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From Science to People: Expecting the Unexpected in Flood and Drought Risk Management

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Return

Theme of the Conference

The impact of floods and drought is often exacerbated by their occurrence with unexpected behaviours. Moreover, climate and environmental changes imply a lower predictability of hydrological extremes, with consequences that are not yet understood. Yet, surprise is still a neglected element in risk assessment and management. Overcoming these knowledge barriers requires an improved understanding of the conditions leading to surprise, that often arise from the interaction of water and societal processes, namely, systems that may be affected by randomness and complexity of different nature. A better understanding of environmental, natural and anthropogenic risks, their interrelation with climate change, the development of up-to-date research methodology and the knowledge transfer to disaster risk managers are timely and necessary. Considering the potential for surprise and devastating consequences requires a shift in thinking.

The conference aims to bring together international hydrologists to discuss how novel scientific findings and methods can assist mitigating the impact of hydrological extremes. Topics may include floods and droughts under environmental change and linkages to societal processes system. In detail, the purpose of the conference is:

- gain a better understanding of the dynamics of hydrological extremes;
- gain an improved insight into the complex relationship between human and water systems;
- providing support to operational flood and drought risk management.

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The conference is organized under the patronage of:

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Location

Aula Prodi - Alma Mater Studiorum University of Bologna
Piazza San Giovanni in Monte 2, Bologna, Italy

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Session I

SURPRISING FLOODS AND DROUGHTS

Oral presentations

From Climate Shifts to Flood Changes at Local and Regional Scales (*Invited lecture*)

Alberto Viglione[1], Luca Lombardo[1], Anna Basso[1], Luigi Cafiero[1] and Francesco Laio[1]
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As climate change intensifies, shifting temperature and precipitation extremes raise concerns about increased river flood risks. Understanding and quantifying how climate change influences floods is relevant from both theoretical and practical points of view. From a research perspective, while flood trend detection has been widely studied, attributing changes to specific causes remains a challenge. From a practical point of view reliable methods are needed to incorporate evolving climate conditions into flood predictions, particularly in ungauged basins, as traditional flood frequency analysis assumes stationarity. In this work, I present some research conducted at Politecnico di Torino on these topics. The objectives are to investigate how floods relate to climate extremes both at small and large-scales, and to propose methods to link flood frequency curve changes to changing precipitation and temperature patterns. The study area is the Greater Alpine Region (GAR) including the Po River valley in Northern Italy. Both data-based and modelling approaches are used. The data-based approach is based on the derived flood frequency framework and estimates the sensitivity of floods to changes in precipitation extremes by linking flood frequency curves and Intensity-Duration-Frequency curves through quantile-quantile relationships at the local scale. The modelling approach is based on the application of a regionally distributed rainfall-runoff model to derive and classify regionally coherent flood events that are then linked to climate extremes and large scale weather patterns.

Flood generation processes - a tool for understanding hydrological changes and impacts

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A wide variety of processes controls characteristics of river flood events. Classifying flood events by their causative processes may assist in understanding the emergence of extremes and support the detection and interpretation of their changes. We show observational evidences of considerable changes in the frequency of different flood generation processes in Europe in the past decades that are likely to manifest in the shifts in the dominant processes by the end of the century under high emission scenario. Our ongoing work on socio-economic impacts of floods generated by different processes indicates that their future shifts and the limitations of our state-of-the-art models might have dire consequences for the flood preparedness in Europe.

Estimating very rare floods at multiple sites in a large river basin with comprehensive hydrometeorological simulations

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Rare to very rare floods - associated to return periods of 1'000 to 10'000 years - can cause extensive human and economic damage. However, their estimation is limited by the comparatively short streamflow records available. Some limitations of commonly used estimation methods can be avoided by using continuous simulation (CS), which provides a multitude of simulated meteorological configurations and uses a conceptual representation of hydrological processes. In addition, CS does not require assumptions about antecedent conditions and their spatial patterns.

We present a CS-based approach for estimating rare and very rare floods in large catchments (area exceeding ~1'000 km²) at multiple sites in a region with complex topography. Following Viviroli et al. (2022), the methodology relies on exceedingly long simulations with a hydrometeorological model chain comprising three components: (1) A multi-site stochastic weather generator (GWEX) that provides 30 meteorological scenarios (precipitation and temperature) spanning 10'000 years each; (2) a bucket-type catchment model (HBV), run at an hourly time step for 330 sub-catchments covering all of Switzerland; and (3) a hydrological routing model (RS Minerve) that implements simplified representations of main river channels, major lakes and relevant floodplains.

A comprehensive evaluation of the simulation results over different temporal and spatial scales confirms that the key meteorological and hydrological characteristics are well represented. This suggests that meaningful insights can be gained for floods with low to very low probabilities. While uncertainties remain considerable, the approach explicitly accounts for important hydrological processes (snow accumulation, snowmelt, soil moisture storage) and routing dynamics (lake regulation, bank overflow, lake and floodplain retention) that determine how catchments respond to weather events, including during flood-triggering configurations. This offers a substantial advantage over conventional streamflow extrapolation as the full spatial-temporal development of floods over large areas is described in a coherent physical way. The approach is also well-suited for estimating more frequent floods. Another key advantage is the availability of full hydrographs rather than peak flow estimates only, allowing for the estimation of representative hydrograph shapes and bivariate statistics, such as peak flow paired with flood volume or duration of exceedance for specific flow magnitudes.

Overall, the framework allows for a comprehensive exploration of possible but unobserved spatial and temporal hydrometeorological patterns. This is particularly valuable in large river basins, where the complex interactions of tributary flows and lake regulations are often poorly captured in streamflow records. However, this can also pose challenges to the practical implementation of CS-

based flood estimates, as return levels may deviate from those expected based on conventional extreme value statistics of observed discharge – especially for very rare floods.

References:
Viviroli D, Sikorska-Senoner AE, Evin G, Staudinger M, Kauzlaric M, Chardon J, Favre AC, Hingray B, Nicolet G, Raynaud D, Seibert J, Weingartner R, Whealton C, 2022. Comprehensive space-time hydrometeorological simulations for estimating very rare floods at multiple sites in a large river basin. Natural Hazards and Earth System Sciences, 22(9), 2891–2920, doi:10.5194/nhess-22-2891-2022

Uncertainties in extreme flood estimates using long continuous simulations

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Reliable flood estimates are an important basis for future water resource planning and ensuring flood safety. Flood estimates, especially for high return periods, are subject to inherent uncertainties that are crucial for assessing hydrological risks, but are also challenging to quantify. These uncertainties stem from different sources, depending on the flood estimation method.

This study quantitatively assesses uncertainties based on a hydrometeorological modeling chain with long continuous simulations. Following the footsteps of Viviroli et al. (2022) our modeling chain consists of a multi-site stochastic weather generator GWEX, which emphasizes intense precipitation events, a bucket-type hydrological model (HBV) and a hydrological routing model (RS Minerve) to account for regulated lakes, river channel hydraulics and floodplain inundation. For the present study of uncertainties, we estimate rare floods with return periods of up to 30,000 years for selected large Swiss catchments with various physiographic characteristics.

The components within our modelling chain that are considered sensitive are associated with the parameterization of GWEX, as well as the structure and parameters of the HBV model. Using analysis of variance (ANOVA), we quantify and partition the contribution of each sensitive component to the overall uncertainty across a wide range of return periods.

While uncertainties always increase for higher return periods, the results demonstrate that the dominant source of uncertainty varies depending on the catchment and return period. The hydrological model structure contributed mist variance in higher-elevation catchments, whereas the the weather generator was more critical in flasier, precipitation-driven catchments. The interactions between the components played a substantial role for specific catchments, highlighting the influence of the selected experimental design and the additive effect of the components involved. These findings illustrate the impact of catchment-specific characteristics like elevation, size and climatology on the uncertainties of flood estimates and highlight the challenge of generalizing them.

Our framework for identifying uncertainties in a modeling chain provides valuable insights for decision-making by showing, for various practical hydrological implications, which sources of uncertainty should be prioritized across a wide range of return levels, especially for infrastructure design and risk mitigation.

References:

Viviroli D, Sikorska-Senoner AE, Evin G, Staudinger M, Kauzlaric M, Chardon J, Favre AC, Hingray B, Nicolet G, Raynaud D, Seibert J, Weingartner R, Whealton C, 2022. Comprehensive space-time hydrometeorological simulations for estimating very rare floods at multiple sites in a large river basin. Natural Hazards and Earth System Sciences, 22(9), 2891–2920, doi:10.5194/nhess-22-2891-2022

Foretelling rivers prone to unprecedented extreme floods from everyday hydrologic dynamics

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River floods have long been among the most impactful natural disasters, suggesting difficulties in the appraisal of this peril which reflect the nature of watersheds as complex systems with random traits. A reliable assessment of the intrinsic flood hazard of different river basins and regions, and how this may evolve in time with changing environmental conditions, especially remains an outstanding challenge.

Here we show that the propensity of rivers to generate unprecedented extreme floods can be predicted by simple metrics of everyday hydrologic dynamics occurring in river basins, namely the discharge variability and the degree of non-linearity of hydrograph recessions. The relevance of these indicators of latent flood hazard is suggested by a mathematical description of runoff generation dynamics with mechanistic and stochastic components, and confirmed by observations spanning a variety of physioclimatic conditions globally.

We utilize these metrics with binary logistic regression to predict the possible occurrence of extreme floods in river basins. Results highlight the efficacy of the method for inferring locations where unprecedented extreme floods shall be expected. We further postulate that these locations may experience more severe impacts of flooding because such events take communities by surprise. Preliminary results support this hypothesis.

The approach enables foreseeing the possible occurrence of unprecedented extreme floods from data (e.g., ordinary discharge records) that are commonly monitored, and easier to infer from other locations (compared to extremes) when local observations are lacking. The use of everyday hydrologic dynamics resembles cultural processes where the accumulation of everyday experiences shapes the perception of environmental risk of individuals and communities. As such, the approach may be valuable for raising awareness of the changing peril of floods in river basins.

Flood risk assessment and management in dynamic human-water systems (*Leonardo Lecture*)

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Effective flood risk management is of paramount importance in the face of ever-increasing flood losses. Risk management must be based on risk assessments that take into account the dynamics, complex interactions and feedbacks in human-water systems. However, the integration of human behaviour into dynamic risk assessments, which are already subject to high levels of uncertainty, is a challenge. Progress in this area includes 1) the collection and analysis of comprehensive qualitative and quantitative data on flood risk changes in case studies using the paired event concept; 2) the development of probabilistic flood loss models using Bayesian networks; and 3) the use of these new models not only for risk assessment but also for impact-based forecasting. Probabilistic flood loss models have the significant advantage to capture changes in vulnerability and inherently provide quantitative information about the uncertainty of the prediction. Forecasting the expected impact hotspots before a flood occurs can significantly aid disaster response decision-making. It is recommended to further develop these approaches and use more dynamic modelling also for large-scale flood risk analyses. These approaches are increasingly feasible due to significant improvements in computational power and data-science.

The Hydrological System as a Living Organism

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The success of modelling extreme events depends on the realism of the model used. Extreme events generally exceed the events on which a model is tuned. And to be able to model system performance under changing circumstances requires that the model is fit to function under these conditions. The fact that models generally are static and tuned to the past, limits the capacity of models to represent extreme circumstances under changing environmental conditions. The argument made in this paper is that the hydrological system is part of a living organism that can adjust itself to changing climatic conditions. A realistic model should be able to act accordingly. In other words, a realistic model should mimic a living organism. If the model is more realistic, the extrapolation to extreme conditions is more reliable.

Hydrology is the bloodstream of the terrestrial system. The terrestrial system is alive, with the ecosystem as its active agent. The ecosystem optimises its survival within the constraints of energy, water, climate and nutrients. The ecosystem can modify the system components that determine fluxes and storages in the hydrological system. In traditional models, these system components are considered static, while their parameters are fixed by calibration on time series of the past. However, the hydrological system is alive and can adjust to changing circumstances. The physical law driving this evolutionary process is the second law of thermodynamics, with the Carnot limit as its constraint. The Carnot limit is a threshold of energy conversion that cannot be passed. Successful evolution leads to more efficient ecosystem behaviour, but this is constrained by the Carnot limit, which, much like a Pareto-space, offers a small subset of all possible realisations. It is hypothesised that the Carnot limit is the reason why relatively simple empirical relations (such as the linear reservoir) exist in nature. Considering catchments as parts of a living organism offers a new direction in the theory of hydrology.

Heavy storm characteristics and extreme precipitation statistics

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Assessing extreme precipitation statistics is crucial for flood risks management and climate change adaptation. This study aims to deepen the physical understanding of extreme precipitation statistics. Using data from approximately 400 rain gauges and temperature stations across the Alpine region, we estimate extreme precipitation depths from sub-hourly to daily durations, with return periods extending up to 100 years. Our approach employs a non-asymptotic approach based on the duration maxima of independent meteorological events (storms). Key characteristics of the storms, such as peak and average intensity, total lifetime, seasonality, temporal profile, temperature, are examined to understand the climatology of the heavy storms and their relationship with extreme precipitation statistics.
Preliminary results indicate that the statistical distribution of extreme precipitation varies with topography and event duration. Short-duration extremes are more intense in lowland areas, exhibiting a "reverse orographic effect," while the pre-Alps experience higher extremes at longer durations. These outcomes can be explained by the patterns of parameters describing intensity and tail heaviness of the statistical distribution of precipitation events. Storm characteristics also change with topography, duration, and extremeness of the event. Front-loaded high intensity storms are more common in the lowlands and coastal areas, in summer, at short durations. At longer durations, the higher extremes located in the Pre-Alps emerge in autumn from more symmetrically-distributed storms. These findings underscore the importance of including topography and duration in the analysis of precipitation extremes and their climatology. Understanding the relationship between storm patterns and extreme precipitation statistics can enhance predictions of heavy rainfall, thereby supporting more effective flood risk management and climate planning.

This study is carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

Investigating temporal changes in ordinary and extraordinary precipitation extremes over Italy

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Understanding how rainfall extremes are evolving over time is essential for infrastructure design, hydrological risk assessment, and climate adaptation strategies. However, detecting trends at a national scale in a complex country like Italy, with its varied topography and meteorological influences, poses significant challenges.

This study aims to evaluate temporal changes in short-duration (1 to 24 hours) rainfall extremes across Italy by analyzing the most extensive and recent dataset of annual maximum rainfall depths, sourced from I^2-RED, the Improved Italian - Rainfall Extreme Dataset. The dataset includes over 5500 time series spanning from 1916 to 2022. Unlike studies relying on reanalysis data or climate model outputs, which may introduce uncertainty due to the model's ability to reproduce extremes and coarse spatial resolution, our analysis is based solely on direct rain gauge observations.

Two complementary methods were used: (i) the non-parametric Mann-Kendall test complemented by Sen's slope estimator to detect trends at individual sites, and (ii) a distributed quantile regression analysis for a gridded investigation. The latter employs a moving window approach, pooling data from nearby rain gauges to enhance the robustness of the estimates.

Our results reveal that changes in rainfall extremes across Italy are highly variable, and regional patterns are present. Notably, the quantile regression method highlighted stronger trends in higher quantiles compared to ordinary rainfall extremes: while median rainfall (50th percentile) showed only slight changes over time, extreme events (95th and 99th percentiles) displayed more pronounced variations. This suggests that the most intense precipitation events are becoming more extreme in certain regions, while ordinary extreme rainfall remains relatively stable.

These findings have important implications for hydrological design and flood risk assessment, emphasizing the need to account not only for mean changes in precipitation but also for shifts in extreme events. The increasing trends in extreme rainfall point to the necessity of updating intensity-duration-frequency (IDF) curves, particularly in regions where significant increases in extreme precipitation have been detected. Conversely, negative trends in some areas may suggest reduced design rainfall values, though caution is necessary in making such adjustments due to the uncertainties surrounding future rainfall variations.

What happened and what did we know about the risk of flooding of the Poyo ravine? The floods in the south of Valencia on October 29, 2024

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The floods of October 29, 2024, in the southern metropolitan area of Valencia (Spain) were a disaster of great magnitude, caused by the hydrological response of three basins covering a total area of 550 km². These basins, characterized by a flash flood-type response, triggered an event of enormous intensity, concentrating their effects mainly on the Rambla del Poyo ravine.

The extraordinary recorded precipitation reached 772 mm in a 24-hour period, an unprecedented volume that overwhelmed natural channels and produced a peak flow at the gauging station, with a catchment area of 198 km², of approximately 2800 m³/s. However, the flow that ultimately crossed the flood-prone area reached an estimated value of 4500 m³/s, which significantly worsened the impacts in the region.

One of the factors that intensified the devastation was the concentration of sediments, estimated at 30% of the total flow, which increased the destructive capacity of the water. The affected area, densely urbanized with residential housing, industries, and shopping centers, suffered catastrophic damage. Direct economic losses amounted to 17.5 billion euros, including 141,000 cars washed away or severely damaged, while the human impact was tragic, with a toll of 227 fatalities.

The hazard assessment was conducted using a storm generator, a distributed hydrological model, and a two-dimensional hydraulic model. This approach allowed for the incorporation of the spatiotemporal variability of hydrological processes, a key factor often inadequately represented by the traditional design storm method. Based on the obtained results, the peak flow at the gauging station during the 2024 event has a return period between 2,000 and 5,000 years.

Regarding risk estimation, vulnerability curves were assessed for different land uses and integrated with a numerical approach to calculate the average direct damages at each pixel within the flood-prone area. The results indicated an annual loss of 15 million euros/year (based on 2006 values). The same methodology, but with variations in hazard magnitude variable and vulnerability curves, was applied to develop a risk map for vehicle displacement within a portion of the flood-prone area.

For flood hazard reduction, different proposals were analyzed in 2006, leading to the selection of a set of Nature-Based Solutions. These solutions had a cost of 150 million euros, provided a protection level of 500 years, and resulted in a risk reduction of 11 million euros per year.

This event highlights the vulnerability of urbanized areas to extreme meteorological events, the importance of considering sediments and debris in our models and the urgent need for prevention and mitigation measures to reduce the risk of future catastrophes of this magnitude.

Session I

SURPRISING FLOODS AND DROUGHTS

Pop-up presentations and posters

Anticipating droughts: A seasonal forecast tool based on spatio-temporal clustering

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Due to the large variety in spatio-temporal scale, drought events are usually difficult to predict, especially within a time frame suitable for an effective activation of drought emergency management plans. In the recent years, sub-seasonal to seasonal dynamic forecasts, where climate and weather forecast data are used as input to simulate the physical processes in the atmosphere, land, and ocean, have significantly advanced in reliability, making seasonal drought forecast appealing for operational early warning systems.
In this study, a three-dimensional spatio-temporal clustering approach is applied to soil moisture anomalies ensemble forecasts to provide an outlook on agricultural drought forecast up to 6-month ahead. A set of case studies, based on past events, are shown to illustrate the unique characteristics of such methodology in providing easy to interpret data in support of drought risk management.
This research activity is part of the Horizon Europe project SEED-FD (Strengthening Extreme Events Detection for Flood and Drought), aiming at enhancing the portfolio of tools of the Copernicus Emergency Management Systems.

The PRIME Index: Prioritization of cultivated Regions IMpacted by drought in agriculturE

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The agricultural sector is particularly affected by drought events due to its direct dependency on precipitation and evapotranspiration. Droughts represent the foremost threat to food security, leading to reduced crop yields and, in severe cases, complete crop failure. A comprehensive understanding of drought is therefore essential for effective risk management and the strategic planning of water resource conservation in both the short and long term. Within the framework of the CASTLE project, this research combines the Standardized Precipitation Evapotranspiration Index (SPEI) at multiple time scales, computed from 1951 to 2024, with crop harvest data to identify Italy's most drought-exposed agricultural hotspots. By integrating these datasets, the study establishes a foundation for the development of targeted adaptation strategies for water management in the agricultural sector. We conducted an initial assessment of agricultural drought across Italy using the SPEI signal at a 6-month timescale, which highlights a significant increase in the number, duration, and intensity of drought events, indicating progressively drought-prone conditions. Building on this, we perform a crop-specific SPEI analysis over the 74-year observation period, identifying the years in which drought conditions coincided with the harvest season. The findings reveal a sharp expansion in the overall extent of drought-affected regions over the past two decades, underscoring not only an intensification and increased frequency of drought events but also a widening geographic impact. These findings are synthesized into the novel “PRIME Index,” which quantifies agricultural drought susceptibility by considering both crop area extent and crop economic value. This index enables the precise identification of regions at the highest risk of agricultural drought, providing a powerful tool for prioritizing interventions and safeguarding agricultural production in Italy.

Data injustice and attribution of drought events: implications for global climate policy

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Extreme event attribution (EEA) studies address the question of the role of anthropogenic climate change in the occurrence of extreme weather events. However, there is an ongoing debate between science and policy actors on whether EEA can inform the Loss and Damage mechanism. Because EEA needs local observational data, it could be affected by the 'data injustice' that plagues data-poor regions. This paper focuses on droughts and assesses whether the geographic location of EEA studies matches the location of recorded drought hazards and observed drought impacts, using a data justice lens and multiple metrics. We find that the location of EEA studies correlates moderately with the location of drought events. It does not correlate with the location of countries where droughts generated famine, food shortage, and crop failure, of countries where people were most affected by droughts, and with countries' agricultural vulnerability to droughts; it correlates negatively with countries facing high water stress. Conversely, we found a strong correlation between EEA studies and drought-related economic damages. This finding provides compelling evidence that data injustice limits the scope of EEA science. In turn, this questions the suitability of EEA results in the international allocation of climate funds for Loss and Damage.
Key policy insights:
Extreme event attributions (EEA) that can quantify climate change impacts are seen as a tool for loss and damage fund allocation.
However, data required for EEA is limited in poorer countries.
EEA studies are not occurring in places with the most severe drought impacts.
Hence, EEA may not be suitable for climate finance allocation and can potentially exacerbate injustices

Investigating Socio-Hydrological Feedbacks in Drought and Flood Risk Adaptation: A Comparative Analysis Using the Paired Events Dataset

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The paired events dataset that was published by Kreibich et al. (2023), provides a unique dataset on drought and flood risk adaptation between two extreme events across a variety of case studies. This study identifies changes in impacts and attributes them to changes in the different components of risk. It concludes that it remains a challenge to manage unprecedented events (Kreibich et al. 2022). This study and dataset have provided valuable insights in the change in impacts and risk, however, from the dataset it is unclear which underlying socio-hydrological dynamics have led to the variety of changes in risk and impacts across case studies. In this study, we develop a generic model to investigate the socio-hydrological feedbacks between hazard, management, vulnerability and exposure leading to the observed changes in impacts.

We use the model to compare the socio-hydrological processes across the different drought and flood case studies to identify differences in management and adaptation strategies. We show that a generic model, such as the model presented here, in combination with a consistent dataset, such as the paired events dataset, can be useful in comparing socio-hydrological processes across case studies. It can help explore the possibility space in an informed manner, though the identification of current pathways and, following from those current pathways, the identification of suitable adaptation strategies that have been successful in other cases.

Assessing the multi-dimensional impacts of drought on irrigated agroecosystems using a holistic set of indicators

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Climate, environmental, and social changes are increasingly exposing irrigated agriculture in the Mediterranean to prolonged and severe droughts, which are difficult to predict in terms of onset, duration, and underlying causes. These extreme events are generating significant negative effects, not only on agricultural productivity, due to the challenges in managing water supply-demand dynamics, but also on broader environmental, economic, and social sectors. Therefore, a more in-depth and structured understanding of the multidimensional impacts of drought on irrigated agroecosystems is fundamental to guarantee an efficient and sustainable management of resources. In this context, the ERASMUS project (PRIN 2022, funded by the European Union, Next Generation EU) adopts a holistic Nexus approach to analyse the impacts of drought on pressurized irrigation systems. Specifically, the project employs a set of multidimensional indicators to evaluate the resilience of irrigated agroecosystems under drought conditions, combining quantitative analysis and stakeholders' perceptions of the problem. To further deepen this analysis, System Dynamics (SD) modelling is applied to investigate the key interactions governing the behaviour of the system over time. By simulating feedback mechanisms and cause-effect relationships, SD modelling helps to identify the primary drivers of system vulnerability and assess how the selected indicators influence each other dynamically.

This study applies this transdisciplinary Nexus approach to the Consorzio di Bonifica della Capitanata, a strategic irrigated agricultural area in Southern Italy, with the aim of assessing the complex relationship between water scarcity and other key aspects such as irrigation efficiency, economic sustainability, user satisfaction and ecosystem resilience.

The analysis focuses on evaluating indicators related to water use efficiency, water supply vulnerability and imbalances in water distribution, in order to identify critical problems and potential discrepancies between water demand and supply. Considering the inherent complexity of irrigated agroecosystems, these indicators are combined with others that take into account broader socio-economic and environmental dimensions, such as water cost for farmers, the percentage of satisfied farmers, and the percentage of soil organic matter loss. The integration of these diverse indicators, coupled with insights from SD modelling, provides a holistic framework for better understanding the broader implications of drought, thus enabling a more informed decision-making process aimed at selecting adaptation measures that deliver cross-sectoral benefits.

Extreme droughts in space and time: A non-asymptotic Extreme Value framework

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As climate change reshapes precipitation and evapotranspiration patterns, the severity, duration, and frequency of drought events are altered across many regions worldwide. Due to their large spatial extent and prolonged timescales, droughts differ from most other hydroclimate processes, requiring a deeper understanding of their spatio-temporal dynamics for effective monitoring, projection, and adaptation strategies. The extended duration of drought events poses challenges for historical observations, limiting our ability to track their evolution across space and time. To mitigate these limitations, this study examines the statistical characteristics of extreme droughts using simulations from the Paleoclimate Modelling Intercomparison Project Phase 4 (PMIP4) and the Coupled Model Intercomparison Project Phase 6 (CMIP6). By integrating historical and paleo-hydrological data, we assess the frequency, intensity, and duration of extreme drought events across multiple geographic regions and time scales, with a particular focus on well-documented climatic periods such as the Medieval Climate Anomaly (MCA, 900-1300 A.D.) and the Little Ice Age (LIA, 1500-1850 A.D.). An advanced non-asymptotic statistical framework, which explicitly separates the intensity and occurrence of the process, is applied to better capture the variability and recurrence of extreme droughts. Results reveal substantial regional differences in extreme drought characteristics, with significant variations across different climatic states and historical periods.

Drought management in north-western Italy: an interview-based characterization

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Recent severe drought periods affecting regions previously considered as water rich, such as the Po basin, and ever-worsening outlooks for the coming years have sparked a renewed interest on droughts in Italy. This new focus has highlighted the need for diverse research topics, including how drought itself is thought of by different actors and thus managed by them. One of the most important outlooks on drought, both on the operational and conceptual level, is that of the institutions managing the integrated water service, responsible both for emergency measures and for structural planning. The objective of this work is thus to evaluate if the quantitative assessments of precipitation and temperature anomalies through indices correspond to drought effects experienced by water managers, and to try and explain the observed results through the managers' perception of drought phenomena. To characterize the water providers' experience of drought, a series of semi-structured interviews are conducted with local, sub-regional and regional professionals in the Cuneo Provence, southern part of Piedmont. The results of the study show that, in agreement with recent literature regarding drought as continuum, water providers in the region generally don't perceive drought mainly as single events, but that this may not be related to a higher awareness of drought risk as an ongoing problem.

Characterizing drought and its impacts on the water supply system in the Province of Cuneo

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Hydrological research in the province of Cuneo (southern Piedmont, Italy) reveals a concerning intensification of meteorological droughts, characterized by increasing duration and intensity. These prolonged dry periods, driven by low precipitation and exacerbated by high temperatures and evapotranspiration, can significantly impact agriculture, surface water resources, and socio-economic systems.

This study employs standardized meteorological and hydrological indices-Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and Standardized Streamflow Index (SSI)-to analyze drought events and their propagation from meteorological to hydrological deficits. By correlating basin-wide precipitation anomalies at various temporal scales with streamflow indices at basin outlets at monthly scale, this work identifies an indication of the drought response time of different catchments using Spearman's correlation coefficient, adjusted for autocorrelation. This step allows the assessment of basin- specific periods of anomalous water availability.

Parallel to the quantitative characterization, insights from water utility managers are integrated, offering a valuable operational perspective on water scarcity periods and their impacts on the sector. This interdisciplinary approach is essential for understanding drought as a multidimensional phenomenon, characterized by a complex interplay between human and water systems.

The goal of integrating these two approaches is to assess whether specific indices can effectively represent actual critical periods and anticipate future challenges for the water supply system in the province of Cuneo. To this end, the analysis also includes peak anomaly indicators, since short-duration extreme rainfall events pose significant threats for the sector.

Operational machine learning aided sub-seasonal forecasting of drought related extremes

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The frequency and severity of droughts in Switzerland is increasing as we undergo climate change, with negative impacts on the environment, economy, and human health. To help reduce these risks, the MaLeFiX project is developing an interdisciplinary extension to the established www.drought.ch platform that provides comprehensive 32-day forecasts of drought-related hazards. We extend the portfolio of drought predictions to a set of related impacts by integrating advanced models across hydrology, forest fires, glacier balance, aquatic biodiversity, groundwater, and bark beetle dynamics. The platform delivers accurate and user-friendly information to help policymakers, stakeholders, scientists, and the public make informed decisions.

The reliability of single forecasts decreases significantly the further they look into the future, making accurate predictions beyond one to two weeks challenging. To overcome this, the models in the MaLeFiX platform use ensemble meteorological forecasts (i.e. 51 forecasts with slight variations in initial conditions) as input, which allows us to estimate the probability of extreme events up to three to four weeks in advance. These are monthly forecasts with daily temporal resolution provided twice per week by MeteoSwiss.

Recent developments include new machine learning models to forecast forest fire danger, and stream water temperature for assessing heat stress to aquatic life forms. In addition, existing models for hydrology, glacier balance, and bark beetle dynamics have been refined to work seamlessly with the same input data, enabling a clearer analysis and interpretation of the overall situation and potential exacerbating factors. Furthermore, the traditional distributed hydrological model PREVAH has been complemented with a multi-model system consisting of 11 different lumped models being operated for 87 headwater catchments.

Our team is currently working to provide users with a comprehensive overview of the drought situation by displaying the possible combined impacts of various drought-related processes (e.g., low runoff and high water temperature).

Spatiotemporal characteristics of drought and hot events in the Adige River basin

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Drought and heatwave events can pose significant threats to social, environmental and economic systems. Their simultaneous or cumulative occurrence can result in amplified consequences compared to isolated events. Due to the current changing climatic conditions, it is increasingly important to investigate these compound extremes beyond individual hazards as well as their potential impacts. In this study, conducted within the framework of the European Space Agency funded EO4MULTIHAZARDS project, single and compound drought and hot events are analyzed across the Adige River basin and its adjacent areas over a 43-year period from 1981 to 2023. Meteorological data derived from SCIA (the Italian National System for the collection, processing and dissemination of climate data, www.scia.isprambiente.it), along with river discharge records, snow depth measurements and impact information retrieved from newspapers and agency reports, are examined to identify occurrences of drought and hot weather conditions and determine their characteristics. Droughts are identified using the Standardized Precipitation Evapotranspiration Index (SPEI) with a 90-days timescale and a threshold value of -1.0. Hot weather conditions are defined as periods characterized by daily maximum temperature exceeding the calendar day 90th percentile of the reference 1991-2020 climatological distribution for at least three consecutive days. Spatio-temporal footprints of drought and hot events are identified and extracted using the Density Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm with calibration of the parameters based on information derived from newspapers and reports. Low flow events are identified in the Adige River discharge time series using the threshold level approach with a fixed threshold at the 10th percentile of discharge, and applying the inter-event time and volume criterion for pooling of mutually dependent events. Winter seasons characterized by exceptionally low snow depths are detected by comparing measurements collected from various monitoring sites across the upstream area over time. Simultaneous occurrences are identified by analyzing the temporal overlap of individual hazards, while cumulative events consist of single or concurrent hazards that occur consecutively or cumulatively without interruptions. The results indicate frequent and intense droughts throughout the analyzed period. In contrast, hot events exceeding the 90th percentile threshold are becoming increasingly frequent and severe, potentially amplifying their impacts, particularly in the presence of compound and cumulative hazards. The multi-hazard analysis highlights 2003 as the most significantly affected year for the Adige River basin, characterized by a higher occurrence of days with simultaneous hot and drought events, along with an elevated number of consecutive days contributing to cumulative effects. The results of this analysis can provide useful insights for enhancing multi-risk assessment and management strategies within the considered river basin and its surrounding areas.

Sensitivity of drought-to-flood transitions to initial hydrological conditions and meteorological forcings

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Floods that occur shortly after streamflow droughts can have potentially enhanced impacts. Despite this increased likelihood of impacts, there are still substantial gaps in the understanding of the hydrological processes and drivers associated with such events. To better understand how initial hydrological conditions (IHC), such as soil moisture and snow water equivalent, and climatic drivers, such as precipitation and temperature, interact and affect the magnitude, duration, and lag time between compound droughts and floods, we ask: What is the sensitivity of drought-to-flood transitions to changes in initial IHC and meteorological forcing? We address this question by calibrating two conceptual hydrological models across a range of near-natural catchments in various regions worldwide, and running them under three stress test experiments: (1) changes in IHC based on perturbations applied to the meteorological forcing (e.g., temperature and precipitation) during the pre-event period; (2) perturbation of observed forcing during the compound event; and (3) modifications to both IHC and forcing during the event (i.e., a combination of cases 1 and 2). Preliminary results indicate that rapid transitions (lag time shorter than 14 days) are primarily explained by the total water storage at the beginning of the event (i.e., IHC) and meteorological drivers, whereas seasonal transitions (lag time shorter than 90 days) may involve other components or interactions that modulate their response (e.g., geomorphological attributes, land cover, etc.). Additionally, changes in the properties of transitions do not depend solely on the hydroclimatology of the catchment, emphasizing the role of catchment characteristics for runoff generation processes. In our continued work, we aim to enhance our understanding of drought-to-flood transitions and their drivers to gain clearer insights into how drought occurrence influences flood generation processes and their impacts.

Understanding Low-Probability Forecasts of High Impact Hydrological Events more useful for Society

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Extreme rainfall has far-reaching societal consequences, triggering catastrophic (flash) floods with high socio-economic impacts. This presentation will investigate historical trends in severe rainfall using ERA5 and ERA5-ecPoint - the probabilistic version of ERA5, statistically post-processed with the "ecPoint" technique developed at ECMWF to improve rainfall estimates for localised extremes. Although media coverage of record-breaking downpours has increased, our study shows that such events are being experienced regularly when viewed from a regional or continental perspective and, hence, should not surprise forecasters or disaster managers.
We also advance the operational utility of "ecPoint" post-processed medium-range global point-rainfall forecasts to equip forecasters with actionable, probabilistic guidance for extreme localised rainfall, delivering finite probabilities for very large, localised totals that ordinarily the raw ensemble system cannot, and should not, predict itself. These have verified very well but could be considered less actionable by users because the probabilities delivered, for a point in a given grid-box, in advance of extreme events, are often very small (e.g. 1-5%). This presentation will outline three developments related to the ecPoint approach that make it more amenable to users by 1) providing an estimate of likely maxima within a grid-box, that 2) tailor better to flash flood risk than purely to rainfall totals by cross referencing a new global point-rainfall climatology, and that 3) demonstrate clear 'financial' utility even if probabilities are small, via computations of potential economic value. Case studies will be used for illustration.

Integrating HPC, AI, and Big Data for Enhanced Early-Warning Systems in Hydrological Extremes: Insights from Ghana's Tree Crop Sector

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Hydrological extremes increasingly defy traditional forecasts due to both climatic shifts and socio-environmental complexities, demanding a fresh perspective on risk assessment (Du et al., 2023). The urgency for better predictive frameworks has been underscored by a recent multi-institutional initiative in Ghana: "Extensive Climate Hazards and Vulnerabilities Assessment of the Tree Crop Sub-Sector." Developed by the Global Center on Adaptation (GCA), the Center for Research and Services for Sustainable Technological Innovation (CeRSITeS) at Sapienza University of Rome, and the University for Development Studies of Ghana—supported by the World Bank's Ghana Tree Crop Diversification Project—the study aimed to map climate risks for key crops, design robust forecasting models for droughts and floods, and identify integrated policies to safeguard livelihoods in vulnerable regions.

Building on a multi-phase study in Ghana's tree crop sector, we focus on enhancing early-warning systems (EWS) for floods and droughts—phenomena whose unexpected behaviors often amplify their impact. Our work integrates big data, high-performance computing (HPC), and artificial intelligence (AI) to tackle the low predictability of extreme events. It leverages advanced deep learning approaches, such as FourCastNet (Pathak et al., 2022) for global-scale forecasts and a super-resolution GAN (E-TEPS) for region-specific downscaling. This synergy addresses large-scale data challenges and delivers high-resolution, timely predictions, even for areas with limited observational infrastructure.

Key results underscore the importance of HPC paradigms in accelerating both model training and inference, enabling hazard analysis and near-real-time forecasting at fine spatial scales. Crucially, these tools performed reliably during recent extreme rainfall events in Italy and a severe 2023 storm in Ghana, demonstrating adaptability and robustness. By integrating uncertainty assessments and enabling rapid deployment on cloud-based platforms, our system offers a pathway to operational EWS capable of anticipating surprises—those rare, high-impact occurrences that often elude conventional methods.

Ultimately, this research illustrates how bridging environmental science, societal needs, and HPC-driven AI can reshape disaster risk management. By incorporating complex feedbacks between water systems and communities, the framework improves readiness for extreme hydrological events. Such advancements in EWS hold vast potential to inform policy, guide infrastructure planning, and foster resilience in both developed and developing contexts under mounting climate pressures.

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Long-Term Influence of Climate Variability on Hydrological Extremes across European Alpine Rivers

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Four of the largest river basins in Europe—Rhine, Rhône, Po, and Danube—are fed by Alpine water resources. Recent hydrological extremes, including catastrophic floods and prolonged droughts, have highlighted the vulnerability of these basins to climatic variability, with significant consequences for downstream populations, economies, and ecosystems. Understanding the potential drivers behind changes in streamflow patterns, particularly the relative contributions of precipitation and temperature, is essential for improving the attribution of extreme hydrological events and informing sustainable freshwater resource management. However, relatively short instrumental hydroclimatic records (i.e., precipitation, temperature and streamflow) in the European Alps limit our understanding of the long-term influence of climate variability on hydrological extremes. Here, by integrating paleo streamflow reconstructions, paleo climatic reanalysis, and climate model simulations, we examine how past and future variability in precipitation and temperature has influenced extreme hydrological events. Through advanced statistical and machine learning approaches, we quantify the relative contributions of precipitation and temperature to observed, reconstructed and projected streamflow anomalies, exploring their respective roles in triggering extreme flood and drought events. By comparing historical trends with future projections across different climate scenarios, we aim to identify the primary climatic drivers of hydrological extremes and their evolution over time. This work highlights the need for a better understanding of long-term climatic forcing mechanisms to improve attributions of hydrological extremes and develop robust adaptation strategies for the Alpine region and its vital river basins.

Assessing the impacts of heavy rainfall events in terms of soil loss: The Emilia Romagna Region case study

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Recently, the eastern part of the Emilia Romagna Region (northern Italy) has been affected by extreme precipitation events, causing significant economic damage to buildings, infrastructures, and crops, as well as casualties among the local population. In the last two years, particularly intense rainfall events have been recorded, one in May 2023 and another two between September and October 2024.

While the impacts of these events in terms of geo-hydrological hazards have been extensively described in institutional reports and scientific publications, their characterization in terms of rainfall erosivity and potential soil loss is still lacking. Such a characterization is particularly important because soil loss phenomena are typically assessed on a multi-annual average scale while a small number of extreme events within a single year often account for the vast majority of potential losses. This work aims at evaluating the exceptional nature of these events in terms of rainfall erosivity over the Emilia-Romagna catchments. The Rainfall Erosivity factor (R factor), which is a component of the Revised Universal Soil Loss Equation (RUSLE), is used as a proxy to evaluate the erosion potential of rainfall considering the joint effect of its cumulative values and intensity over sub-hourly time scales. The used rainfall data were available from a regional observation network with a temporal resolution of 15 minutes, covering, in many cases, a period of about 20 years. Three parameters were selected to compare the events: total event precipitation, event duration, and the rainfall erosivity associated with each event. The objective was to understand the significance of these events in the erosion annual budget, their exceptionality compared to multi-annual estimates, and whether the conditions exist to support an event-based characterization of soil erosion dynamics.

Evaluating and Ranking High-Resolution Climate Models Using Machine Learning and the Aras Diagram: A Case Study Over Emilia-Romagna, Italy

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The increasing frequency of extreme climate events, such as floods and droughts, has been widely attributed to climate change and global warming. Climate models are essential tools for understanding the climate system, improving impact assessments, and guiding decision-making. However, evaluating these models remains a challenge, as conventional statistical metrics often yield conflicting results, making it difficult to determine the most reliable models. To address this issue, we applied the Random Forest (RF) machine learning technique to systematically rank high-resolution climate models from the EURO-CORDEX initiative over the Emilia-Romagna region of Italy. Our evaluation focused on daily precipitation, analyzing both mean and extreme values using three key indices: annual total precipitation, annual maxima, and consecutive dry days. To further validate our findings, we employed the Aras Diagram (Izzaddin et al., 2024), a novel visualization technique that enhances climate model evaluation by illustrating the similarity between model outputs and observational data, the diagram confirmed that the Random Forest algorithm effectively identifies and ranks the most reliable models, giving greater weight to those with higher correlations to the reference dataset. The results indicate that while EURO-CORDEX models effectively simulate mean precipitation, they struggle to capture extreme values accurately. The combined use of RF and the Aras Diagram provides a more transparent, data-driven framework for climate model assessment, simplifying model selection for impact studies and decision-making. Our study highlights the potential of machine learning and advanced visualization techniques in climate science, offering a powerful and intuitive approach for evaluating and ranking climate models. This methodology supports more accurate climate impact assessments and enhances adaptation strategies, ultimately aiding policymakers in making informed, science-based decisions in the face of increasing climate extremes.

Reuse of treated wastewater in agriculture: is it always a sustainable adaptation measure?

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The reuse of treated wastewater (TWW) in agriculture is considered one of the most effective measures to cope with water scarcity issues. Based on official data from the Italian national institute of statistics (Istat), in Italy approximately 4% of urban TWW was reused in 2020, mainly for irrigation purposes, while at least secondary treated sewage plant effluents (those ones suitable for reuse in agriculture) account roughly 42% of the annually estimated volumes for irrigation at national level. However, despite EU proactive policies and the doubtless advantages of this practice (firstly disengaging from seasonality and availability during dry periods) it is worth stressing that one of the possible drawbacks of such a practice is a lack of resource to the surface water bodies. To estimate the contribution of TWW to the surface streamflow in the Po River basin (Italy), mainly during drought events, we compared the total volume of TWW from urban wastewater treatment plants (UWWTP) with at least secondary treatments over the entire basin (available data of 2020 on regional scale) with the discharge measured at Pontelagoscuro, at the basin's closure, in 2022 (extreme drought event). To this aim, a preliminary assumption of considering Valle D'Aosta, Piemonte, Lombardia and Emilia-Romagna regions was made to represent Po River basin. Hence, it was assumed a constancy of the flowrates from UWWTPs (data available on annual basis): TWW resulted 14% of the mean annual river discharge and almost 50% when referred to the monthly mean discharge in July 2022 (the worst Po River discharge ever observed). Based on this evidence, we detailed the analysis performed at basin scale on some sub-basins, pointing out possible local impacts of re-use on the secondary basins, especially under dry conditions.

When water quality drives a water scarcity situation: The North of Córdoba water crisis 2023-2024

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Meteorological droughts are intrinsically linked to the variability of the Mediterranean climate. Historically, its population has dealt with the hydrological implications of this changeable climate. A clear example is the construction of hydraulic infrastructures to store water during precipitation-rich periods, which has helped dispose of water resources in meteorological-drought periods. Therefore, we have been able to disacouple the lack of rain from the lack of water resources. However, this ideal situation can be altered by using non-efficient water planification. The tipping points at which systems enter into a water scarcity situation are generated by multiple factors that limit water resources, such as extremely low rainfall, the expansion of irrigated crops with the correspondent increase of water demand, or the contamination of water sources for consumption. Among them, we have paid less attention to this last factor, which, under certain circumstances, can be the main conditionant of the water scarcity.

This work presents the water scarcity situation that affected 24 municipalities in the northern part of the province of Córdoba in southern Spain. For more than a year, from March 2023 to April 2024, 80000 inhabitants of this region did not have drinking water at home. Drinking water in these municipalities comes from the stored water in two reservoirs, La Colada (58 hm^3) and Sierra Boyera (41 hm^3). It is important to note that this region is an agricultural-based area with a considerable livestock load. We have analyzed the factors contributing to this situation - precipitation, water volumes, and water quality - to identify the tipping points that have driven this situation. The water scarcity situation was achieved by a combination of different factors. First, the region did not suffer any meteorological drought. In fact, the precipitation during the winter of 2013 was above the mean. Second, a clear imbalance between water availability and consumption made the Sierra Boyera reservoir empty in April 2023. Third, despite the option of transferring water from the La Colada dam, which had water, to the Sierra Boyera dam, the water quality of this reservoir was not apt for consumption. The above mean precipitation led to the leaching and removal of nutrients and organic matter stored in the soil, which caused a buildup of sediment and pollutants in this reservoir. This case study highlights the need to go a step further in drought awareness systems, including indicators that allow us to foresee water issues connected to water quality.

Water Quality Following Hydrologic Extremes: Four Decades of Local and Regional Scale Events in the Itaipu Reservoir

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Floods and droughts rapidly change land structure and connectivity in water resources systems, directly affecting water quality in unexpected ways. While drivers of extreme events are relatively well understood, their impacts on water quality are confounded by environmental, climatic and societal factors on local and regional scales. Here we leverage four decades of a unique water quality dataset of the Itaipu Reservoir, the second largest hydropower plant in the world, to examine how extremely dry and wet conditions affect water quality and eutrophication risk. We analyze the water quality in the reservoir's main inflow and outflow points, influenced by the vast Paraná River Basin (880,000 km²), and in the smaller reservoir branches. These branches are influenced by local scale inputs from intensively farmed catchments as well as by the main Paraná river. We classify dry and wet months based on streamflow quantiles and evaluate its effects on turbidity, nutrients and chlorophyll-a concentrations. Our results show an unexpected distinction in how droughts and floods influence eutrophication risk across different reservoir zones. While we anticipated that eutrophication would be intensified by reduced water renewal and increased transparency and residence time during droughts, this pattern holds true only for the reservoir's inflow and outflow monitoring points. In the reservoir branches, the opposite occurs, where nutrients and chlorophyll-a concentrations are significantly enhanced by floods in the smaller catchments. We hypothesize that during floods nutrient-rich runoff from rural catchments boosts algal biomass in the tributaries, which combined with higher retention times in the branches amplifies eutrophication even more than expected. Such events can temporally compromise water security of populations that depend on the reservoir for water intake and economical purposes. We conclude that despite the vast volume of the reservoir and the Paraná River's dominant inflow, small tributary inputs can significantly impact water quality in the reservoir branches—critical zones for local socioeconomic activities. We highlight the need to anticipate water quality change following hydrologic extremes and to implement local management strategies that mitigate water security risks.

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Advancing decadal predictions of floods and droughts

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Accurate long-term predictions of hydrological variability and extremes are increasingly needed for flood and drought risk management in a changing climate. However, their skill is limited by the underestimation of climate variability in climate models. Here, we force a statistical streamflow model with a large ensemble of dynamical CMIP5-6 predictions of precipitation and temperature. We find that predictions of UK winter flooding have low skill when using the raw 676-member ensemble averaged over lead times of 2–5 years from the initialization date. However, the predictions are significantly improved by sub-selecting 20 ensemble members that better capture the multiyear temporal variability in the North Atlantic Oscillation (NAO). Accordingly, we show positive skill in 46% of stations compared to 26% using the raw ensemble. The greatest improvements occur in northwest UK, where higher winter rainfall is positively correlated with the NAO. Our findings highlight the potential of decadal predictions to inform flood and drought risk management at long lead times.

An Open-Source Tool for Generating Hourly Synthetic Streamflow Series in Ungauged Basins Using Regional Flow-Duration Curves

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Predicting streamflow in ungauged catchments using regionalization methods has been extensively studied. While numerous free and open-source software (FOSS) tools exist for predicting regional flow-duration curves (FDCs) at ungauged sites, a general FOSS tool specifically designed to generate continuous streamflow series from these FDCs is lacking. This study introduces FDC2Qt, an R-package developed within a collaboration between the University of Bologna, the Po River Basin Authority, and the Emilia-Romagna Regional Authority. FDC2Qt generates long synthetic hourly streamflow series in ungauged catchments, utilizing a regional dataset of daily streamflow observations from neighboring sites and basin morphoclimatic descriptors. The methodology comprises three key steps: (1) FDC Prediction: a regional period-ofrecord FDC is predicted for the ungauged site by combining an index-flow approach (Castellarin et al., WRR, 2004) with a region of influence approach (Burn, WRR, 1990); (2) Daily Streamflow Synthesis: a synthetic daily streamflow series is generated at the ungauged site using a non-linear spatial interpolation method based on FDCs (Smakhtin et al., HSJ, 1997; Smakhtin, J. Hydrol., 2001), referencing one or more observed daily streamflow series from neighboring catchments; (3) Hourly Streamflow Downscaling: the synthetic daily series is downscaled to an hourly time step using a scaling law that primarily considers the morphological features of the ungauged catchment. Validation experiments demonstrate that the synthetic hourly streamflows accurately capture the primary hydrological characteristics of observed streamflow series and exhibit reliability comparable to that of hourly streamflow series simulated by regionalized lumped rainfall-runoff models.

Geophysical Investigations for Assessing Bridge Foundation Stability and Riverbed Erosion

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Bridge foundations are particularly vulnerable to riverbed erosion, necessitating advanced monitoring techniques to assess their stability. This study explores the application of near-surface geophysical methods for identifying excavation footprints around bridge piles, with a potential estimation of foundation depth. The final objective of the research is the development of a geophysical characterization protocol to enhance monitoring and risk assessment.

To support the interpretability of field measurements, an experimental basin was constructed with stratified sand and gravel layers, gradually flooded to simulate natural riverbed conditions. Ground-penetrating radar (GPR) and electrical resistivity tomography (ERT) measurements were conducted in various configurations, including GPR surveys from both a small boat and the soil surface. Results indicate that GPR effectively detects water depth variations and subsurface layers, despite challenges such as multiple reflections and localized anomalies. These findings confirm the method's validity for studying river erosion processes in controlled environments and provide a foundation for its application in real-world bridge stability assessments.

The Role of Building Roofs in Pluvial Urban Flood Modeling

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Pluvial floods occur in small urban catchments when intense rainfall exceeds the stormwater drainage capacity. These events have been happening more frequently and with increasing impacts due to ongoing urbanization and the intensification of sub daily precipitation extremes. Modeling these fast-evolving phenomena at very high spatial resolutions (1-5 m) is crucial to understand their dynamics and mitigate the impacts. In this work, we focus on better quantifying the role of building rooftops in the rainfall-runoff transformation involved in pluvial flooding. We adopted a modeling framework based on the LISFLOOD-FP rain-on-grid hydrodynamic model forced with gridded inputs of net precipitation, which accounts for the roof effects. A significant challenge in incorporating roofs lies in accurately representing how the distinct effects of construction type, slope, surface material, and drainage systems affect rainfall losses, runoff delays, and, ultimately, water depths on the streets. We evaluate two methodologies inspired by recent research. The first involves categorizing buildings assigning a runoff coefficient based on roof typologies and the second considers the distribution of downspouts to take into account the spatial variability in flood water discharged from the roofs. We test these methods in an urban catchment of Brooklyn in New York City, basing the modeling on a real event of precipitation that on September 2023 lead to many flood events that have caused a lot of diseases to the borough. This work provides useful insights into the role of roof runoff in urban flooding, contributing to increase the knowledge about the micro-topography's importance on flood dynamics' and to improve flood management strategies in highly urbanized areas like New York City facing similar challenges of increased pluvial flooding due to climate change.

Understanding Urban Flood Resilience: The Role of Green Roofs in Risk Reduction

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Pluvial Floods are perceived to be one of the most pressing challenges in the Disaster Risk Reduction framework, mainly due to climate change-induced variability of extreme events. (Mahmoud & Gan, 2018). Although many studies focus on infrastructure solutions, the current study emphasises how the interplay of extreme precipitation events and Nature-Based Solutions (NBS) such as green roofs (GRs) can reduce the risk of pluvial floods. The study focuses on the urban area of Milan as a representative case study. We focus on the variability of flood losses arising from shifts in rainfall behaviour, which are characterised by Generalized Extreme Value (GEV) analysis. In addition, the study also incorporates the direct impact of extreme precipitations through different GR implementation scenarios using information available at the GR database (Comune di Milano, 2024). The study builds a framework that integrates rainfall extremes with the Integrated Valuation of Ecosystem Services and Tradeoffs (inVest model ADD REF), Urban Flood Risk Mitigation Model (URFM). Moreover, using downscaled ERA5 data (1980–2024), GEV distributions were applied to derive rainfall intensities for 2- to 200-year return periods across three durations (1-, 6-, and 24-hour events). The GEV analysis indicated a Weibull-type distribution as the shape parameters were negative. Additionally, results for GEV analysis were validated using QQ-plots. These rainfall results were used as an input for the InVest model to simulate flood water depths under a baseline (0% GR coverage) condition, followed by a series of green roof implementation scenarios ranging from 5% to 100% coverage, with 5% increments. The implementation of GR was incorporated in the framework by modifying the Land Use Land Cover (LULC). All the data sets used in the study, including rainfall data, the GR dataset, and LULC, are available on open access. Building exposure data was extracted from OpenStreetMap. After incorporating these results with the exposure dataset, the losses were quantified using seven depth-damage functions (). Using all these outputs, risk curves were generated, leading to the calculation of Annual Average Loss (AAL). The study also advocates its findings by using a sensitivity analysis. Moreover, the study also evaluates the difference in AAL across the 1-hour, 6-hour, and 24-hour GEV-derived events. Similarly, comparing the results for multiple return periods indicated that an increase in rainfall intensity, such as moving from a 100-year to a 150-year rainfall extreme, can cause a large increase in flood losses. However, under a 50% GR implementation scenario, the same increase in rainfall leads to a much smaller rise in losses. The findings suggest the GR coverage can significantly contribute to urban resilience. To further assess the sensitivity of results, the flood losses calculated using the seven depth damage vulnerability functions were compared. Each model applies a different damage curve based on water depth, resulting in a spread of loss estimates. Additionally, a noise analysis was performed to assess the sensitivity of the results. A 30% noise inclusion in the results indicated a maximum 22.11% of Mean Absolute Error (MAE), indicating that no model reacted unpredictably to the induced noise. Finally, the calculated flood losses under each scenario served as a basis for evaluating the primary benefit of implementing the GR. By linking the extreme rainfall events, exposure, and vulnerability models, the study offers an assessment tool for Risk-Based Design of nature-based solutions. Ultimately, this work lays the foundations for a comprehensive cost-benefit analysis wherein the primary benefit will be the reduced AAL.

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Building Climate Resilience through Integrated Flood and Drought Management

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Climate change significantly affects communities, ecosystems, and economies by increasing the frequency and severity of floods and droughts. Droughts cause water shortages for plants, while floods lead to excess water on normally dry land. To enhance resilience, an integrated approach to managing both floods and droughts is essential. The aim of this research is to examine strategies that include risk assessment, early warning systems, adaptive infrastructure, and community-based solutions to reduce the negative impacts of hydrological extremes.
Combining nature-based solutions, such as wetland restoration and sustainable land management, with technological advancements like data analytics and remote sensing, offers promising pathways for climate adaptation. Furthermore, policy coordination and stakeholder engagement are crucial for ensuring the sustainable management of water resources.
Successful applications of integrated flood and drought management from various regions will be examined, explaining how proactive measures can increase resilience to climate variability. This study emphasizes the importance of interdisciplinary collaboration and long-term planning to build adaptive capacities in vulnerable regions.

The probability of rapid swings in streamflow across Europe

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Rapid changes, or swings between opposite streamflow extremes such as drought and floods present the potential for exaggerated impacts from either or both events. For instance, disaster risk reduction strategies designed for flood management can negatively impact preparedness for droughts. Although research into the probability and occurrence of these events has increased in recent years, most applications have used event definitions which are applied top-down across many locations, thus not adequately accounting for dissimilarities between hydrological catchments. Here, we develop a probabilistic approach to understand rapid transitions from drought to flood, as well as rapid swings in streamflow that do not fit strict definitions of drought and flood events. We aim to provide context on how the likelihood of substantial changes in streamflow volume scale with changes in event parameters and vary spatially and between flow regimes, irrespective of strict top-down drought and flood definitions.

Projecting Hydropower Production Across the Upper Colorado River Basin

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The Colorado River is the most important source of water in the western United States: it provides water to 30 million people, irrigates over 16,000 km² of agricultural land, and produces over 8 billion kilowatt-hours of hydroelectric power annually. We focus on the hydropower production in the Upper Colorado River Basin (UCRB) and in particular on the Glen Canyon Dam, which impounds Lake Powell, one of the largest reservoirs in the United States. This reservoir plays a critical role for water supply, flood risk management, and hydropower production, and has been the topic of extensive interest in the news due to its extremely low levels in recent years. Here we first develop statistical models that relate spatially and temporally averaged precipitation across the basin to the monthly hydropower production by the Glen Canyon Dam during the 2005-2022 period. We then use these models forced with bias-corrected projections of precipitation across the basin to assess the projected changes in hydropower production under four future scenarios or Shared Socioeconomic Pathways (i.e., SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5).

This research provides insights with global relevance, as many reservoirs face issues of water scarcity, with implications for hydropower production. More broadly, the outcomes of this work aim to provide key information for applications such as flood, drought and power outage risk analysis, dam and reservoir design and management, highlighting the necessity for appropriate water resource management to cope with extreme events and changes in precipitation amounts under future climate conditions.

Comparison of physics-based and machine learning approaches for sustainable groundwater management: a case study in Emilia-Romagna (Italy)

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The Emilia-Romagna region (Italy) is characterized by extensive agricultural and industrial activities alongside densely populated urban centres. Groundwater plays a critical role as a freshwater source, especially during drought periods, which are expected to become more frequent and intense due to climate change.

This study aims to evaluate the future groundwater dynamics in a portion of Emilia-Romagna, considering climate change and human-induced impacts. The goal is to assess the resilience of the regional multi-layered aquifer system to droughts, and to possibly identify guidelines for long-term sustainable groundwater management.

To achieve this, a numerical groundwater flow model and a random forest algorithm (implemented in MODFLOW 6 and R, respectively) are employed to compare the performance of a physics-based and a machine learning approach in simulating past and future groundwater levels, and to investigate the benefits of their combination. Input data are sourced from a regional groundwater model by the Regional Agency for Prevention, Environment and Energy of Emilia-Romagna (Arpae), and from publicly available datasets on the Emilia-Romagna Region and Arpae repositories. Both techniques are then applied to conduct a scenario analysis focused on the effects of precipitation reduction and altered groundwater pumping regime in the study area, evaluating their combined influence on the aquifer system.

Results show that the aquifer system is vulnerable to future droughts. Increased groundwater pumping exacerbates the impacts of reduced precipitation, while decreased abstraction may partially mitigate them. Critical hotspots are identified, suggesting the necessity of multi-scale approaches to effectively develop mitigation and adaptation strategies.

While the random forest model offers valuable insights into factors influencing groundwater head distribution and enhances the interpretation of the groundwater model results, its lack of physical grounding limits its generalization potential. The integration of both methods demonstrates their complementary strengths, emphasizing the benefits of combining physics-based and machine learning approaches for more effective groundwater modeling.

Predicting Vector-Borne Disease Risk using Earth Observation and Machine Learning: A Case Study in northern Italy

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Climate change, driven by alterations in atmospheric composition and land-use modifications, has consequences including global warming, biodiversity loss and shifts in precipitation patterns. This results in increased frequency of extreme weather events, such as droughts and floods, locally. These changes also affect the life cycle and adaptability to heterogeneous conditions of different animal species like mosquitoes. Indeed, longevity, the gonotrophic cycle duration and the abundance of mosquitoes are influenced by meteorological and ecological factors. Increasing mosquitoes abundance has a negative impact due to the nuisance directly caused by these insects and the possibility of transmission of arboviruses like West Nile (WN). Culex pipiens, known as the "common mosquito," is the species most involved in the circulation of WN virus in Italy. Therefore, implementing preventive strategies to identify risk areas and prevent WN outbreaks is crucial.
The EASTERN project focuses on the direct and indirect consequences of flooding, leveraging Earth observation (EO) and meteorological data to implement Machine Learning (ML) models that can support prevention and monitoring of direct and undirect effects of floodings. Among the uses cases considered, ML-based predictive tools are developed to identify areas suitable for vector proliferation, using meteorological parameters and ecological information.
This study investigates the correlation between meteorological, ecological, and entomological factors and the abundance of Culex pipiens. Meteorological parameters considered include temperature, humidity, precipitation, and wind speed, while ecological parameters derived from Sentinel-2 optical imagery encompass Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), and Normalized Difference Water Index (NDWI). The choice of all these specific parameters is supported by literature, which shows a correlation between them and vector spreading. Entomological data were collected by IPLA S.p.A. at around 100 trap sites in the Piedmont region, monitored every two weeks from June to October. Models have been trained on data collected from 2017 to 2023, and then further validated for year 2024. The amount of captured mosquitoes has been divided into two classes, class 0 for the low and class 1 for the high density of collected insects, in order to define a binary classification problem. Several models have been trained, and the current best model divides the high- and low-density classes with a threshold of 5 captured mosquitoes. Its F1 score is 0.75 for class 0 and 0.73 for class 1. The predictors with the highest feature importance are month of capture, altitude of capture site, temperature, humidity, rain, NDMI, and NDWI.
Our preliminary study shows how the integration of meteorological data, satellite imagery, and ML models could represent a valuable tool for monitoring vector populations, assessing health risks, and informing targeted interventions, particularly in data-limited regions.

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Understanding human-water relationships across the Water-Energy-Food-Ecosystems Nexus in a mountain catchment in Northern Italy

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Once water-abundant, parts of the Alps are now experiencing more frequent water scarcity and drought conditions, impacting both human activities and ecosystems. In addition to lower water availability due to climate change, water scarcity is also strongly shaped by how water resources are allocated, used and managed. It thus represents a socio-hydrological phenomenon that concerns all sectors reliant on water and their interdependencies, i.e., the Water-Energy-Food-Ecosystems (WEFE) Nexus. While previous research on the WEFE Nexus in water-scarce contexts have primarily focused on hydrological analysis, this study employs a mixed method approach to reveal hydrological, social and governance conditions that jointly contribute to water scarcity. The approach is applied to the Orco catchment, a sub-basin of the Po River in Northern Italy, characterised by significant storage capacity in hydropower reservoirs in the highlands and large irrigation withdrawals in the lowlands. The qualitative analysis consists of mapping the interrelationships - synergies, trade-offs and feedback loops - between sectoral water users, water resources, and governance systems through the Causal Loop Diagram and the Network of Action Situation methods. On a quantitative level, a water resources management model of the Orco catchment is developed and used to simulate water allocation strategies across sectors for the period 2011 – 2022. Results show that irrigation needs were only fully met in a few years and that the upstream-downstream positioning influenced the frequency and intensity of water shortages, as well as the impact of prioritising environmental flows on water withdrawals by different irrigation districts. Water stored in hydropower reservoirs could potentially help mitigate irrigation water deficits in late July and August, resulting however in a reduction of hydropower production in winter months. Furthermore, addressing water scarcity would require overcoming socio-economic barriers associated with current agricultural practices, a radical transformation of the irrigation distribution system, the adaptation of withdrawal permits to a changing climate and further cooperation between upstream and downstream water users. Nevertheless, signs of cooperation were already found in the Orco watershed, indicating the willingness of the local community to address the issue of water scarcity collectively.

Comparing Snow Water Equivalent Reanalyses and Optimizing Rainfall-Runoff Models in Northern Italy

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Snow processes play a critical role in Mediterranean mountainous regions, functioning as natural reservoirs that store winter precipitation and release meltwater during spring and summer, thus regulating water resources availability. However, direct measurements of Snow Water Equivalent (SWE) are spatially and temporally limited, necessitating reliance on large-scale reanalysis products or rainfall-runoff models, both of which face reliability problems.
In this study, we evaluated SWE estimates across more than 100 catchments in Northern Italy (2010-2020) using the high-resolution IT-SNOW dataset as reference. We systematically compared three reanalysis products — ERA5-Land, CERRA-Land, and VHR-REA_IT — alongside SWE simulations from the GR6J-CemaNeige rainfall-runoff model calibrated with streamflow observations.
To enhance SWE simulations with GR6J-CemaNeige, we implemented and evaluated three distinct calibration strategies: (i) a sequential approach optimizing snow parameters first using SWE data followed by streamflow-based calibration, (ii) NSGA-II multi-objective optimization simultaneously considering both data sources, and (iii) a weighted objective function combining streamflow and SWE performance metrics.
Our evaluation revealed significant variations in SWE estimates with elevation-dependent patterns. ERA5-Land showed the closest alignment with IT-SNOW at lower elevations (0-1200m), while streamflow-calibrated CemaNeige-GR6J performed best above 1200m. CERRA-Land demonstrated strong agreement with the reference dataset in high-elevation winter conditions but consistently overestimated summer SWE. VHR-REA_IT underestimated SWE across all elevation bands throughout the seasonal cycle.
Integration of IT-SNOW data into the rainfall-runoff model calibration process significantly improved SWE simulations while maintaining high-quality streamflow simulations, demonstrating the value of incorporating multiple observational constraints in hydrological modeling. Future research will focus on parameter equifinality and uncertainty quantification to advance regionalization studies by enhancing parameter transferability to ungauged basins.

AI-Driven Structural Health Monitoring for Enhancing Flood Resilience in Critical Infrastructure

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As climate-induced hydrological hazards escalate worldwide, flooding presents significant risks to infrastructure systems, especially in susceptible metropolitan areas. This study examines the incorporation of Artificial Intelligence (AI) into Structural Health Monitoring (SHM) systems to improve the resilience of essential civil infrastructure vulnerable to flood hazards. Our methodology utilises real-time sensor networks, comprising Bluetooth-enabled strain gauges and Internet of Things (IoT) equipment, to gather structural data, which is then analysed using machine learning algorithms for damage diagnosis, localisation, and predictive maintenance. The methodology is based on current breakthroughs in AI-assisted Structural Health Monitoring, including time-frequency feature extraction, anomaly detection, and deep learning models, which have been validated using experimental setups and case studies of flood-affected bridges. AI systems provide a dual purpose by monitoring deterioration caused by hydraulic stressors and guiding proactive reinforcement tactics. Implementing an AI-driven SHM framework enables stakeholders to identify early indicators of structural weaknesses, decrease maintenance expenses, and enhance the reliability of infrastructure vulnerable to flooding. The results endorse extensive climate adaption objectives and illustrate how advanced construction methods might revolutionise catastrophe risk management in smart cities.

Rain-on-snow floods in climate scenarios in Germany

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In Germany, severe trans-basin winter floods are often driven by rain-on-snow (ROS) events. Under the right conditions, rainfall on snowpack can melt the snow and produce extreme amounts of runoff. In a warming climate, the frequency of ROS events is expected to change depending on elevation and general climate conditions. This will also induce a change in the characteristics of ROS driven winter floods. To investigate these changes, for an ensemble of downscaled climate projections, the river discharge for multiple gauge stations in Germany was simulated using a neural network. Germany, as a representative for a mid-latitude country, has a large spatial cover of hydrological observations with long temporal extends. By applying explainable machine learning techniques, the flood-generating processes behind the resulting flood peaks were revealed. Changes in frequency, feature importance, and magnitude were calculated for each individual station and on a trans-basin scale. It was found that for single stations and on the trans-basin scale, the frequency of ROS floods will decrease for the Rhine, Elbe and Weser regions, while the Danube region mostly faces an increase. However, for all regions, snow melting during ROS floods becomes less important, and the floods become more rain driven. At the same time, the severity of the average and the most extreme ROS floods is projected to increase compared to the historical period for all regions on the trans-basin scale. In contrast, some of the individual stations will face a decrease in magnitude.

Compound, Cascading, and Multihazard Perils: Lessons Learnt from Hurricanes Helene and Milton

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The 2024 hurricane season presented unique challenges in hydrological and risk modeling with the consecutive landfalls of Hurricanes Helene and Milton in Florida, USA. This study investigates the compounded, cascading, and multihazard perils associated with these events, focusing on the interplay of antecedent conditions, vulnerability, and exposure.

One of the factors considered was the influence of antecedent soil moisture and river storage on hydrological modeling. Hurricane Helene, which made landfall in early September, saturated the soil and filled river systems to near capacity. These conditions significantly altered the hydrological response to Hurricane Milton, which struck just two weeks later. Hydrological models had to account for the already saturated soils and high river levels, which exacerbated flooding and runoff, leading locally to more extensive inundation than would have been predicted for Hurricane Milton in isolation.

Another point of focus is the impact on vulnerability, particularly the presence of debris from Hurricane Helene affecting the region's resilience. Debris obstructed drainage systems increased the potential for secondary flooding, and complicated emergency response efforts. Additionally, the weakened infrastructure and partially damaged buildings from the first hurricane heightened the susceptibility of the population to the subsequent event, resulting in higher overall damage and more prolonged recovery periods.

Finally, the study examines the effect on exposure, including the "build-back-better" phenomenon observed in even previously to the aftermath of Hurricane Helene. While some structures were rebuilt to higher standards, providing increased resilience against Hurricane Milton, many areas remained in a state of recovery, with temporary shelters and makeshift repairs that were less able to withstand the impact of the second hurricane. This mixed state of exposure created a complex landscape for risk assessment and emergency planning.

Overall, the lessons learnt from Hurricanes Helene and Milton underscore the importance of incorporating antecedent conditions into hydrological models, considering the cumulative impacts on vulnerability, and recognizing the dynamic nature of exposure in multi-hazard scenarios. These insights are crucial for improving predictive models and enhancing resilience strategies in regions prone to sequential natural disasters.

A massive compilation of interpretable features for analyzing Alpine storm precipitation climatology

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Storm precipitation analysis characterizes the magnitude and temporal details of precipitation events, playing a crucial role in understanding evolving precipitation patterns in a changing climate. It also aids in enhancing flood hazard assessments and developing more effective adaptation strategies. Traditional storm analyses often rely on feature compilations that summarize only a fraction of the available data, potentially limiting insights. To address this, we present the first massive compilation of features for rainstorm analysis. This compilation integrates a diverse set of over 50 highly interpretable features across four key categories: precipitation, temperature, wind speed, and static features.

Additionally, we provide a ranking of these features based on their relative importance for better understanding Alpine storm climatology. To achieve this, we utilize unsupervised machine learning and a vast sub-hourly precipitation dataset comprising hundreds of thousands of storms across the Alps. Overall, we believe that the feature compilation we propose supports a wide range of applications, from analyzing storm climatology in different regions around the globe to evaluating stochastic model performances, and predicting future storm features when combined with climate model outputs.

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Indicator-based analysis of climate extremes using a convection-permitting model

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As climate change progresses, extreme weather events—such as floods and droughts—as well as compound events are becoming increasingly frequent and more likely to occur in succession, exerting severe impacts on agriculture, society and infrastructures. It is well recognized that compound climate extremes can lead to significantly greater adverse consequences compared to isolated extreme events.

This study, therefore, seeks to analyze both individual and compound drought and extreme precipitation (CDEP) events using an indicator-based approach.

Indeed, despite the well-established credibility of ERA5 reanalysis data, its relatively coarse spatial resolution may limit its ability to accurately represent localized extreme weather events. In this regard, the ongoing advancements in convection-permitting regional climate models (CPRCMs, resolution <4 km) offer a promising avenue to partially address this limitation. In this study, precipitation data have been utilized, derived through the dynamical downscaling of ERA5 reanalysis dataset to a convection-permitting scale of 0.02° (â‰ƒ2.2 km) with an hourly temporal resolution.

The indicator-based analysis proposed in this study covers a 30-year period (1989–2018) across nine distinct domains encompassing a significant portion of Europe. The downscaling is performed using the Regional Climate Model (RCM) COSMO-CLM (CCLM), incorporating the TERRA-URB module to account for urban land surface processes.

The results are used to assess extreme events as floods and droughts in the different study regions over Europe using a selected set of climate indices and indicators, chosen to capture different aspects of climate extremes. These include the consecutive dry days (CDD), the standardized precipitation index (SPEI), the ratio between the precipitation due to very wet days and the total precipitation in wet days (R95pTOT/PRCPTOT), the 99th percentile of daily precipitation considering only the wet days (R99th), the maximum three-days precipitation (RX3d) and the coincidence rate between droughts and extreme precipitation events at different time lags. The results obtained are then compared with those from ERA5 and other reference gridded products, in order to highlight the added value of downscaled data used in detecting droughts and extreme precipitation.

Impact of time aggregation on dominant high-flow regimes

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Flood processes and trends are typically studied using daily streamflow data and therefore focus on dominant flood processes that are apparent at the daily timescale. At this resolution, floods are often driven by snowmelt, wet antecedent conditions and/or stratiform rainfall events. This daily perspective is informative about the driving processes behind many flood events, trends and future changes, however, many rivers experience short, but very intense, floods triggered by sub-daily processes. These rapid flood events may not last long enough for their true severity to be captured in a daily mean flow estimate. Consequently, when we look at peaks estimated from mean daily time series, we might either completely miss sub-daily processes or categorize them as non-dominant. Here, we investigate how a shift from daily to sub-daily (hourly or higher resolution) streamflow data can change our view of what the dominant high-flow processes are across several catchments in the Alps. To this end, we analyse high-flow regimes (i.e. high-flow seasonality) in the frequency domain to represent the timing of the first and second most frequent floods, using daily mean and daily maximum hourly streamflow aggregations. We identify the hydro-climatic drivers of the differences in flood timing and magnitude according to daily and daily maximum aggregations and map this information onto flood frequency analyses by relating flood seasonality and drivers to return levels and magnitudes. Preliminary research has revealed that some catchments in the Alpine region show markedly different dominant flood seasons and drivers depending on the data aggregation choice. The framework and analyses presented here are useful for identifying where hourly data are needed to study flood processes, trends and future changes, and may further offer insights into shifts in hazard type if expected future high-flow regime changes occur.

Substantial Increase in Unprecedented Flood Risk Revealed by Kilometer-Scale Rainfall Projection with Emergent Dynamics Constraint

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Escalating extreme floods worldwide poses threats to current hydraulic infrastructure's capabilities to address unprecedented flood risks. While high-resolution flood projections offer foundations for improved infrastructure designs, such detailed projections are not yet readily available. Here we propose a framework of flood projection that integrates a chain of atmospheric and hydrodynamic simulations. We identify an emergent constraint in atmospheric dynamics through factual and counterfactual experiments. The constraint is applied to kilometer-scale rainfall projections from thermodynamics-perturbed simulations. We reveal a tenfold increase in inundation area of an unprecedented flood by the century's end in the North China Plain, driven by intensified rainfall and more frequent favorable synoptic conditions. A spatial offset exists between areas with heightened flood risk and extreme rainfall, emphasizing the need for capturing fines pace-time rainfall structures in flood projection. This framework offers a promising approach for projecting global future flood hazards in diverse regions facing escalating flood challenges.

Regional Calibration of a Lumped Hourly Hydrological Model Using a Decision-Tree Approach

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Hydrological simulation in ungauged basins is essential for analysing extreme events and reconstructing historical data. A major challenge is deriving consistent model parameters that reflect basin characteristics. Regionalization methods address this by transferring information from gauged to ungauged basins, linking catchment attributes to model parameters.
An innovative approach - PArameter Set Shuffling (PASS) - uses a machine learning decision tree algorithm to establish relationships between locally calibrated parameters and basin descriptors, enabling spatially distributed and lumped parameter predictions. PASS has yielded valid results with semi-distributed hydrological models in flat terrains such as Germany and in more complex regions like the Alpine areas, but its application to lumped models remains largely unexplored.
This study investigates the performance of PASS for regionalizing an hourly lumped rainfall-runoff model, GR5H, in the eastern mountainous region of Emilia-Romagna, Italy. Specifically, the method was applied to a pool of 23 medium-small mountainous basins, using hourly discharge data covering up to 20 years for many of the catchments considered. The selection of the study region is motivated by the devastating 2023-2024 floods, causing casualties, significant losses and widespread displacement. Extensive levee breaches and damaged river gauges hindered accurate flood flow measurements.
KGE and NSE were adopted as efficiency measures in the calibration process and two independent analyses were conducted, providing additional insight into the potential, strengths, and weaknesses of these two metrics. The results demonstrate that the PASS procedure enables the attainment of good regional model efficiencies without significant loss of performance when transitioning from calibration to leave-one-out cross-validation, confirming the robustness of the methodology in handling complex terrains and diverse hydrological conditions with a simpler hydrological model. These findings highlight the potential of PASS to streamline parameter estimation for ungauged basins and provide a reliable tool for hydrological modelling with reduced computational complexity.

Session II

TECHNOLOGY TRANSFER AND INNOVATIVE SOLUTIONS TO ENHANCE INFRASTRUCTURE RESILIENCE

Oral presentations

When 'shifts' are the extremes in hydrology: how to face, manage, and communicate water risks in highly regulated river basins (*Invited lecture*)

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Extremes in hydrology are a long-lasting hot topic in our research, not only due to the variability and complexity of their nature, occurrence, and forecasting, but also because of the magnitude of their impacts on society, with dramatic consequences in too many cases. During the last decades, many examples of exacerbation of extremes magnitude and frequency have been reported in literature, and a vast majority of future climate projections result in the same direction on both the mean annual and decadal scales.

In many regions in the world, flood and scarcity risks are managed by joint structures and elaborated protocols of operation. Many reservoirs serve both as flood amelioration and seasonal and multiyear storage for the dry periods. Initial risks have been decreased for the high and medium frequency events (for floods but also for scarcity conditions); however, high magnitude events have eventually increased the associated risk as the potentially affected areas have been further occupied (due to "the human factor" or a potential call-effect of the protection measures). These undesired impacts pose a challenge for water resource and reservoir managers, especially when the occurrence of scarcity and flood successively take place in very short periods within hydrological time scales. These "extreme shifts" involve new needs for an efficient risk management in terms of operational rules, thresholds for reservoir volumes, priorities, etc., for new socioeconomic models for water resource allocation and soil use planning, but also for an advanced and efficient strategy for communication of these needs and plans to society.

This work aims to showcase this paradigm based on the last drought period (years) in Spain, with a severe and long scarcity situation in most of the basins, that abruptly ceased in 2024 spring after one wet month in different regions, and was then followed by a tragic flood event in October and the wettest March since records in 2025. Today, with most of their reservoirs discharging flows to prevent loss of future floods storage and the potential failure of the structures, the resulting social euphoria is masking the risk of the future droughts that will undoubtedly occur again. Lessons already learnt, lessons not learnt yet, and the role of science in communicating hydrological extremes and their shifts will be also discussed.

Have river flow droughts become more severe? A review of the evidence from the UK – a data-rich, temperate environment

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When extreme hydrological events (floods and droughts) occur, there is inevitably speculation that such events are a manifestation of anthropogenic global warming. The UK is generally held as a wet country, but recent drought events in the UK have led to growing concerns around droughts becoming more severe – for sound scientific reasons, given physical reasoning and projections for future. In this presentation, we ask whether such claims are reasonable for hydrological droughts in the UK. The UK has a well-established monitoring programme and a very dense body of research to call on, and hence provides a good international case study for addressing this question. We firstly assess the evidence for changes in the well-gauged post-1960 period, before considering centennial scale changes using model-based reconstructions. We then seek to provide a synthesis of the state-of-the-art in our understanding of the drivers of change, both climatic and in terms of direct human disturbances to river catchments (e.g. changing patterns of water withdrawals, impoundments, land use changes). These latter impacts confound the identification of climate-driven changes, and yet human influences are themselves increasingly recognised as potential agents of changing drought regimes. Perhaps *surprisingly*, we find little evidence of compelling changes towards worsening drought, apparently at odds with climate projections for the relatively near future and widely-held assumptions of the role of human disturbances in intensifying droughts. Scientifically, however, this is perhaps *unsurprising* (given uncertainties in future projections, the challenge of identifying signals in short, noisy records, and a lack of datasets to quantify human impacts) but it presents challenges to water managers and policymakers. We dissect some of the reasons for this apparent discrepancy and set out recommendations for guiding research and policy alike. Several major themes emerge, including: 1) integration of observational trend studies with hydroclimate modelling using large ensemble and 'storyline' approaches, seeing the observed past as only one instance among 'worlds that might have been' to help better frame emerging risks for policymakers; 2) improved understanding of the drivers of drought, both climate forcings (going beyond straightforward analysis of the North Atlantic Oscillation and so on) and the 'human factor' (i.e. disturbances due to water withdrawals or land use) to enable us to discern their relative roles in driving change. This latter grand challenge is an extremely ambitious one, but is the crux of '*expecting the unexpected*' - we set out some recent UK developments helping to tackle this problem. While our focus is the UK, we envisage the themes within this presentation will resonate with the international community and we conclude with ways our findings are relevant more broadly.

Exploitation of Satellite Data for Flood Mapping of the November 2023 Flood in Tuscany, Italy

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Climate change has led to an increase in the frequency and intensity of extreme weather events, thereby heightening risks for vulnerable urban areas. The exposure of these regions results in significant socioeconomic losses, particularly from flooding and other climate-induced hazards. Satellite-based services and advanced technologies, such as GIS-driven Digital Twin models, enable the simulation of flooding scenarios and real-time flood monitoring and short-term forecasting, supporting evidence-based urban planning through financial risk management strategies.
The evaluation of the efficiency of these systems can be critical as it requires the validation of flood maps. Typically this type of validation is carried out through the use of satellite-derived data, particularly from Synthetic Aperture Radar (SAR), which is robust under diverse meteorological conditions. This study investigates the validation of flood maps for urbanized environments utilizing a robust, established methodology (Pulvirenti et al. 2023, DOI: 10.3390/w15071353), which has been further improved to enhance flood detection in urban settings. The methodology was applied to a major precipitation event in November 2023 in Prato Plain (Tuscany, Italy), which caused the flooding of several areas. During this event, the Copernicus Rapid Mapper was activated, and the flood area estimates were used as validation data to assess the method's reliability and robustness.
This study focuses on flood detection in urban areas using satellite data, highlighting the importance of satellite mapping services while addressing challenges like limited revisiting time, which can delay early flood detection. To improve this, next-generation multisatellite and multiservice constellations, such as ASI/ESA IRIDE, are being developed. For rapidly evolving events, higher time resolution is crucial for early data acquisition. The integration of modeling, sensor data, and citizen science through Digital Twins is essential for enhancing climate resilience in coastal cities, as shown by the four-year EU-funded SCORE project (https://score-eu-project.eu/).

Transdisciplinary modeling of unexpected drought risks: A human-water systems approach for historically water-abundant rural-urban regions

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Unexpected water scarcity risks are becoming increasingly likely in historically water-abundant rural-urban regions, due to shifts in hydro-climatic regimes. These risks are driven by decreasing water availability, shifting sectoral demands, and degrading water quality under intensifying droughts, heat waves, and compound events. So far, there has been insufficient research into how our behaviors, institutions, and infrastructure can be adapted to mitigate rural-urban water conflicts.

We present a transdisciplinary human-water systems modeling framework designed to co-develop and evaluate future water scarcity scenarios and to identify robust adaptation strategies. To address the deep uncertainty inherent in the socio-economic drivers and their complex interactions with hydrological systems, our approach integrates stakeholder knowledge and preferences with methods from behavioral science, machine learning, and hydro-economic modeling. This integrated framework is applied to a case study in Eastern Germany, a region increasingly affected by seasonal water scarcity, rising water demands linked to urbanization and structural change, and long-distance rural-to-urban water transfers.

Preliminary findings indicate that increases in irrigation demand and urban consumption threaten to intensify rural-urban competition for limited water resources. Without precautionary measures to mitigate urban water consumption peaks, rural water availability for agricultural, industrial, and ecological needs may come under severe strain. Strengthening resilience to these water conflicts will require adaptation strategies that coherently address uncertainties in both human and natural scarcity drivers, while consistently accounting for the value of water across rural and urban sectors.

Session II

TECHNOLOGY TRANSFER AND INNOVATIVE SOLUTIONS TO ENHANCE INFRASTRUCTURE RESILIENCE

Pop-up presentations and posters

Monte Carlo based reconstruction of a historical flood event

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Reconstructing historical flood events can offer critical insight into past hydrological responses to extreme weather, informing contemporary flood risk management and infrastructure design. However, often the magnitude of these events have to be inferred from secondary data such as flood marks on buildings, newspaper stories and photographs. This study focusses on a flash flood event in the South West of England in July 1968. The magnitude of the event is unknown as the gauging station on the river was overwhealmed, but there is evidence in surrounding villages in the form of flood marks, photographs and oral history from first-hand witnesses. Combining a hydraulic model (HEC-RAS) with a Monte Carlo framework, this study demonstrates the development of a new stochastic framework for reconstructing the magnitude of this event (165 m^3/s), including an assessment of the uncertainty of the reconstructed peak (95% confidence interval between 140 - 180 m^3/s). The analysis brings together advanced hydraulic modelling with uncertainty analysis and different data types, including historical information and offers detailed insight into this extraordinary event, which is about 4.5 times larger than any other event recorded on this river over the past 65 years.

Estimates of Point Rainfall Extremes from Satellite Precipitation Products: Test of Sensitivity

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Reliable extreme precipitation estimates are essential for understanding, predicting, and mitigating natural disasters. However, their inference at a global scale is limited by the sparse and uneven distribution of direct rainfall observations. Satellite-based estimates provide a promising source of information for extreme value analysis, but their high uncertainty and low spatial resolution hinder their applicability. Additionally, grid sizes ranging from 10 to 600 km^2 prevent direct comparisons with point-scale extreme value estimates, as point- and area-averaged statistics inherently differ in their construction.

This study addresses this limitation by assessing the sensitivity of a downscaling method for extreme value statistics, based on random field theory and the Metastatistical Extreme Value Distribution (MEVD). We use a comprehensive dataset of approximately 200 rain gauges in northeastern Italy, along with multiple satellite precipitation products, including IMERG, CMORPH, CHIRPS, SM2RAIN, MSWEP, and PERSIANN. The downscaling process, based on the autocorrelation structure of precipitation fields, is applied individually to each product at the grid cells corresponding to the available rain gauges.

To perform the downscaling process, two key variables must be obtained: the variation in the wet fraction (Beta) and the variation in the rainfall spatial correlation (lambda), both between satellite pixel and point scale. However, this requires defining a neighborhood centered on the point of interest, as well as a function that represents the decay of spatial correlation within this neighborhood. Therefore, we assess the method's sensitivity by considering three different neighborhood sizes (3, 5, and 7 pixels) and two functions to represent the spatial correlation (Exponential kernel with Power law tail and Stretched exponential).

Finally, downscaling results for extreme daily event magnitudes with a 50-year return period at the point scale are obtained from the above methodology and are validations against those derived from rain gauge time series.

Catchment-scale perspectives on future changes in sub-daily extreme precipitation: insights from convection-permitting climate models

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Understanding the scale-dependent behavior of extreme precipitation in mountainous catchments is critical for developing effective adaptation strategies to increasing flood risks. This study assesses future changes in how extreme-event intensity varies when rainfall is averaged over finite areas, a process usually expressed through an Areal Reduction Factor (ARF), with application to the Greater Alpine Region. Specifically, we explore how projected changes in sub-daily extreme precipitation at the point scale translate into changes at the catchment scale for the same return periods.
Projections are derived from a 9-member ensemble of convection-permitting climate models (CPMs) provided by the CORDEX-FPS Convection project. The dataset covers historical (1990–1999) and far-future (2090–2099) periods under the high-emission scenario (RCP8.5), with precipitation outputs remapped to a 3 km spatial resolution and hourly temporal resolution. Extremes are analyzed using the Simplified Metastatistical Extreme Value (SMEV) framework, a robust statistical method suitable for short data records.
Our spatial analysis investigates mean areal precipitation extremes computed over multiple spatial scales, from the single-cell scale (3 km) to approximately 4000 km² (21 × 21 grid cells). The dependence of the ARF on duration and return period under future climate scenarios reveals potential shifts in spatial structures and intensities of extreme precipitation events. Our study underscores the importance of using high-resolution ensemble modeling to capture the complex interplay between spatial variability and extreme precipitation, and contributes to addressing the challenges posed by changing precipitation extremes in mountainous regions.

Risk assessment of riverine flood hazards on the topology of the Italian highway network

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In this study, we analyze the impact of river flood events on the Italian highway network (excluding islands) by modeling the network as a directed graph using data from OpenStreetMap [3]. Highway segments are represented as links, and junctions are represented as nodes. The hazard scenarios are based on a catalog of 11,205 river flood events that had significant socio-economic impacts in Europe between 1950 and 2020 [4], allowing for the reconstruction of flood intensity and spatial footprints. We apply a speed reduction curve based on flood depth to each graph element, setting an operability threshold of 0.3 meters, beyond which a node or link is considered inoperable [5]. A cascading failure mechanism is implemented: a road element fails primarily if it is directly hit by the hazard and the inoperability threshold is exceeded; a link fails secondarily if at least one of its end nodes becomes inoperable, while a node fails if it becomes isolated, i.e., without any active connections.

Our research aims to identify significant risk metrics, such as the final diameter of the network and the average fraction of resisted paths. The first metric determines the number of connections in the longest path within the network, indicating the graph's maximum extent. The second metric determines the percentage of all possible paths between given origin and destination points in the highway network that resist the hazard, quantifying the residual connectivity of the network after the event.

The findings reveal that an increase in graph diameter, alongside a limited reduction in the average fraction of resisted paths, indicates partial damage to the network without inducing fragmentation. In such cases, the network remains functional and connected but relies on longer pathways to bypass affected areas, potentially delaying emergency response efforts. Conversely, network fragmentation into disconnected components is linked to a decrease in diameter and a significant drop in connectivity, resulting in isolated subgraphs. The diameter then reflects the size of the largest still-connected component. Under these conditions, mobility and accessibility are severely compromised, leading to disrupted emergency response and isolation from critical routes.

Our simulations show that analyzing these metrics allows for the assessment of natural hazard risks, identifying vulnerable sections of the Italian highway infrastructure and critical points whose failure could severely disrupt connectivity due to fragmentation. A key strength of this research is its independence from transport modeling, which, while providing more precise estimates, is far more computationally intensive. Additionally, this approach aims to guide investments in modernizing the Italian highway network, mitigating damage, and reducing costs associated with potentially catastrophic weather events.

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A distributed rainfall-runoff model to explore the connection between floods and climate extremes in the European Alps

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Given the current warming trend of our climate system, the frequency and intensity of extreme weather events are expected to have a significant impact on flood dynamics. In this evolving context, the *Clim2FlEx* project aims to assess how floods of different types are linked to climate extremes under potential future climate scenarios.

The work focuses on the European Alps, an optimal natural laboratory for this topic due to the complex hydro-meteorological processes occurring in the region and its unique position at the intersection of the Mediterranean and continental Europe.

The methodology uses an innovative and integrated version of the TUWmodel combined with a machine learning based regionalisation approach, *HydroPASS*. Once validated, the regional model enables hydrological runoff predictions for both current and future scenarios across the Greater Alpine Region. Based on these simulations, we identify flood events in time and space, link them to climate extreme indices and, ultimately, to the large-scale climatic phenomena that drive their dynamics.

Assessing the potential for surprising megafloods in Austria: the September 2024 event

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In September 2024 Central Europe (part of Austria, Germany, Czech Republic and Poland) experienced record-breaking floods with devastating consequences. In Lower Austria multiple rivers were affected, with peak discharge estimates exceeding previous record flood at 15 river gauges, 6 of which recorded discharge at least 2 times higher than previous peaks. This unprecedented event caught both residents and flood managers by surprise, raising urgent questions about how to better prepare for similarly unexpected future events.
Here we assess the magnitude of record floods in Austria using annual maximum flood data from more than 900 river gauges, and we compare the 2024 flood event to the resulting regional envelope curves. We find that during the 2024 event, peak discharge exceeded (up to 1.65 times) the regional envelope curve for Lower Austria at four gauges (river Perschling at Boeheimkirchen, Kleine Tulln at Sieghartskirchen, and Michelbach at Plosdorf), indicating that this event was record-breaking also from a regional perspective.
In a second step, we assess the potential for surprising megafloods in Austrian catchments, based on a dataset of flood series from more than 8,000 European catchments. Recent studies have in fact shown that it is possible to anticipate the magnitude of megafloods using information from other, similar catchments on the continent. Our findings show that, although this event exceeded the envelope curve of the region, the magnitude of the peak discharge could have been anticipated based on European floods.

Non-stationary analysis of satellite rainfall extremes in Italy

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We use precipitation estimates from satellite precipitation products to improve the spatial understanding of extreme rainfall across Italy. Data homogeneity and independence is first assessed, suggesting the existence of statistically significant trends in the extremes in a few areas. To account for these trends, the extreme-value analysis is performed by implementing a non-stationary SMEV model. This model allows us to look for causative relations between trends in extremes and trends in intensity, and/or occurrence frequency of ordinary values. A non-stationary two-parameters Weibull distribution with both scale and shape parameter values linearly dependent on time is adopted. A left-censoring approach is implemented as per the SMEV approach. Parameters are estimated with a Maximum Likelihood method. The method is applied to four different rainfall durations (1h, 3h, 6h and 24h) to CMORPH satellite rainfall estimates from 1998 to 2023. Preliminary results using the Likelihood Ratio test show statistical significance (10-26% of the Italian territory) of the non-stationary model if compared with a partially non-stationary model (where only the scale parameter is allowed to depend on time), and, especially, with a stationary model. A few areas of Italy (e.g., in Sardegna, Sicily, Valle d'Aosta, Friuli-Venezia-Giulia, Piemonte) show significant increase (up to 50% at some locations) in the scale parameter. This increase seems to be emphasized at increasing rainfall durations. Central Italy, instead, shows some negative changes, generally less than 10-50% per decade. Further work is necessary to analyze the trends in the quantiles and to quantify uncertainty.

Simulation of wide road network flows to identify critical bridges in flash-flood events

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Floods pose a significant threat to transportation networks, particularly bridges, which serve as critical links in road infrastructure. Prioritizing bridge retrofitting is essential to enhance network resilience, minimize disruptions, and optimize resource allocation. This study, funded by the European Union - Next Generation EU, Mission 4 Component 1 (FLOOD@ROAD – CUP: B53D23006770006), develops a systematic approach for prioritizing bridge retrofitting based on macroscopic traffic assignment. The proposed approach is designed to be practical for transportation authorities and planners, enabling quick decision-making in response to floods at a regional scale, encompassing both urban and rural areas. The methodology is broadly applicable, leveraging publicly available online data and open-source software for geographic analysis (QGIS) and traffic simulation (SUMO). It integrates flood hazard maps, traffic flow modeling, and vulnerability analysis to evaluate the impact of potential bridge failures on network performance. By employing macroscopic traffic assignments, the study assesses the consequences of bridge disruptions on regional traffic flow, identifying critical structures that warrant immediate retrofitting.
The research applies the proposed framework to a case study in Tuscan region of Italy, a flood-prone area with an extensive road network. The study evaluates multiple bridge closures in flood scenarios and their impact on traffic flow. The assessment is based on key performance indicators such as travel cost increase, reduced speed, and network connectivity loss. The findings highlight the most critical bridges and provide a data-driven basis for decision-makers to allocate resources effectively. The macroscopic simulation provides a perspective by identifying the most critical edges of the road network. The results reveal key weak points where even minor disruptions could cause delays and traffic congestion, providing valuable insights for targeted mitigation and retrofitting strategies. This study contributes to the growing field of transportation resilience by offering a quantitative framework for infrastructure adaptation planning. Future research could enhance the model by integrating dynamic traffic simulations and considering climate change projections to simulate long-term infrastructure vulnerabilities.

Annual Maxima or Peaks over Threshold: a study of UK flood records

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Flood and rainfall frequency analysis is typically carried out on samples of extremes defined as either the maxima of fixed-sized blocks of observations (for example yearly) or as exceedances above a high threshold. The analysis is often based on well-established results from probability theory which identify the Generalized Extreme Value (GEV) and the Generalized Pareto (GP) as the limiting distributions of block maxima and exceedances, under the assumption of stationarity of the underlying series. There are well established connections between these two limiting distributions. In general, the GEV is the distribution of maxima extracted from series such that the number of threshold exceedances for each block can be assumed to be Poisson-distributed, while their magnitudes follow a Generalized Pareto distribution. The assumption of the counts of exceedances to be well described by a Poisson is often not valid for environmental extremes such as rainfall or flood extremes: the frequency distributions tend to be overdispersed, ie to exhibit a variability higher than expected under a Poisson distribution. Under the scenario of overdispersed threshold exceedance counts, the distribution of annual maxima has been shown to be related to the Kappa distribution, of which both the GEV and GP are particular cases. This study investigates the validity of different modelling assumptions under the block maxima and threshold exceedances approaches for a national dataset of extreme peak flows from gauging stations in the UK. We also investigate the possibility of employing the more flexible Kappa distribution rather than the GEV distribution for the analysis of annual maxima, by employing both L-moments and likelihood-based estimation approaches.

Universal Multifracals characterization of Intensity-Duration-Frequency curves in Northern Italy

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Quantifying rainfall extremes and their evolution is important in hydrologic risk analysis and design. It usually relies on the use of intensity-duration-frequency (IDF) curves. Numerous approaches have been developed over the years to estimate them empirically from point measurements. Here we suggest to implement and further develop a framework initially introduced by Bendjoudi et al. (1997), in which IDF curves are theoretically derived from a Universal Multifractals (UM) framework. It is a mathematically robust framework which relies on the physically based notion of scale invariance, inherited from the governing Navier-Stokes equations. It is parsimonious since it relies only on three parameters with physical interpretation. UM have been extensively used to characterize and simulate geophysical fields extremely variable over wide range of space-time scales such as rainfall.
The method is here applied to 5-min resolution data from rain gauges located in a complex topography area in North-eastern Italy, with a temporal coverage of 25-35 years. For each station, UM parameters are estimated through an analysis carried out on the whole available continuous time series, which enables to ultimately derive IDF curves. Comparison with extreme value approaches as well as spatial variations of the obtained results over the studied area will be discussed.

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Automating Flood Analysis: A QGIS Plugin for Accessible and Rapid Flood Event Assessment

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Floods are among the most devastating natural disasters, causing significant loss of life and economic damage. As extreme flood events become more frequent, rapid and accessible flood analysis tools are crucial for effective risk management. This study presents a QGIS plugin developed to provide a quick and easy workflow for flood event analysis. By automating the processing and visualization of flood extent data from the Global Flood Monitoring (GFM) product, derived from remote sensing, in combination with building footprints, the plugin enables users to analyse past flood events without requiring expert knowledge or expensive proprietary software.
The plugin operates within the widely used open-source GIS platform QGIS, making it highly accessible. Users manually download raster data and shapefiles from the web, which serve as inputs for automated analysis. The plugin then processes the data and generates output files, including a shapefile showing which buildings were flooded and for how long. Additionally, it compiles a HTML report including graphs that further describe the area of interest and summarize the plugin's results. The effectiveness of the tool was evaluated using case studies in Pakistan and Germany, where results were compared against ground truth data.
Preliminary results highlight significant uncertainties in flood extent, primarily originating from the GFM input data. Large exclusion mask areas indicate zones of high uncertainty, especially in urban environments where flood detection is more challenging. Temporal uncertainties also arise from gaps in satellite coverage, limiting data availability in certain regions.
Future improvements will focus on reducing runtime and integrating statistical uncertainty assessments in the plugin's output. Further, direct data retrieval from the Global Flood Awareness System would eliminate the need for manual downloads and thereby streamline the analysis process. By bridging the gap between high, complex data amounts and the need for a rapid response to flooding events, this tool provides decision-makers with a sound basis for dealing with the consequences of flooding.

Modeling cascading economic impacts of floods on critical infrastructure: a case study of Italy

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Critical infrastructures, such as roads and bridges, play a fundamental role in daily economic and social activities and for this reason it is essential to quantify the impacts of natural hazards, and in particular floods, for building resilient systems. Yet, traditional risk assessment approaches mainly focus on direct physical damage to infrastructure, often overlooking the broader cascading effects that disruptions can have on supply chains and regional economies. In order to address this gap, this study adopts the Disrupt-SC model, a spatially-explicit agent-based model for modelling supply-chain disruptions, to simulate the economic impacts of flood events and flood related disruptions to the road network. The model first develops a static representation of commercial inter-firm relationships and integrates economic flows within the transport infrastructure. Subsequently, a flood scenario is modelled adopting the open-source CLIMADA platform to quantify direct infrastructure damages from flooding events. These impacts are then used in the model to simulate how disruptions have cascading effects through the economy and firms, affecting transport routes, increasing logistics costs, and forcing firms to adapt by changing suppliers or reducing production.

Applied for the first time to a European economy, the study focuses on Italy, where the transport and logistics sector contributes approximately 10% to the national GDP. This work adopts regional input-output tables from IRPET along with detailed business registry data with information on the sectoral classification, location of production units and number of employees, in order to capture the interdependencies of supply-chains and transportation networks.

By modelling the effects of infrastructure disruptions and their propagation across economic networks, this work offers a fresh perspective on indirect losses. The results provide valuable insights for policymakers, urban planners, and supply chain resilience managers, contributing to the development of more integrated risk assessment strategies that strengthen systemic resilience in the face of climate-related hazards.

Impact of Groundwater in Compound Flooding: A Case Study of the Conwy Estuary in Wales, UK

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Compound flooding occurs when multiple flood drivers act concurrently, leading to more severe and complex flood events. Low-lying deltas and estuaries are particularly vulnerable as they face storm surges, high river discharge, intense rainfall, tides, and sea-level rise. Globally, 2.15 billion people reside in near-coastal areas, including 898 million in low-elevation coastal zones. The UK has a long history of estuarine flooding driven by compound events. Despite its importance, the role of groundwater and soil moisture in compound flooding remains under-researched due to its lesser frequency and perceived lower severity. Recent studies highlight coastal aquifers' increasing exposure to flooding, yet few have examined the compound effects of groundwater rise and other flood drivers. This study integrates a coupled catchment and groundwater model using Caesar Lisflood to assess groundwater's influence in compound flooding within the Conwy estuary in North Wales, UK – a flashy catchment with a history of flood events. A notable example occurred during Storm Ciara in February 2020, where record river levels, intense rainfall, and high storm tides combined to inundate 172 properties. Conwy River drains a 600 km² catchment, receiving 1,700 mm of annual precipitation, with baseflow contributing 27% of total streamflow. The model is calibrated using historical fluvial and tidal data to assess how different drivers influence flood magnitude, timing, and behavior. The study also examines sensitivity of the estuary to hydrogeological variations by analysing changes in modelled groundwater heads and discharge in response to changes in aquifer properties such as hydraulic conductivity and specific yield.
This research delves into the lesser-studied role of groundwater in estuarine hydrology, providing insights into its potential impact on compound flood dynamics under future climate scenarios.

Assessing the impact of detention dams on flood frequency distributions: application to the Ottenstein (Austria) and Camastra (Italy) dams

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In recent decades, there has been a growing global perception of flood risks, driven by the catastrophic effects of several floods that have caused significant damage to the environment and communities (Merz et al., 2021). The increasing frequency and intensity of floods have highlighted the urgent need for mitigation strategies. In this regard, detention dams can serve as effective solutions for flood mitigation. Dams are commonly implemented to attenuate peak discharges and reduce flood severity, although their impact on flood dynamics is complex, context-dependent, and influenced by hydrologic and hydraulic factors.
With this aim, several analytical-probabilistic approaches have been developed to interpret the functional relationships between inflows and expected outflows from dams (Manfreda et al., 2021; Di Chiano et al., 2023). However, these approaches tend to neglect the reservoir pre-filling from previous flood events, leading to an underestimation of storage volume (Raimondi and Becciu, 2015). Therefore, a new simplified analytical-probabilistic approach has been developed to assess the impact of detention dams on flood frequency distributions. Specifically, a joint probability distribution of two theoretically derived probability distributions (TDD) of the peak outflow from the dam (Manfreda et al., 2021) and of the water level in the reservoir has been implemented. In particular, the TDD of water level in detention dams has been obtained by combining the stage-storage capacity curve and the probability density function of water volume in the reservoir, by exploiting the approach in Manfreda and Fiorentino (2008) based on the water balance equation for the water accumulated in the basin.
The proposed framework extends the range of applications of the original formulation by Manfreda et al. (2021) by incorporating the initial state of water storage prior to each flood. This approach has been applied to two case studies: the Ottenstein (Austria) and Camastra (Italy) dams to assess its reliability. The comparison between the derived flood distribution and the empirical distribution of observed flood peaks shows very promising results. This research contributes to a better understanding of dam-flood interactions and offers insights for improving flood forecasting and management policy.

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Flood risk and public perception: insights from Emilia-Romagna and Tuscany after the 2023 flood events

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In 2023, the Emilia-Romagna and Tuscany regions in Italy experienced severe flooding events which had devastating consequences. With severe storms and their accompanying devastating floods projected to become more frequent and intense, and with an increasing concentration of people living close to rivers, Europe must urgently scale up its adaptation efforts. Understanding the preparedness of flood-prone regions and their populations is therefore crucial. This work examines flood risk perception following the flood events that occurred in May 2023 and November 2023 in the Emilia-Romagna and Tuscany regions, respectively.
A recent survey among 3,472 residents of Emilia-Romagna and Tuscany conducted in July 2024 (after the devastating flood events in May and November 2023) investigated their flood risk awareness and preparedness to face such crises. The survey reveals that most respondents were unprepared for flood event and that providing accessible information on local flood risk can play a vital role in bolstering personal adaptation measures. Respondents reported that providing educational resources on flood preparedness and the provision of guidance on flood prevention and management are also fundamental to effective flood responses and enhanced citizens' resilience. Effective risk communication can also generate a spillover effect, fostering broader climate awareness and a commitment to mitigation. We therefore envisage that adaptation initiatives must prioritize citizen involvement and access to reliable flood risk information. Engaging citizens as active participants in adaptation planning ensures that strategies align with local needs and are more likely to gain public support. In this way Europe can create more resilient communities and stimulate meaningful climate action.

Teleconnection-informed frequency analysis of rainfall extremes

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Several scientific studies show the benefits of using climate indexes (or "teleconnections") as covariates when modeling the frequency regime of annual maximum rainfall across diverse geographical regions worldwide. Typically, these analyses are based on a few, and often spatially sparse, single time series. However, the presence of regional structures in the dependency of annual maximum rainfall on teleconnections is still poorly explored. This study provides a comprehensive assessment of the effectiveness of teleconnections for representing and modeling the frequency regime of rainfall extremes at a regional scale. The study area is a large and climatically diverse region in Northern Italy. Our dataset consists of 680 annual maximum series (AMS) of rainfall depth for 1- and 24-hour durations. We select six climate indexes based on a literature review. Instead of analyzing the original AMS, we define sliding time windows to obtain time series of L-moments, which characterize the distribution of rainfall extremes. In the first phase of the study, we evaluate the correlation between teleconnections and time series of spatially gridded L-moments. To analyze the spatial patterns of the correlation with gridded L-moments, we discretize the study region into tiles with resolutions of up to 100 km. In the second phase of the study, we present a preliminary application of climate-informed regional frequency analysis of rainfall extremes, in which the L-moments are modeled as functions of the most influential teleconnections. These are selected based on (1) their significantly higher number of correlations with the L-moments of sub-daily rainfall maxima compared to other teleconnections and (2) the presence of clear spatial patterns in their correlation fields across the study area, whose robustness is confirmed by their limited sensitivity to grid resolution. Overall, our research suggests promising pathways for climate-informed local and regional frequency analysis of rainfall extremes.