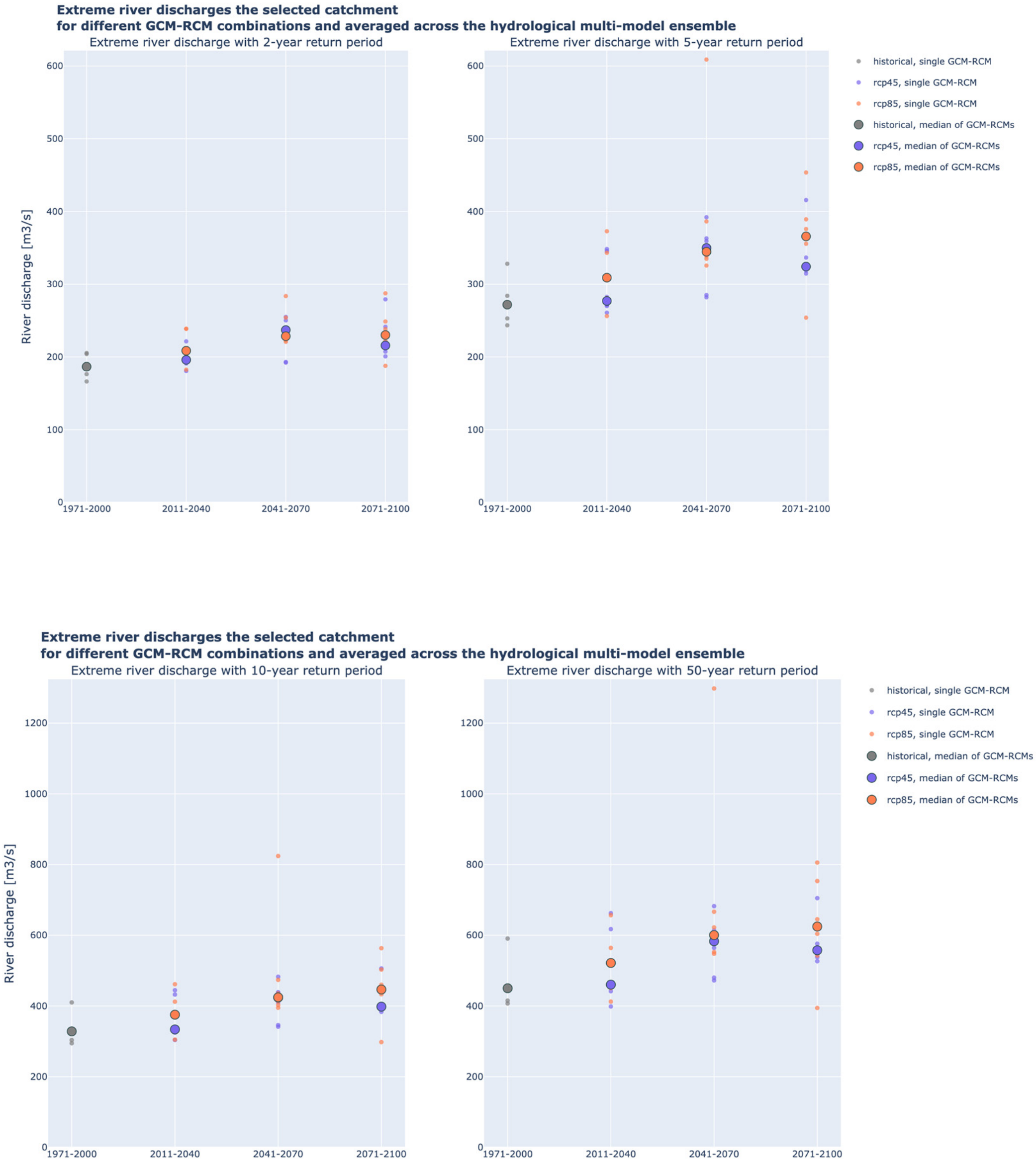


Figure A11. Extreme river discharge (m3s-1) for Acqualagna point of interest Top: 2 years return period (left) and 5 year return period (right); Bottom: 10 years return period (left) and 50 years return period (right).

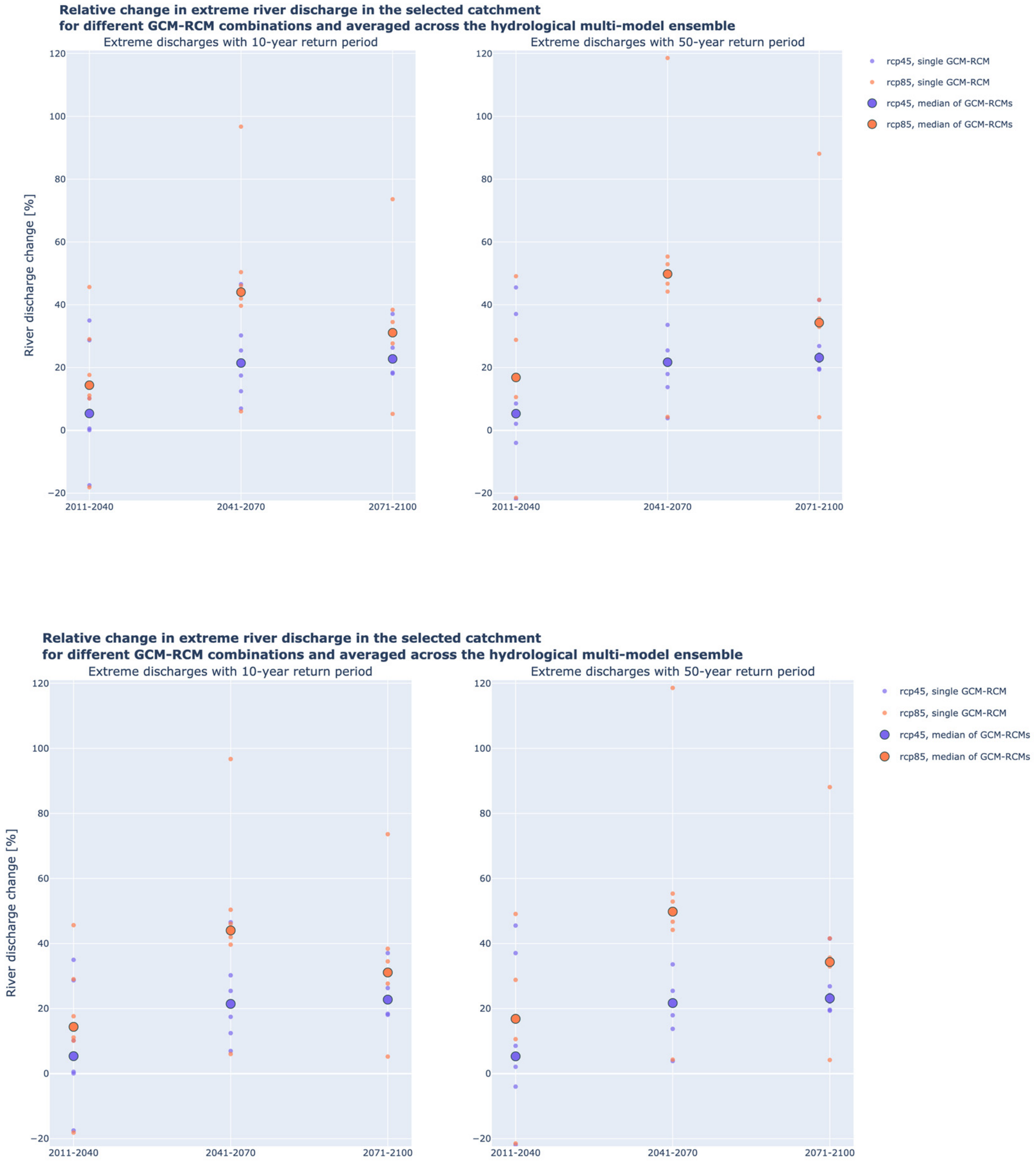


Figure A12. Extreme river discharge (%) for Acqualagna point of interest Top: 2 years return period (left) and 5 year return period (right); Bottom: 10 years return period (left) and 50 years return period (right).

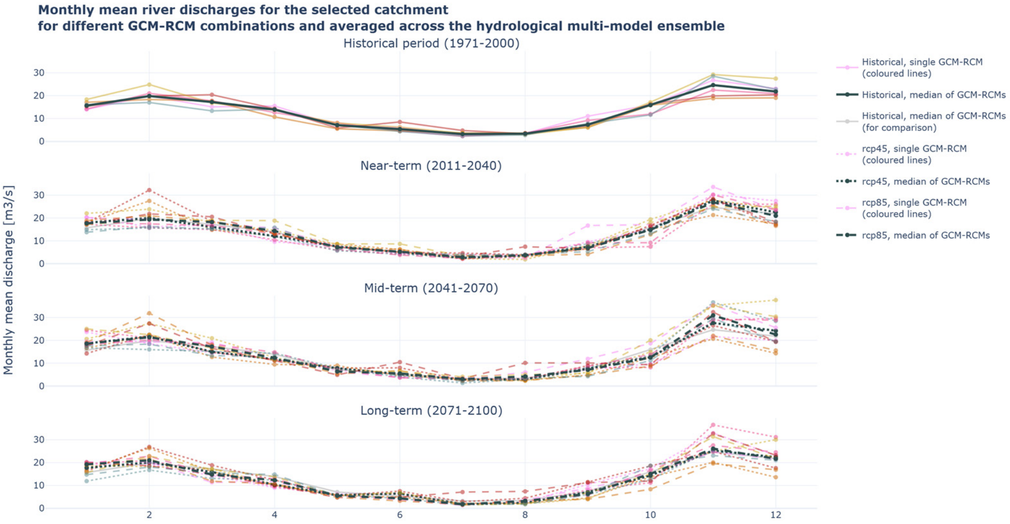
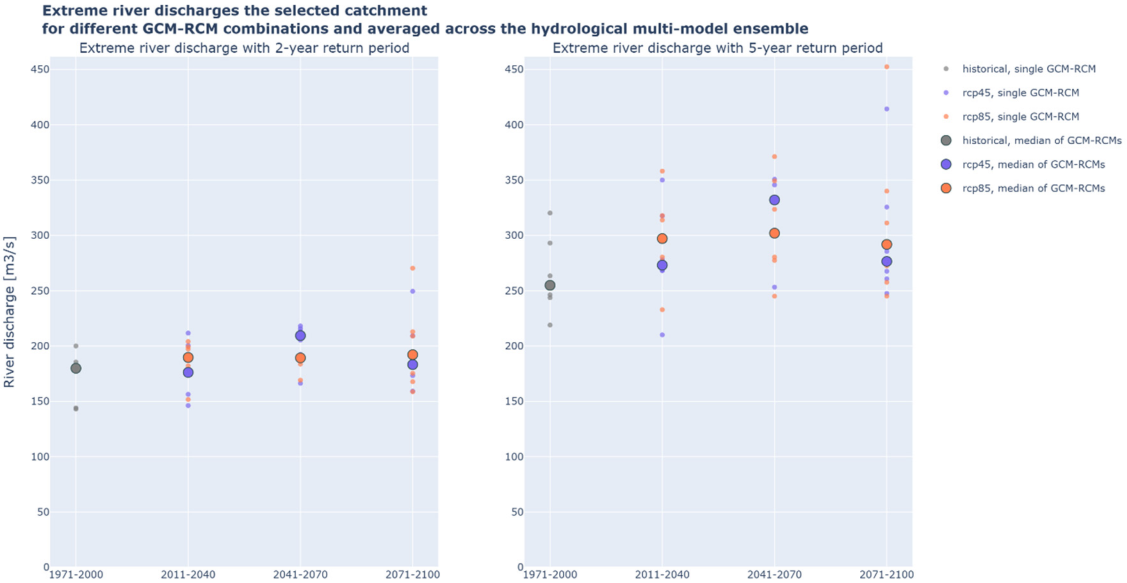


Figure A13. Monthly mean river discharges – Acqualagna point of interest: 12 months simulation for each climate scenario.



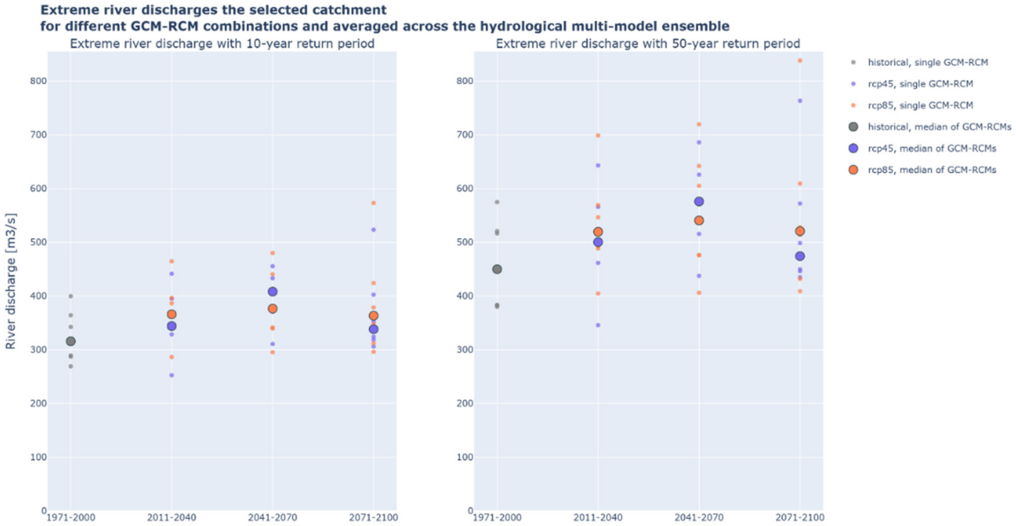


Figure A14. Extreme river discharge (m3s-1) for Camponocecchio point of interest Top: 2 years return period (left) and 5 year return period (right); Bottom: 10 years return period (left) and 50 years return period(right).

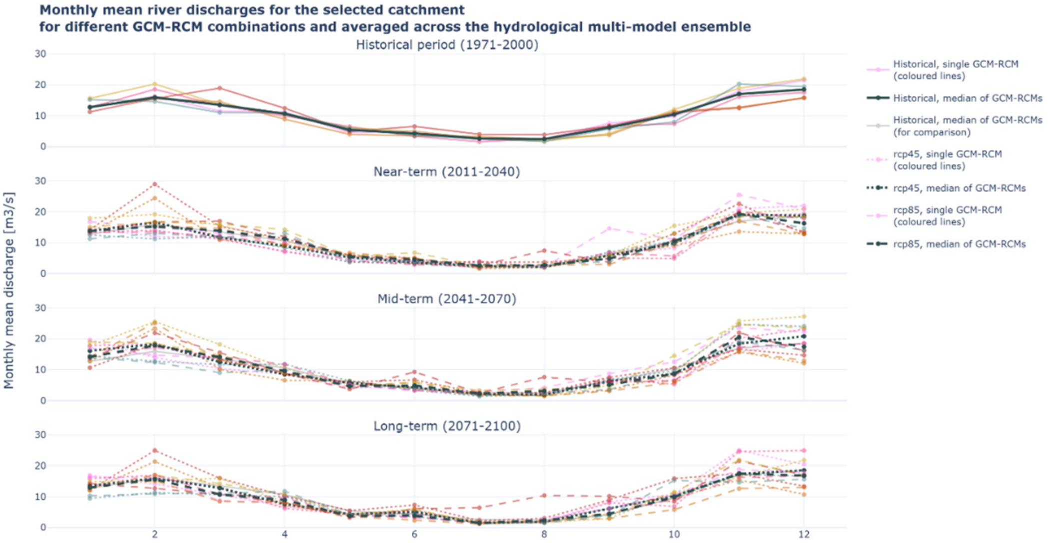


Figure A15. Monthly mean river discharges – Camponocecchio point of interest: 12 months simulation for each climate scenario.

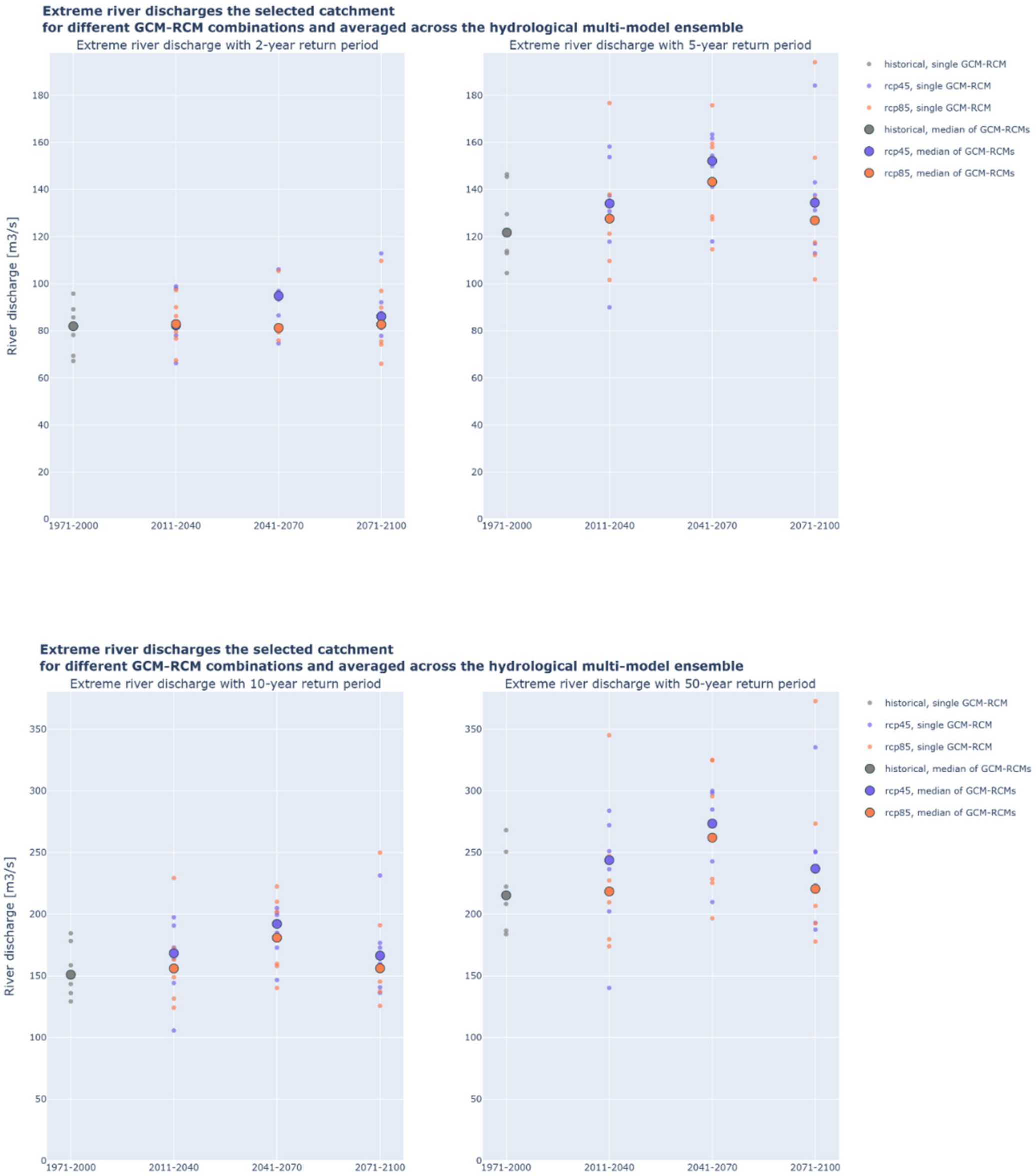


Figure A16. Extreme river discharge (m3s-1) for San Severino point of interest Top: 2 years return period (left) and 5 year return period (right); Bottom: 10 years return period (left) and 50 years return period (right).

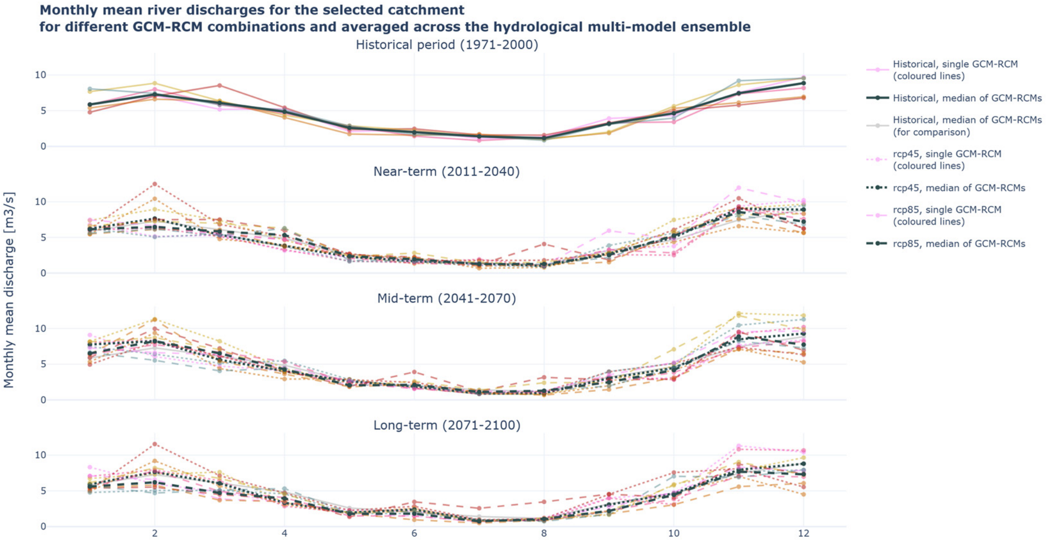
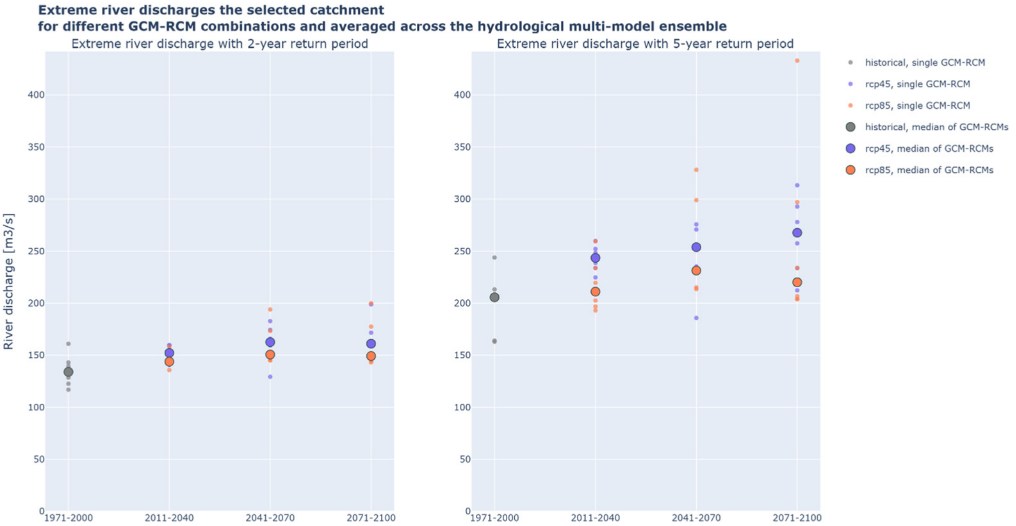


Figure A17. Monthly mean river discharges – San Severino point of interest: 12 months simulation for each climate scenario.



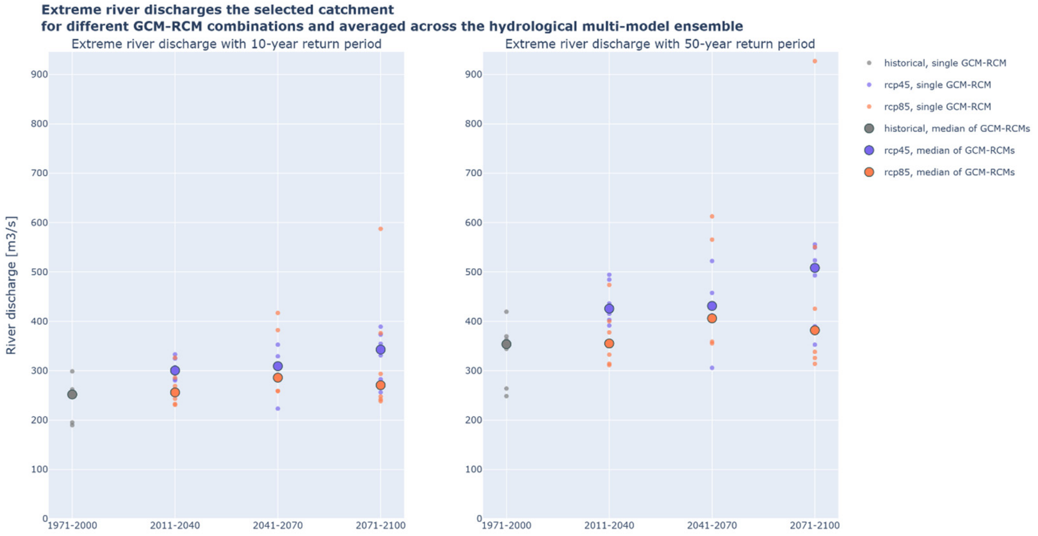


Figure A18. Extreme river discharge (m3s-1) for Brecciarolo point of interest Top: 2 years return period (left) and 5 year return period (right); Bottom: 10 years return period (left) and 50 years return period (right).

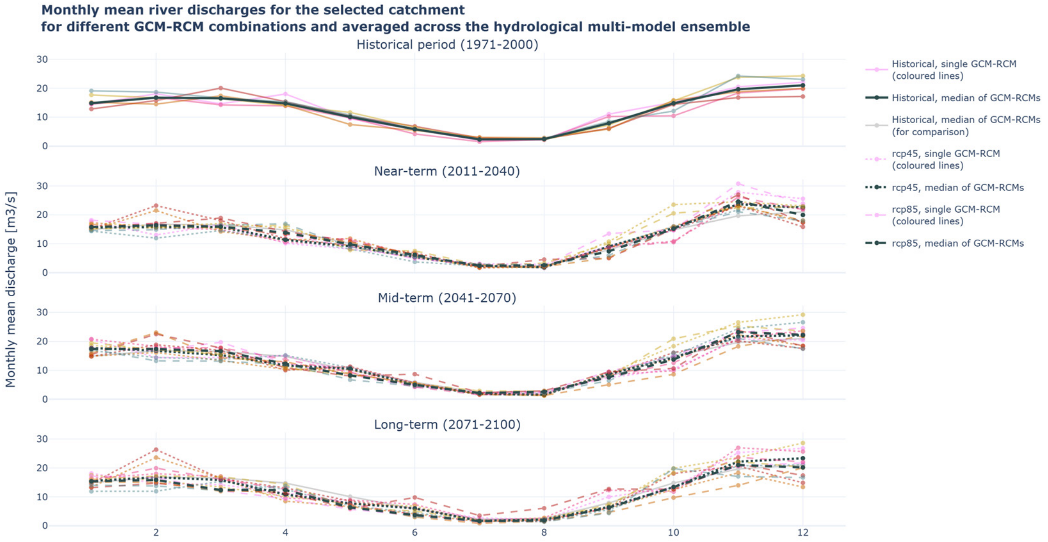


Figure A19. Monthly mean river discharges – Brecciarolo point of interest: 12 months simulation for each climate scenario.

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