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MASTER THESIS

TITLE in English

A semi-distributed rainfall-runoff model for the simulation and prediction of daily flows in the Po River basin

TITLE in Italian

Un modello afflussi-deflussi semi-distribuito per la simulazione e la previsione dei deflussi giornalieri nel bacino del fiume Po

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Chapter 1: Introduction

1.1 Background and context

Many environmental and socio-economic processes, including water supply, irrigation, ecosystem balance, hydropower production, and flood and drought management, are affected by river flows. Therefore, hydrological modelling has become an important tool for analysing river behaviour by understanding and predicting river flows. This is important for water resources management and to support decision-making, especially in large and complex river basins (Beven, 2012).

Different approaches are being used in hydrology, among which rainfall–runoff models are widely applied to describe how precipitation is transformed into streamflow. These models are especially useful when the objective is to simulate river discharge over time and to evaluate how a basin may respond under different hydro-climatic conditions. These hydrological models range from simple lumped approaches to more detailed distributed frameworks. Among these, semi-distributed models provide a balance between physical representation and modelling efficiency, as they consider the spatial variability within the basin while avoiding the complexity of a fully distributed model.

Changes in precipitation patterns, temperature, and the frequency of extreme events as a result of climate change may affect the hydrological response of river basins in different ways, such as the average water availability or the timing and intensity of river flows. As a result, the need for a reliable hydrological model that is able to simulate basin response under both observed and perturbed conditions is even more important, especially in the case of complex basins.

The Po River basin can be mentioned as a complex basin considering the fact that it is the largest river basin in Italy that has a major hydrological, economic, and environmental importance, and also that a combination of climatic and physiographic factors, including alpine snow processes, rainfall-driven runoff, internal storage, and human-related water use, is influencing its behaviour. Therefore, to simulate daily river flow in the Po basin, a modelling framework capable of considering both the main hydrological processes and the spatial variability of the basin should be applied (Camici et al., 2014).

Within this framework, the present study focuses on the application of the MISDc semi-distributed conceptual rainfall–runoff model to simulate and predict daily flows in the Po River basin (Brocca et al., 2011; Camici et al., 2025). The model setup used in this thesis was provided within the research framework of Prof. Montanari's group, and the present work was carried out in collaboration with this team. The study first evaluates the reliability of the model under historical conditions and then uses it to investigate the effect of climatic scenarios on river discharge. In this way, the aim of this thesis is to provide a better understanding of basin response under hydro-climatic stress and climate-related impacts on water resources.

1.2 Problem statement

In large basins, like the Po River basin, that are characterised by spatial variability and interacting hydrological processes, streamflow is influenced not only by precipitation, but also by snow accumulation and snowmelt, soil water storage, flow routing through the river network, and, in some cases, water regulation and abstraction. This complexity makes it hard for simple modelling approaches to correctly simulate the daily river flow, while a highly detailed approach may require large amounts of data and become difficult to apply efficiently (Blöschl & Sivapalan, 1995; Tshimanga & Hughes, 2014).

It is even more challenging when the objective is also to analyse the basin's response under changing climatic conditions in addition to reproducing historical discharge. Changes in precipitation and temperature may lead to different responses, which are not always proportional to the applied perturbation. Therefore, a modelling framework that can represent internal basin processes and provide a consistent basis for comparing different scenarios is needed in order to understand basin sensitivity.

In the case of the Po River basin, considering the basin's size, hydro-climatic diversity, and socio-economic role, a reliable modelling framework is needed in order to evaluate whether the main features of the daily flow regime can be reproduced and to analyse how the basin may respond under climate-related stresses. For this reason, the present study focuses on the application of the MISDc semi-distributed conceptual rainfall–runoff model that can represent the main hydrological processes while remaining suitable for multi-scenario analysis at the basin scale.

1.3 Aim of the study

The main aim of this study is to evaluate the reliability of the MISDc semi-distributed conceptual rainfall–runoff model for the simulation and prediction of daily river flow in the Po River basin. More specifically, the study investigates whether the selected modelling framework is able to reproduce the main features of the observed daily flow regime at several control sections of the basin under historical conditions.

A second aim of the study is to use the same modelling framework to explore the response of the basin under climate-related perturbations. In particular, the model is applied to assess how river discharge may change under drying, warming, and extreme precipitation scenarios. Therefore, the focus of the study is on analysing the model performance and sensitivity under both the present condition and the modified hydro-climatic forcing condition.

Overall, the aim of this thesis is to provide a modelling-based assessment of daily flow behaviour in the Po River basin and to contribute to a better understanding of how a large and hydrologically complex basin may respond to climate-related stress.

1.4 Research objectives

The present study is developed around the following main objectives:

1. To describe the main hydrological and hydro-climatic characteristics of the Po River basin, with more attention to the factors that control daily river flow at the basin scale.

2. To apply the MISDc semi-distributed conceptual rainfall–runoff model to the Po River basin in order to simulate daily discharge at selected control sections.

3. To evaluate the reliability of the model under historical conditions by comparing simulated and observed discharge.

4. To analyse the hydrological response of the basin under drying, warming, and extreme precipitation scenarios, in order to investigate how different hydro-climatic perturbations may affect river discharge behaviour.
5. To interpret the basin response through suitable response indicators, such as elasticity, sensitivity, and amplification, and to assess how these results are related to the climate-related hydrological change.

1.5 Research questions

Based on the objectives of the study, the following research questions are addressed:

1. Can the selected semi-distributed conceptual rainfall–runoff model reliably reproduce the daily flow regime of the Po River basin under historical conditions?
2. How does the Po River basin respond to progressive reductions in precipitation under drying scenarios?
3. How sensitive is the simulated river discharge to temperature increase under warming scenarios?
4. Can a redistribution of rainfall toward more intense events affect basin discharge behaviour even when the total amount of precipitation remains unchanged?
5. Do different sections of the Po River basin show different levels of hydrological sensitivity under the considered perturbation scenarios, and can these responses be interpreted through indicators such as elasticity, sensitivity, and amplification?

1.6 Scope of the thesis

The scope of this thesis is limited to the simulation and analysis of daily river flow in the Po River basin through a semi-distributed conceptual rainfall–runoff modelling approach. The study focuses on the application of the selected hydrological model to historical conditions and to a set of scenario-based perturbations designed to explore basin sensitivity under climate-related stress.

To evaluate the overall model reliability and the spatial differences in the model's response within the basin, a daily time-scale analysis was performed at several control sections. The scenario analysis specifically includes drying scenarios, warming scenarios, and extreme precipitation scenarios, which help to understand how different forms of hydro-climatic perturbation may affect the river discharge.

At the same time, the aim of the thesis is not to develop a fully distributed physically based model, or to produce long-term climate projections based on global or regional climate models. Instead, it adopts a scenario-based modelling framework to examine the sensitivity of the basin under controlled perturbations of the input variables. Therefore, this work is designed as a hydrological modelling and response-analysis study rather than a complete climate projection study.

In addition, the thesis includes the analysis of spatial patterns in the model response just in order to support the interpretation of basin behaviour; thus, GIS-based methodological development is not primarily an objective of the study.

1.7 Structure of the thesis

This thesis consists of five chapters.

Chapter 1: The first chapter introduces the general background of the study, defines the research problem and the aim and objectives of the thesis, and outlines the scope and structure of the work.

Chapter 2: In this chapter, the main scientific background that is relevant to the study is reviewed. It focuses on rainfall–runoff modelling, semi-distributed conceptual approaches, hydrological modelling in large river basins, and the role of climate-related perturbations in the analysis of river flow.

Chapter 3: This chapter presents the methodological framework of the thesis by describing the Po River basin, the datasets used in the study, the structure of the selected hydrological model, the model setup and evaluation procedure, and the scenario design adopted for the analysis. Furthermore, the response indicators that are used to interpret basin sensitivity are introduced in this chapter.

Chapter 4: This chapter presents and discusses the results of the study. It includes the evaluation of model performance under baseline conditions and the analysis of basin response under drying, warming, and extreme precipitation scenarios. The chapter also includes the interpretation of the results in terms of basin sensitivity, spatial response patterns, and the different effects of the analysed scenario families on river discharge.

Chapter 5: Finally, this chapter presents the main conclusions of the thesis, summarises the major findings, discusses the main limitations of the study, and outlines possible directions for future research.

Chapter 2: Literature Review

2.1 Introduction

This chapter reviews the main scientific background relevant to the present study. It begins with a general overview of rainfall–runoff modelling, and then the main types of hydrological models that are commonly used in river basin analysis are discussed. Semi-distributed conceptual models are explained in more detail, since they provide the modelling framework that is most related to the objectives of this thesis.

The literature about hydrological modelling under climate-related perturbations is also reviewed in this chapter. Then, the Po River basin is introduced as a hydrologically relevant case study, and the MISDc model is introduced as a suitable framework for basin-scale simulation and scenario-based analysis (Camici et al., 2025; Cislaghi et al., 2020). This study was developed in collaboration with the University of Bologna, which also provided a broad academic context in which the model application and scenario analysis were carried out.

Overall, the theoretical and scientific context for the methodological choices adopted in the thesis is provided by this literature review. It helps to find the position of the present study within the broader field of rainfall–runoff modelling and climate-related hydrological assessment.

2.2 Rainfall–runoff modelling

Rainfall-runoff modelling describes how precipitation is transformed into streamflow by representing the relationship between meteorological input data, such as rainfall and temperature, and the hydrological response within a river basin. There are many interacting processes, including infiltration, storage, evapotranspiration, and routing, that affect the river flow; therefore, rainfall–runoff models are used to simplify and analyse the behaviour of hydrological systems in a structured way (Sitterson et al., 2018).

The application of these models in hydrology includes streamflow simulation, flood and drought studies, water resources assessment, and scenario-based analysis under changing environmental conditions. Rainfall-runoff models are considered to have an essential role in hydrological analysis, since they evaluate basin response when direct observation alone is not sufficient to understand the behaviour of the system (Jehanzaib et al., 2022).

Another important aspect of rainfall–runoff modelling is its flexibility. Different modelling approaches can be adopted based on the purpose of the study, the available data, and the complexity of the basin. Some models are designed to generally predict the discharge, while others are mostly used for sensitivity analysis, scenario testing, or water resources planning. This makes rainfall–runoff modelling useful not only for reproducing historical flow conditions, but also for investigating how river basins may respond under modified climatic forcing (Jehanzaib et al., 2022; Sitterson et al., 2018).

The aim of the present thesis is not limited to the simulation of historical daily discharge, and the rainfall-runoff modelling framework is also used to analyse how the Po River basin may react under different scenario conditions, including precipitation reduction, warming, and changes in rainfall distribution. Therefore, in this work, rainfall-runoff modelling provides the basis for both flow simulation and basin response analysis (Jehanzaib et al., 2022).

The analysis of hydrological systems depends on their scale, complexity, data availability, and study objectives; therefore, rainfall-runoff models have also evolved into different categories. This leads to the need for a general classification of hydrological models, which is discussed in the following section (Sitterson et al., 2018).

2.3 Types of hydrological models

Hydrological models can be classified based on how they represent the watershed and the physical processes involved. Spatial representation is one of the most common classification approaches that divides the hydrological models into lumped, semi-distributed, and distributed models (Sitterson et al., 2018).

Lumped models treat the entire river basin as a single unit and use average or aggregated variables to represent the basin's behaviour. In this type of approach, model parameters such as rainfall, soil properties, topography, and land use are not represented spatially. Lumped models are generally simpler, require less input data, and are often easier to calibrate. Therefore, they can be useful in studies where a simplified basin representation is sufficient for streamflow simulation (Devia et al., 2015; Sitterson et al., 2018).

On the other hand, fully distributed models represent the spatial heterogeneity of the basin in a more explicit way. They divide the basin into a large number of spatial elements and describe hydrological processes for each element. These models represent the basin response in a more detailed way. However, distributed models require more data, greater computational effort, and a more complex calibration process (Jehanzaib et al., 2022; Sitterson et al., 2018).

Semi-distributed models can be considered as an intermediate approach between lumped and distributed frameworks. In these models, the basin is divided into a limited number of sub-units, such as sub-catchments, and the processes within each unit are represented in a simplified way. Therefore, the spatial variability of the basin is considered without the complexity of a fully distributed model. Semi-distributed models provide the balance between realism and efficiency, especially for large and complex basins (Bhadra et al., 2010; Devia et al., 2015; Sitterson et al., 2018).

Another important classification approach is how hydrological processes are conceptualised. Based on this approach, models are classified as empirical, conceptual, or physically based. Empirical models use data to reproduce the relationship between inputs and outputs without considering the physical processes involved. Conceptual models describe basin behaviour using simplified reservoirs, parameters, and process representations. Physically based models use equations and detailed basin properties to represent hydrological processes (Jehanzaib et al., 2022; Sitterson et al., 2018).

The choice between these modelling approaches depends on the aim of the study, the scale of analysis, the availability of data, and the level of detail required. A modelling framework that is suitable for one basin or one objective may not be the best choice in another case. For this reason, the purpose of the study and the characteristics of the basin should be considered before selecting the model (Bhadra et al., 2010; Devia et al., 2015).

In the case of large river basins, with internal variability and processes involved, semi-distributed conceptual models often provide a useful balance between physical representation and efficiency. Therefore, these models are particularly relevant for this thesis, which combines basin-scale simulation with scenario-based analysis (Bhadra et al., 2010; Devia et al., 2015).

2.4 Semi-distributed conceptual models in large river basins

In large river basins, a considerable spatial variability can be seen in characteristics such as precipitation, topography, soil conditions, land use, and hydrological response. Therefore, to simulate large basin behaviour, a framework that can show these differences while being applicable and efficient is needed to avoid both oversimplification and excessive complexity (Beven, 2012; Blöschl & Sivapalan, 1995).

To analyse large and complex basins where routing effects, internal storage, and sub-basin variability play an important role, lumped models provide limited results. On the other hand, large amounts of input data, greater computational time and effort, and more complicated calibration procedures are needed to run fully distributed models. Therefore, these two model types are not the most practical options to analyse large river basins, especially when multiple simulations and different scenarios are involved (Blöschl & Sivapalan, 1995; Tshimanga & Hughes, 2014).

Semi-distributed conceptual models divide the basin into smaller units, such as sub-catchments, and represent hydrological processes in a simple and interpretable way. Therefore, in this approach, the complexity of fully distributed modelling is avoided while part of the heterogeneity of the basin is taken into account. Therefore, semi-distributed conceptual models can be considered as a compromise between reality, efficiency, and data requirements (Beven, 2012; Blöschl & Sivapalan, 1995; Tshimanga & Hughes, 2014).

Another important advantage of using semi-distributed conceptual models for large river basins is that they are structured to represent runoff generation, river routing, and basin storage with sufficient detail while remaining computationally manageable. This is useful, especially when the objective of modelling is to analyse the response of the basin under different scenarios in addition to reproducing historical discharge (Loukas & Vasiliades, 2014; Tshimanga & Hughes, 2014).

In large basins, complex interactions exist between the elements, such as upstream and downstream areas, delayed hydrological responses, and different forms of natural and managed storage. These systems need a modelling framework that takes these interactions within the basin into account. In studies where the interpretation of the hydrological response is also considered as an objective for prediction, assessment, and scenario analysis, semi-distributed conceptual models can be very useful (Blöschl & Sivapalan, 1995; Brocca et al., 2011; Loukas & Vasiliades, 2014).

For these reasons, semi-distributed conceptual models provide an appropriate modelling basis for the analysis of large river basins. They provide a balance between process representation and practical applicability, making them suitable for studies that seek to evaluate model reliability and basin response under different hydro-climatic conditions, as in the case of the present thesis.

2.5 Hydrological modelling under climate-related perturbations

Hydrological modelling has become increasingly important in the study of climate-related impacts on river basins. Changes in precipitation, temperature, and the pattern of extreme events can affect the behaviour of hydrological systems in different ways. Therefore, rainfall–runoff models are used to investigate how river discharge may respond under modified climatic conditions and also to analyse the sensitivity of the basin under future scenarios (Camici et al., 2014; Kling et al., 2012).

One of the most important applications of hydrological modelling is to investigate how the hydrological response is affected by changes in precipitation, since these responses are not always proportional to the applied perturbation. These changes may lead to an amplified or buffered runoff response, based on the basin characteristics, internal storage, and seasonal dynamics. Therefore, hydrological modelling is a useful tool for analysing basin sensitivity under drying conditions and also for comparing the response of different sub-catchments (Kling et al., 2012; Krysanova & Hattermann, 2017).

Another important hydrological perturbation is temperature variation, which may affect the basin response even when the precipitation is unchanged. Different mechanisms are involved in how warming affects the basin, including increased evapotranspiration, changes in snow accumulation, and shifts in snowmelt timing. Therefore, warming changes the seasonal distribution of runoff and flow conditions. Hydrological models allow us to analyse not only the changes in discharge, but also the internal processes that are involved (Hattermann et al., 2017; Kling et al., 2012).

Considering the effect of modified rainfall patterns and more intense extremes may also reveal interesting results. In such cases, hydrological models investigate how the changes in rainfall distribution may affect discharge in terms of variability, peak-flow behaviour, or short-term runoff response. This is particularly relevant in studies that explore the sensitivity of the system to different hydro-climatic stressors in addition to the average basin response (Camici et al., 2014; Gosling et al., 2017).

Scenario-based analysis allows for exploring the basin's response under different assumptions, which help identify the common tendencies and possible sources of uncertainty in future climatic conditions. Therefore, hydrological modelling under climate-related perturbations is used to analyse the sensitivity of basin behaviour across a range of plausible conditions, and it is not limited to predicting one future outcome (Camici et al., 2014; Hattermann et al., 2017; Krysanova & Hattermann, 2017).

In the present thesis, the selected modelling framework is applied not only to reproduce historical daily flows, but also to analyse basin response under drying, warming, and extreme precipitation scenarios. Therefore, the use of scenario-based hydrological modelling provides the basis for evaluating how a watershed may react under different hydro-climatic perturbations and interpreting the response patterns.

2.6 The Po River basin as a hydrological case study

The Po River basin is one of the most important hydrological systems and a relevant case study for hydrological analysis in Italy. This river basin is not only large, but also plays important environmental, economic, and social roles. Due to its effect on different agricultural, industrial, and urban activities, its behaviour directly affects water availability, river management, and climate-related risk assessment (Camici et al., 2025; Cislaghi et al., 2020).

The hydrological characteristics of the Po River basin, including Alpine and Apennine headwaters, seasonal precipitation, snow accumulation and snowmelt, and the contributions of tributaries, are responsible for the spatial heterogeneity of the basin. Therefore, the flow in the basin is influenced by the complex interaction between rainfall-driven runoff, snow-related processes, internal storage, and routing along the river network (Camici et al., 2014, 2025).

The hydrological behaviour of the Po River basin is also influenced by human-related activities such as water abstraction, irrigation, and water management. The basin responds to these activities in the form of changes in low flows, seasonal water availability, and hydrological stress conditions. Therefore, the Po River basin is suitable for studies in which both natural hydrological response and water-resource-related impacts are considered (Camici et al., 2025; Cislaghi et al., 2020).

Many studies have focused on the Po River basin because of its size and complexity. The combination of the Po River basin characteristics, such as climatic diversity, storage effects, and water-management relevance, makes it suitable for testing modelling frameworks like semi-distributed rainfall–runoff models to analyse basin responses under changing hydro-climatic conditions (Camici et al., 2014; Cislaghi et al., 2020).

For these reasons, the Po River basin is a proper setting to investigate the reliability and sensitivity of hydrological models under scenario-based perturbations. Its characteristics make it suitable to understand how a large and complex basin may respond to drying, warming, and extreme precipitation scenarios.

2.7 MISDc model and related modelling framework

For basin-scale studies in which spatial variability and modelling efficiency are important, semi-distributed conceptual models, among the other modelling approaches mentioned earlier, can be considered suitable. MISDc model combines a simplified conceptual structure with the ability to represent internal basin processes across sub-catchments (Camici et al., 2025; Cislaghi et al., 2020).

The MISDc modelling approach focuses on the dominant processes involved in runoff generation, storage, and river flow, rather than describing every process in detail.

Therefore, they are suitable for studies in which the objective is not only to reproduce observed discharge, but also to analyse basin response under multiple what-if or climate-related scenarios (Brocca et al., 2011; Camici et al., 2025).
Another important characteristic of MISDc is its modular framework, which allows the representation of key hydrological components such as snow-related processes, soil water balance, runoff routing, and selected human impacts, including irrigation and water use. This modular structure makes the model more flexible, so it can be used in complex river basins in which natural and human-induced processes are involved in the hydrological response (Brocca et al., 2011; Camici et al., 2025; Cislaghi et al., 2020).
The MISDc model has been applied in studies that focus on water resources assessment, basin-scale discharge simulation, and hydrological sensitivity analysis. In large basins where the interaction between internal elements plays an important role in shaping daily river flow, the structure of this model is also very useful to evaluate the internal basin response at multiple sub-sections (Camici et al., 2025; Cislaghi et al., 2020).
The spatial complexity of the Po River basin and the objective of this study make the MISDc framework an appropriate choice. On the one hand, it provides a semi-distributed conceptual representation suitable for simulating daily river flow under historical conditions. On the other hand, it offers the basis for investigating basin response under different climatic scenarios and analysing the basin sensitivity.

2.8 Research gap and position of the present study

Based on the previous sections, rainfall-runoff modelling is a useful tool, developed in various forms, to address different basin conditions in hydrology (Jehanzaib et al., 2022; Sitterson et al., 2018). Moreover, a useful framework is provided by the semi-distributed conceptual models for large and heterogeneous river basins (Blöschl & Sivapalan, 1995; Tshimanga & Hughes, 2014).
The importance of analysing hydrological response under climate-related perturbations is also mentioned in previous studies. Scenario-based modelling has become an important tool for analysing how changes in precipitation, temperature, and rainfall

extremes can influence runoff generation and river discharge (Camici et al., 2014; Kling et al., 2012). This is particularly important in large basins, where the response may vary across space and may be influenced by internal basin heterogeneity (Kling et al., 2012; Krysanova & Hattermann, 2017).

The reviewed literature also confirms that the characteristics of the Po River basin, such as size, climatic diversity, snow-related contribution, and socio-economic importance, make it a relevant case study to evaluate river flow behaviour and basin response under changing hydro-climatic conditions (Camici et al., 2025; Cislaghi et al., 2020). The MISDc framework provides a semi-distributed conceptual structure that represents the main natural and human-induced components influencing the hydrological behaviour of the basin (Brocca et al., 2011; Cislaghi et al., 2020).

However, despite this strong scientific background, it is still important to apply such a framework to simulate daily river flow in the Po River basin, and to combine the assessment of model reliability with the analysis of basin response under drying, warming, and extreme precipitation scenarios. Using historical flow simulation and response indicators to interpret the sensitivity of the basin helps to understand how different parts of the basin may respond to various forms of hydro-climatic stress.

Therefore, the present thesis is focused on rainfall–runoff modelling, climate-related hydrological response analysis, and basin-scale application to the Po River system with the objective of evaluating the reliability of the selected modelling framework for daily discharge simulation and to use it as a tool for analysing basin response under selected perturbation scenarios. This will lead to a better understanding of hydrological sensitivity in a large and complex river basin.

Chapter 3: Methodology and Data

3.1 Introduction

This chapter presents the methodological framework and the data used in this study to simulate and analyse the daily discharge of the Po River. The main purpose of this chapter is to describe how the semi-distributed hydrological model was applied to the basin and how the different climate-related scenarios were constructed.

An overview of the Po River basin, describing its geographical, topographical, and hydro-climatic characteristics, is first given. Then, the meteorological and hydrological datasets used in the modelling process are defined. The next step is an introduction to the MISDc model's structure and its modular framework. Finally, the approach for evaluating model performance and developing climate scenarios is explained.

The main goal is to understand the model's ability and accuracy to reproduce the daily flow discharges of the Po River basin under observed conditions and to examine the basin response to different climatic conditions.

3.2 Study area: the Po River Basin

The study was carried out in the Po River basin, the largest and most important river basin in Italy. It covers an area of about 71,000 km² and plays a major role in the country, both hydrologically and socio-economically.

From a physical point of view, the basin is characterised by a complex topography. It is bounded by the Alps to the north and west and by the Apennines to the south, while the central part is dominated by the wide Po plain.

Because of these climatic and topographic contrasts, the Po River basin shows a complex flow regime. In general, streamflow is influenced by both spring and early summer snowmelt from alpine areas and rainfall-driven runoff, especially during wetter periods in autumn.

For the present study, the basin was represented using a semi-distributed configuration. To better represent processes of runoff generation, flow propagation across the river network, and the effect of storage elements such as major lakes, the Po

River basin was divided into 99 sub-basins. The model outputs were analysed at 18 main control stations along the main river and its tributaries.

3.3 Dataset description

To apply the MISDc model to the Po River basin, a long-term daily dataset was used. The dataset includes the main meteorological inputs required by the model, together with hydrological observations used to assess model behaviour. Since the model follows a semi-distributed approach, the input data were organised at the level of individual sub-basins rather than treating the whole basin as a single lumped unit.

The available dataset covers about 24 years of daily observations, from 2000 to 2023. The main forcing variables are precipitation and mean air temperature, while the hydrological dataset includes observed discharge and storage-related information for selected control points. These data form the basis for the baseline simulations and for the construction of the climate scenarios analysed later in this thesis.

3.3.1 Meteorological forcing data

Two primary meteorological variables that drive the MISDc model are daily precipitation and mean daily air temperature. These variables are available for 99 sub-basins, enabling the model to simulate hydrological processes more accurately. In the Po River application, daily precipitation data for the period 2000–2023 were derived from the ArCIS dataset, while daily air temperature data for the same period were obtained from the UniMi/ISAC-CNR observational dataset. These data were resampled to a common 5 km spatial grid and 1-day temporal resolution and then extracted for each of the 99 sub-basins used in the semi-distributed model configuration (Kalimisetty et al., 2026).

Precipitation represents the main water input of this hydrological model and directly controls runoff generation. Any change in the amount or intensity of rainfall input can cause significant changes in river discharge, especially during high-flow or dry periods.

Temperature is also an important variable due to its influence on several hydrological processes, particularly in the snow module, as it is used to estimate snowmelt rates using the degree-day approach, and also to distinguish precipitation into liquid and solid phases (rainfall and snowfall). On the other hand, temperature contributes to evapotranspiration estimates, which become especially relevant under warming scenarios.

One advantage of using only precipitation and temperature as the main forcing variables is that the model remains relatively efficient while still preserving a physically meaningful representation of the dominant processes.

3.3.2 Hydrological observations

For the purpose of calibration and validation of the model, the observed hydrological data were used to compare simulated and measured flows at selected control sections of the basin. This comparison is essential to check whether the model is able to reproduce the main dynamics of the Po River daily flow regime before being used for scenario analysis. In the dataset used in this thesis, observed discharge data were available for five selected control stations and were used for comparison with simulated discharge under baseline conditions. In the Po River application, daily river discharge data over the period 2000–2022 were obtained from the Italian Civil Protection Department and the Po River Basin Authority. In addition, daily storage volume and outflow data for the major regulated lakes were provided by the Po River Basin Authority (Kalimisetty et al., 2026).

On the other hand, the model outputs were extracted at 18 main control stations across the basin to analyse the spatial distribution of the simulated response. This distinction is important for interpreting model performance. The observed data series were used to compare simulated and measured hydrological behaviour at the available control sections. In contrast, the 18 control stations were used to analyse the spatial distribution of the simulated response from upstream to downstream parts of the basin in order to analyse model performance at different spatial scales.

Table 3.1 summarises the main meteorological and hydrological variables used in the MISDc model, together with their description, data structure, and temporal resolution.

Variable Name	Description	Data structure (rows × columns)	Temporal Resolution
PMA_obs	Observed Precipitation per sub-catchment	8766 x 99	Daily
TMA	Mean Air Temperature per sub-catchment	8766 x 99	Daily
outflow	Observed River Discharge at main cross-sections	8766 x 5	Daily
StorObs	Observed storage in sub-catchments/lakes	8766 x 5	Daily

Table 3.1. Main meteorological and hydrological input variables used in the MISDc model.

In the table above, the data structure is reported as rows × columns, where rows correspond to daily observations, and columns correspond to sub-basins or selected stations, depending on the variable.

In addition to the main meteorological and hydrological input data, the MISDc setup also included supplementary irrigation and water-use-related input data, which are summarised in Table 3.2.

Input/dataset	Description	Source	Use in the model	Temporal basis
Irrigation-related data	Irrigated areas and agricultural water use information	SIGRIAN database; ADBPO	Irrigation module applied over irrigated areas during the irrigation period	Seasonal/growing season
Water-use data	Civil and industrial water-use information	Po River Basin Management Plan (PdgP 2010; 2016), prepared by ADBPO	Civil and industrial water-use module	Monthly/seasonal factors

Table 3.2. Additional irrigation and water-use-related inputs considered in the MISDc model.

Unlike the main meteorological and hydrological time-series inputs reported in Table 3.1, the inputs summarised here represent supplementary information used to describe irrigation and civil and industrial water use within the model framework.

3.3.3 Spatial and static data

Another important step is to define the structure of the basin, so spatial and basin-structure information is also needed for the model's operation. These data are necessary to represent the geometry of the river network, the boundaries of the sub-basins, and the connections between upstream and downstream elements.

In order to obtain the semi-distributed representation needed for this study, spatial data are needed for identifying the 99 sub-basins and their corresponding spatial relationships. Therefore, Geographical coordinates, sub-basin identifiers, and routing connections are needed to ensure that each sub-basin is correctly positioned within the basin and linked to the downstream section. In the Po River application, the basin representation was based on topographic information derived from a DEM dataset (e.g. HydroSHEDS), together with the spatial distribution of the 18 river gauge stations. On this basis, the study area was subdivided into 99 sub-basins. In addition, irrigated areas were identified using the SIGRIAN district dataset, while the major regulated lakes were included as the main storage elements of the basin structure (Kalimisetty et al., 2026).

This type of information is particularly important in the Po River basin because of its size, its topographic diversity, and the presence of internal storage.

The spatial distribution of the 18 control stations considered in the analysis is shown in Figure 3.1. The sections with available observed hydrological data are highlighted separately from the other stations.

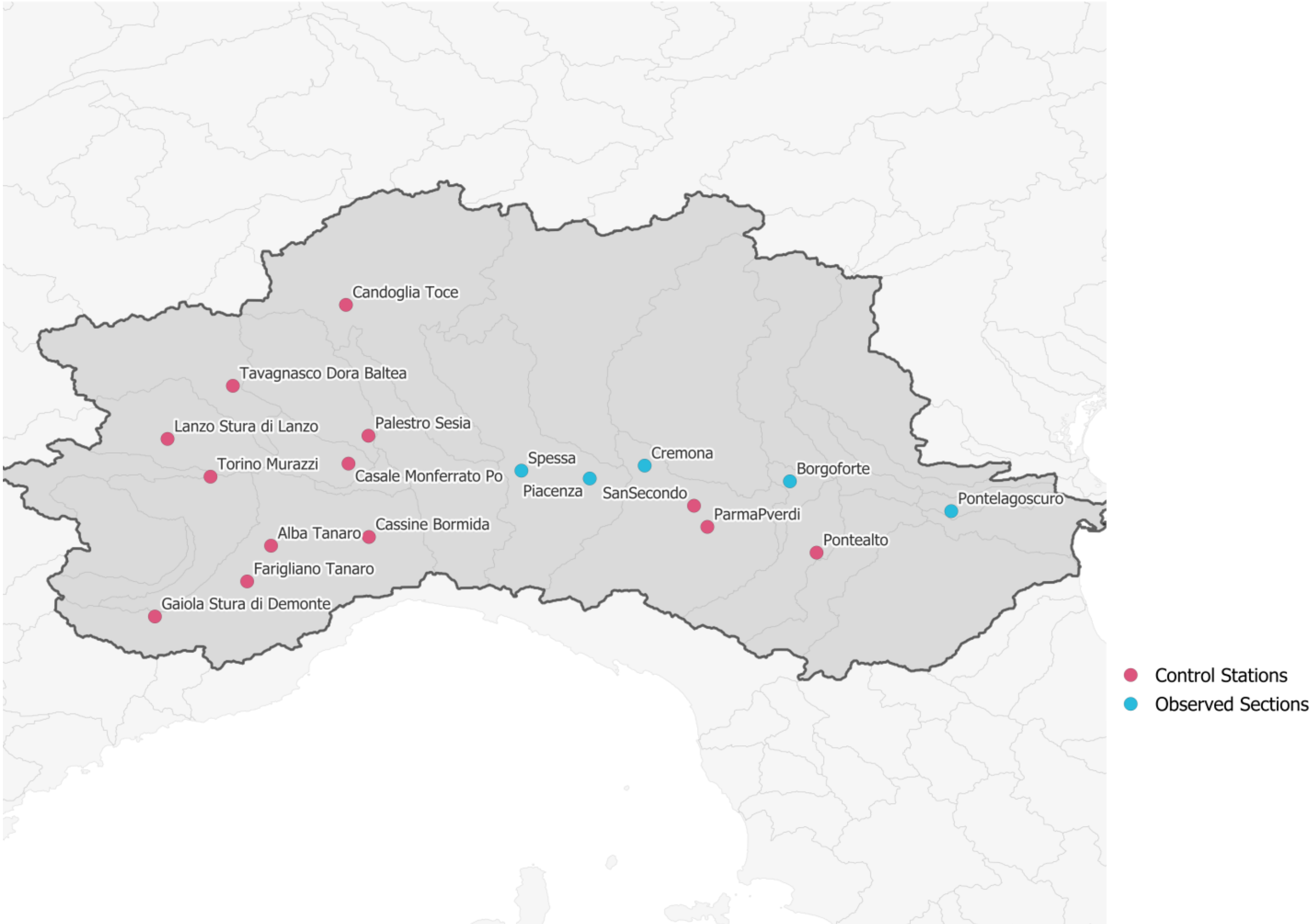


Figure 3.1. Location of the 18 control stations used in the Po River basin analysis. The sections for which observed hydrological data are available are highlighted separately.

3.4 Hydrological Model Structure

3.4.1 General Overview

The MISDc, Modello Idrologico Semistribuito in Continuo, is a semi-distributed conceptual rainfall–runoff model used to simulate the main rainfall–runoff processes at the basin scale. The version used in this study (v3.0) is a modular system that is able to represent both natural and human-induced processes at the basin scale.

The MISDc is developed by Brocca et al. for basin-scale hydrological simulation and scenario-based analysis (Brocca et al., 2011). The present study applies this modelling framework to the Po River basin in collaboration with the University of Bologna to estimate water availability in different parts of the basin, including rivers, snow storage, soil water, and regulated components, while keeping a relatively simple structure with a limited number of parameters to minimise computing load. This is useful especially when long-term simulations and multiple scenario runs are required.

To achieve the semi-distributed structure of the model, the Po River basin is divided into spatial elements that help to represent hydrological processes such as runoff generation, storage, and routing in a more realistic way. In this study, this structure includes 99 sub-basins and 18 main control sections.

For this research, the model combines five main modules to represent the hydrological cycle of the Po River basin under both baseline and perturbed climate conditions:

- Snow Module: divides total precipitation into liquid and solid phases and simulates snowpack dynamics.
- Soil Module: Simulates infiltration, evaporation, and percolation processes through two soil layers (surface and root zone).
- Irrigation Module: Triggers irrigation when soil moisture falls below specific thresholds to simulate agricultural water demand.
- Water Uses Module: Accounts for water extracted for civil and industrial purposes based on monthly average flow rates.
- Routing Module: Transfers the generated runoff through the river network to the outlet sections using a geomorphological approach.

3.4.2 Snow module

The snow module is one of the most important components of the MISDc model, especially for a basin such as the Po River basin, where alpine areas play a major role in seasonal runoff generation. Precipitation and air temperature are the input variables that this module uses to simulate snow accumulation and snowmelt processes.

The first step is the partitioning of total daily precipitation into liquid and solid components. This separation depends on two temperature thresholds, a lower threshold and an upper threshold. In the present model structure, these thresholds are set to Tinf = -0.5 °C and Tsup = 0.5 °C. Below the lower threshold, precipitation is considered fully solid, while above the upper threshold it is considered fully liquid; between the two thresholds, a mixed form is assumed (Camici et al., 2025; Kalimisetty et al.,

2026). In this way, the model can represent the effect of temperature on the form of precipitation.
After precipitation is partitioned, the solid part can be considered as the snow water equivalent stored in the basin. Then the module estimates the amount of snowmelt through a degree-day approach. The assumption here is that melting increases with air temperature above a threshold value. Although this method is relatively simple, it is widely used in conceptual hydrological models and is suitable for daily-scale applications.
The role of the snow module becomes more and more important, particularly during late spring and early summer, when snow stored in upstream alpine areas becomes an important source of discharge. Therefore, a good representation of snow processes is essential for simulating the seasonal flow regime of the Po River.

3.4.3 Soil module and runoff generation

The role of the soil module is to simulate the main processes related to the continuous soil water balance, including infiltration, evapotranspiration, percolation, and the generation of runoff. In MISDc, soil moisture is represented through a two-layer structure, which includes a surface layer and a deeper root-zone layer. By using this simplified representation, the model is able to simulate both fast and slower hydrological responses.

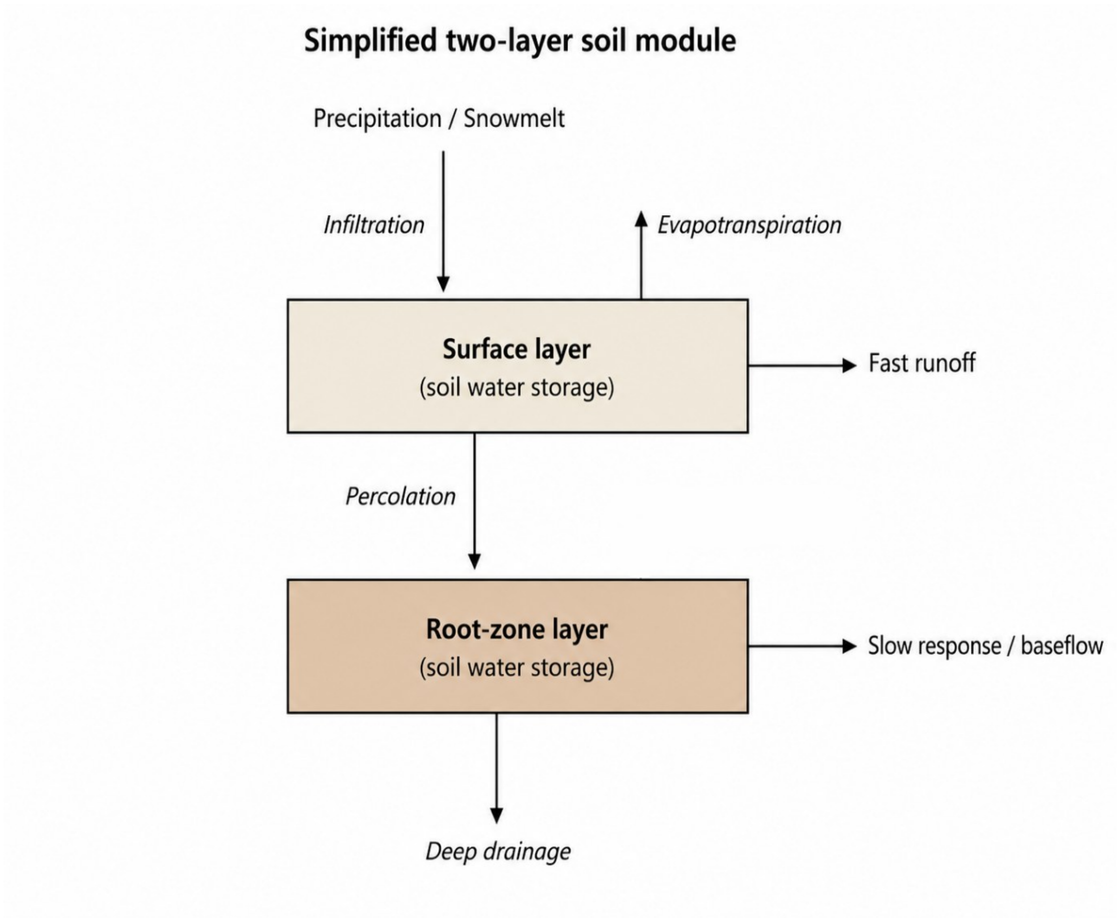


Figure 3.2. Simplified schematic representation of the two-layer soil structure used in the MISDc model. Adapted from the model structure described in Camici et al. (2025) and Kalimisetty et al. (2026).

This simplified scheme shows that rainfall and snowmelt first enter the surface layer, where part of the water can return to the atmosphere through evapotranspiration, and part can contribute to fast runoff. The remaining water percolates downward to the root-zone layer, which mainly contributes to the slower hydrological response of the basin. The deep drainage term represents the downward loss of water from the lower soil layer.

The water capacity of these two layers and the hydraulic parameters that control the vertical movement of water within the soil are the factors that control the soil storage. When liquid water from rainfall or snowmelt reaches the ground, a part of it infiltrates into the soil, while the excess turns into direct runoff. In this way, the model links meteorological forcing to both soil storage and discharge.

Soil moisture condition determines the potential evapotranspiration by which the actual evapotranspiration is later estimated. As a result, evapotranspiration is limited when soil water becomes limited and increases when soil moisture is more available. This mechanism is important, especially when analysing warming scenarios, since higher temperatures may lead to a decrease in available soil moisture and consequently lower runoff.

Drainage from the two layers of the soil leads to a delayed discharge and baseflow. In the model, these fluxes are controlled by non-linear relationships, which help reproduce the slow-release behaviour of the hydrograph. This is important for the Po River basin, where part of the discharge response is not immediate and depends on internal storage and delayed discharge processes.

3.4.4 Routing module

The routing module describes the transmission process of the generated runoff from sub-basins towards the main outlet sections through the river network. This module is essential in the Po River basin because discharge at downstream sections depends on both local runoff generation and the timing and attenuation of flows coming from upstream areas.

In the MISDc structure, the basin is divided into tributary draining areas and directly draining areas. For tributary draining areas, runoff is routed through a Geomorphological Instantaneous Unit Hydrograph approach (V. K. Gupta et al., 1980), while directly draining areas are represented by means of a linear reservoir formulation (Nash, J. E., 1957). This approach increases the efficiency of the model response while keeping the overall structure simple.

For both components, the flow propagation along the main river channel is managed by a diffusive linear approach, which is controlled by two physical parameters: celerity (C) and diffusivity (D). These parameters help the model to reproduce downstream flow propagation in a more realistic way by controlling the time and growth elements of the hydrograph along the channel network.

Overall, the main role of this module is to connect the local hydrological response of each sub-basin to the unified discharge at the main control stations. This is especially important in the present study, where one of the objectives is to analyse the simulated daily flows at several sections of the Po River system.

3.4.5 Irrigation module

The irrigation module represents the water needed for agricultural purposes within the basin. This component becomes active when soil moisture falls below predefined thresholds, which triggers the irrigation module to address water deficits in cultivated areas. In the present application, information on agricultural water use was derived from the Po River Basin Authority (AdBPO), while the spatial distribution of irrigated areas was based on the SIGRIAN database. In this way, the model accounts for one of the main human influences on the water balance of the Po River basin.

This module is essential because the Po basin is strongly characterised by agricultural activities and irrigation demand. Therefore, it helps the model to make more realistic simulations, especially during dry periods when water demand and hydrological stress may increase at the same time.

This module uses a simplified approach to consider the effect of irrigation on the basin's water availability rather than representing every irrigation practice. In this way, the physical meaning behind this process is considered while keeping the computational efficiency, which is consistent with the general philosophy of MISDc.

3.4.6 Water use module

This module ensures that another important human-induced stress is included in the simulation by accounting for water abstraction related to civil and industrial activities. In the present application, the information on water use was derived from the Water Balance Plan for the Po River District (PdgP, 2010, 2016) prepared by the Po River Basin Authority (AdBPO). In the model structure, these withdrawals are based on monthly average flow rates, which include the main anthropogenic pressures on the river system in a simple way.

This module is essential because the Po River basin includes both natural and anthropogenic components. Water withdrawals for human use can influence the available discharge, particularly during low-flow periods, and may affect the basin response under climate-stress conditions. For this reason, these processes should be considered to keep the results more realistic.

In this study, which focuses on the simulation of basin-scale daily discharges and scenario comparison, this simplified representation of water use is adequate.

Further information on parameter definition and calibration is provided in the following section.

3.5 Model setup and performance evaluation

3.5.1 Model setup for the Po River basin

For this study, MISDc was applied to the Po River basin using daily precipitation and temperature data distributed over 99 sub-basins. The model produced simulated discharge series at 18 main control stations, which represent the hydrological behaviour of the basin and allow the analysis of its performance by providing comparable outputs.

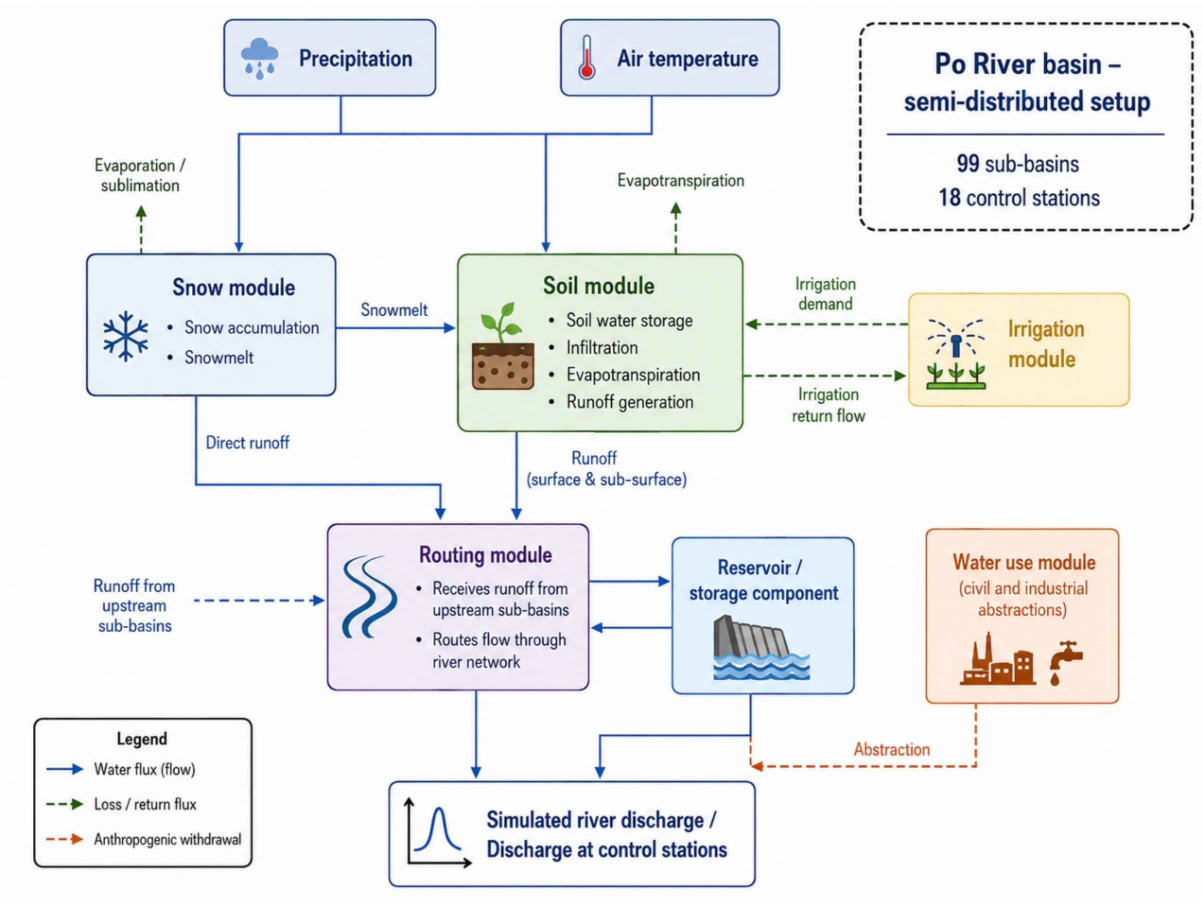


Figure 3.3. Simplified conceptual scheme of the MISDc model used for the Po River basin.

The figure shows the main structure of the model used in this study. Precipitation and air temperature drive the snow and soil modules, which generate runoff. Runoff is then transferred through the routing module to simulate river discharge at the control stations. The scheme also includes the irrigation, water use, and storage components considered in the model.

A baseline was defined by running the model using the observed meteorological data as inputs. The baseline provides the reference hydrological behaviour of the basin and allows the comparison of different scenarios and understanding the effect of each of these climatic scenarios.

All scenario simulations were performed using the same model structure, spatial discretisation, and routing scheme as the baseline run. In this way, differences in the simulated discharge can be linked to the modifications in precipitation or temperature rather than to changes in the model configuration.

There is a distinction between calibrated and fixed parameters in the MISDc structure. The calibrated parameters mainly control the snow, soil, and routing components of the model. On the other hand, the fixed parameters are assigned and validated through tuning phases and earlier MISDc applications in different catchments (Kalimisetty et al., 2026).

The simulations analysed in this thesis were performed using the MISDc configuration previously adopted for the Po River basin. No new calibration or optimisation was carried out within the present study. Accordingly, the parameter values and threshold conditions used for the snow, soil, routing, irrigation, and water-use modules were those of the adopted model setup. In the original Po River application, the model parameters were constrained through calibration against the available observed discharge records at the selected control sections, following a KGE-based sequential calibration procedure. The present work, therefore, relied on this pre-defined calibrated configuration to assess baseline model performance and to analyse basin response under the considered drying, warming, and extreme precipitation scenarios (Kalimisetty et al., 2026).

Module	Threshold/condition	Symbol/value	Role in the model
Snow module	Lower temperature threshold	Tinf = -0.5 °C	Lower threshold used to distinguish solid precipitation conditions
Snow module	Upper temperature threshold	Tsup = 0.5 °C	Upper threshold used to distinguish liquid precipitation conditions
Irrigation module	Initial soil moisture threshold	Thini = 0.3	Threshold below which irrigation demand is activated
Irrigation module	Target soil moisture threshold	Thirr = 0.5	Target soil moisture condition used for irrigation supply
Irrigation module	Irrigation period	May–August	Period during which irrigation is active in the adopted setup

Table 3.3. Main threshold values adopted in the MISDc setup used in this study.

The threshold values reported in this table were not newly calibrated in the present thesis, but were adopted from the MISDc configuration previously defined for the Po River basin.

3.5.2 Model performance evaluation

An important step before analysing the scenario results is verifying the model's ability to reproduce the observed daily flow regime under baseline conditions. Therefore, simulated and observed discharge series were compared at the available control sections. This comparison provides an initial assessment of the model's reliability for the purposes of the study.

To evaluate the model's performance, both visual and statistical characteristics were used. By Visual comparison of observed and simulated hydrographs, the timing and magnitude of the main discharge variations can be checked.

Moreover, performance indicators such as the Kling–Gupta Efficiency (H. V. Gupta et al., 2009), the Nash–Sutcliffe Efficiency (Nash & Sutcliffe, 1970), and the correlation coefficient (Pearson, 1895) can be used to measure the agreement between simulated and observed discharges.

This evaluation of the model's reliability is very important because the scenario analysis is only valid if the model is able to reproduce the present hydrological behaviour of the basin.

3.6 Climate scenario design

3.6.1 Rationale of the scenario approach

Using synthetic scenarios, which are defined by modifying the observed meteorological inputs, helps in understanding the sensitivity of the Po River basin to possible hydro-climatic changes. This way, it is possible to analyse how changes in precipitation and temperature affect the basin behaviour.

The main advantage of this method is that it isolates each climatic stress, and it makes it easier to evaluate its effect and to interpret it clearly. In this way, the changes in simulated discharge can be directly linked to changes in rainfall amount, rainfall distribution, or temperature, since other model parameters, model structure and spatial discretisation of the baseline remained unchanged.

The purpose of designing these scenarios is to represent different aspects of climate stressors. Therefore, this analysis focused on three main groups of scenarios, including progressive reductions in precipitation, uniform increases in temperature, and changes in rainfall distribution toward more intense events.

This scenario-based analysis can also be useful for water-resource analysis and decision-support applications.

3.6.2 Baseline scenario

The baseline scenario is defined using the observed daily input data from 2000 to 2023, containing the original daily precipitation and temperature series without any modifications, so it represents the present-day hydrological condition of the Po River basin. The result is a discharge series that acts as a reference condition used to evaluate the effect of all the other scenarios, which include drying, warming, and extreme precipitation scenarios, and are interpreted as deviations from this baseline.

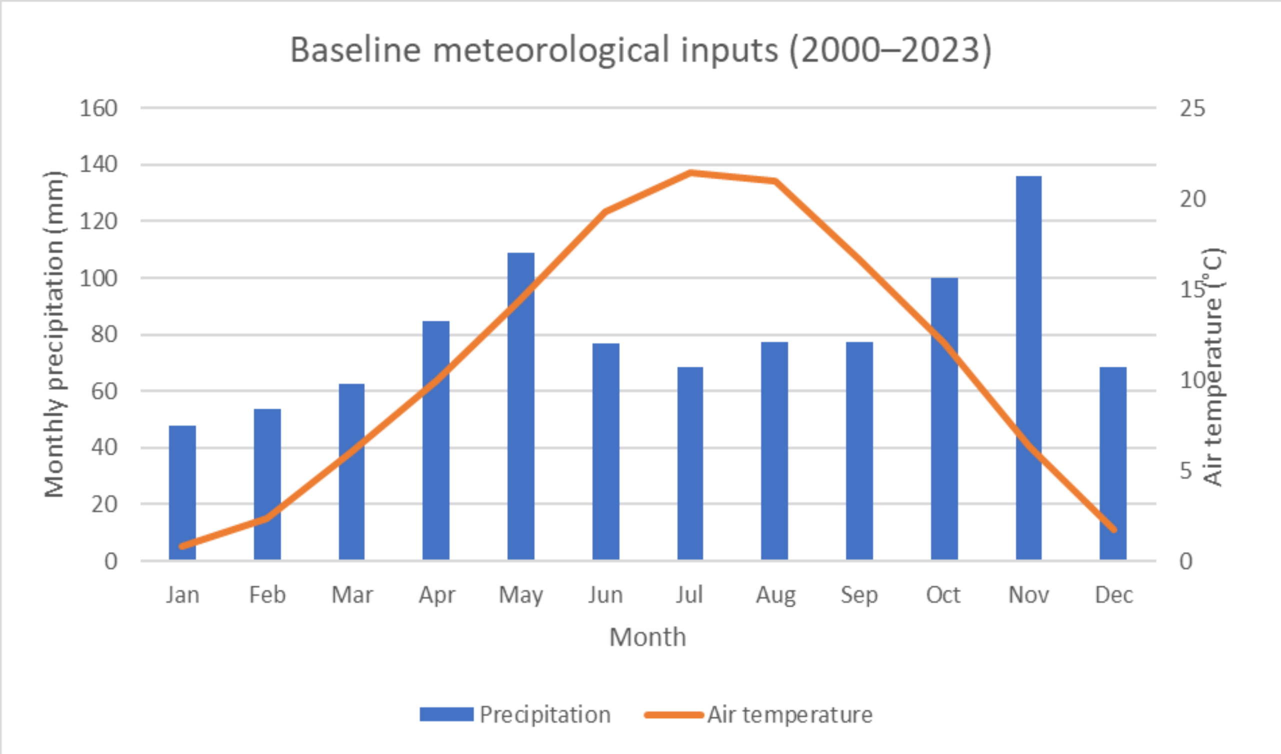


Figure 3.4. Baseline meteorological input data used in the MISDc simulations for the period 2000–2023, shown as mean monthly precipitation and mean monthly air temperature.

The figure summarises the baseline climate inputs used in the model. Monthly values were obtained from daily precipitation and temperature data by averaging the basin-scale input series over the full study period.

3.6.3 Drying scenarios

To design these scenarios, a uniform reduction in daily precipitation was applied, with no modification in the original temporal structure of the observed data. To achieve this, I considered three levels of reduction: −10%, −20%, and −30%. These scenarios were identified as DRY_0.9, DRY_0.8, and DRY_0.7, respectively. These scenarios were introduced to analyse the response of the basin under progressively drier conditions.

These scenarios were generated by multiplying the observed daily precipitation series by a constant reduction factor. Therefore, the total amount of water input to the basin was reduced while keeping the temporal sequence of precipitation events unchanged.

No changes were applied to the temperature series, and the model structure and parameterisation remained the same as in the baseline simulation. After modifying the precipitation input, the model was run again for each drying level, and the resulting discharge series were compared with the baseline condition.

By considering this type of modification, the effect of reduced water input can be analysed in a simple and systematic way. These drying scenarios are useful for evaluating changes in mean discharge, low flows, and the possible amplification of hydrological stress across the basin.

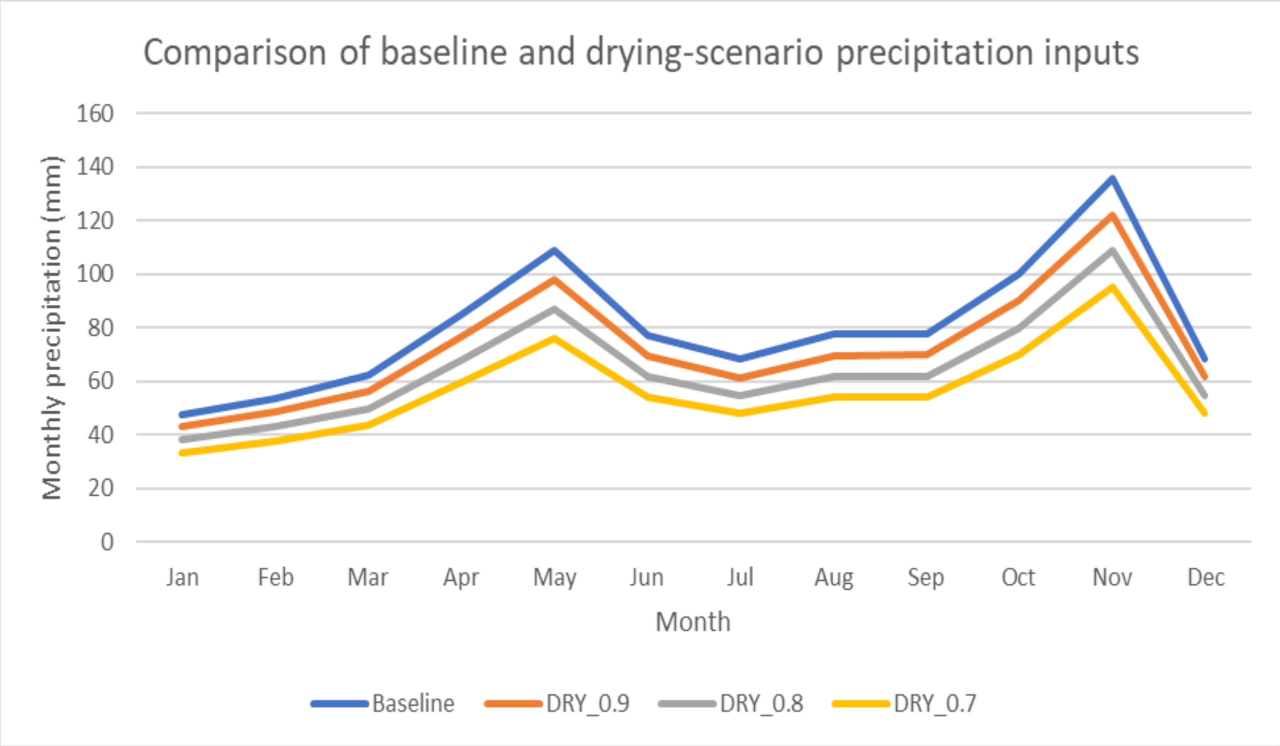


Figure 3.5. Comparison between the baseline precipitation input and the drying scenarios used in this study.

The figure shows that the drying scenarios were generated by applying uniform reductions of 10%, 20%, and 30% to the observed precipitation series, while preserving the original temporal pattern of the baseline data.

3.6.4 Warming scenarios

The main goal of analysing these scenarios is to isolate the effect of temperature increase on the hydrological response of the basin. To define warming scenarios, the observed daily air temperature was uniformly increased over the basin, while precipitation remained unchanged. For this purpose, two levels of warming were analysed: +1 °C and +3 °C. These two perturbations represent moderate and stronger warming conditions.

After modifying the temperature series and defining the scenarios, the MISDc model was run again using the same basin configuration adopted for the baseline simulation. The resulting discharge series was then compared with the baseline outputs in order to isolate the impact of warming.

Higher temperatures in these scenarios can affect discharge through several processes, including increased evapotranspiration and changes in snow processes, for example, snowmelt timing and accumulation. So these changes in temperature may affect not only the amount of flow but also the seasonal distribution of the river flow.

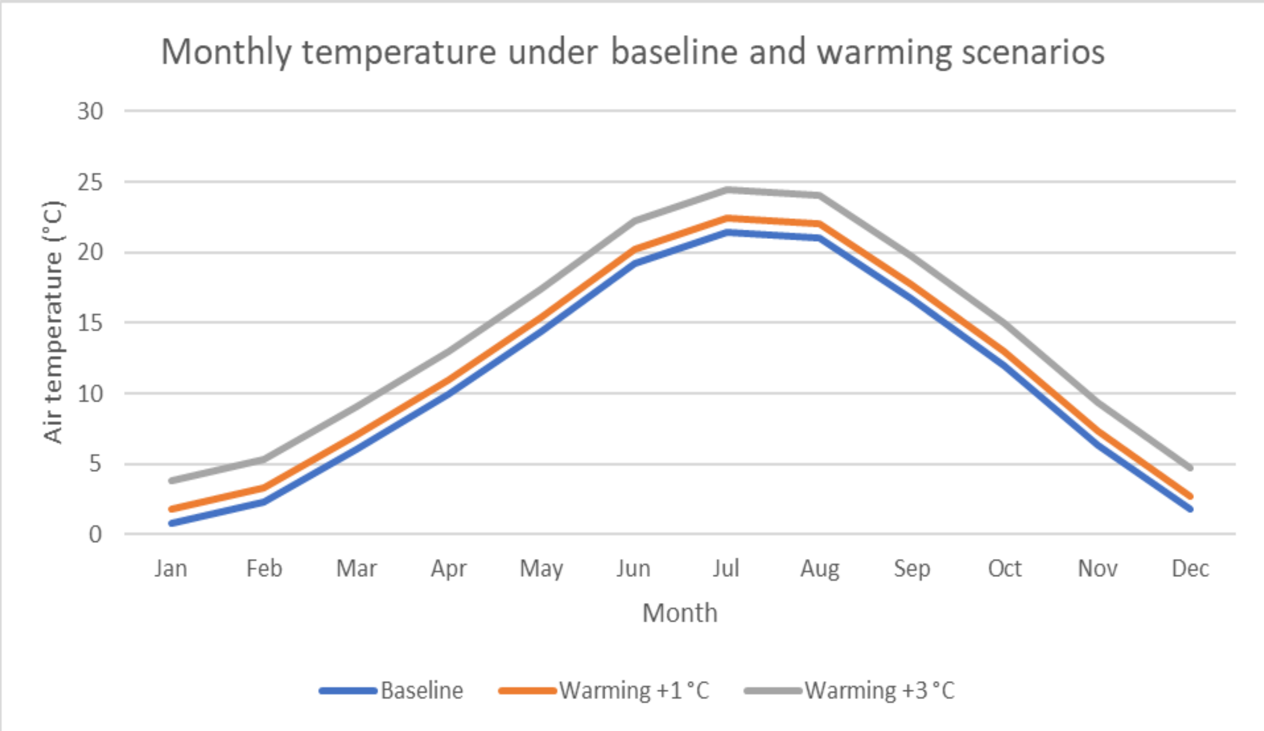


Figure 3.6. Monthly air temperature under the baseline and warming scenarios used in this study.

This figure shows that the warming scenarios were generated by applying uniform temperature increases of +1 °C and +3 °C to the observed daily air temperature series, while preserving the original temporal structure of the baseline data. The values shown represent the mean monthly basin-average air temperature.

3.6.5 Extreme precipitation scenarios

Extreme event scenarios are designed to evaluate the basin's response to intensified rainfall distribution while keeping the total average annual precipitation unchanged. These scenarios represent a future condition where storms are more concentrated and intense. In other words, to maintain the same overall average precipitation, the highest rainfall values were increased, and the lower rainfall values were slightly reduced. Three levels of extreme scenarios were considered: EXTR_1.1, EXTR_1.2, and EXTR_1.3.

These scenarios are useful because they help us understand how the basin reacts when it receives the same overall volume of rainfall, but with a different pattern, in which a larger part of that water falls during more intense events, which may generate faster runoff, higher discharge peaks, and stronger flow variability.

The procedure to construct these scenarios included centring the original series around its mean value, applying a variance scaling factor to increase the magnitude of deviations, restoring the original mean, correcting negative values by setting them equal to zero, and renormalising the modified series to ensure the average precipitation matched the baseline case.

After generating the modified rainfall series, the model was run again using the same temperature data, model structure, and basin discretisation adopted in the baseline simulation. Then, in order to evaluate the effect of extreme scenarios on the basin behaviour, the simulated discharge series was compared with the baseline outputs.

The main steps adopted to generate the extreme precipitation scenarios are summarised in Table 3.4, while the effect of the adopted procedure on the precipitation distribution is illustrated in Figure 3.7.

Step	Description	Purpose
1	Centring the original daily precipitation series around its mean value	To express daily precipitation as deviations from the baseline mean
2	Applying a variance scaling factor	To increase the magnitude of deviations and intensify rainfall variability
3	Restoring the original mean	To preserve the average precipitation amount of the baseline series
4	Correcting negative values by setting them equal to zero	To ensure physically meaningful precipitation values
5	Renormalising the modified series	To match the mean precipitation of the baseline scenario and allow direct comparison

Table 3.4. Main steps adopted to generate the extreme precipitation scenarios.

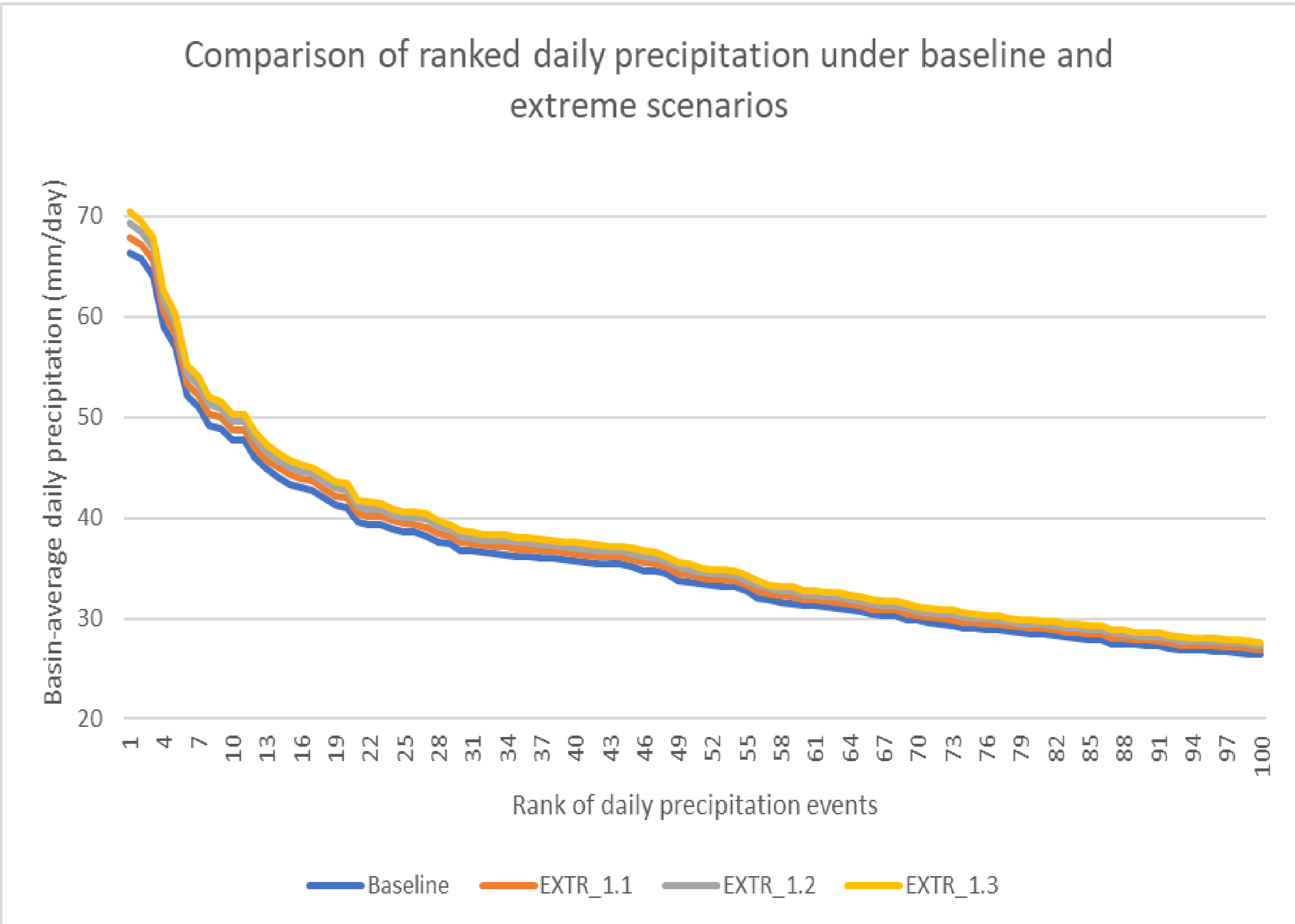


Figure 3.7. Comparison of the top 100 ranked basin-average daily precipitation values under the baseline and extreme precipitation scenarios.

This figure shows how the extreme precipitation scenarios are different from the baseline input. While the average precipitation is preserved, the upper part of the ranked distribution becomes progressively larger from EXTR_1.1 to EXTR_1.3, indicating stronger high-intensity rainfall events.

3.6.6 Summary of scenario framework

Overall, these three groups of scenarios are designed to understand the impact and importance of hydro-climatic stress.

The drying scenarios represent reductions in water input, the warming scenarios isolate the effect of temperature increase, and the extreme precipitation scenarios examine the impact of rainfall redistribution toward more intense events.

Analysing how these scenarios shape the basin's response helps assess the sensitivity of the Po River basin under a range of climate-related stresses.

3.7 Hydrological elasticity framework

3.7.1 Purpose of the elasticity analysis

After designing different climate scenarios, it is essential to define a consistent measuring approach to measure and compare the effect of each of these stressors on the river's discharge. For this purpose, an elasticity-based response framework was adopted for quantifying the sensitivity of streamflow towards the climate perturbations.

The response indicator was separately defined for each type of forcing scenario in relation to the corresponding climate variable, including precipitation reduction, temperature increase, or increase in rainfall variance.

This approach not only focuses on a simple qualitative comparison between scenarios, but instead of just considering an increase or decrease in values, elasticity makes it possible to evaluate the magnitude of the response and to compare this response across stations and scenarios.

3.7.2 Elasticity under drying scenarios

For the drying scenarios, elasticity was used to evaluate the response of the river basin to precipitation reduction in terms of strength. In this case, the elasticity is represented by the relative change in the response of the simulated discharge divided by the relative change in precipitation with respect to the baseline condition (Sankarasubramanian et al., 2001).

This formulation, which is a sensitivity indicator, makes it possible to determine whether discharge decreases proportionally to precipitation or whether the response is amplified or buffered. If the relative reduction in discharge is close to the relative reduction in precipitation, the basin response can be considered approximately proportional. If discharge decreases more strongly than precipitation, the response indicates amplification. On the contrary, if discharge decreases less than precipitation, the basin shows buffering behaviour.

The elasticity analysis can also be applied to other flow indicators, such as mean discharge, high flows, or low flows, which depend on the objectives of the analysis.

$$E_{dry} = \frac{\Delta Q\%}{\Delta P\%} = E_{dry} = \frac{\left(\frac{Q_{scen} - Q_{base}}{Q_{base}}\right)}{\left(\frac{P_{scen} - P_{base}}{P_{base}}\right)} \quad (3.1)$$

where $Q_{base}$and $Q_{scen}$are the mean simulated discharges over the full simulation period under baseline and scenario conditions, respectively, and P_{base} and P_{scen} are the corresponding mean precipitation inputs over the same period. In this study, the elasticity indicator was computed using period-averaged values rather than annual totals.

Values close to 1 indicate a nearly proportional response, values greater than 1 indicate amplification, and values lower than 1 indicate buffering.

3.7.3 Elasticity under warming scenarios

For warming scenarios, elasticity analysis was conducted in order to quantify the sensitivity of river discharge to temperature increase. In this case, basin sensitivity was quantified by expressing the relative change in simulated discharge per degree of imposed warming. In comparison with the drying scenarios, the interpretation of elasticity under warming conditions is less direct. Since temperature increase affects discharge through a combination of processes, including increased evapotranspiration, changes in snow accumulation, and shifts in snowmelt timing, it is important to interpret the sensitivity values as a combined measure of the hydrological response to these warming scenarios.

In addition to the limitations of elasticity analysis under warming scenarios, it provides a basis to compare the sensitivity of different river sections to temperature increase.

In this study, it was used to assess whether some parts of the basin show a stronger discharge response under warming conditions than others, and to support the interpretation of the scenario results that are presented in the following chapter.

$$S_{warm} = \frac{\Delta Q\%}{\Delta T} \quad (3.2)$$

where $\Delta Q\%$ represents the percentage change in the mean simulated discharge over the full simulation period relative to the baseline simulation, and ΔT is the imposed temperature increase in °C. In this study, the indicator was therefore computed using period-averaged discharge values rather than annual totals.

3.7.4 Elasticity under extreme precipitation scenarios

For extreme scenarios, a similar method is used; however, in these scenarios, the total rainfall amount is unchanged, and the distribution of rainfall across events is affected, with more concentration during intense events.

So, elasticity evaluates how strongly river discharge responds to changes in rainfall distribution to understand whether the flow behaviour is proportional or produces a stronger amplification in high-flow conditions.

In this scenario, the long-term average precipitation is preserved; therefore, the observed changes in the basin response can be interpreted as the result of the redistribution of rainfall intensity rather than an increase in total water input. This means the elasticity approach distinguishes between simple transmission and a more sensitive hydrological amplification.

$$E_{ext} = \frac{\Delta Q\%}{\Delta K\%} \quad (3.3)$$

Where $\Delta Q\%$ represents the percentage change in the selected discharge indicator relative to the baseline simulation. In the extreme precipitation scenarios, this indicator was mainly interpreted for maximum discharge, since rainfall redistribution primarily affects peak-flow behaviour. $\Delta K\%$ is the imposed percentage increase in the scaling factor applied to the precipitation series, equal to 10%, 20%, and 30% for the EXTR_1.1, EXTR_1.2, and EXTR_1.3 scenarios, respectively.

Since the long-term mean precipitation remains unchanged in these scenarios, the indicator measures the sensitivity of discharge to a redistribution of rainfall toward more intense events. Therefore, the index helps distinguish between a limited hydrological response and a stronger amplification under more variable rainfall conditions.

3.7.5 Spatial interpolation and preparation of elasticity maps

In order to better represent the response indicators under the different scenario groups at the basin scale, elasticity maps were generated. Since the elasticity and sensitivity values were available only at the 18 main control stations, spatial interpolation was used to better show the distribution of the basin response.

For this purpose, the station coordinates were first projected into a UTM coordinate system in order to work in a consistent metric reference system. Then, the Inverse Distance Weighting (IDW) method was used to interpolate the elasticity and sensitivity values over the Po River basin (Li & Heap, 2014; Shepard, 1968). Since the number of available stations was limited, this approach was selected as a simple way to represent the spatial response pattern.

The interpolation was performed separately for each scenario. After generating the interpolated raster surface, the output was clipped to the Po River basin boundary in order to avoid representation outside the study area. In this way, the final maps provided a clearer spatial interpretation of the elasticity and sensitivity results obtained at the station level.

A consistent legend range was adopted for each group of scenarios to simplify the comparison within them. This helped to evaluate the differences between scenarios of the same type more clearly and without introducing visual inconsistencies related to automatic map scaling.

3.7.6 Interpretation of elasticity values

The interpretation of elasticity values provides a useful basis for understanding the hydrological behaviour of the basin under stress conditions. For drying and extreme scenarios, values close to one indicate an approximately proportional response of the discharge towards the forcing. Values lower than one suggest that the basin buffers the imposed perturbation, while values greater than one indicate an amplified hydrological response. However, for the warming scenarios, larger absolute sensitivity values show stronger thermal sensitivity, while smaller values indicate weaker response.

In other words, elasticity analysis is useful for understanding the stability of the model's behaviour and to find where the basin becomes more sensitive to climatic stressors.

And this is particularly important for comparing different sections of the Po River system, since upstream and downstream catchments may respond differently due to storage effects, routing processes, snow contribution, and human influences on the water balance.

In addition to elasticity analysis, the results were also checked to see whether they support the "wet gets wetter and dry gets drier" paradigm, which is a hydrological concept assuming that wetter conditions tend to produce stronger flow responses under more intense rainfall patterns, and drier conditions become more severe under precipitation reduction or warming. This perspective provides a meaningful interpretation of the model results and helps with understanding the response of different parts of the Po River basin to climate-related stressors. In this study, this concept was used only as a general framework for interpreting the results, not as a fixed assumption.

Chapter 4: Results and Discussion

4.1 Introduction

This chapter presents the main results obtained from the application of the MISDc model to the Po River basin. First, the model performance under baseline conditions is evaluated to understand if the model can reproduce the main features of the historical daily flow regime. The results from this step provide the basis for comparison of the scenarios.

After the baseline condition, the basin response under three groups of climate-related perturbations, including drying scenarios, warming scenarios, and extreme precipitation scenarios, is analysed. The analysis includes changes in discharge behaviour, spatial variability across the control stations, and response indicators such as elasticity, sensitivity, and amplification.

Then the results from different scenario groups are compared to identify patterns of basin response. Finally, the spatial representation of selected indicators, in the form of maps, helps visualise how hydrological sensitivity varies across the Po River basin.

4.2 Baseline model performance

4.2.1 Comparison between observed and simulated discharge

The model's reliability was first assessed under baseline conditions, before analysing the response of the Po River basin to perturbed conditions. Therefore, to carry out the baseline simulation over the Po River basin, the observed meteorological input data for the period 2000–2023, including precipitation and air temperature series extracted for the 99 sub-basins of the semi-distributed basin configuration, were used to run the MISDc model. The model response was then analysed at 18 main control stations distributed across the basin.

The resulting simulated discharge values were then compared with the observed discharge values available at 5 control stations over the period 2000–2022. This comparison was used to verify whether the model was able to reproduce the main hydrological behaviour of the Po River basin under baseline conditions.

The comparison between observed and simulated discharge shows that the model was able to reproduce the main dynamics of the daily flow regime. The overall temporal variability of discharge was captured, which provided a reasonable representation of the main flow conditions at the basin scale. Therefore, it can be concluded that the selected modelling framework is suitable for reproducing the historical hydrological behaviour of the Po River basin before being used for scenario analysis.

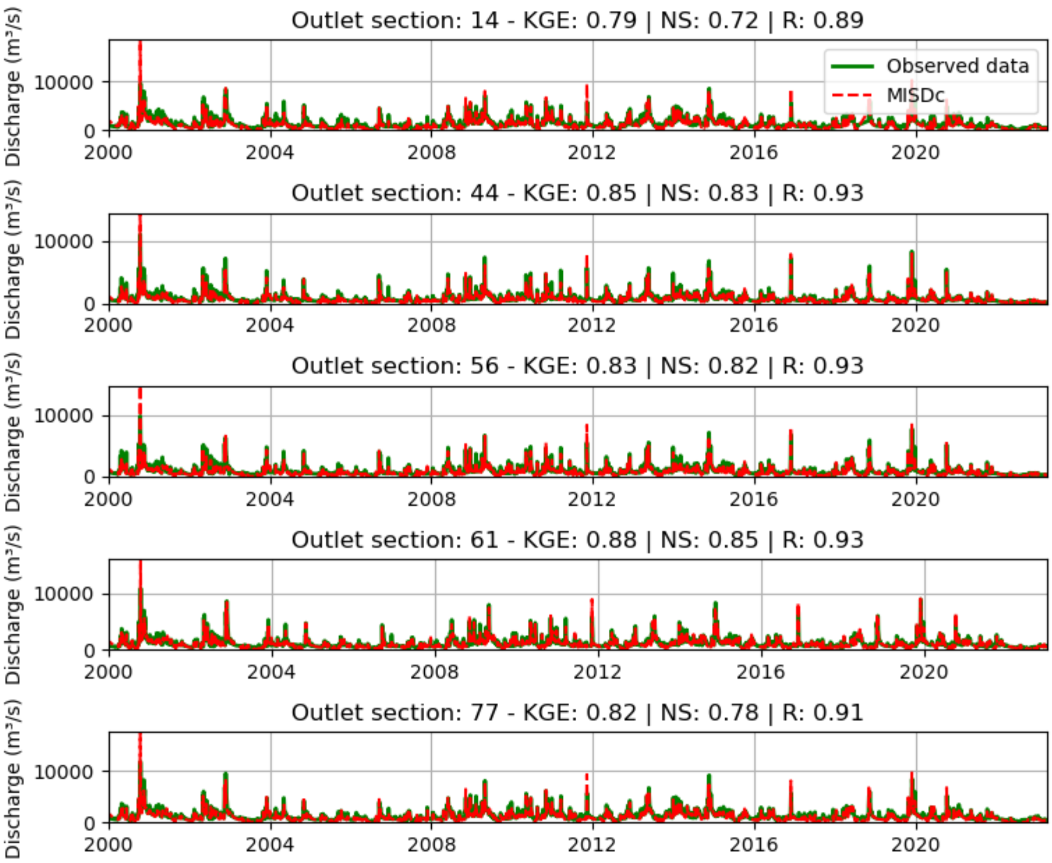


Figure 4.1. Comparison between observed and simulated daily discharge under baseline conditions at five selected outlet sections of the Po River basin.

Although the basin response was analysed at 18 control stations, observed discharge data for baseline comparison were available only at five sections; their spatial location is introduced in Chapter 3 (Figure 3.1). For each outlet section, the corresponding performance indicators, including KGE, NS, and R, are also reported.

As shown in Figure 4.1, the baseline simulation reproduces the main discharge dynamics with a good level of agreement between observed and simulated series. The overall performance supports using the model for the following scenario-based analyses.

The baseline results presented in this chapter were obtained using the MISDc configuration previously adopted for the Po River basin. No new calibration or optimisation was carried out within the present study. Accordingly, the parameter values and threshold conditions used in the simulations were those of the adopted model setup described in Chapter 3. In the original Po River application, the model parameters were constrained through calibration against the available observed discharge records using a KGE-based sequential calibration procedure. Therefore, the agreement shown here should be interpreted as the performance of the adopted calibrated configuration under baseline conditions.

The parameter values and main threshold conditions adopted in the simulations are summarised in Chapter 3 (Table 3.3). These settings were kept unchanged in the baseline and scenario runs discussed in this chapter.

4.2.2 Performance indicators

To assess the reliability of the baseline simulation, standard performance indicators, including the Kling–Gupta Efficiency (KGE), the Nash–Sutcliffe Efficiency (NS), and the correlation coefficient (R), were used.

Although the reported results refer to selected stations rather than to the full set of 18 control stations, they still show that the modelling framework is reliable to support the following scenario-based analyses and examine basin response under drying, warming, and extreme precipitation scenarios. However, in large and complex basins, some differences between stations are also expected.

Station name	KGE	NS	R
Pontelagoscuro	0.79	0.72	0.89
Spessa	0.85	0.83	0.93
Piacenza	0.83	0.82	0.93
Cremona	0.88	0.85	0.93
Borgoforte	0.82	0.78	0.91

Table 4.1. Baseline performance indicators for the five selected stations for which observed discharge data were available for comparison under baseline conditions.

Table 4.1 summarises the performance indicators of the baseline simulation at the selected stations for which observed discharge data were available. The reported KGE, NS, and R values show a good level of agreement between simulated and observed discharge and confirm that the model is able to reproduce the main temporal behaviour of daily discharge.

4.2.3 Basin-scale model behaviour

The baseline simulation also provides useful information on the general hydrological behaviour of the basin. Discharge statistics such as mean flow, maximum flow, and minimum flow were derived from the model outputs. These values help identify the variability of discharge conditions across the basin.

Analysing the baseline results shows that discharge conditions are different from one station to another, and this reflects the spatial complexity of the Po River basin and the effect of tributaries, storage, and routing processes. This confirms that the basin cannot be treated as a hydrologically uniform system and shows the importance of using a semi-distributed framework to represent its internal variability. In addition to a model validation step, the baseline simulation also acts as the reference condition for comparing the results of the perturbed scenarios.

Station name	Mean Flow (m^3/s)	Max Flow (m^3/s)	Min Flow (m^3/s)
Gaiola Stura di Demonte	12.50	949.08	0.00
Cassine Bormida	18.04	1042.46	0.00
Torino Murazzi	31.68	679.19	0.55
Lanzo Stura di Lanzo	36.72	2189.00	0.00
Pontealto	48.74	3012.22	0.00
San Secondo	15.76	1437.95	0.00
Candoglia Toce	36.61	678.49	0.00
Palestro Sesia	29.64	593.34	0.00
Casale Monferrato Po	42.98	2451.49	0.00
ParmaPverdi	61.96	2068.09	5.24
Tavagnasco Dora Baltea	74.07	2124.94	0.00
Spessa	46.99	1347.28	0.60
Piacenza	29.53	1108.73	0.00
Pontelagoscuro	121.99	7823.95	0.00
Cremona	79.20	1882.78	0.00
Borgoforte	52.91	1576.65	0.00
Farigliano Tanaro	51.91	956.16	3.69
Alba Tanaro	142.08	2817.35	0.00

Table 4.2. Baseline simulated discharge statistics for the 18 control stations of the Po River basin.

Table 4.2 presents the main baseline simulated discharge statistics for the 18 control stations. These values provide an overview of flow conditions across the basin.

4.2.4 Interpretation of baseline model performance

For a large and complex basin such as the Po River basin, which is influenced by spatial variability in precipitation, tributary contribution, routing effects, seasonal storage, and snow-related processes, we cannot expect perfect agreement between observed and simulated discharge at all stations. Therefore, the aim of the basin-scale analysis is to evaluate the reliability of the baseline simulation rather than an exact reproduction of all local flow details.

Another reason for the importance of the evaluation of the baseline is that it provides the basis for the interpretation of the scenario-based simulations. The results under the drying, warming, and extreme precipitation scenarios can be interpreted with more confidence when the model is able to reproduce the main features of the historical flow.

The baseline results indicate that the model performance is different from one station to another, which can be considered as a result of the scale and complexity of the Po River basin. Therefore, it is important to define the level at which the results of the model should be interpreted. For the present study, the model is used to find and analyse basin-scale patterns and compare scenario responses, rather than reproducing every detail in discharge changes with the same accuracy.

Overall, the baseline performance supports the use of the MISDc framework for the purpose of this thesis. Therefore, the baseline simulation can be considered as a reference condition for comparing basin response under the different hydro-climatic perturbation scenarios analysed in the following sections.

4.3 Results under drying scenarios

4.3.1 Changes in discharge under precipitation reduction

To evaluate the response of the Po River basin under progressive reductions in precipitation, the drying scenarios were designed. Three levels of rainfall reduction, including −10%, −20%, and −30%, were considered. The original temperature data remained unchanged. The results show that across all 18 control stations, as the imposed precipitation reduction increases, the simulated discharge declines.

The overall behaviour indicates that the reduction in the simulated discharge is more than proportional in comparison to the rainfall reduction. The results show that, on average, the reduction in mean discharge is about 17% under the −10% scenario, by about 30% under the −20% scenario, and by about 45% under the −30% scenario. Therefore, the response of the basin is non-linear and drying conditions lead to significant reductions in water availability.

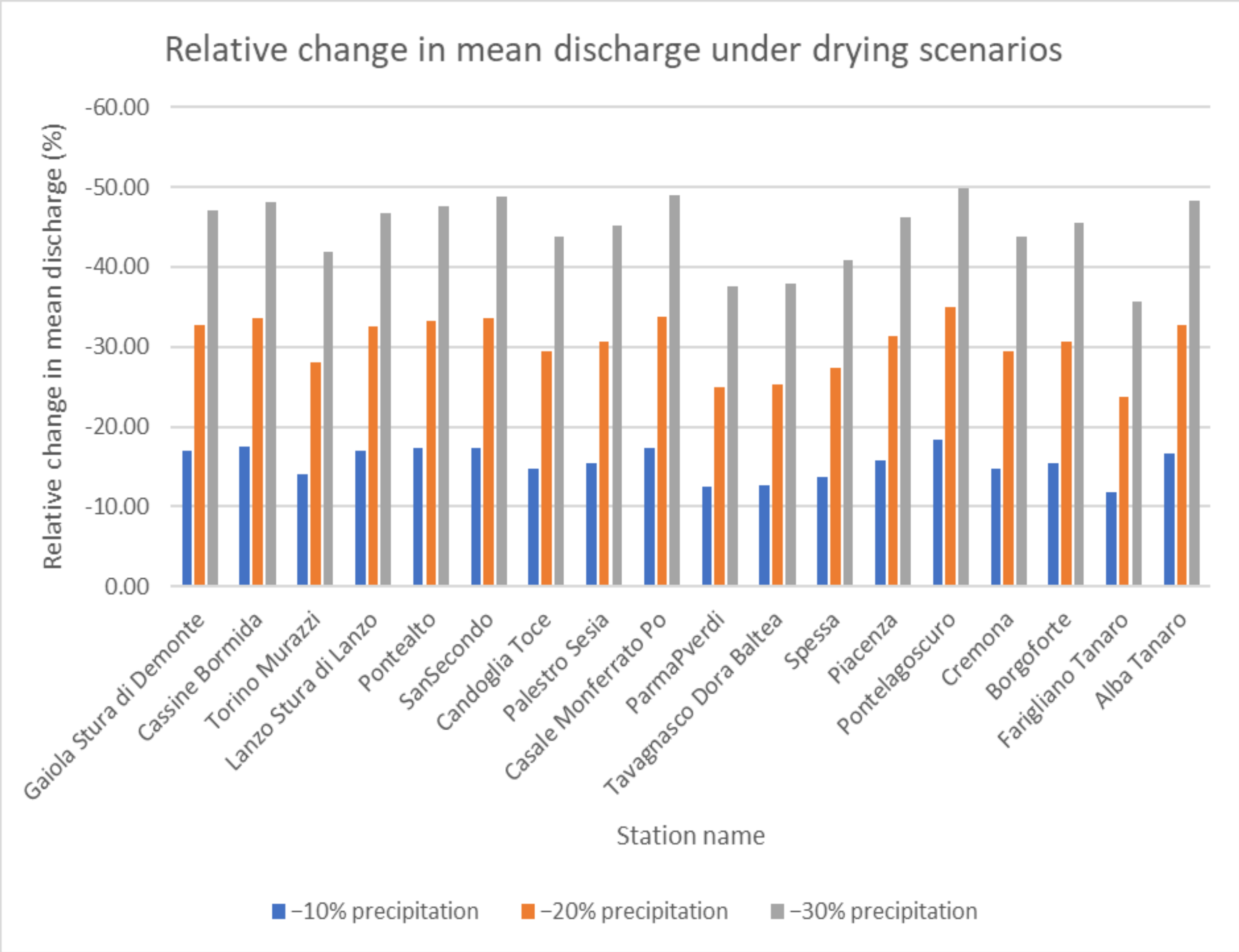


Figure 4.2. Relative change in mean discharge under the drying scenarios at the 18 control stations of the Po River basin.

As shown in Figure 4.2, all stations have negative relative changes in mean discharge, which means the response of the basin is consistent. The strongest reductions are observed under the −30% scenario.

This pattern is also confirmed by the station-based analysis of the results. For example, at Piacenza, mean simulated discharge decreases by about 15.8% under −10% precipitation and by about 31.3% under −20% precipitation. At Pontelagoscuro, a similar behaviour is observed, where mean discharge decreases by about 18.3% under −10% precipitation and by about 35.0% under −20% precipitation. In both stations, the maximum discharge is also reduced, which shows that drying affects not only average flow conditions but also higher-flow events.

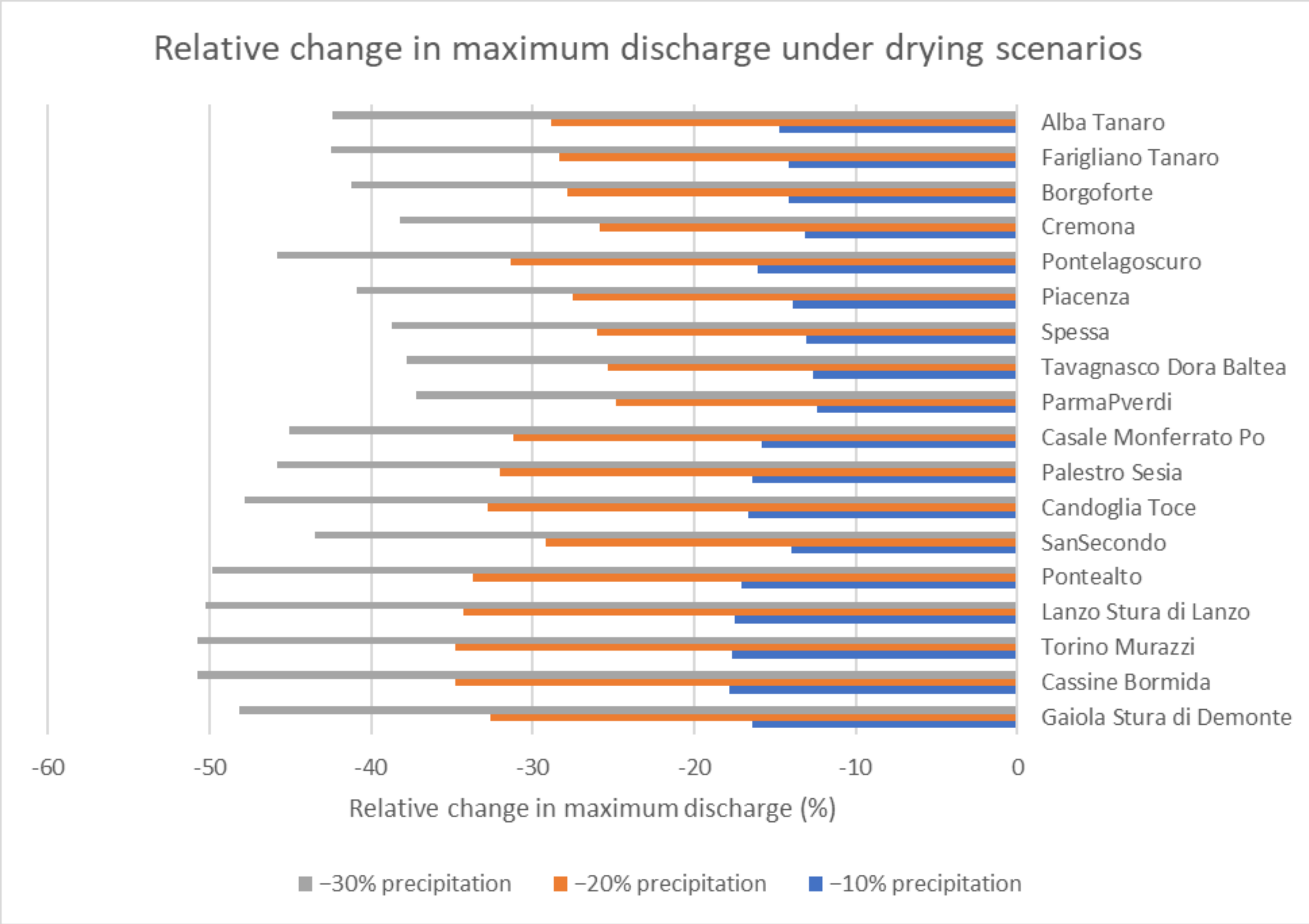


Figure 4.3. Relative change in maximum discharge under the drying scenarios at the 18 control stations of the Po River basin.

Figure 4.3 shows that maximum discharge also decreases under all drying scenarios at the 18 control stations of the Po River basin. As expected, the strongest reductions are generally observed under the −30% precipitation scenario, while the −10% scenario produces the smallest changes. This result indicates that drying affects not only mean flow conditions, but also peak-flow behaviour across the basin.

4.3.2 Sensitivity of different basin sections

The intensity of the discharge reductions varies from one control station to another. The strongest reductions are observed at downstream stations such as Piacenza, Cremona, Pontelagoscuro, and Casale Monferrato Po, where larger absolute and relative flow losses are produced due to the cumulative effect of upstream precipitation deficits. In contrast, some upper and alpine stations, such as Gaiola and Tavagnasco, also show reductions, but the intensity of their response is slightly smaller.

This variation in spatial behaviour suggests that the hydrological response to drying is not uniform across the basin, and downstream catchments have a stronger response. On the other hand, some upper catchments appear to have a buffering capacity, which may be related to local storage, snow processes, or groundwater support. However, the overall pattern of the reduction in the simulated discharge remains consistent across the basin.

Station Name	−10% precipitation	−20% precipitation	−30% precipitation
Gaiola Stura di Demonte	-16.99	-32.75	-47.00
Cassine Bormida	-17.42	-33.56	-48.04
Torino Murazzi	-14.02	-27.98	-41.85
Lanzo Stura di Lanzo	-17.02	-32.62	-46.70
Pontealto	-17.39	-33.31	-47.52
SanSecondo	-17.32	-33.66	-48.74
Candoglia Toce	-14.80	-29.48	-43.88
Palestro Sesia	-15.52	-30.59	-45.17
Casale Monferrato Po	-17.38	-33.78	-48.95
ParmaPverdi	-12.51	-25.02	-37.50
Tavagnasco Dora Baltea	-12.69	-25.35	-37.99
Spessa	-13.65	-27.28	-40.86
Piacenza	-15.81	-31.29	-46.30
Pontelagoscuro	-18.30	-35.04	-49.84
Cremona	-14.76	-29.41	-43.85
Borgoforte	-15.50	-30.71	-45.52
Farigliano Tanaro	-11.84	-23.71	-35.63
Alba Tanaro	-16.59	-32.73	-48.21

Table 4.3. Relative change in mean discharge at the 18 control stations under the three drying scenarios.

The values shown in Table 4.3 confirm that the response to drying is not spatially uniform across the basin. In general, downstream stations show larger reductions, while some upstream and alpine stations show smaller relative changes.

A comparison of the −10% and −20% scenarios shows that the basin sensitivity becomes more evident under stronger perturbation. In the −10% scenario, the mean relative discharge reduction in most stations is about 12–18%, while under −20% precipitation, these values increase to about 24–35% depending on the station.

Therefore, even moderate reductions in rainfall can lead to noticeable changes in basin response.

4.3.3 Response indicators under drying scenarios

Response indicators were used to evaluate the results based on the relative change in discharge compared with the imposed precipitation reduction. For all drying scenarios, the amplification factor value is larger than one, which means that the discharge response is stronger than the rainfall perturbation. The amplification values range from about 1.4 to 1.8, and the average is close to 1.6. This means that a 10% reduction in precipitation leads to a discharge reduction of about 15–18%, while stronger rainfall deficits lead to even larger impacts.

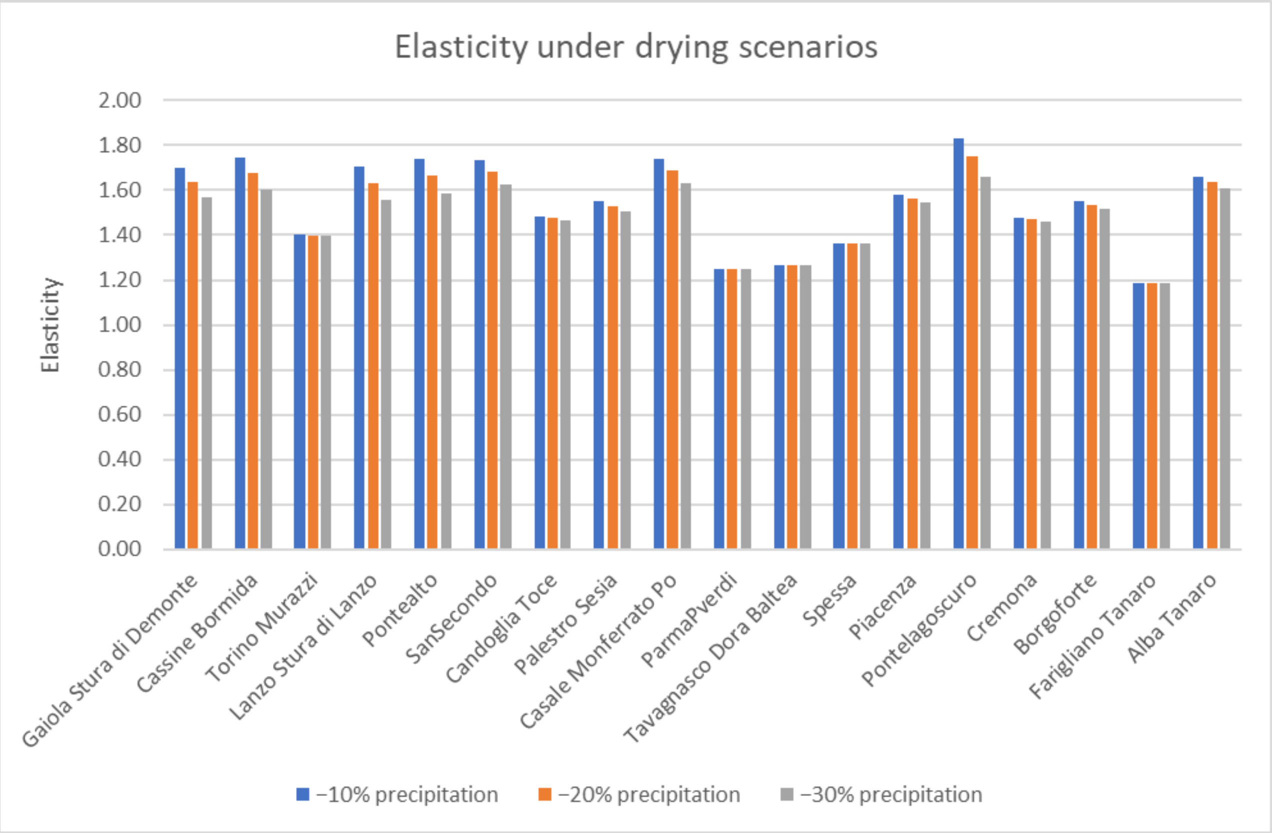


Figure 4.4. Elasticity of mean discharge under the drying scenarios at the 18 control stations of the Po River basin.

Considering a station level, a slight decrease in amplification values can be observed as the imposed reduction in precipitation increases. For example, Pontelagoscuro shows amplification values of about 1.83 under −10%, 1.75 under −20%, and 1.66 under −30%. It is also similar for Piacenza, with values of about 1.58, 1.56, and 1.54

under the same scenarios. Therefore, the basin response remains amplified while showing a slight tendency toward saturation as the drying becomes more intense.

The pattern in maximum discharge reduction is similar. Both mean and maximum discharges decrease consistently, showing that the whole basin is affected by the drying scenarios, and the magnitude of both regular and higher-flow discharge behaviour is reduced.

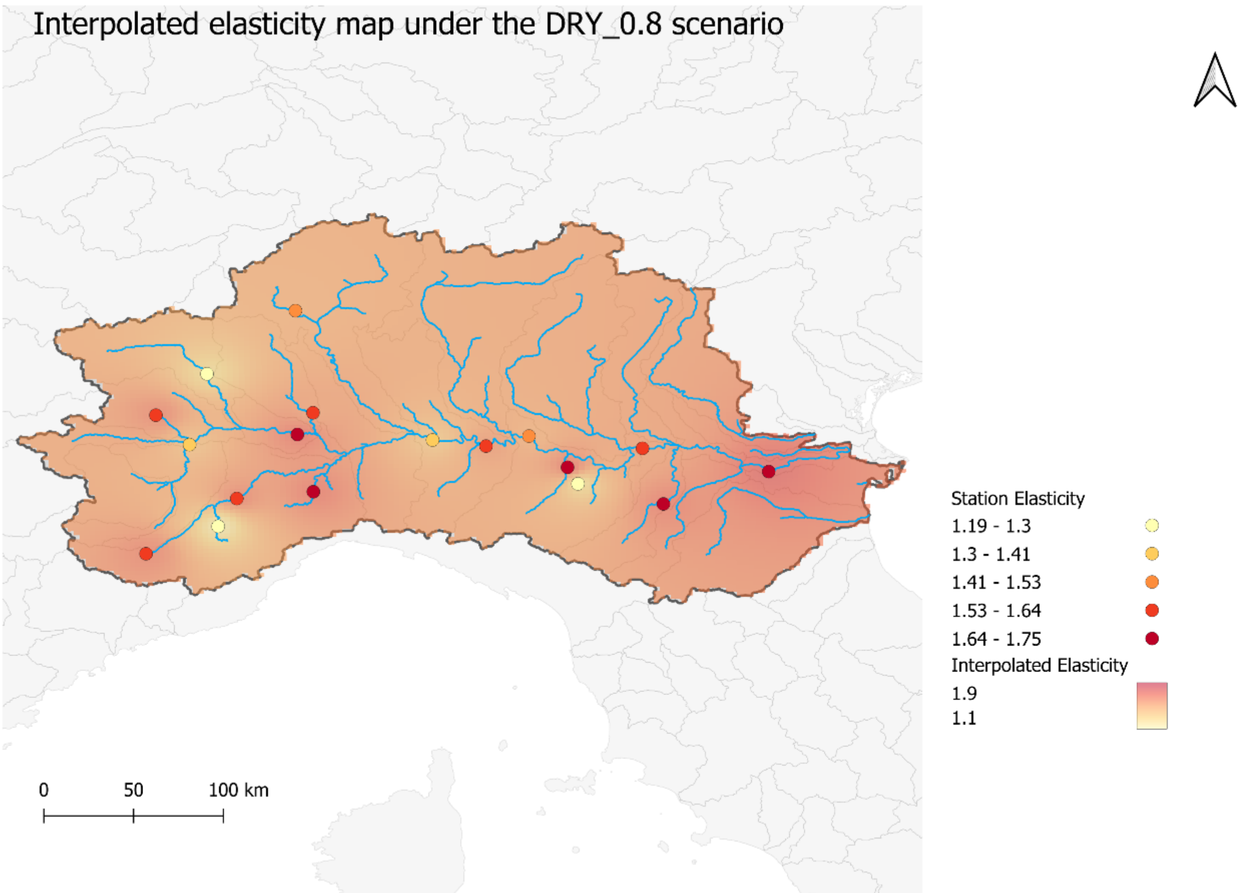
4.3.4 Main patterns under drying conditions

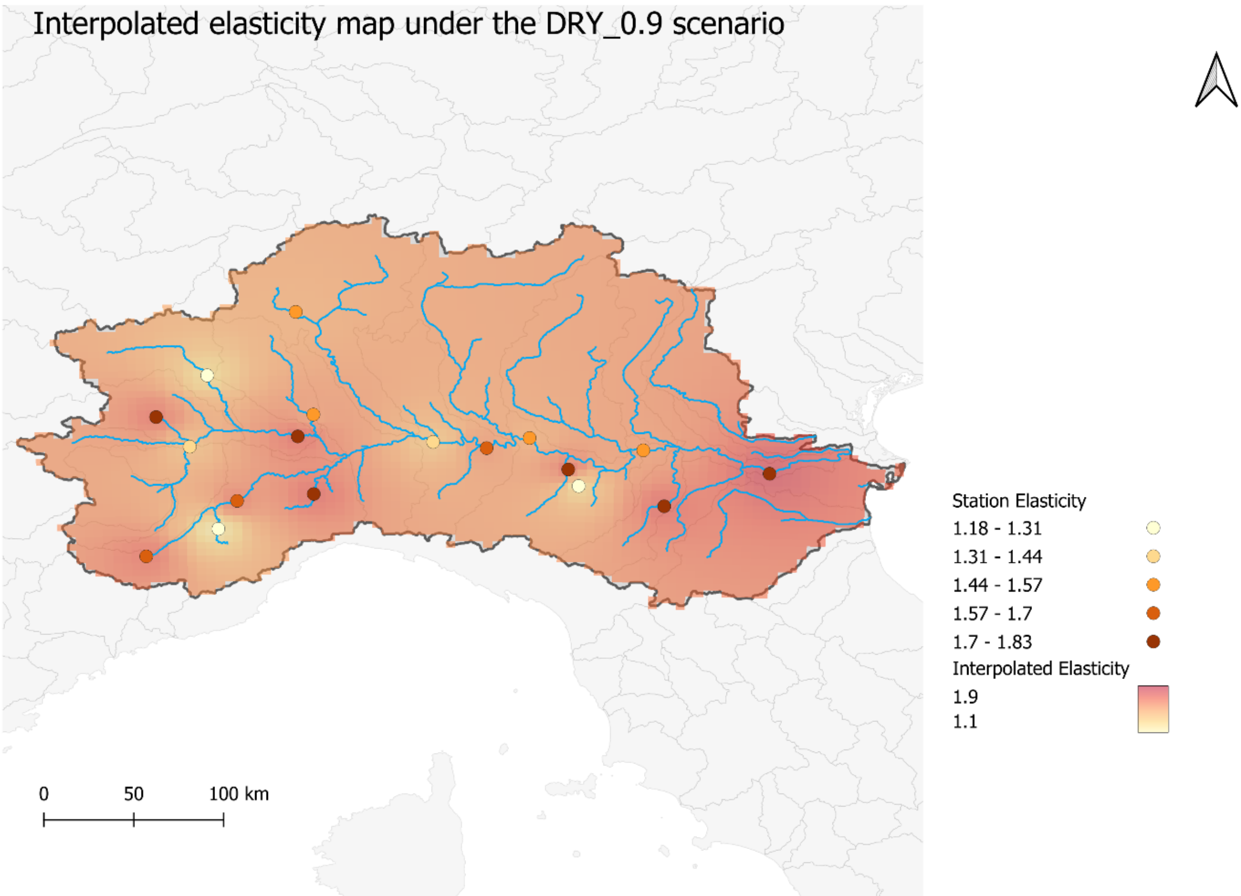
Overall, analysing the drying scenarios shows the sensitivity of the Po River basin to reductions in precipitation. This response is regular across all sub-catchments and becomes stronger as the imposed perturbation increases. Moreover, a non-linear response is confirmed by the fact that simulated discharge reductions exceed rainfall reductions. Therefore, an amplified discharge loss is observed under this group of scenarios.

At the downstream catchments, this behaviour is more intense since accumulated upstream deficits lead to stronger mean-flow reductions. It can be concluded that drying creates a strong source of hydrological stress for the basin. These findings provide the basis for comparison between different groups of scenarios that will be discussed in the following sections.

4.3.5 Interpolated spatial patterns under drying scenarios

To better visualise how the basin response is distributed across the Po River basin, spatial interpolation maps were prepared. Since the elasticity and sensitivity values were available only at the 18 main control stations, they were interpolated using the Inverse Distance Weighting (IDW) method after projection to the UTM coordinate system. Then the resulting surfaces were clipped to the basin boundary. A consistent legend range was used for each group of scenarios to make the comparison within each group easier.


Interpolated elasticity map under the DRY_0.8 scenario
Station Elasticity
1.19 - 1.3
1.3 - 1.41
1.41 - 1.53
1.53 - 1.64
1.64 - 1.75
Interpolated Elasticity
1.9
1.1
0
50
100 km


Interpolated elasticity map under the DRY_0.9 scenario
Station Elasticity
1.18 - 1.31
1.31 - 1.44
1.44 - 1.57
1.57 - 1.7
1.7 - 1.83
Interpolated Elasticity
1.9
1.1
0
50
100 km

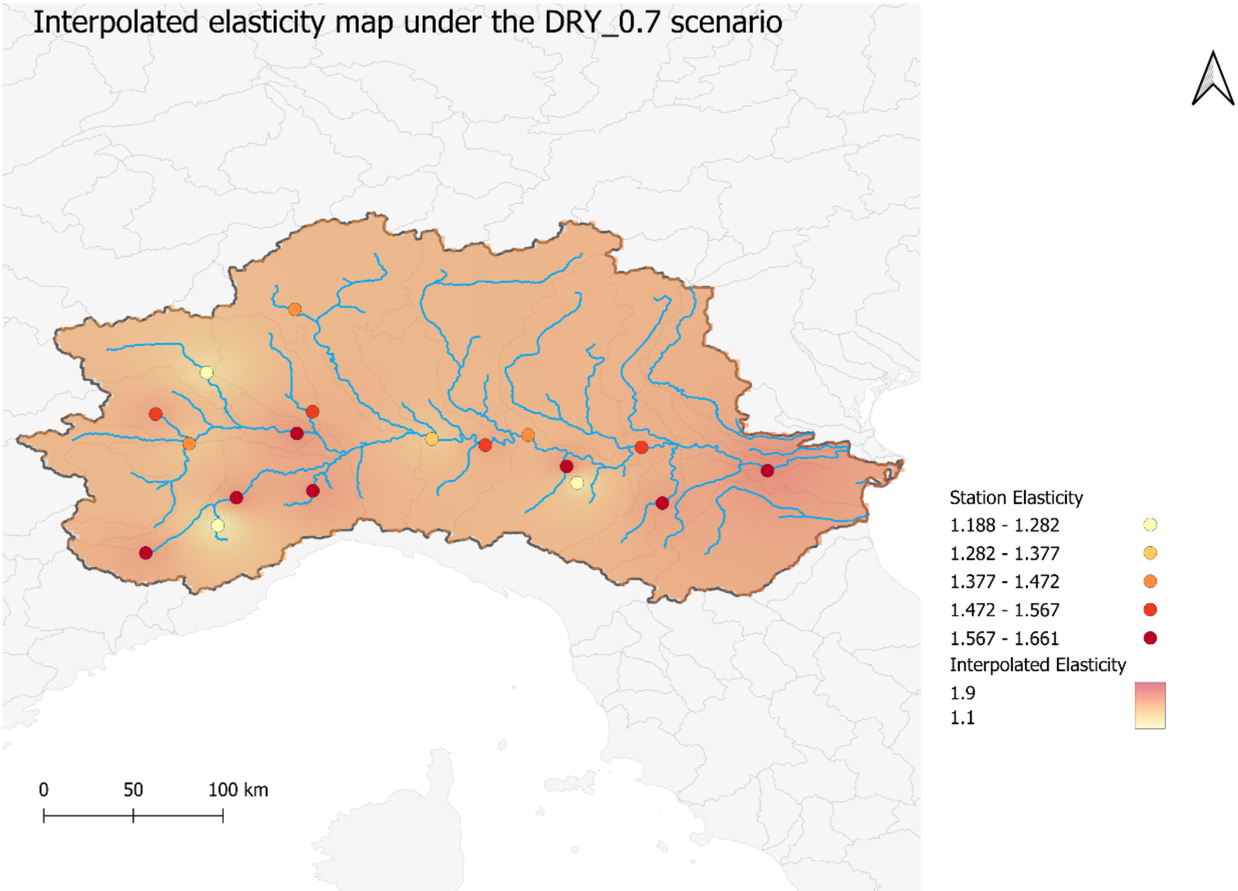


Figure 4.5. Interpolated spatial distribution of basin response under the drying scenarios DRY_0.9, DRY_0.8, and DRY_0.7 across the Po River basin.

Figure 4.5 shows that in many parts of the basin, the hydrological response to precipitation reduction is stronger than the imposed reduction itself. The maps highlight the stations with an amplified response. The spatial patterns shown by the maps suggest that the response is not uniform and some areas are more sensitive than others. Spatial variability in storage capacity, tributary contribution, and routing effects are most likely responsible for this behaviour.

4.3.6 Interpretation of drying scenario results

The clearest and strongest response among the scenario families is produced by the drying scenarios. The effect of precipitation reduction on basin discharge is more direct and easier to interpret in comparison with other scenarios. The reduction in rainfall limits the available water input for runoff generation.

This behaviour shows that the Po River basin is very sensitive to drying conditions and even a moderate decrease in precipitation can lead to a strong reduction in river discharge. This non-linear response of the basin may be due to cumulative hydrological effects within the basin. Precipitation reduction means less water is available for runoff generation, soil moisture storage and maintaining stream flows. Therefore, the resulting discharge decrease becomes more evident than the initial rainfall reduction.

It is noteworthy that in a large and complex basin such as the Po River basin, the behaviour of all stations is not the same, and it is influenced by tributary contribution, storage effects, routing, and local hydrological components that are active at each station. However, the overall pattern is the same: precipitation reduction leads to an amplified decrease in discharge across the basin. Therefore, drying is the most severe hydrological stress among the analysed scenario families in terms of its effect on mean discharge.

Overall, the analysis of drying scenario results shows that the Po River basin is strongly dependent on precipitation input and that reductions in rainfall can lead to a strong loss in river discharge. This result is important and suggests that water availability at the basin scale can be vulnerable under drying conditions. It also provides a useful reference for the interpretation of the other scenarios, which affect the basin through different mechanisms.

4.4 Results under warming scenarios

4.4.1 Changes in discharge under +1 °C and +3 °C warming

To evaluate how increasing air temperature affects the simulated discharge, the warming scenarios were designed. For this group, two levels of temperature increase were analysed, namely +1 °C and +3 °C, while keeping the precipitation inputs unchanged. The results show that the average basin discharge is affected in a systematic but non-uniform way, with stronger responses under +3 °C compared to +1 °C.

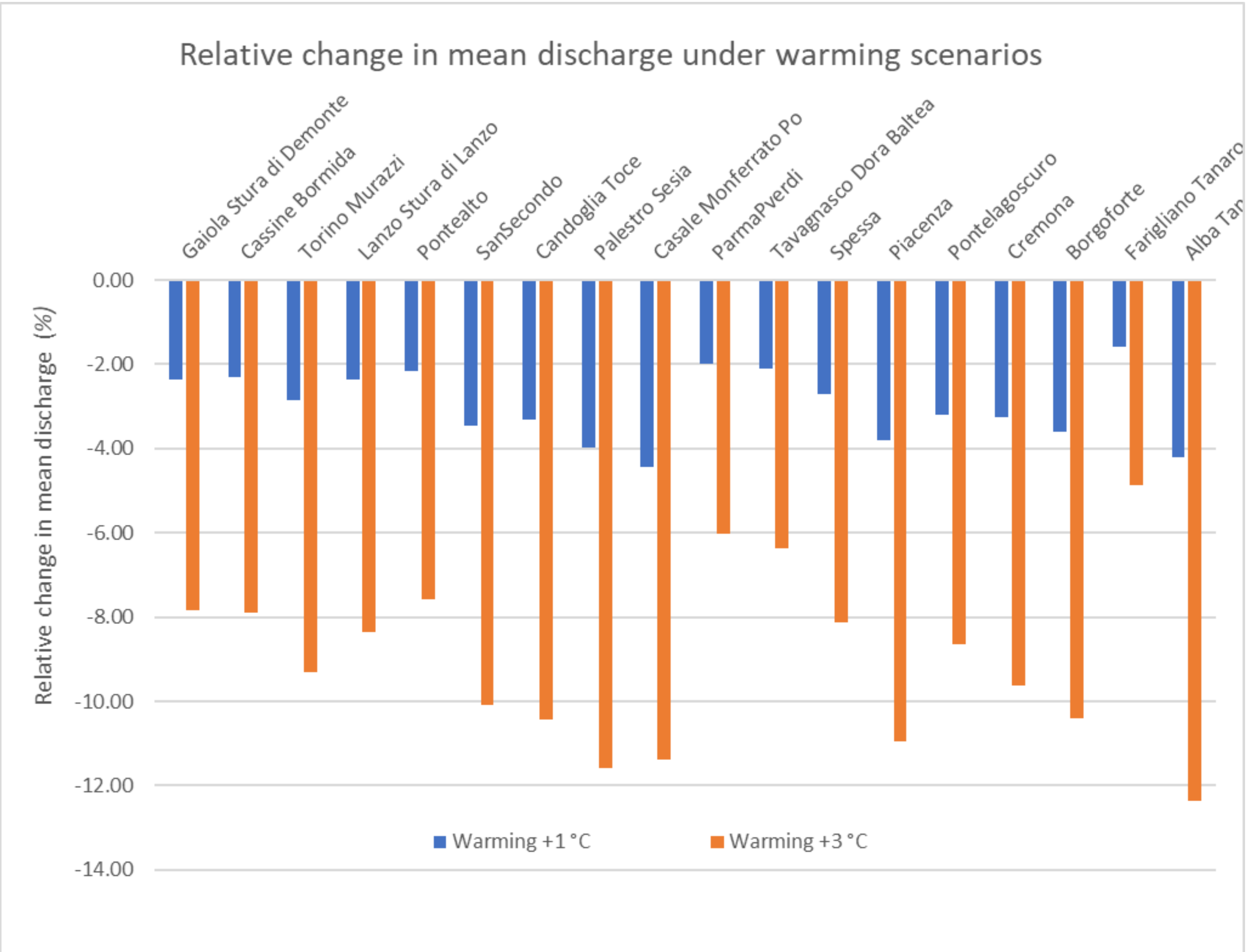


Figure 4.6. Relative change in mean discharge under the +1 °C and +3 °C warming scenarios at the 18 control stations of the Po River basin.

As shown in Figure 4.6, the mean discharge decreases at all stations under warming conditions, with stronger reductions under +3 °C.

Station	Warming +1 °C	Warming +3 °C
Gaiola Stura di Demonte	-2.37	-7.83
Cassine Bormida	-2.31	-7.90
Torino Murazzi	-2.87	-9.31
Lanzo Stura di Lanzo	-2.36	-8.37
Pontealto	-2.18	-7.57
SanSecondo	-3.45	-10.09
Candoglia Toce	-3.31	-10.43
Palestro Sesia	-3.99	-11.59
Casale Monferrato Po	-4.44	-11.39
ParmaPverdi	-2.00	-6.03
Tavagnasco Dora Baltea	-2.11	-6.36
Spessa	-2.72	-8.12
Piacenza	-3.81	-10.96
Pontelagoscuro	-3.19	-8.64
Cremona	-3.26	-9.64
Borgoforte	-3.60	-10.41
Farigliano Tanaro	-1.59	-4.88
Alba Tanaro	-4.22	-12.36

Table 4.4. Relative change in mean discharge at the 18 control stations under the +1 °C and +3 °C warming scenarios.

At the basin scale, a moderate reduction in mean discharge is seen under +1 °C in most stations, generally about 2–4%, while under +3 °C this reduction becomes stronger and reaches about 7–12% across a large part of the basin. In contrast, maximum discharge responds less uniformly. Under +1 °C, the changes are small and inconsistent, while under +3 °C, many stations show an increase in peak flow, between about 3% and 15%.

This behaviour is also observed in the selected station results. At all control stations, mean discharge decreases under both warming scenarios, with a stronger reduction under +3 °C than under +1 °C. The magnitude of the response varies from one section to another, but the overall pattern remains consistent across the basin. This confirms that warming produces a basin-wide reduction in mean discharge even when precipitation remains unchanged.

4.4.2 Effect on basin hydrological behaviour

The change in discharge magnitude is not the only way that temperature increase affects the basin; modifications in the internal hydrological behaviour of the system are also a part of the warming response. The decrease in mean discharge is generally associated with changes in hydrological processes, such as increased evapotranspiration and reduced seasonal snow storage, both of which affect runoff generation by lowering the amount of water available. Therefore, the differences in the magnitude of the basin response from one control station to another confirm that the local hydrological processes play an important role in controlling basin behaviour under warming conditions.

Considering the spatial pattern of the response, downstream stations such as Piacenza, Cremona, Pontelagoscuro, and Casale Monferrato Po show the largest absolute changes, reflecting the cumulative effect of upstream basin processes. In contrast, alpine stations such as Gaiola, Tavagnasco, and Lanzo Stura di Lanzo show smaller absolute changes due to the buffering effect of snowmelt; however, in some cases, noticeable relative reductions in mean flow are related to earlier snowmelt timing and interactions between temperature and snow processes.

Therefore, warming affects the seasonal formation of runoff rather than causing a uniform shift in discharge across the basin. Moderate warming slightly modifies the average flow conditions at several stations, while stronger warming causes a more intense reduction in mean flow and, in some stations, a sharper peak-flow response. In comparison with drying scenarios, the hydrological effect of temperature increase is more process-driven and spatially variable in warming scenarios.

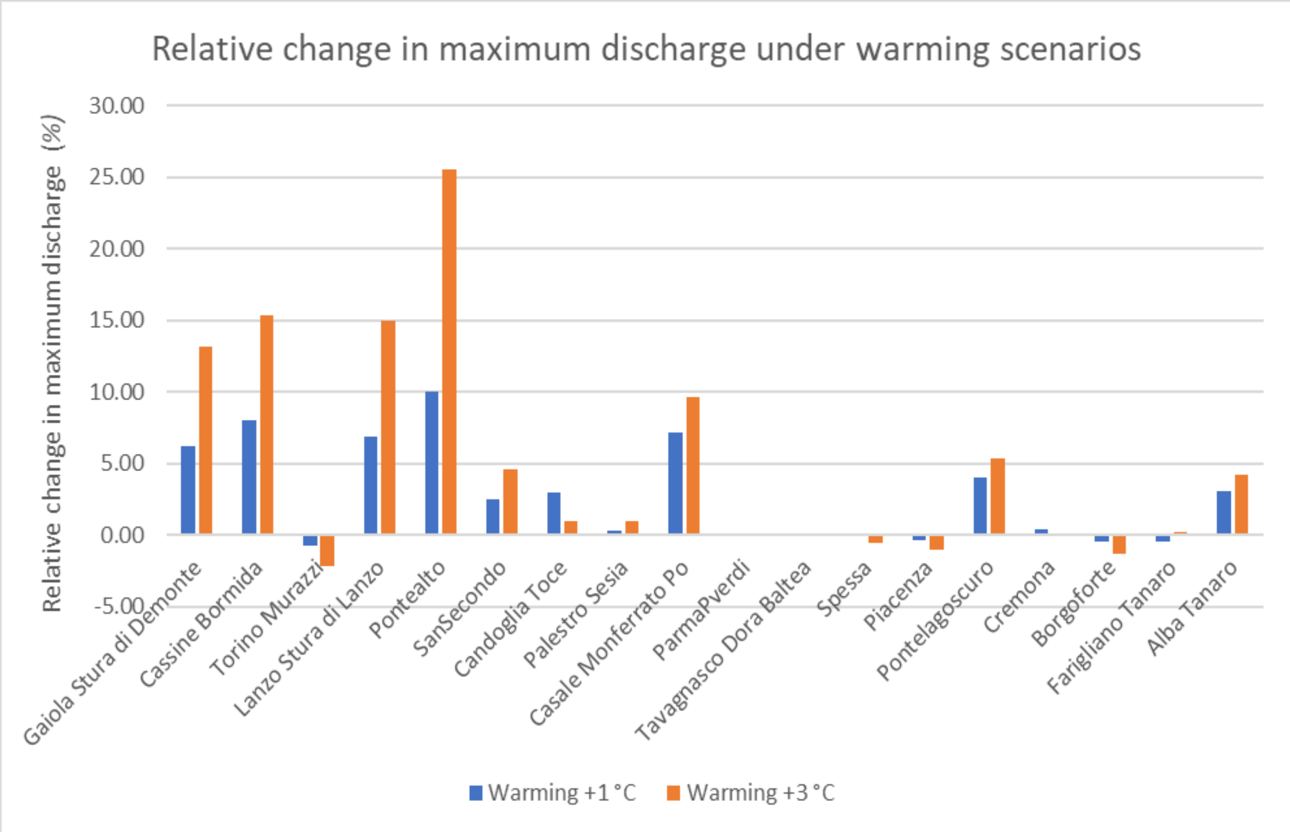


Figure 4.7. Relative change in maximum discharge under the +1 °C and +3 °C warming scenarios at the 18 control stations of the Po River basin.

As shown in Figure 4.7, maximum discharge is not uniform across the basin. In several stations, stronger warming leads to an increase in peak discharge, which shows that warming may affect not only average flow conditions but also peak-flow behaviour.

4.4.3 Sensitivity indicators under warming scenarios

The thermal sensitivity values were computed as the relative change in simulated discharge per degree of warming to quantify basin sensitivity to temperature increase. To make it possible to compare the thermal sensitivity of different control stations, the percentage of discharge variation is divided by the imposed temperature increment.

$$S_{warm} = \frac{\Delta Q\%}{\Delta T} \quad (4.1)$$

where $\Delta Q\%$ represents the percentage change in the mean simulated discharge over the full simulation period relative to the baseline simulation, and ΔT is the imposed temperature increase in °C. In this study, the indicator was therefore computed using period-averaged discharge values rather than annual totals.

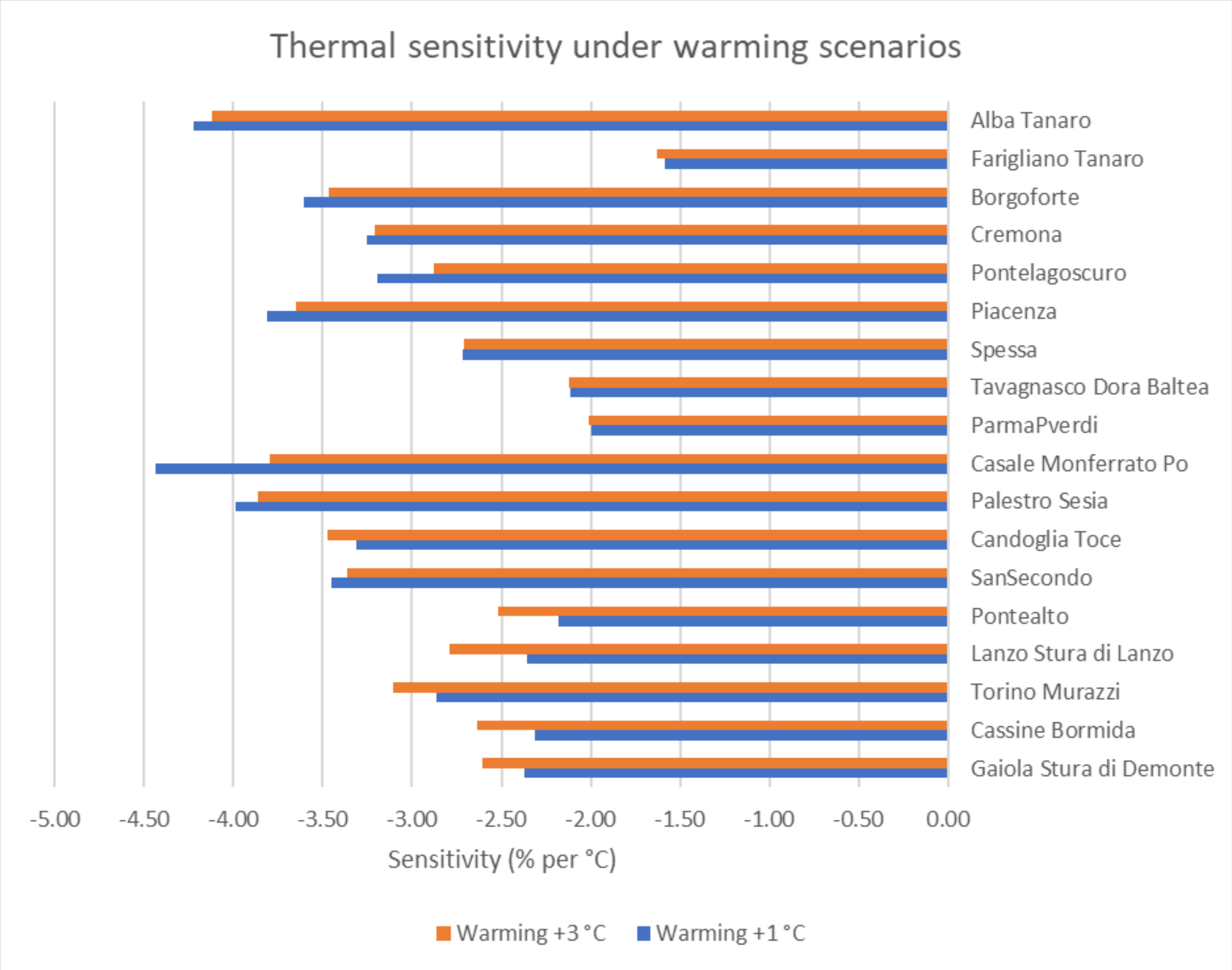


Figure 4.8. Thermal sensitivity of mean discharge under the +1 °C and +3 °C warming scenarios at the 18 control stations of the Po River basin.

As shown in Figure 4.8, negative thermal sensitivity across the basin confirms that warming reduces mean discharge. At the same time, the magnitude of sensitivity is different between stations, which means that local hydrological components influence the response to temperature increase.

The negative mean-flow sensitivity that is shown across the basin confirms that warming tends to reduce average discharge conditions. The mean thermal sensitivity values are in the range of about −2% to −4% per degree of warming. Therefore, temperature increase generally leads to a moderate but consistent reduction in basin discharge. The strongest responses are observed at downstream stations, while upper alpine stations tend to show smaller absolute changes due to the buffering effects of snow-related processes.

The sensitivity of peak-flow behaviour is more complex. Under stronger warming scenarios, the maximum discharge increases in many stations, with sensitivity values between +3% and +5% per degree. This means that even though warming reduces average water availability, it may intensify some high-flow responses by affecting the timing of seasonal runoff and the intensity of the related events. Therefore, the sensitivity indicators confirm that different hydrological components are affected by the warming scenarios in different ways.

4.4.4 Main patterns under warming conditions

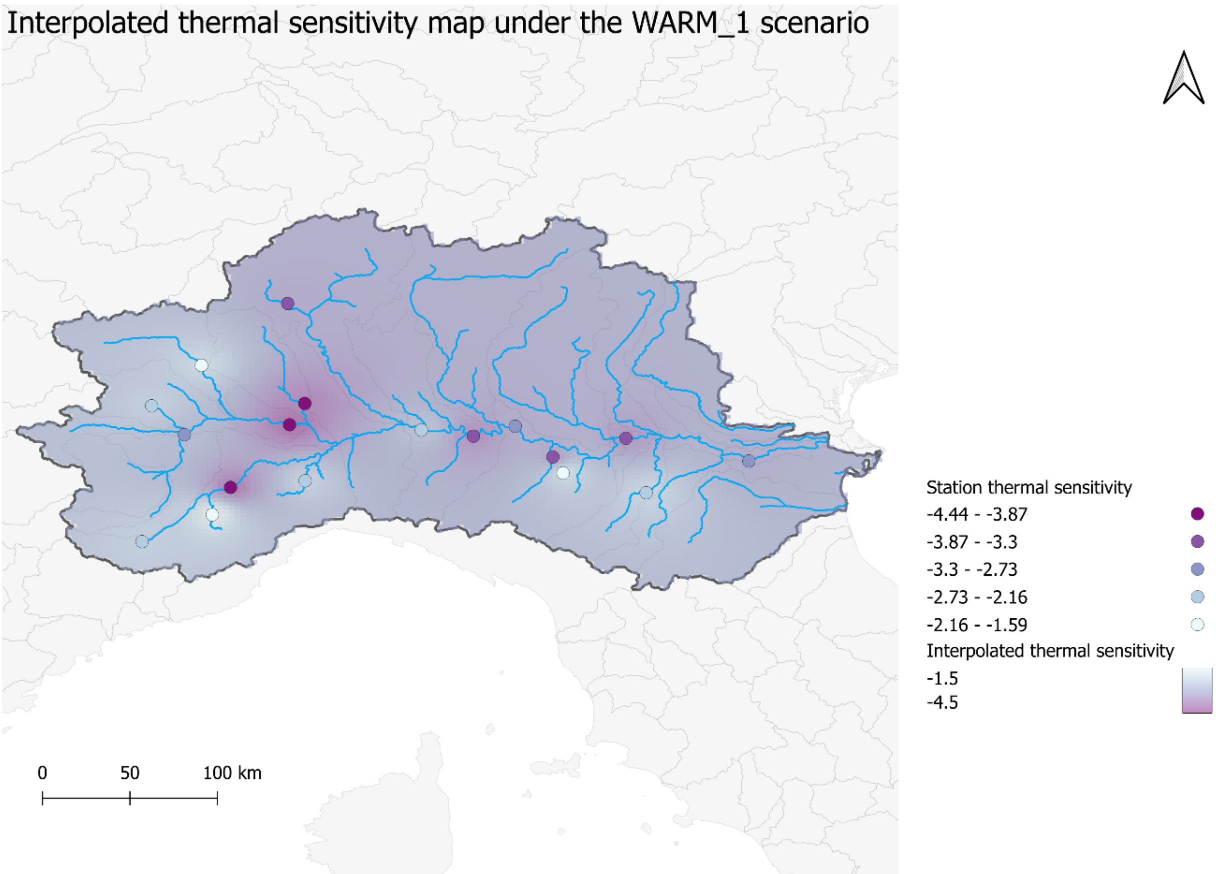
Overall, analysing the warming scenarios shows that the Po River basin is sensitive to temperature increase, although in comparison with the drying scenario, the response is weaker and more spatially variable. The +1 °C scenario produces relatively small and inconsistent changes, while the +3 °C scenario causes a clearer basin response, with stronger reductions in mean discharge and a more evident modification of peak-flow behaviour.

Therefore, the main pattern is a gradual decline in average discharge under rising temperature, combined with a more complex and non-uniform response in maximum flow. This shows that warming affects different hydrological processes, especially evapotranspiration and snow-related components.

Compared with the drying scenarios, the warming response is less amplified, but it still affects basin-scale water availability and allows a detailed comparison with the other scenario families in the following section.

4.4.5 Interpolated spatial patterns under warming scenarios

The spatial distribution of thermal sensitivity under the +1 °C and +3 °C scenarios is represented by the warming maps. The values are mainly negative, which shows the reduction in discharge as a result of the increased temperature. More negative values mean stronger responses. Therefore, the sub-catchment with lower sensitivity values is the one more strongly affected by the warming.



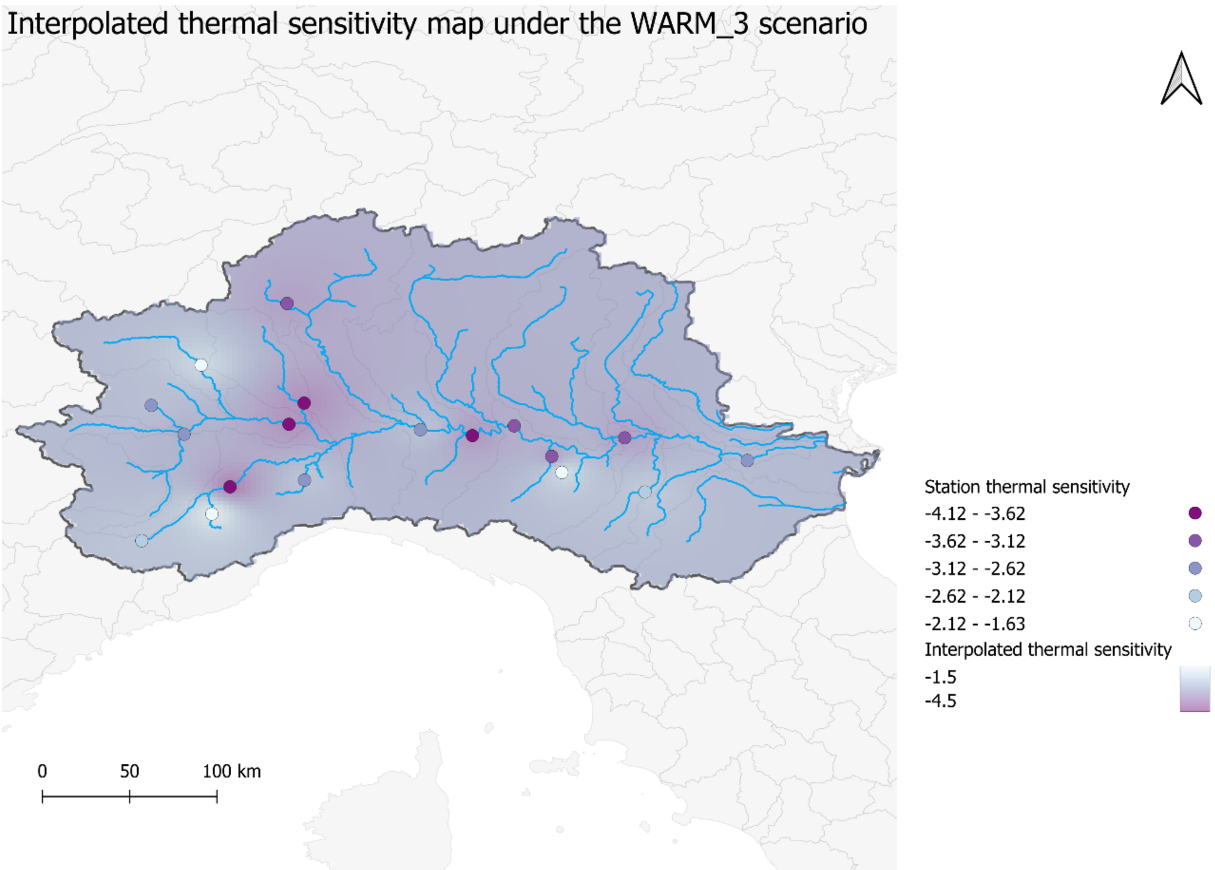


Figure 4.9. Interpolated spatial distribution of thermal sensitivity under the warming scenarios WARM_1 and WARM_3 across the Po River basin.

Figure 4.9 shows that the warming response is predominantly negative across the basin, although its intensity is not uniform. This pattern confirms the station-based analysis, which suggested that thermal sensitivity depends on local hydrological components such as evapotranspiration and snow-related processes. Therefore, the maps provide a clearer picture of how warming affects different parts of the Po River system.

4.4.6 Interpretation of warming scenario results

The type of response produced by the warming scenarios is different from that of the drying scenarios. In drying scenarios, the available water is directly reduced, while warming affects the internal hydrological processes involved in discharge generation. Therefore, the basin's response to warming is less uniform; however, a reduction in mean discharge values can be considered as the overall effect.

One of the hydrological processes that is affected by the warming scenario is evapotranspiration. The increase in temperature raises the atmospheric demand for water; as a result, the amount of available water for runoff generation is reduced. In the Po River basin, an important factor in controlling the response is the balance between precipitation input, seasonal storage, and losses due to evaporation.

In addition to evapotranspiration, snow-related processes also play an important role in the warming response, especially in upper and alpine control stations. Under warming scenarios, both snow accumulation and the timing of snowmelt can be affected, and as a result, the seasonal generation of runoff is altered. This means that not only does warming reduce water availability, but it may also shift the way water is released through time.

The behaviour of maximum discharge also supports this interpretation. Under warming scenarios, the response of peak discharge is less regular and even positive in some stations. This shows that warming does not affect all components of the hydrograph in the same way. The reduction in mean discharge is a result of increased water losses and changes in storage conditions, while maximum discharge is affected by changes in runoff timing, seasonal concentration, or the interaction of local processes.

Overall, the warming experiments show that the Po River basin is sensitive to temperature increase, although in a more gradual and process-dependent way. These results suggest that warming does not simply produce “less flow” in a uniform way. Instead, it modifies the balance between storage, evapotranspiration, snow-related processes, and runoff timing. This makes the warming response more complex to interpret, but also more informative in terms of understanding how the basin behaves under changing hydro-climatic conditions.

4.5 Results under extreme precipitation scenarios

4.5.1 Changes under EXTR_1.1, EXTR_1.2, and EXTR_1.3

To investigate how the Po River basin responds to more intense rainfall events while the long-term average precipitation remains approximately unchanged, extreme precipitation scenarios were designed. For this reason, three perturbation levels were analysed, namely EXTR_1.1, EXTR_1.2, and EXTR_1.3, which are related to the level of rainfall variance increase. The results show that in this group of scenarios, the mean discharge remained almost unchanged; however, the behaviour of higher flows and peak responses is influenced by this type of perturbation.

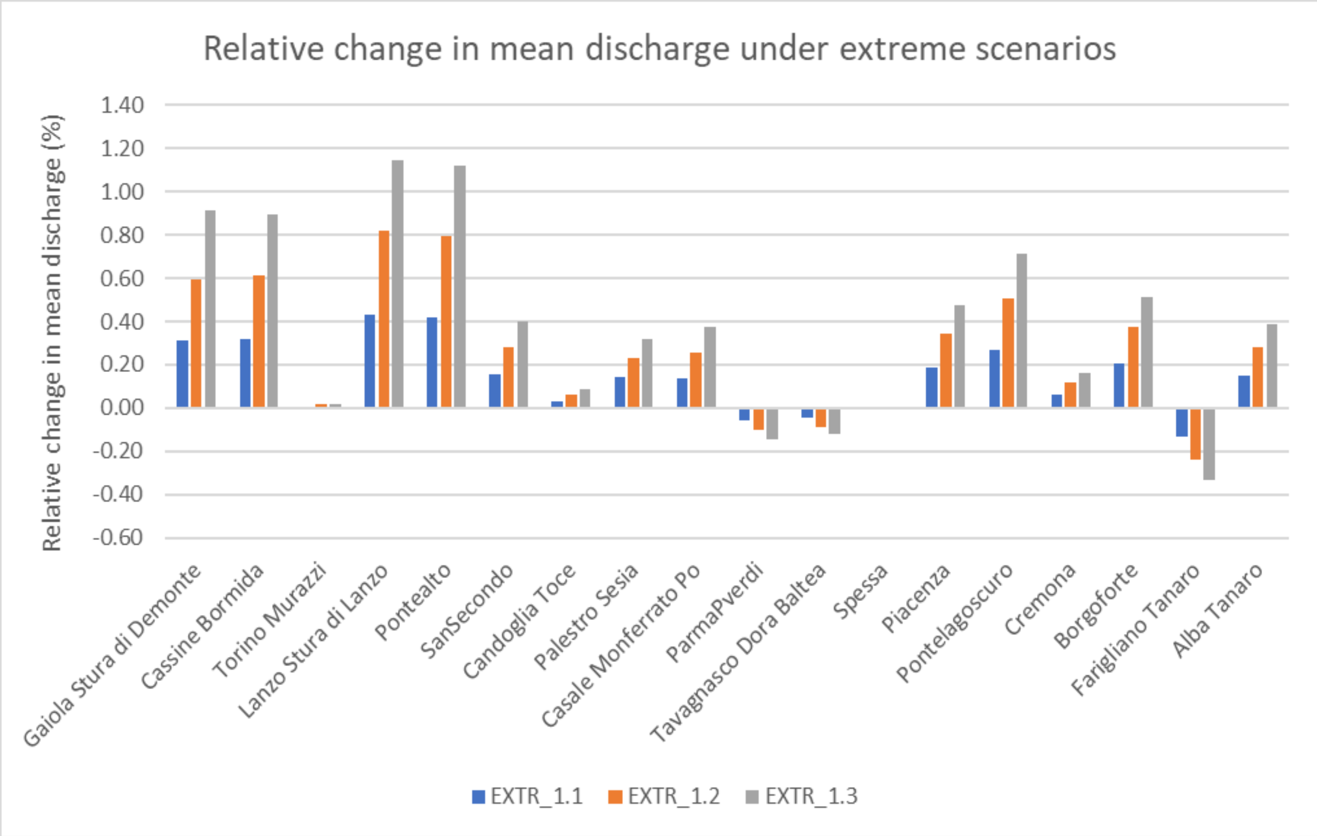


Figure 4.10. Relative change in mean discharge under the extreme precipitation scenarios at the 18 control stations of the Po River basin.

As shown in Figure 4.10, the changes in mean discharge are small across most stations, even under the strongest perturbation. This indicates that the extreme scenarios do not affect the average water availability of the basin.

At the basin scale, the mean flow remains generally unaffected, confirming that the redistribution of rainfall intensity does not lead to a significant modification of the average water volume available for runoff generation. In contrast, the maximum discharge becomes more influenced as the perturbation increases. Under EXTR_1.1, the average relative increase in maximum discharge is about 3.5%, while under EXTR_1.3 it increases to approximately 9–10% across the basin. This indicates that more intense rainfall events mainly affect higher-flow behaviour rather than average discharge conditions.

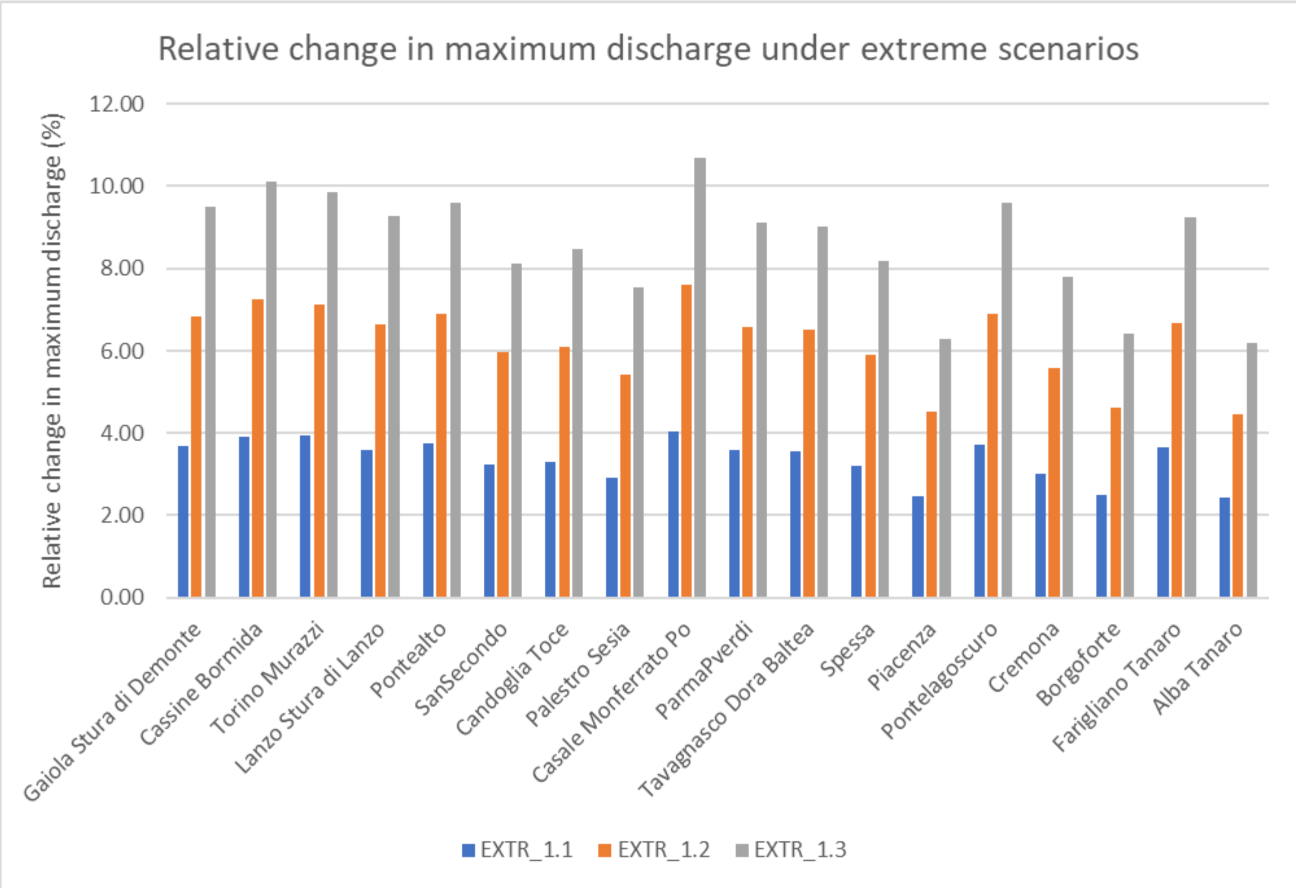


Figure 4.11. Relative change in maximum discharge under the extreme precipitation scenarios at the 18 control stations of the Po River basin.

As shown in Figure 4.11, the change in maximum discharge becomes stronger as the variance factor increases from EXTR_1.1 to EXTR_1.3. This confirms that peak flow is mainly affected by the extreme scenarios.

This behaviour is also observed in the station-level results. In most control stations, larger increases in peak discharge are produced as a result of stronger perturbation levels. Therefore, the basin is sensitive to the redistribution of rainfall intensity even in cases where the total precipitation input remains approximately unchanged.

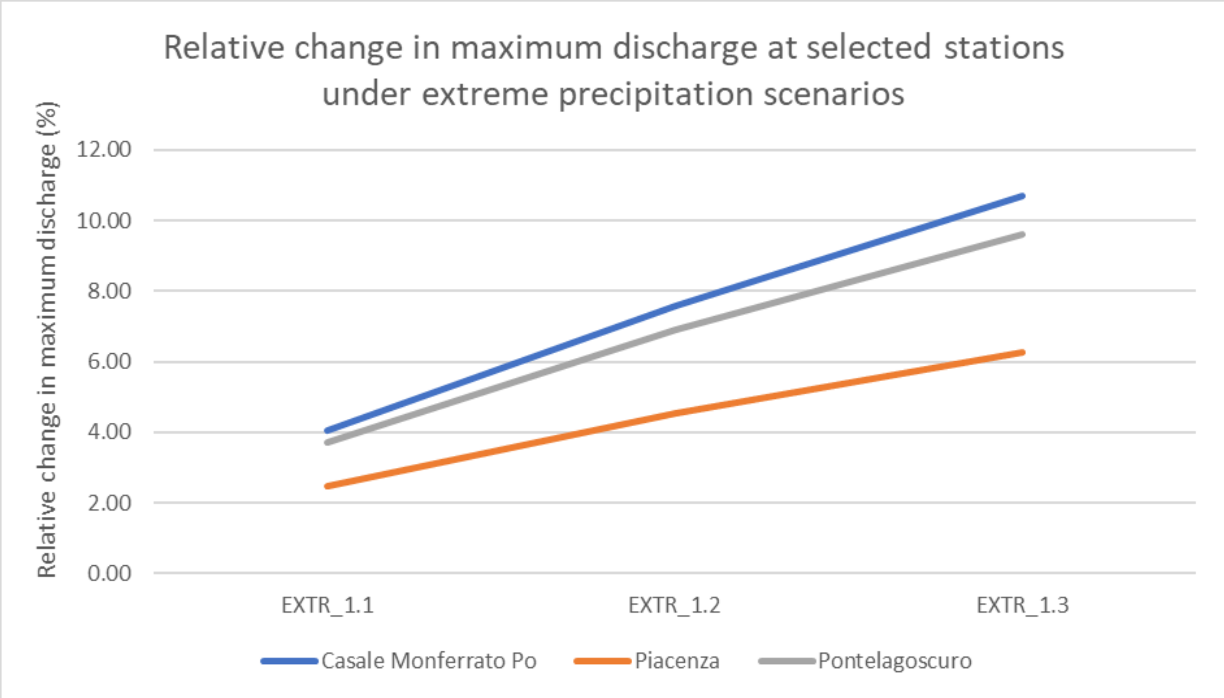


Figure 4.12. Relative change in maximum discharge at selected control stations under the extreme precipitation scenarios.

Figure 4.12 shows the station-level response of maximum discharge for three selected control stations under the extreme precipitation scenarios. Casale Monferrato Po, Piacenza, and Pontelagoscuro were selected to represent different response levels and different positions along the main river system, including a downstream control section. The selected stations show a clear increase from EXTR_1.1 to EXTR_1.3, confirming that stronger rainfall redistribution produces a stronger peak-flow response.

4.5.2 Response to rainfall redistribution

The results show that the hydrological effect of the extreme scenarios is mainly due to rainfall redistribution rather than to changes in total water input. Since the average precipitation remains almost unchanged, the observed discharge response reflects the fact that a larger share of rainfall occurs during more intense events. Under these conditions, mean discharge remains approximately stable, while the peak flow behaviour seems to be mostly affected.

A comparison between mean, maximum, and minimum discharge values reveals that the mean discharge shows only minor variations, while maximum discharge increases more regularly as the variance factor increases. Minimum discharge, on the other hand, shows irregular behaviour and depends highly on the station characteristics. Therefore, low-flow conditions are less affected by rainfall redistribution and more influenced by local hydrological components such as storage, routing, or baseflow-related processes.

Station	EXTR_1.1	EXTR_1.2	EXTR_1.3
Gaiola Stura di Demonte	3.70	6.83	9.50
Cassine Bormida	3.91	7.25	10.12
Torino Murazzi	3.93	7.13	9.87
Lanzo Stura di Lanzo	3.59	6.64	9.27
Pontealto	3.74	6.90	9.60
SanSecondo	3.25	5.95	8.12
Candoglia Toce	3.29	6.09	8.49
Palestro Sesia	2.90	5.42	7.55
Casale Monferrato Po	4.03	7.59	10.68
ParmaPverdi	3.58	6.57	9.12
Tavagnasco Dora Baltea	3.55	6.51	9.03
Spessa	3.21	5.90	8.19
Piacenza	2.45	4.52	6.28
Pontelagoscuro	3.72	6.90	9.60
Cremona	3.02	5.57	7.80
Borgoforte	2.51	4.62	6.41
Farigliano Tanaro	3.65	6.68	9.25
Alba Tanaro	2.42	4.45	6.19

Table 4.5. Relative change (%) in maximum discharge at the 18 control stations under the three extreme precipitation scenarios.

The values reported in Table 4.5 show that the increase in maximum discharge varies between stations across the basin. This means that the peak-flow response to intensified rainfall events is influenced by local basin characteristics.

Analysing the overall basin response supports the idea that modified rainfall distribution can affect basin discharge behaviour even if there is no great change in the total precipitation amount. In these conditions, the most evident effect is seen in higher-flow conditions and runoff variability.

4.5.3 Response indicators under extreme scenarios

To quantify the hydrological response under the extreme precipitation scenarios, response indicators were computed by relating the relative change in discharge to the imposed increase in rainfall variance. The results show that the behaviour of maximum discharge is mostly affected. The elasticity values for peak flow, indicated as E_{MAX}, range between about 0.25 and 0.40 depending on the station and level of perturbation.

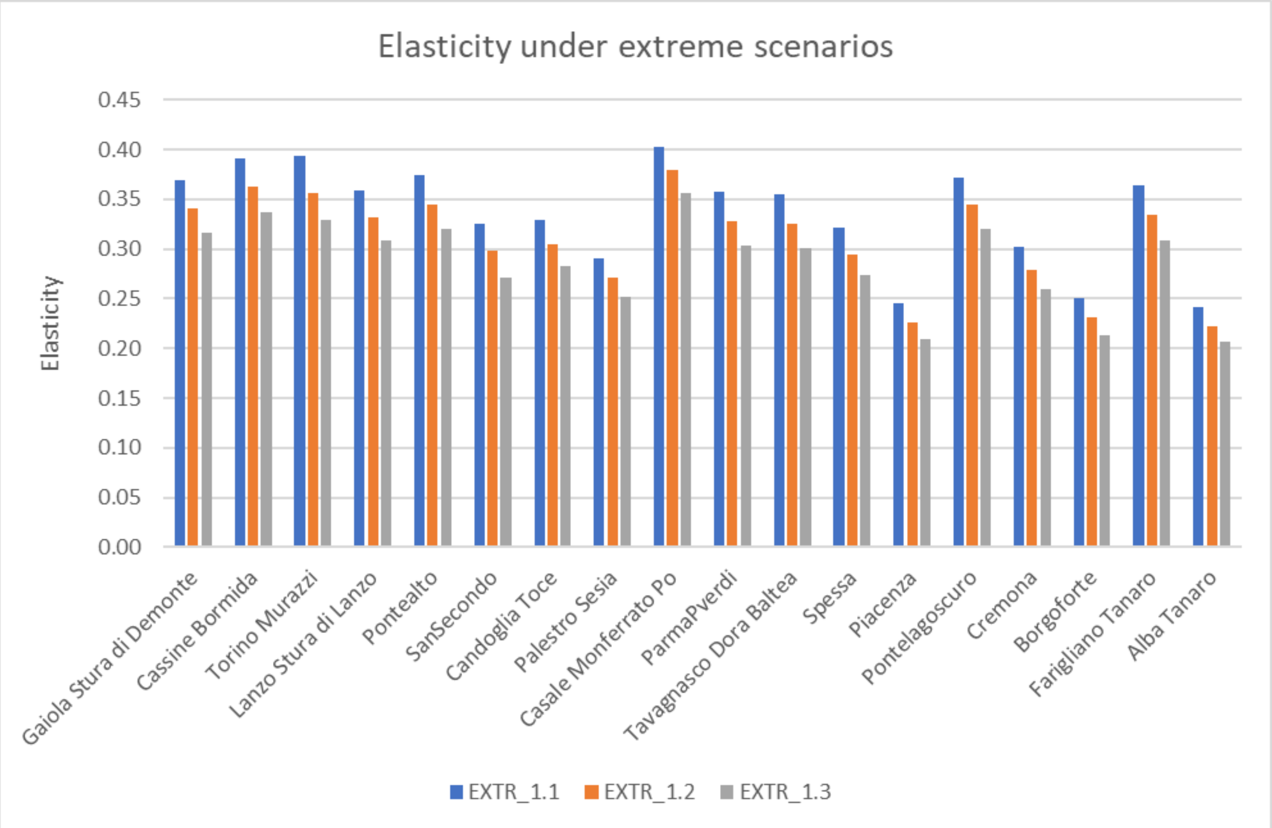


Figure 4.13. Elasticity of maximum discharge under the extreme precipitation scenarios at the 18 control stations of the Po River basin.

As shown in Figure 4.13, elasticity values are positive across the basin, confirming that rainfall redistribution produces a significant and consistent change in maximum discharge. At the same time, the magnitude of elasticity varies across the control stations, which shows the impact of local hydrological components.

Analysing these values indicates that the response is more attenuated and not fully amplified since the increase in maximum discharge remains smaller than the percentage of increase in rainfall variance. This behaviour is consistent across the three scenarios; however, stronger perturbations produce larger absolute changes in peak flow.

The response indicators for mean discharge values remain close to zero, which confirms that the effect of the extreme scenarios on average flow conditions is limited. In the case of low-flow conditions, the results are variable. In several cases, the response becomes weak, undefined, or difficult to interpret. This behaviour is in line with the purpose of scenario design, in which rainfall values with lower intensity were slightly modified, and the main perturbation was concentrated in the upper tail of the distribution.

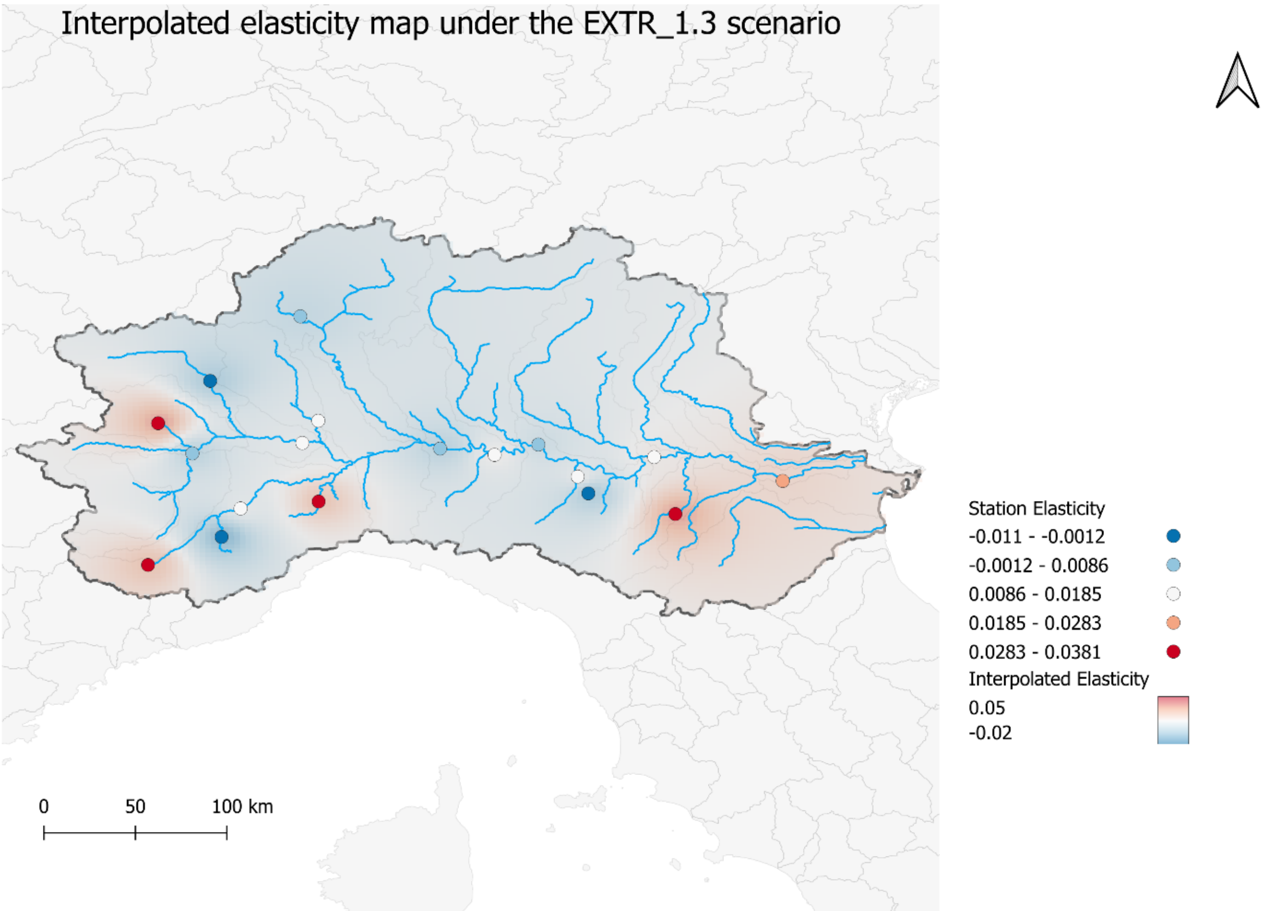
4.5.4 Main patterns under extreme precipitation conditions

Overall, the extreme precipitation scenarios show that the Po River basin is sensitive to changes in rainfall distribution even when the total amount of precipitation remains nearly constant. The most evident hydrological effect is the increase in maximum discharge, while mean flow remains comparatively stable, and low-flow response is more irregular. This indicates that rainfall redistribution mainly affects the dynamic and peak-related components of basin response.

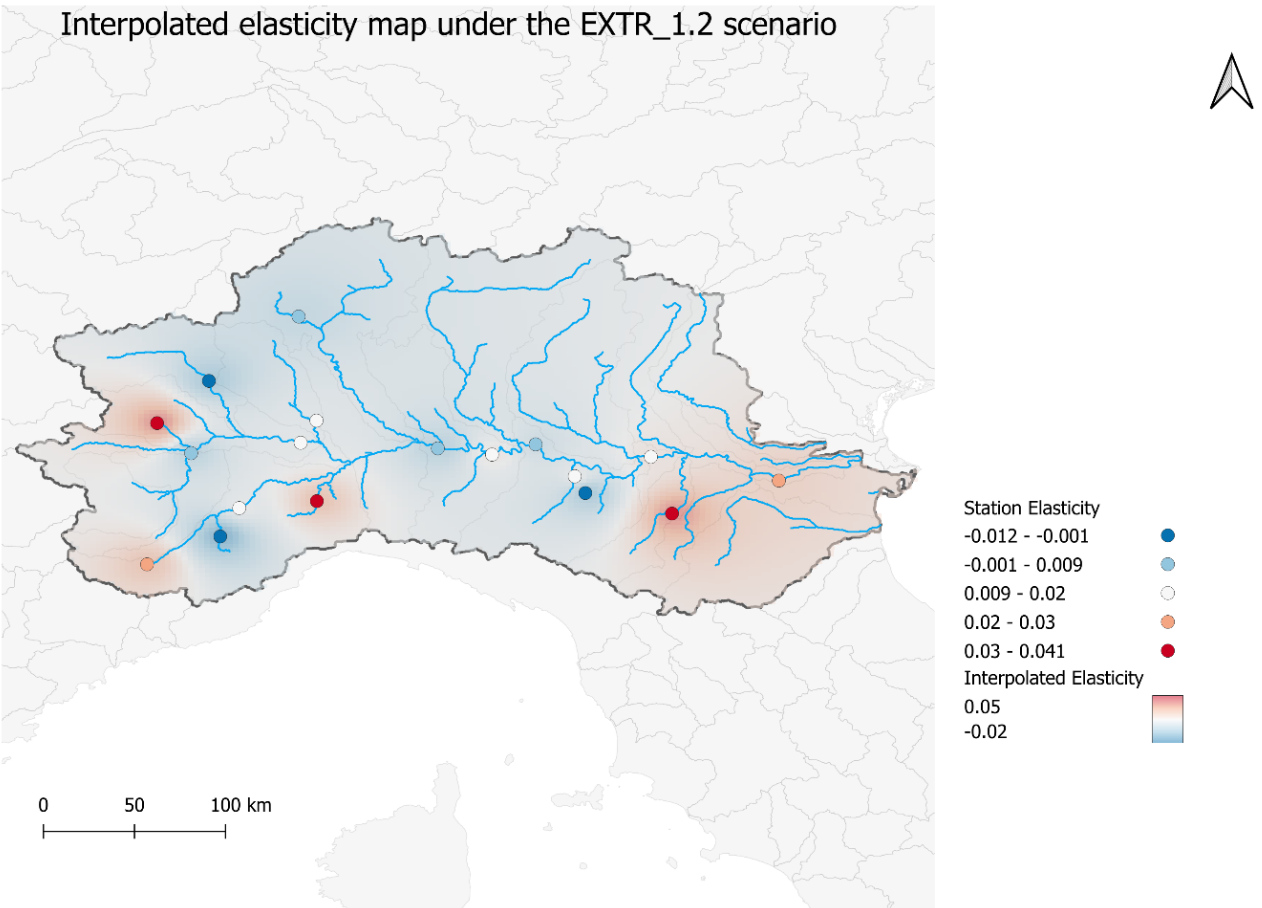
The response produced by the extreme scenarios is different compared with the drying and warming scenarios. Their response is more concentrated in high-flow behaviour instead of a broad reduction in mean discharge. Therefore, the extreme scenarios do not change basin water availability, but the way in which the basin reacts to intense rainfall events. These findings provide an important basis for the comparative analysis presented in the following section.

4.5.5 Interpolated spatial patterns under extreme precipitation scenarios

Under the extreme precipitation scenarios, the interpolated maps show a weaker and more spatially varied response than the drying maps. The patterns shown in the maps reflect how the basin responds to rainfall redistribution and more intense events, rather than to a change in total water input. Having both positive and negative responses means that the effect of more intense rainfall events depends on basin characteristics and routing conditions.



Interpolated elasticity map under the EXTR_1.3 scenario
Station Elasticity
-0.011 - -0.0012
-0.0012 - 0.0086
0.0086 - 0.0185
0.0185 - 0.0283
0.0283 - 0.0381
Interpolated Elasticity
0.05
-0.02
0
50
100 km



Interpolated elasticity map under the EXTR_1.2 scenario
Station Elasticity
-0.012 - -0.001
-0.001 - 0.009
0.009 - 0.02
0.02 - 0.03
0.03 - 0.041
Interpolated Elasticity
0.05
-0.02
0
50
100 km

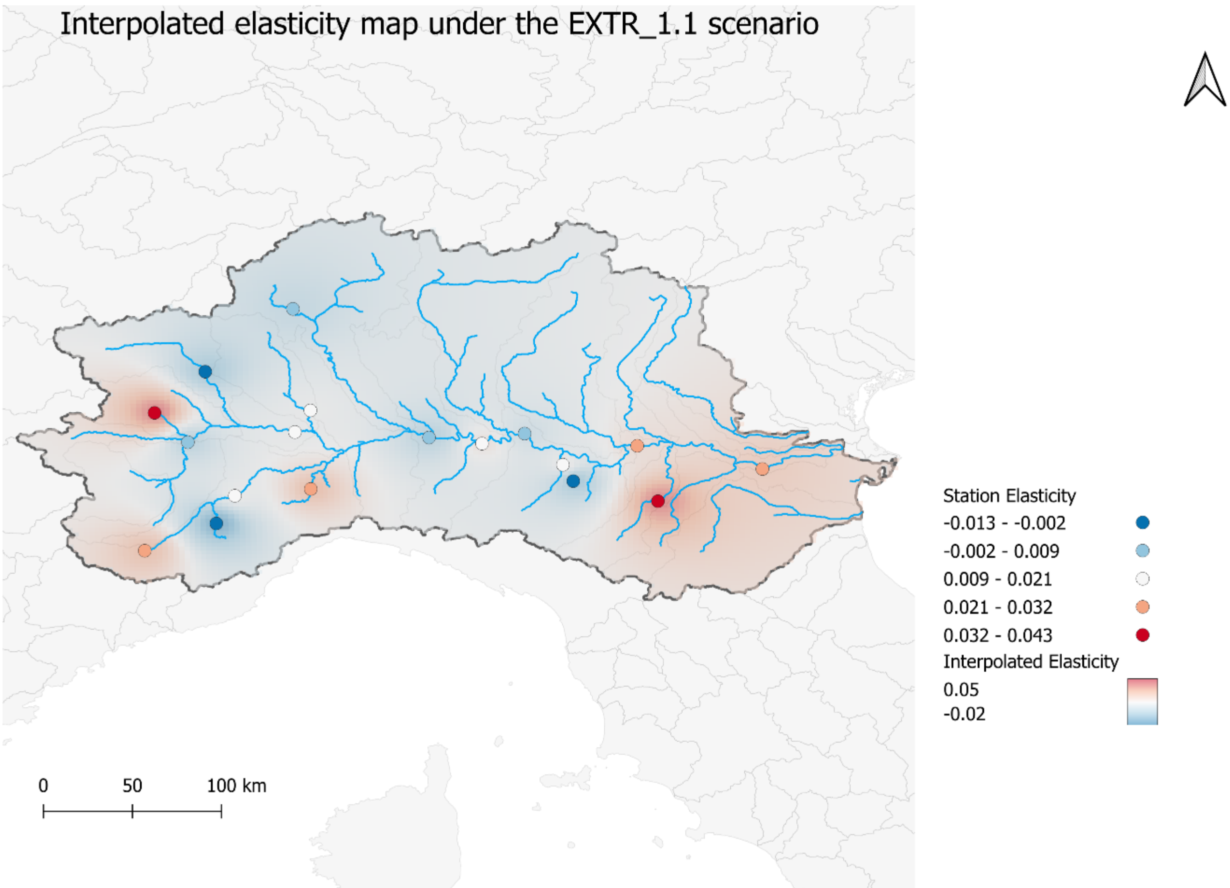


Figure 4.14. Interpolated spatial distribution of basin response under the extreme precipitation scenarios EXTR_1.1, EXTR_1.2, and EXTR_1.3 across the Po River basin.

Figure 4.14 shows a non-uniform response across the river network, which is a result of the spatially varied behaviour of the basin. Therefore, the spatial representation confirms that the resulting hydrological response is more dependent on local processes that are active at the specific station. The pattern shown by the maps is consistent with the station-based results, indicating that rainfall redistribution mainly affects peak-flow behaviour of the basin.

4.5.6 Interpretation of extreme precipitation scenario results

The response produced by the extreme precipitation scenarios is different from both the drying and warming experiments. Under this group of scenarios, the total amount of precipitation remained approximately unchanged, while the distribution of rainfall was modified to more intense events. Therefore, the hydrological response of the Po River basin depends not only on the amount of precipitation that enters the system but also on how that precipitation is distributed.

These results suggest that the mean discharge behaviour is controlled mainly by the total water input, whereas peak-flow behaviour is more sensitive to rainfall concentration and event intensity. Therefore, the same total volume of rainfall may cause a more intense maximum discharge response when it is redistributed toward more intense events. This helps understand why the extreme scenarios generated only weak changes in mean discharge while producing a clearer increase in maximum discharge.

The results also show that the response to rainfall redistribution is not uniform across the basin, and some stations show a stronger increase in maximum discharge than others. This suggests that the response under extreme precipitation scenarios is also affected by the local basin characteristics and processes. Storage, routing, tributary contribution, and local runoff generation processes may all influence how more intense rainfall events are transformed into a discharge peak.

In comparison with drying scenarios in which the available water is reduced through a strong reduction in mean discharge, the extreme precipitation scenarios change the basin response by affecting peak-flow behaviour. Therefore, these scenarios show that the basin becomes more sensitive to intense events, not that the basin becomes uniformly wetter with higher average discharge.

Overall, the extreme precipitation scenarios show that the Po River basin is sensitive to changes in rainfall distribution even when the total precipitation amount remains almost unchanged. This result shows that different hydro-climatic perturbations affect different components of the flow regime and should not be interpreted in the same way.

4.6 Comparative analysis of scenario responses

4.6.1 Comparison between drying, warming, and extreme scenarios

A comparison of the three scenario families shows that the Po River basin responds differently depending on the type of hydro-climatic perturbation applied. The drying scenarios produce the strongest and most regular effect on basin discharge, with clear reductions in mean flow across all control stations. At the basin scale, average discharge decreases by about 17% under −10% precipitation, about 30% under −20%, and about 45% under −30%. These results indicate a strong and non-linear sensitivity to rainfall reduction.

The warming scenarios produce a weaker but still relevant response. Under +1 °C, the effect on mean discharge remains relatively modest and varies in some stations, while under +3 °C, a clearer decrease is seen across the basin. In general, warming affects average discharge less strongly than drying, but it has a more complex effect on the hydrograph because it also modifies snow-related processes and losses due to evapotranspiration. In addition, some stations show an increase in peak discharge under stronger warming, which differentiates this scenario family from the drying experiments.

The extreme precipitation scenarios produce a different type of response. In this case, the mean discharge remains almost unchanged, while the most evident effect is found in the maximum discharge. As rainfall becomes more concentrated in intense events, average peak flow increases by about 3.5% under EXTR_1.1 and by about 9–10% under EXTR_1.3. This shows that the extreme scenarios mostly affect high-flow behaviour rather than basin-scale water availability.

Scenario family	Main hydrological response	Mean discharge response	Maximum discharge response	Response indicator	General interpretation
Drying scenarios	Strong basin-wide flow reduction	Clear and progressive decrease at all stations	Decrease in most stations	Elasticity is generally greater than 1	The basin shows an amplified response to precipitation reduction, with discharge losses stronger than the imposed rainfall deficit.
Warming scenarios	Moderate but consistent thermal response	Basin-wide decrease, stronger under +3 °C	Mixed response; increases observed at several stations under stronger warming	Negative thermal sensitivity across the basin	Warming mainly reduces mean flow through process-related effects, while peak-flow response is more spatially variable.
Extreme precipitation scenarios	Peak-flow-oriented response	Limited or weak change in mean discharge	A clear increase in maximum discharge as rainfall variance increases	Positive elasticity of maximum discharge	Rainfall redistribution affects the dynamic and peak-related component of basin response more than the average water availability.

Table 4.6. Summary of the main basin response patterns under the drying, warming, and extreme precipitation scenarios.

As shown in Table 4.6, the three families of scenarios affect the basin through different dominant mechanisms. Drying is associated with a strong decrease in discharge across the basin and an amplified response to precipitation reduction. Warming produces a generally negative response in mean flow, although its effect on maximum discharge is more spatially variable. In contrast, extreme precipitation scenarios leave the mean discharge only weakly affected while generating a clearer increase in maximum discharge. This comparison highlights that basin sensitivity depends not only on the magnitude of the perturbation, but also on the hydrological component being considered.

Altogether, these results show that the drying scenarios mainly reduce basin discharge, the warming scenarios modify both average flow and hydrograph behaviour in a more process-driven way, and the extreme scenarios mostly increase responses related to peak flow. Therefore, each scenario family highlights a different dimension of basin sensitivity.

4.6.2 Differences across control sections

Considering the basin scale, the response patterns are clear; however, across the 18 control stations, the responses are not spatially uniform. Under drying conditions, the strongest relative reductions in mean discharge are generally observed at downstream stations such as Piacenza, Cremona, Pontelagoscuro, and Casale Monferrato Po, in which the cumulative effect of upstream rainfall deficits is evident. Upper and alpine stations also show reductions, but in several cases, the response is less intense.

It is almost similar for warming scenarios; however, more heterogeneity can be seen. Downstream stations show greater absolute changes, especially under +3 °C, while some upper catchments have more limited or mixed responses because of the buffering effect of snow-related processes and local hydrological components. This means that warming does not affect all parts of the basin in the same way, and its effect depends more on local hydrological structure than on the precipitation reductions used in the drying experiments.

Spatial variability is also present under the extreme precipitation scenarios, but the pattern is different. The maximum discharge is increased by different magnitudes across most parts of the basin. In contrast, indicators related to low flow behaviour are less consistent, which suggests that the response of minimum flow is more strongly affected by local basin conditions and cannot be described by a single uniform pattern.

These results confirm that the Po River basin cannot be interpreted as a hydrologically uniform system. The response to the same perturbation is different across the river network depending on tributary contribution, routing, storage effects, and local hydro-climatic characteristics.

4.6.3 Overall basin sensitivity

A good understanding of the basin sensitivity is provided by the comparison of response indicators across the three scenario families. Under drying conditions, amplification values remain consistently above unity, usually between about 1.4 and 1.8, showing that discharge loss is stronger than the imposed rainfall reduction. Therefore, precipitation deficit is identified as the strongest hydrological stress among the tested scenarios.

Under warming conditions, the mean discharge is affected, but the change is not as significant as the results in the drying scenario. The sensitivity indicators show that the reduction in mean flow discharge is about 2–4% per degree of warming. Meanwhile, an increase in the maximum discharge is seen in some stations under stronger warming. Therefore, the effect of warming is mainly based on the hydrological processes, such as evapotranspiration, snow storage, and runoff timing, that are involved at that specific station.

Under extreme precipitation scenarios, the mean flow remains limited, but analysing peak-flow indicators confirms that the basin reacts to rainfall redistribution. The maximum discharge responses range between about 0.25 and 0.40. These results show that the perturbation still affects the hydrograph, but in a moderate way. Therefore, the extreme scenarios help understand how basin response may be influenced even when average precipitation remains almost unchanged.

Overall, the basin sensitivity analysis reveals three main patterns: first, precipitation reduction produces the strongest and most amplified decrease in discharge; second, temperature increase causes a more moderate but process-sensitive response; and third, rainfall redistribution mainly enhances peak-flow behaviour without significantly changing average flow. The comparison between these groups of scenarios provides the basis for understanding the basin behaviour and the interpretation of the results.

Taken together, these three families of scenarios show different aspects of the basin sensitivity. The overall behaviour of the Po River basin under climate-related perturbations cannot be described by a single indicator. Mean discharge helps understand the effect of drying and, to a lesser extent, warming; however, to interpret the effect of rainfall redistribution, maximum discharge is more relevant. Therefore, the response of the basin depends not only on how strong the perturbation is, but also on whether it affects water input, thermal conditions, or rainfall structure.

Comparing the results under all scenario families suggests that the Po River basin is more vulnerable to reductions in water input than to isolated changes in temperature or rainfall intensity alone. On the other hand, the behaviour of peak flow under extreme precipitation scenarios shows that the basin may be affected even when average water availability is almost unchanged. Therefore, the impact of different climate-related perturbations is not interchangeable. A reduction in precipitation, an increase in temperature, and a redistribution of rainfall toward intense events may all be associated with climate change, but they do not affect the flow regime in the same way.

Overall, the comparison of responses shows that the Po River basin is strongly sensitive to drying, moderately sensitive to warming, and selectively sensitive to extreme precipitation through its peak-flow response.

Chapter 5: Conclusions

5.1 General conclusions

This thesis investigated the reliability of a semi-distributed conceptual rainfall–runoff model for the simulation of daily river flow in the Po River basin and for the analysis of basin response under selected hydro-climatic perturbation scenarios. The study combined baseline model evaluation with drying, warming, and extreme precipitation experiments in order to examine how different types of perturbation affect discharge behaviour at the basin scale.

The results showed that the main hydrological behaviour of the Po River basin under historical and scenario conditions is represented by the MISDc framework. The scenario analysis showed that the basin response is not uniform but depends on the type of perturbation and on the discharge component considered. The analysis showed that the basin is highly sensitive to precipitation reduction, moderately sensitive to warming, and selectively sensitive to rainfall redistribution through changes in maximum discharge.

Overall, it is confirmed by the study that the Po River basin is a complex and spatially variable system with different response patterns to different climate-related perturbations. For this reason, a combined analysis based on multiple scenario families is needed to have a better understanding of basin sensitivity than considering only one type of perturbation.

5.2 Main findings of the study

The results of this thesis show that the MISDc model provides a suitable framework for analysing the daily flow behaviour of the Po River basin and for investigating basin response under controlled hydro-climatic perturbations. A satisfactory agreement was observed between the observed and simulated discharge under the baseline conditions, which supports the use of the model for basin-scale scenario analysis.

Among the tested scenarios, the strongest and most uniform response was produced by the drying scenarios. A progressive reduction in precipitation caused a clear decrease in mean discharge across all control stations, and the elasticity values showed that the response was amplified with respect to the imposed rainfall deficit. This shows the sensitivity of the Po River basin to reduced water input and that precipitation deficit can be considered as the most severe hydrological stress among the analysed scenarios in terms of average flow conditions.

The warming scenarios also produced a negative response in mean discharge, although with a lower magnitude and a more spatially variable pattern than the drying experiments. The results under warming scenarios suggest that basin behaviour is mainly affected through internal hydrological processes, especially evapotranspiration and snow-related dynamics. For this reason, the warming response was more process-dependent and less uniform across the basin.

The extreme precipitation scenarios affected the basin response in a different way. In this case, the maximum discharge was mainly affected by the redistribution of rainfall toward more intense events, while only limited changes in mean discharge were produced. This shows the sensitivity of the basin to both the total amount of precipitation and how the intensity of rainfall is distributed among the events. Therefore, the dynamic and peak-related component of basin response was mainly affected by the extreme scenarios rather than the water availability across the basin.

Another important result of the study is that basin sensitivity was not spatially uniform. The response varied across the control stations, especially between upper and downstream parts of the river network. This confirms the use of a semi-distributed framework to analyse a hydrologically heterogeneous system such as the Po River basin.

Overall, the main findings of this thesis show that the response of the Po River basin depends on the type of perturbation which is applied. Drying mainly affects mean discharge through a strong, amplified reduction in flow; warming alters basin response through more gradual, process-related mechanisms; and extreme precipitation scenarios mainly enhance maximum discharge by modifying rainfall distribution. Taken together, these findings provide a structured picture of basin sensitivity under different hydro-climatic stresses.

5.3 Limitations of the study

Although a useful basis for interpreting the response of the Po River basin is provided under different perturbation scenarios, there still remain some limitations. A semi-distributed conceptual model like the MISDc model represents basin behaviour in a simplified way. This framework is appropriate for large-scale hydrological analysis, but it also cannot reproduce some local processes, tributary interactions, and storage effects with complete precision. For this reason, the results are more reliable for basin-scale interpretation than for detailed local prediction.

A second limitation is related to the scenario design and the spatial interpretation of the results. The drying, warming, and extreme precipitation scenarios were not exact forecasts of future climatic conditions. On the other hand, an interpolation of the results obtained at the main control stations was used to produce the spatial maps. These maps are useful to visualise general patterns of response rather than an exact representation of local behaviour between control stations. Therefore, the findings of this study should be considered as the assessment of the basin's hydrological response under simplified and controlled conditions.

5.4 Final remarks and possible future developments

The results of this thesis show that the Po River basin reacts in different ways depending on the type of hydro-climatic perturbation applied. This means that basin response cannot be described through a single and uniform sensitivity pattern. Instead, changes in precipitation amount, temperature, and rainfall distribution affect different components of the flow regime and highlight different aspects of basin behaviour.

In the present study, the hydrological response of the basin under controlled perturbation scenarios is interpreted. The combination of baseline simulation, scenario analysis, response indicators, and spatial representation made it possible to examine how the basin reacts and also how that reaction changes according to the type of perturbation. Therefore, a better understanding of the hydrological behaviour of the Po River basin and of its sensitivity to different forms of climate-related stress is provided.

At the same time, the study also suggests some possible directions for future work. For the first development, a more detailed climate projection, which is close to realistic future conditions, could be used. A second improvement could involve a denser network of control stations to have a more detailed spatial analysis. Moreover, additional hydrological variables could be explored to obtain a better picture of basin behaviour under changing hydro-climatic conditions.

Overall, this thesis provides a useful basis for future investigations on the Po River basin. It also suggests that large-scale hydrological systems are better analysed through multiple scenario perspectives rather than a single type of perturbation. Therefore, the present work can be considered both as a basin-scale assessment of hydrological sensitivity and as a starting point for more detailed future applications.

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