POLICY BRIEF

Enhancing Climate Services in the European Water-Energy-Food Nexus

Executive Summary

AI boosts accuracy of river discharge forecasts, enabling better preparedness for floods, droughts, and water allocation

Hydropower resilience can be strengthened with AI-based methods that better integrate hydroclimatic projections into energy models

AI-driven crop modelling delivers rapid, scalable yield outlooks, providing early warnings for agricultural management

Integrated Climate Services across the Water–Energy–Food Nexus reveal systemic risks requiring coordinated adaptation strategies

Rethinking drought risk with AI using impact-based indices allows capturing real impacts and anticipating shifting hotspots

Context

This policy brief demonstrates how Artificial Intelligence (AI) and Machine Learning (ML) can transform European Climate Services by making them more accurate, timely, and actionable for managing risks across the water–energy–food nexus. Building on results from large-scale demonstrations, we show advances in river discharge prediction, hydropower resilience under climate variability, agricultural yield forecasting, drought risk assessment, and integrated cross-sectoral analyses.

These examples illustrate how AI/ML methods go beyond traditional approaches by uncovering hidden patterns, combining diverse data sources, and delivering forecasts and impact indicators with unprecedented reliability. Such innovations are critical at a time when Europe faces mounting pressures from climate extremes, resource competition, and systemic risks that span multiple sectors.

By bridging cutting-edge science with real-world applications, the work presented here highlights how AI-enhanced Climate Services can directly support EU strategies on adaptation, disaster risk reduction, and sustainable resource governance, ultimately helping to safeguard Europe’s economy, ecosystems, and citizens against a rapidly changing climate.

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Using AI to Improve River Discharge Predictions Across Europe

Accurate river discharge predictions are essential for managing water, preparing for floods and droughts, and protecting ecosystems. A new hybrid AI-enhanced hydrological model learns from over 2,000 monitoring stations across Europe, and unlike traditional continental models, it can predict discharge much more accurately, even in river systems without local data. By introducing local physiographic information, the hybrid model significantly improves predictions of total volumes, but also during high- and low-flow periods, particularly in hydrologically complex areas like mountainous and coastal regions (Figure 1).

Our approach supports better decision-making in water management, and helps fill data gaps in remote or ungauged regions. Developers and purveyors of early warning systems and hydro-climate services are encouraged to adopt such AI-enhanced tools to evolve national water strategies, improve climate resilience, and support EU-wide efforts for sustainable water management.

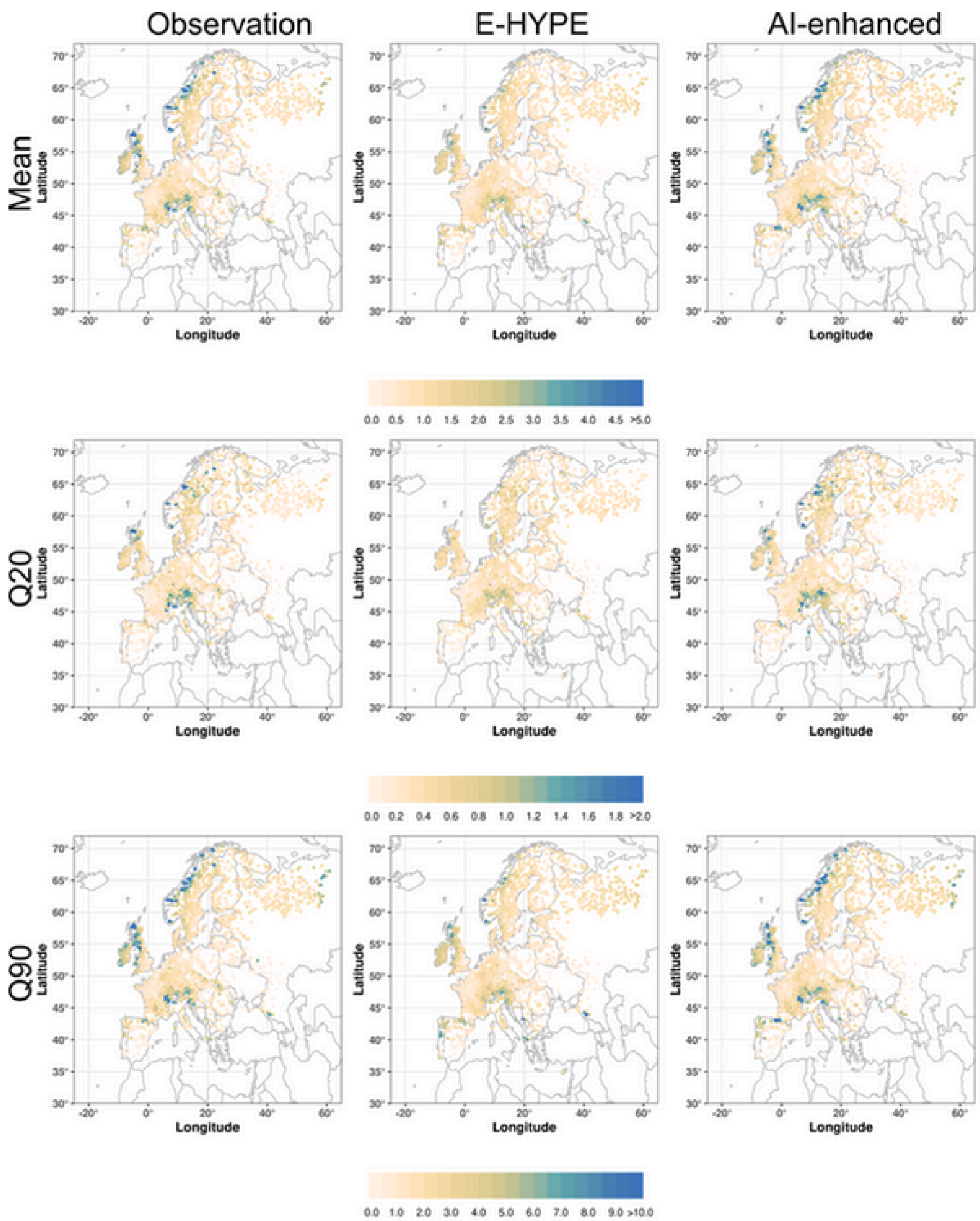

Figure 1. Spatial comparison of river discharge characteristics (mean, low (Q20) and high (Q90) flows) across Europe showing observations, the continental E-HYPE hydrological model, and the hybrid AI-enhanced predictions. Runoff values (in mm) are represented by the color scales.

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Hydropower in a Changing Climate: Variability, Resilience, and the EU's Energy Future

Hydropower remains a cornerstone of the EU clean energy system, but its contribution is increasingly shaped by climate variability. Model-based projections suggest that interannual inflow variability will intensify under high-irradiation scenarios, with particularly strong impacts expected in Southern and Eastern Europe, including Portugal, Spain, and France by mid-century (Figure 2). New AI-based methods for spatial climate data processing improve integration of climate projections into energy models by enabling more detailed assessments at catchment level and aligning hydropower operations with observed national generation patterns.

At the same time, hydropower operations must balance competing demands such as agriculture, hydrologic flows, and market dynamics, which adds uncertainty to future projections. To safeguard decarbonisation pathway, the EU will benefit from short-term measures that strengthen system resilience, demand-side flexibility, and cross-border coordination, while also accelerating structural investments in storage, interconnections, and diverse low-carbon resources to ensure long-term system flexibility.

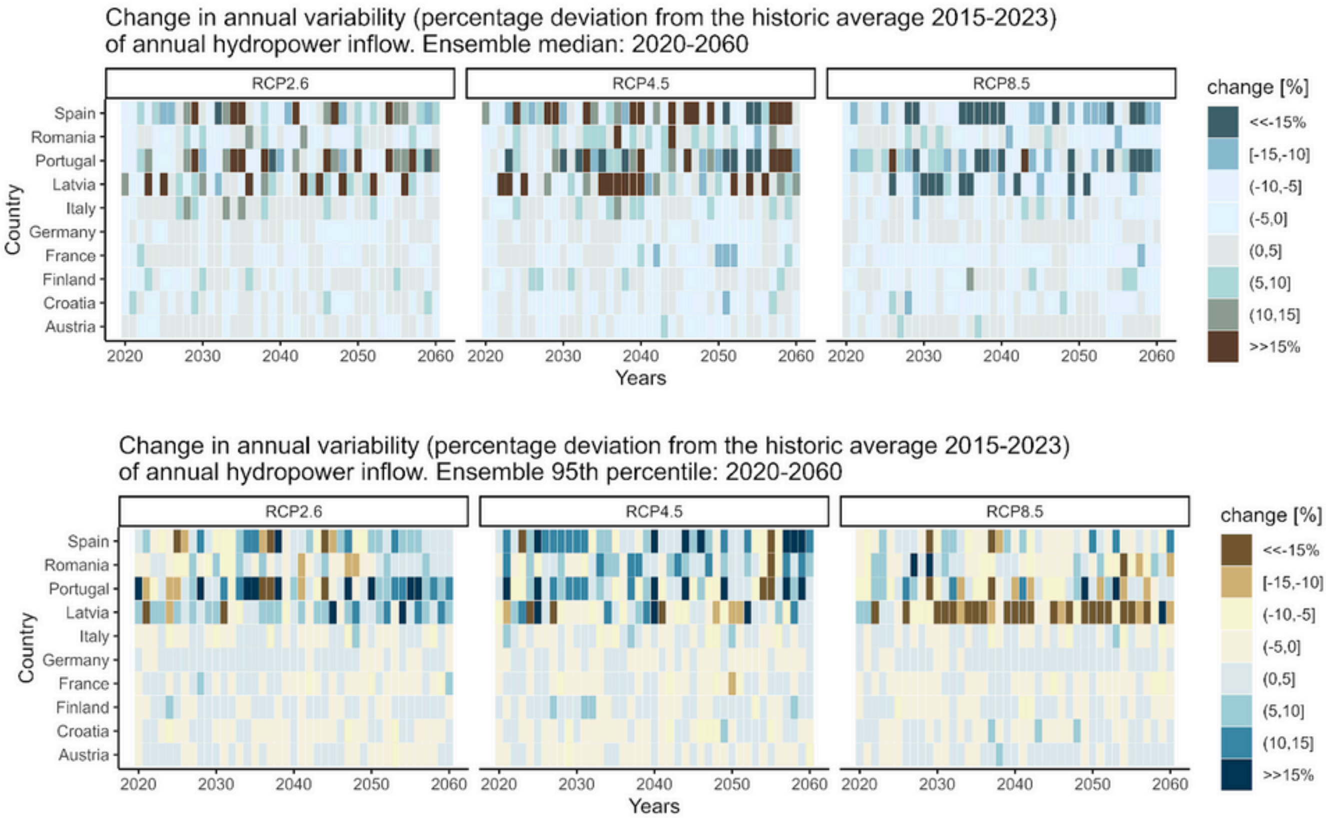

Figure 2. Projected changes in annual ROR hydropower inflow variability (2020–2060): median vs. 95th percentile ensemble estimates for selected EU countries.

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AI-based surrogate impact modelling as a climate service for maize yield

SECS4M is a deep-learning surrogate crop growth model of the European Commission's -Joint Research Center's (EC-JRC's) ECroPS mechanistic crop model that delivers continental-scale, water-limited maize yields using only daily min and max temperature and precipitation. It reproduces crop growth timing with high skill while cutting computational time from ~70s to ~0.008s per grid-cell-year, enabling large ensembles forced by seasonal forecasts (ECMWF's SEAS5.1) and climate scenarios (CMIP6). It turns simulations into probabilistic -for SEAS5.1- or binary -for CMIP6- Areas of Concern maps for early warning and resource prioritization (Figure 3).
In terms of immediate utilization, SECS4M can be a standalone climate service or can be integrated into national and EU climate services to issue in-season yield outlooks, trigger drought support, and guide agromanagement decision making. Scientifically, it operationalizes reproducible, scalable emulation for uncertainty quantification and scenario stress-testing.

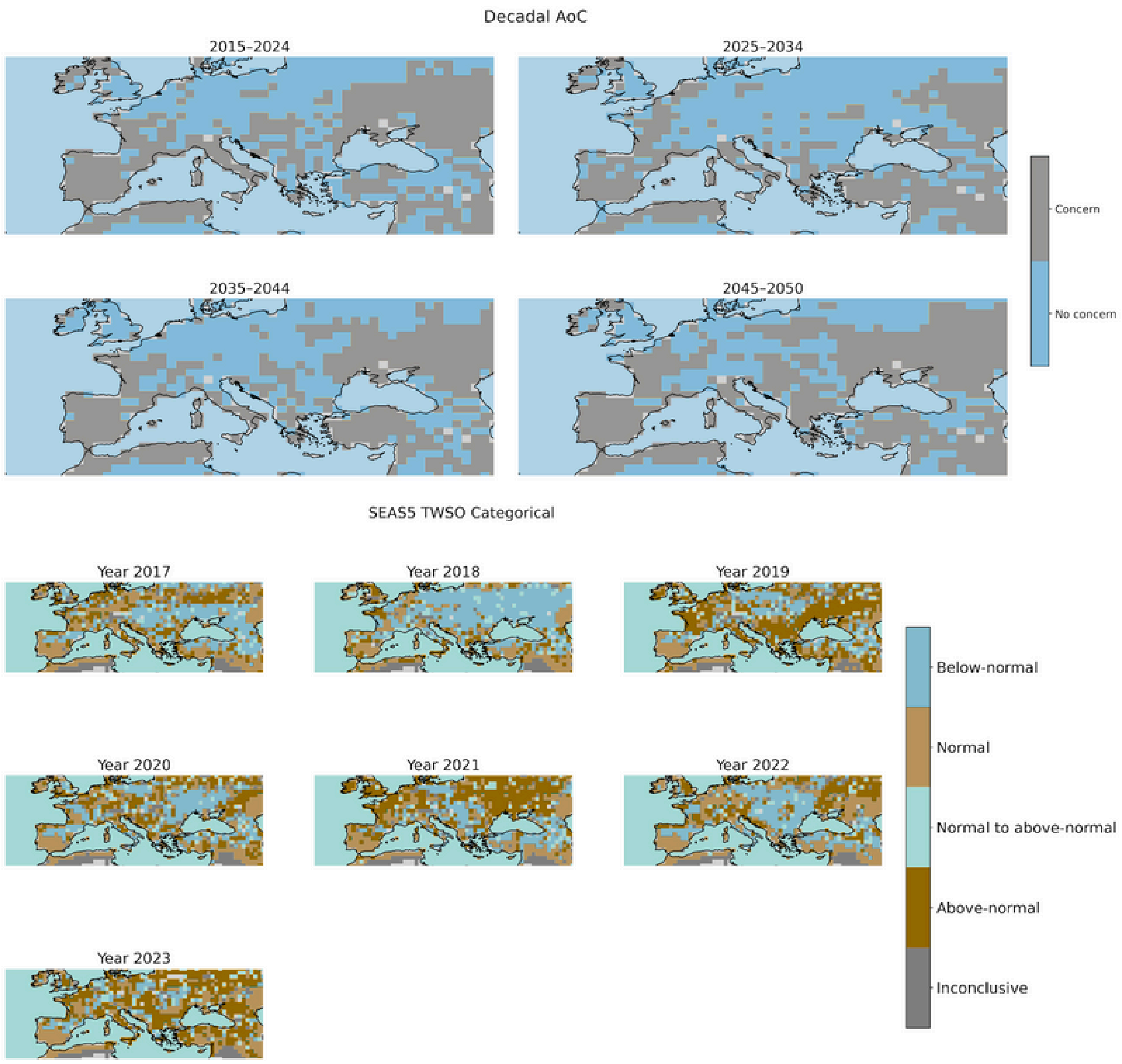

Figure 3. 10-yearly average Areas of Concern maps for GFDL-ESM4 derived yield under SSP3-7.0 and probabilistic Areas of Concern for each year of the 2017-2023 period based on yield from 51 ensemble members of SEAS5.1.

Identification of risk-prone areas across the Water–Energy–Food Nexus

The strong interconnections across the water–energy–food sectors highlight the need to complement sector-specific Climate Services with coordinated cross-sectoral approaches. Only a harmonized Climate Service can provide a coherent analysis of systemic impacts from extreme events, revealing whether these impacts occur in parallel across sectors, emerge through interdependencies, or remain largely independent.

To demonstrate this potential, we conducted a cross-sectoral experiment assessing projected climate impacts across the Water-Energy-Food Nexus under the RCP8.5 scenario. By harmonizing input data and connecting sectoral models, we produced consistent estimates of climate change impacts across Europe for the mid-century period (2030–2050) relative to historical baselines.

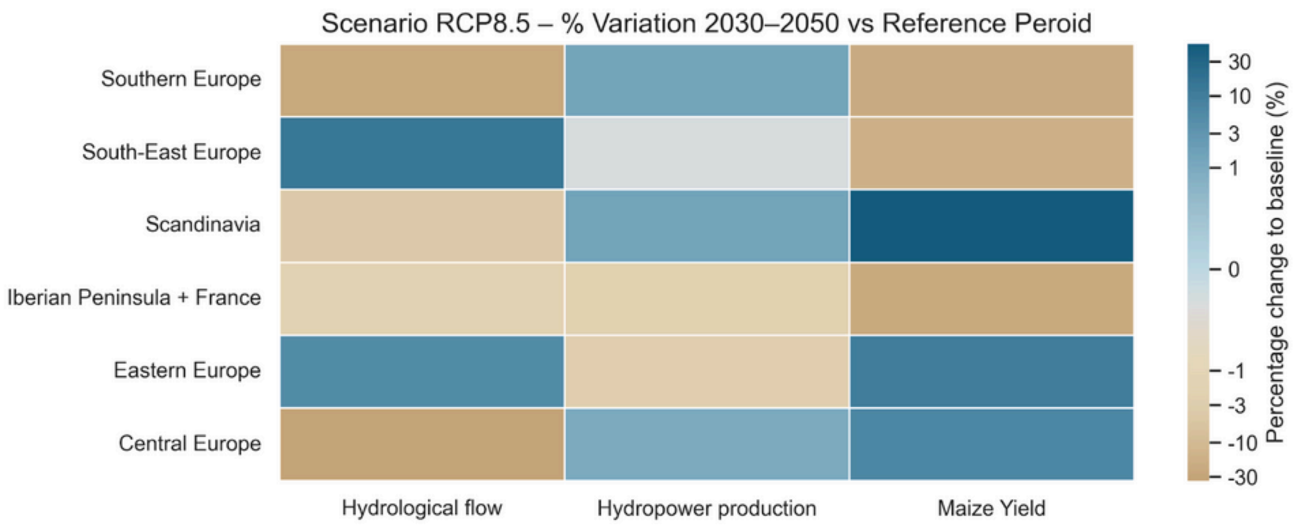

Figure 4. Projected mid-century changes (2030–2050) in hydropower production, hydrological flow extreme, and maize yield across six European regions, relative to the baseline period (1994-2024 for hydrological flow, 2020-2025 for hydropower and 1994-2014 for maize yield) under the RCP8.5 climate scenario. Each cell represents the percentage change in the respective metric, with a diverging color scale from deep blue (strong increase) to beige (strong decrease). Regions are defined as follows: Southern Europe: Cyprus, Greece, Italy, Malta; South-East Europe: Bulgaria, Croatia, Hungary, Romania, Slovenia; Scandinavia: Denmark, Finland, Sweden, Ireland; Iberian Peninsula + France: Portugal, Spain, France; Eastern Europe: Czech Republic, Estonia, Latvia, Lithuania, Poland; Central Europe: Austria, Belgium, Luxembourg, Netherlands, Germany

Our analysis explored the interplay of sectoral risks and their spatial convergence, with drought exposure measured by changes in dry-day frequency in river basins, hydropower risk captured by projected shifts in production, and agricultural vulnerability assessed through maize yield variations.

Findings show that sector-specific vulnerabilities are not always spatially aligned, yet most regions experience overlapping pressures from at least two sectors (Figure 4). This convergence underscores the systemic nature of climate risks and the need for integrated adaptation strategies. The Iberian Peninsula emerges as a critical hotspot, where reduced agricultural yields, increasing drought frequency, and unstable hydropower production intersect most severely, pointing to the urgency of coordinated, cross-sectoral responses.

Rethinking Drought Risk with AI navigating the Water-Energy-Food Nexus

Drought is a complex hazard with profound socio-economic and ecological impacts. Yet, conventional drought indices that focus only on hydroclimatic anomalies often fail to capture its real impacts. To address this gap, we propose impact-based Combined Drought Indices that leverage Machine Learning (ML) methods to navigate the Water-Energy-Food Nexus and directly link hydroclimatic drivers to observed impacts. Applied to over 35,000 European river basins, our ML-based approach substantially improves the correspondence between drought indices and remotely sensed vegetation stress (a proxy for agricultural impacts), raising average correlation from 0.25 with traditional indices to 0.61 (Figure 4).

Future projections of these impact-based indices (Figure 5) reveal a marked northward shift in drought impacts, identifying Central Europe as an emerging hotspot—contrary to standardized indices that mainly highlight Mediterranean regions as the primary areas of concern. This spatial reconfiguration of risk underscores the urgent need for impact-oriented metrics to better anticipate risks and design climate-resilient drought management strategies.

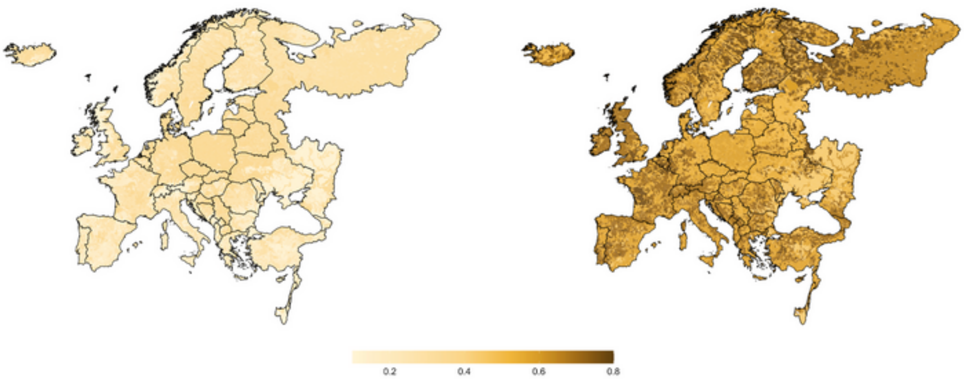

Figure 4. Correlation values between vegetation stress and traditional drought indices (left) or impact-based Combined Drought Indices (right).

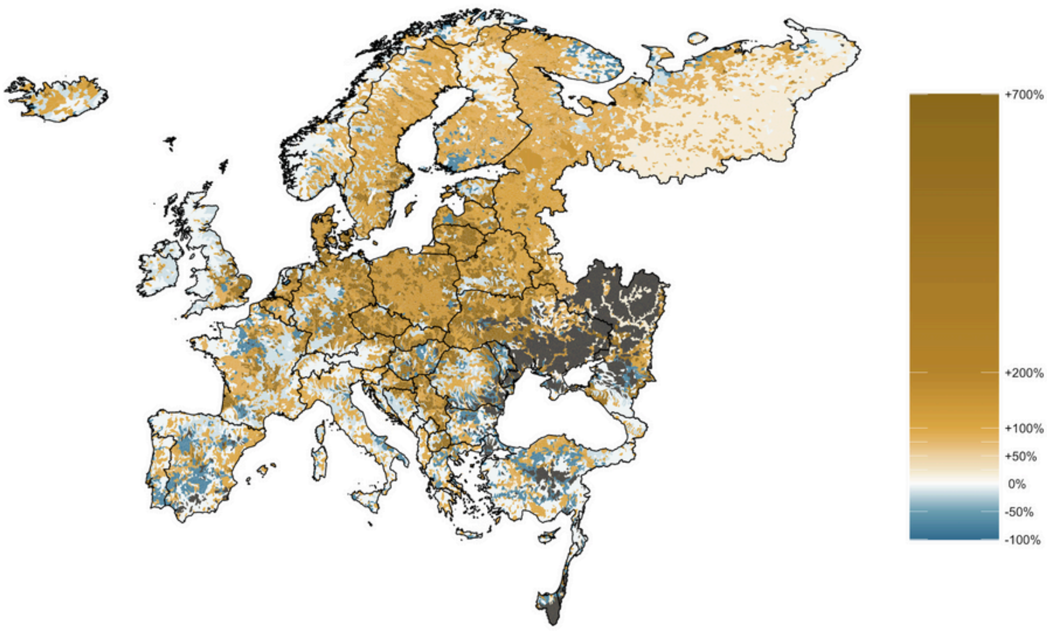

Figure 5. Percentage change in the frequency of drought impact events between the future period (2019–2050, RCP4.5 scenario) and the historical baseline (2002–2018). A gray mask is used for sub-basins that had no impact events in the historical period to avoid misinterpretations due to numerical artifacts.

Bios

Professor Andrea Castelletti is a professor of Natural Resources Management at Politecnico di Milano. From 2014 to 2022 he was a senior scientist at the Department of Civil and Environmental Engineering, ETH Zurich, Switzerland. He is the founder and head of the Environmental Intelligence Lab at Politecnico di Milano and Chair of the PhD Program in Science, Technology, and Policy for Sustainable Change. Dr. Castelletti research interest includes water systems planning and control under uncertainty and risk, decision-making for complex engineering systems, machine learning for environmental applications. He has been working for more than 15 years on African and Asian water resources systems, exploring novel approaches to sustainable and robust design and operation of water infrastructure.

Dr. Yiheng Du is a Research Leader and Senior Researcher in hydrology at the Swedish Meteorological and Hydrological Institute (SMHI). Her work focuses on AI-enhanced hydrological forecasting, hybrid modelling approaches, and sub-seasonal to seasonal (S2S) prediction of hydrological extremes. She leads research activities that bridge process-based models with machine learning to improve flood and drought forecasting across scales, and contributes to European projects on early warning systems.

Dr. Matteo Giuliani is an Associate Professor in the Environmental Intelligence Lab at Politecnico di Milano. From 2018 to 2020, he was Academic Guest at ETH Zurich for a collaboration with the Swiss Competence Center for Energy Research Supply of Electricity (SCCER-SoE). The primary focus of his research is the integrated management of water resources in complex engineering systems involving multiple actors and exposed to evolving multisectoral demands and global change.

Dr. Kristina Govorukha has over nine years of professional experience in research and scientific projects, primarily focusing on the energy sector, European energy policy, the electricity market, and energy-intensive industries. She has worked intensively on projects related to the impact assessment of EU-wide policies and their impacts at a country level. Before her current role, she served as a consultant at the World Bank and worked as a research associate at TU Freiberg.

Dr Konstantinos Kavvadias has over 20 years of professional and research experience in energy system analysis, modelling, and project deployment. Among others, he has worked on topics related to power system analysis, renewables and storage integration, power-heat-water sector interactions, and climate change mitigation. Besides, he is an expert in power system flexibility in a variable climate, including the water-energy nexus, the impact of cogeneration and thermal storage on the flexibility of the power system, and the quantification of power self-consumption linked to solar home battery system.

Martina Merlo is a PhD student at the Environmental Intelligence Lab, Politecnico di Milano. Her research focuses on developing impact-based, machine learning-enhanced drought indices to improve both detection and management of drought events. These indices aim to identify vulnerable areas and support targeted adaptation measures to enhance the resilience of multi-sector systems under climate change.

Dr. Ilias Pechlivanidis is an Associate Professor and Senior Researcher in hydrology and water resources at the Swedish Meteorological and Hydrological Institute (SMHI). He is a Fellow of ECMWF, while he serves as a Member in the Strategic Advisory Board of the Destination Earth initiative, Member of the WMO Research Board and EUMETSAT, Co-Chair of the Hydrologic Ensemble Prediction Experiment (HEPEX), and Reference Member of the Centre of Natural Hazards and Disaster Science (CNDS). His research focuses on hydrometeorological predictions, environmental change impacts, science communication, and the integration of Earth observations into early warning and climate services.

Veronica Piuri is a research fellow and project manager at the Environmental Intelligence Lab (Politecnico di Milano). Her research focuses on integrated water management strategies in arid and transboundary basins, hydrological modelling and climate-risk analysis, and the design of adaptation measures for water-stress management.

Dr. Odysseas Vlachopoulos is a research engineer in climate & geospatial AI at Justus Liebig University Giessen, working on extreme/compound events, big-data analysis, super-resolution, and agriculture with the help of AI/ML, HPC and GIS toolsets. He has contributed to EU/national R&I programs and previously worked with Canadian institutions and the National Observatory of Athens, founded an EO/UAS precision-ag startup under an ESA award, and held software/analyst roles in industry.

Dr. Elena Xoplaki is a Senior Scientist at the Euro-Mediterranean Centre on Climate Change, Italy. From 2011 to 2025 she was Akademische Rätin at the Department of Geography, Justus Liebig University Giessen, Germany. She is a leading expert on Mediterranean climate change, with research spanning weather and climate extremes, early warning systems, paleoclimatology, climate reconstructions and model intercomparisons, and the role of atmospheric circulation in shaping European and Mediterranean climate. She serves as Co-Chair of the ITU/UNEP/UNFCCC/UPU/WMO Global Initiative on Resilience to Natural Hazards through AI Solutions and has coordinated or contributed to numerous European, Swiss, German, and US-funded research projects.