POLICY BRIEF

AI-enhanced Climate Services for climate adaptation and disaster risk management at the local scale

Executive Summary

Integrating AI-enhanced forecasts into early warning has the potential to strengthen drought preparedness in the delta of the Netherlands

Smarter sub-seasonal to seasonal inflow predictions balance competing water demands in the Italian Alps

AI boosts seasonal streamflow predictability and hydropower resilience at Lake Kariba in Southern Africa

AI-enhanced forecasts support informed water allocation balancing water use among socio-economic and environmental needs

Machine Learning methods support Flood Risk Management in a changing climate

Context

This policy brief concerns the potential uptake of artificial intelligence and machine learning in climate services to enhance water management preparedness and adaptation for extreme events at the local scale. Our recommendations are based on various climate change hotspots, including semiarid regions (Southern Africa, Iberian Peninsula), river deltas (the Netherlands), and snow-dependent river basins (Italian Alps). These hotspots were selected because they are prone to severe impacts from extreme events under current and future climate conditions, and because they display a wide range of socio-economic development and adaptive capacity.

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AI-enhanced forecasts and climate change impact analyses support drought and flood risk management in the delta of the Netherlands

In the Netherlands, two drought preparedness case studies were addressed for regional water authorities, Rijnland and Aa en Maas, and one flood risk management case study for the national executive agency on water management, Rijkswaterstaat. In Rijnland, prolonged dry spells in summer in combination with low flows of the river Rhine lead to salinity problems and potential dike instability along the canals and lakes. Aa en Maas faces recurring challenges from groundwater droughts in summer. In the CLINT project, we developed AI-enhanced sub-seasonal-to-seasonal precipitation deficit and groundwater level forecasts (Figure 1) for early drought awareness and mitigation actions. For flood risk management, Machine Learning-based clustering was employed to analyse whether Tropical Cyclones transitioning to the North Sea region would affect current storm characteristics and frequency under climate change.

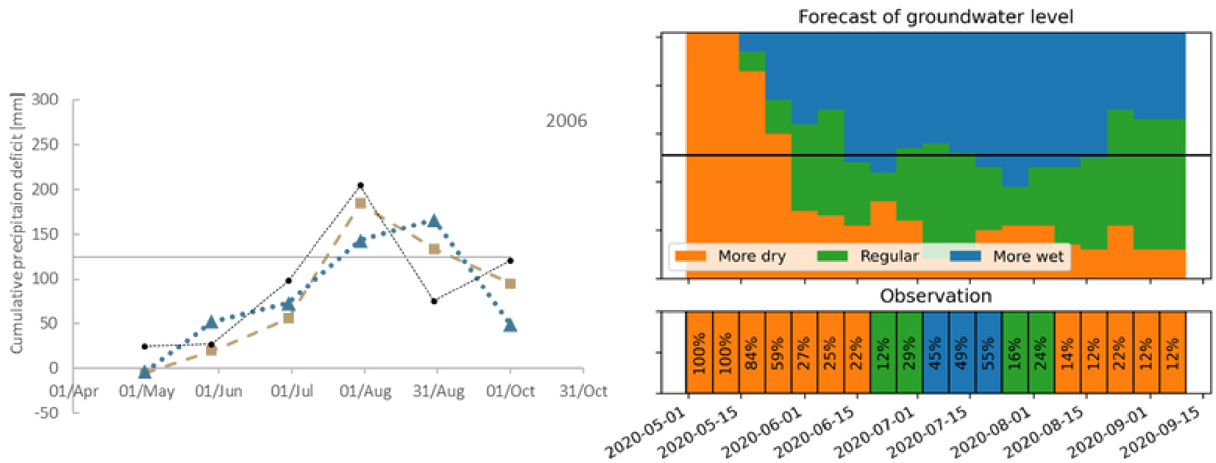

Figure 1. Example sequences of monthly forecasts of precipitation deficit (left panel) by AI-enhanced (CLINT, beige line) and physically based numerical weather models (ECMWF ER ensemble mean, blue line), against the observed cumulative precipitation deficit (black line). The horizontal line indicates the lowest of pre-alert levels applied for drought awareness in Rijnland, the Netherlands. Groundwater level forecast in Aa en Maas basin and skill assessment in terms of hit ratio (right panel). The orange colour indicates more dry conditions in comparison with long-term average climatological conditions, the blue colour indicates more wet conditions, and the green colour represents average conditions.

For the delta of the Netherlands, AI-enhanced forecasting and analysis of climate change impact, showed to have potential added value for drought and flood risk management. For Rijnland, compared to numerical weather predictions, the AI-enhanced forecasts showed an increase in hits and decrease of false alarms, but not uniformly for all drought alert thresholds. We recommend the use of AI-enhanced drought forecasts in conjunction with traditional forecasts to maximise early awareness of upcoming drought events, and mitigation measures at limited cost should the forecast drought not materialise. Machine learning analysis of storm characteristics and frequency suggests that tropical cyclones transitioning to the North Sea region may become more frequent in the future. Storm and surge characteristics are similar, but tropical cyclones typically occur in late summer, potentially affecting the current maintenance strategy for barriers.

Smarter AI forecasts boost drought resilience of Lake Como

Located in the Italian Alps, the Lake Como basin is a highly controlled water system, including a large regulated lake serving a wide irrigation-fed cultivated area (1,320 km²). The hydro-meteorological regime is typical of sub-alpine regions, characterized by dry periods in winter and summer, and flow peaks in late spring and autumn fed by snowmelt and rainfall, respectively. The regulation of the lake is driven by two primary competing objectives: water supply, mainly for irrigation, and flood control along the lake shores. The agricultural districts downstream prefer to store snowmelt in the lake to satisfy the peak summer water demands, when the natural inflow is insufficient to meet irrigation requirements. Yet, storing such water increases the lake level and, consequently, the flood risk. Additional interests are related to navigation, fishing, tourism, and ecosystems, that further challenge the existing water management strategies and motivate the search for more efficient solutions relying on hydroclimatic services. Yet, current dynamical systems often fall short of the accuracy required for basin-scale decisions. To address this gap, we developed AI-enhanced seasonal-to-subseasonal hydroclimatic forecasts of extreme droughts for informing the operation of the lake that will contribute to improving the reliability of the irrigation supply, particularly in facing severe dry conditions, as well as to mitigate existing conflicts between competing sectors.

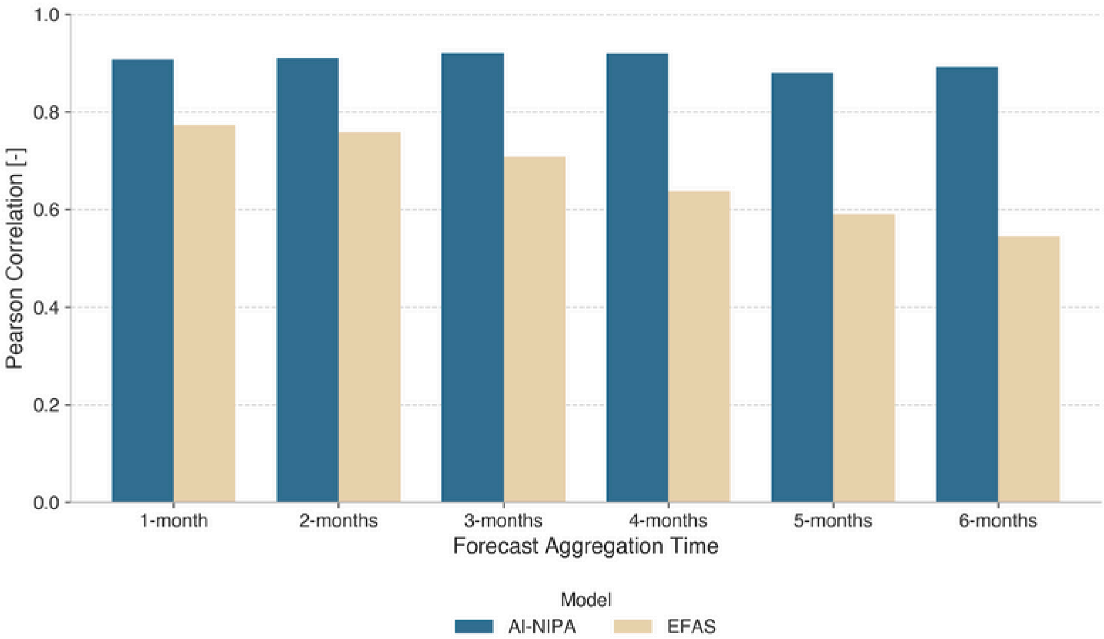

Figure 2. Comparison of AI-NIPA forecasts and EFAS reforecasts of Lake Como inflow at lead times from one to six months. AI-NIPA maintains correlations with observed inflows above 0.87 even at six months, while EFAS correlations drop below 0.6.

Our forecasting system integrates global teleconnections and local meteorological data to predict inflows 1–6 months ahead, combining feature selection, dimensionality reduction, and Random Forest regression. Results demonstrate a marked improvement over the European Flood Awareness System (EFAS), achieving high skill across multiple aggregation times (Figure 2). The greatest benefits for Lake Como's multipurpose operations emerge using forecasts at 2- and 4-month aggregation times, increasing the performance by +6% compared to the current operations relying on 3-day locally calibrated forecasts (and by +14% relative to a no-forecast baseline), whereas EFAS products provide no improvement.

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Powering Africa with AI-Enhanced Forecasts

The Zambezi river basin is the fourth largest basin in Africa, with an area of 1.32 million km² shared by eight countries (Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe) and populated by almost 40 million inhabitants. The high runoff in the upper part of the basin, combined with a fall of more than 1000 m during its course to the ocean, provides a good opportunity for hydropower production. Existing irrigated areas cover about 182,000 ha; major cultivated crops are sugar cane, rice, wheat, and maize.
Reliable seasonal streamflow forecasts are essential for managing water and energy security in hydroclimatically volatile regions like southern Africa. Yet, current global forecast systems often fail to capture the combined impacts of large-scale climate drivers at the basin scale, limiting their usefulness for decision-making. To address this gap, we developed an AI-enhanced Climate Service for Lake Kariba in the Zambezi Watercourse that will contribute to improving the system performance in terms of hydropower generation, thereby strenghtening the energy security of Zambia and Zimbabwe.

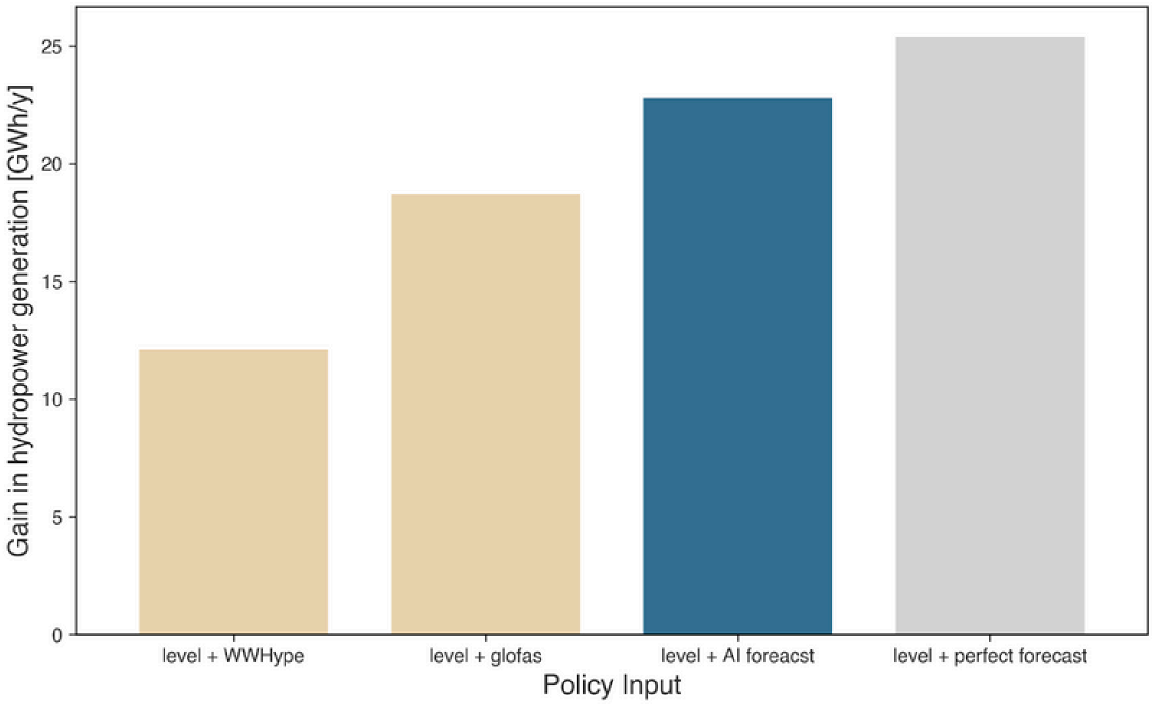

Figure 3. Gain in annual average hydropower generation at Kariba with respect to a no-forecast baseline operations.

Our forecasting system integrates global teleconnections, such as El Niño–Southern Oscillation and the Pacific Decadal Oscillation, with causal feature selection methods to produce accurate seasonal inflow predictions. Results show clear gains over leading global systems (GloFAS and WW-HYPE), especially for drought extremes. When used to inform optimal reservoir operating policies, our AI-enhanced forecasts yield a 4 GWh/year gain in hydropower production (Figure 3) - equivalent to $320,000 in additional annual revenue for local utilities - covering 90% of the maximum space for improvement ideally provided by perfect forecasts.

Water allocation and sustainable drought risk management in the Douro River Basin

The Douro river basin is the largest river basin in the Iberian Peninsula. It stretches over 98,000 km² and is shared by Spain (80% of its territory) and Portugal (20%). The Spanish part of the basin (Douro River Basin District) is markedly rural and is scarcely populated. There are over 65 large dams that are used to satisfy the water demands in the basin, the hydropower of which corresponds to about 22% of Spain's installed hydropower capacity. Droughts are one of the most recurrent and high-impact extreme events affecting the region, due to the uneven distribution of limited water resources and the strong dependence of irrigated crops and hydropower production. For example, the severe 2016/2017 drought affected the agricultural production of different crops in Spain, including tomatoes and wine grapes, and hydroelectric power production reached a historical minimum.
In the Orbigo system, water allocation decisions rely mainly on current reservoir levels and historical climate data. However, droughts create uncertainty about the evolution of reservoir levels and streamflow in the upcoming months, often leading to unnecessary restrictions on irrigation water and environmental flows (e-flows), and difficulties in reconciling trade-offs between water uses. We developed AI-enhanced subseasonal-to-seasonal hydroclimatic forecasts of extreme droughts for informing decisions about water allocation among users and the application of restrictions to established e-flows in case of extreme drought.

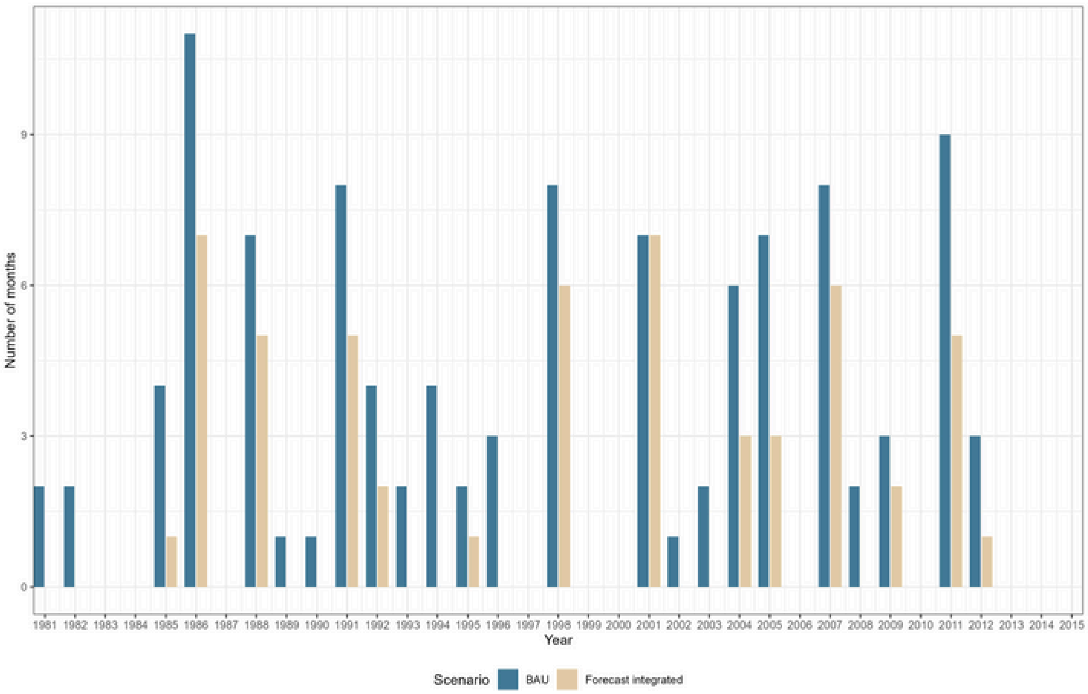

Figure 4. Number of months under e-flow restrictions for the period 1981–2015, grouped by water year. By integrating bias-corrected forecasts into the currently used drought indicator, the number of months under e-flow restrictions decreases. This approach prevents unnecessary e-flow restrictions during short or less intense drought periods.

AI-enhanced forecasts have proven similar quality than that of locally calibrated, bias corrected rainfall–runoff models for 1-month streamflow predictions (Figure 4), offering a useful alternative where such models are unavailable. Still, bias-corrected physically based models remain more flexible for integration into the drought indicators and decision-making of the Douro River Basin Authority (RBA). Bias-corrected forecast from locally-calibrated, semi-distributed models expands the RBA's knowledge base, improving the management of irrigation–e-flow tradeoffs. Successful uptake depends on close collaboration with decision-makers to adjust forecast thresholds and communicate forecast uncertainty effectively.

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. Claudia Bertini is a lecturer in the Hydroinformatics group at IHE Delft Institute for Water Education, the Netherlands. She holds an MSc degree in Civil Hydraulic Engineering and a PhD degree in Environmental and Hydraulics Engineering from Sapienza University of Rome, Italy. Her background is in hydrology, with experience in rainfall data analysis, rainfall extreme events, remote sensing, and hydrological modelling. Her research focus at IHE Delft is on the application of Machine Learning to improve forecasting of extreme events.

Dr. Lucia De Stefano is an Associate Professor at the Faculty of Geological Sciences at the Complutense University of Madrid and Deputy Director of the Botin Foundation's Water Observatory. She has worked as an international consultant for USAID, the World Bank, the University of Oxford, among others. She also worked as an expert in water policy for WWF International and WWF Spain, and as a specialist in water and land management in the private sector (Geosys, SL). Her main areas of work are hydrological planning and water resources management, the evaluation of environmental public policies, drought management, and the analysis of resilience to climate variability.

Dr. Andrea Ficchì is a postdoctoral researcher in the Environmental Intelligence Lab (Politecnico di Milano) and a data science consultant at the European Commission's Joint Research Centre (JRC) for the development of the CEMS Drought Observatories. In 2022, he was awarded an AXA Research Fund Postdoctoral Fellowship, to lead the PRINTFLOODS project (UNESCO Ocean Decade Action) advancing flood risk prediction using AI. His current main research focus is on climate services and hydrological forecasting for early warnings and anticipatory action.

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.

Paulina Kindermann is a PhD candidate at TU Delft. Her research focuses on the impact of climate change on extreme storms in the North Sea. The aim of her research is to better understand how extreme storms arise, how climate change can influence them and what this means for water safety along the Dutch coast in the future. Her work focuses on the design of dikes and dunes, as well as on developing forecasting models used for the timely closing of storm surge barriers. Paulina is also advisor at HKV Lijn in Water in the Flood Risk and Disaster Management group.

Giulio Palcic is a PhD student in the Environmental Intelligence Lab at Politecnico di Milano. His research employs machine learning to improve forecasts of hydroclimatic variables to better inform adaptation strategies in complex multisector systems such as water, energy, and agriculture.

Dr. Michiel Pezij is advisor freshwater availability at HKV Lijn in Water. His main research interests include the impact of climate change and socio-economic developments on freshwater availability, both now and in the future, drought forecasting, and modelling and analysis of the interactions between groundwater and surface water systems. He is particularly motivated to connect state-of-the-art scientific knowledge with practical applications for water managers.

Celia Ramos Sánchez is a PhD candidate at Complutense University of Madrid and IHE Delft Institute for Water Education. Her research investigates the scope and limitations of seasonal forecasts, tailored through climate services, to inform innovative water allocation policies during droughts that promote sustainable approaches that prevent disproportionate impacts on aquatic ecosystems. She also examines how current drought policies address freshwater ecosystems.

Dr. Schalk Jan van Andel is an associate professor of Hydroinformatics at IHE Delft Institute for Water Education. His main research interests include hydrological ensemble prediction, anticipatory water management, and flood and drought forecasting and early warning. To contribute to these areas, he focuses on coupling meteorological and hydrological data and models, developing probabilistic (ensemble based) verification and evaluation methods, and decision support.

Dr. Micha Werner is an Associate Professor in the Water Resources and Ecosystems Department at IHE Delft Institute for Water Education. His research and experience are primarily on the application of hydrological knowledge, data and models in operational water management; with a focus on hydrological extremes, in particular on droughts and drought risk management.