



STARS 4 Water

Guidance for river basin management practitioners: a synthesis report

Deliverable: 5.2

Date: September 2026

Guidance for river basin management practitioners: a synthesis report

Work Package	5: Upscale and uptake for preparedness
Due date	April 2026
Actual submission date	September 2026
Lead beneficiary	Deltares
Lead author(s)	Harm Duel
Contributors	Norbert Cremers, Judith ter Maat, Trine Jahr Hegdahl, Virginie Keller, Maria-Helena Ramos, Maggie Kossida, Africa de la Hera Portillo, Helmut Habersack, Albert Scrieciu

Dissemination Level		
PU	Public	X
SEN	Confidential, only for members of the consortium and the granting authority (including other EU institutions and bodies)	
CI	Classified, as referred to EU Decision 2015/444 and its implementing rules	

Version log			
Version	Date	Released by	Nature of Change
0.5	31-8-2026	Harm Duel	First draft version
0.6	7-9-2026	Maria-Helena Ramos	Internal feedback
0.7	9-9-2026	Harm Duel	Draft version
0.8	10-9-2026	Pedro Martinez	Review draft version
0.9	23-9-2026	Harm Duel	Final draft
1.0	29-9-2026	Michiel Blind	Approval final version

Citation

Duel, H., N. Cremers, J. ter Maat, T. Jahr Hegdahl, V. Keller, M.H. Ramos, M. Kossida, A. de la Hera Portillo, H. Habersack & A. Scrieciu (2026): Synthesis report for guidance to river basin management practitioners. Horizon Europe project STARS4Water. Deliverable D5.2. Grant Agreement No 101059372.



The STARS4Water project has received funding from the European Union's Horizon Europe research and innovation program under the Grant Agreement No 101059372

Disclaimer

The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed herein lies entirely with the author(s).

Summary

This report brings together the key findings, lessons learned, and best practices from the STARS4Water project to support river basin management practitioners in strengthening water resilience. The report responds to the growing challenges posed by climate change, including increasing droughts, floods, water scarcity, ecosystem degradation, and competing demands for water resources. It provides guiding principles for translating scientific knowledge into actionable strategies for climate-resilient river basin management.

A central conclusion of the report is that water management must move beyond responding to current climate-related water risks and instead adopt a proactive and **forward-looking approach** based on risk and Safe-Operating-Space assessment, water resources availability projections under climate change and scenario and water management analysis. River basin authorities need to anticipate future conditions rather than rely solely on historical hydrological patterns, which are becoming less reliable under changing climatic conditions. Planning processes should therefore incorporate uncertainty, evaluate alternative futures, and identify pathways for implementing solutions that remain effective across a range of climate scenarios.

The report highlights the importance of **science-stakeholder collaboration** as a foundation for effective adaptation and building water resilience. Experiences from the STARS4Water case studies demonstrate that shared understanding of climate and water use risks, vulnerabilities, and adaptation options can be achieved when scientists, water managers, policymakers, and stakeholders work together throughout the assessment and planning process. Such collaboration improves the relevance, legitimacy, and acceptance of adaptation measures and supports their commitment, ownership and successful implementation.

Building on the experiences gained across the seven river basin hubs, STARS4Water recommends adopting the following guiding principles for integrated and climate-resilient water resources management within river basins:

- Build strong science-stakeholder partnerships.
- Promote a shared source-to-sea understanding.
- Co-create knowledge to drive innovation.
- Define shared narratives and explore scenarios collaboratively.
- Assess risks, vulnerabilities, and opportunities holistically.
- Enable evidence-based decision-making.
- Explore a broad range of adaptation options.
- Design adaptive pathways towards water resilience.
- Foster open and transparent communication.
- Stimulate international cooperation for transboundary rivers.

The report further emphasizes that resilience is not achieved through technical measures alone. Institutional cooperation, governance capacity, stakeholder engagement, collaborative understanding of the water system and knowledge exchange are equally important. Effective adaptation requires coordination across sectors and administrative boundaries, integration of environmental and socio-economic objectives, and the flexibility to adjust management strategies as new information becomes available.

Table of contents

Summary	ii
Table of contents	iii
1. Introduction	1
1.1. STARS4Water project	1
1.2. Upscale and uptake for preparedness.....	2
1.3. Synthesis of STARS4Water insights on co-creation with basin stakeholders.....	3
1.4. The structure of this report	3
2. The STARS4Water science-stakeholder engagement processes	4
2.1. Introduction.....	4
2.2. The STARS4Water stakeholder engagement approach	5
2.3. Stakeholder engagement in the STARS4Water river basins.....	7
2.4. From stakeholder engagement to shared ownership	13
3. Integrated perspective on water related climate risks in Europe.....	16
3.1. Introduction.....	16
3.2. European rivers under stress: cases across Europe	18
3.3. What have river basin stakeholder learned?	27
4. Guiding principles for water resilience at basin level	29
5. Final remarks and conclusions	33
References	36

1. Introduction

1.1. STARS4Water project

STARS4Water (Supporting Stakeholders for Adaptive, Resilient and Sustainable Water Management) is a four-year Horizon Europe research project that contributes to the implementation of the European Water Resilience Strategy and broader EU water policies. The ambition of the project was to improve understanding of how climate change affects water resources and related vulnerabilities across ecosystems, communities, and economic sectors at the river basin scale.

The ambitions of STARS4Water were:

- To create a new generation of data services and data-driven models tailored to stakeholders' needs and requirements;
- To enhance the knowledge base and the scientific underpinning of climate risks and impacts at river basin scale;
- To provide improved projections of future water resources availability;
- To improve decision making by stakeholders through the development of a Safe-Operating-Space framework, and the provision of actionable information.

To ensure that project outcomes responded to real-world needs, STARS4Water applied a stakeholder-driven co-creation approach. Working closely with river basin organisations and other key actors in seven European river basins, namely the Danube, Drammen, Duero, East Anglia, Messara, Rhine and Seine (Figure 1.1), the project co-designed data services, assessment methods, and decision-support tools tailored to stakeholder requirements. Central to this approach was the establishment of dedicated stakeholder communities within each river basin. These communities provided a platform for dialogue, knowledge exchange, and collaborative development, ensuring that STARS4Water solutions were relevant, usable, and capable of supporting climate-resilient and sustainable water management.

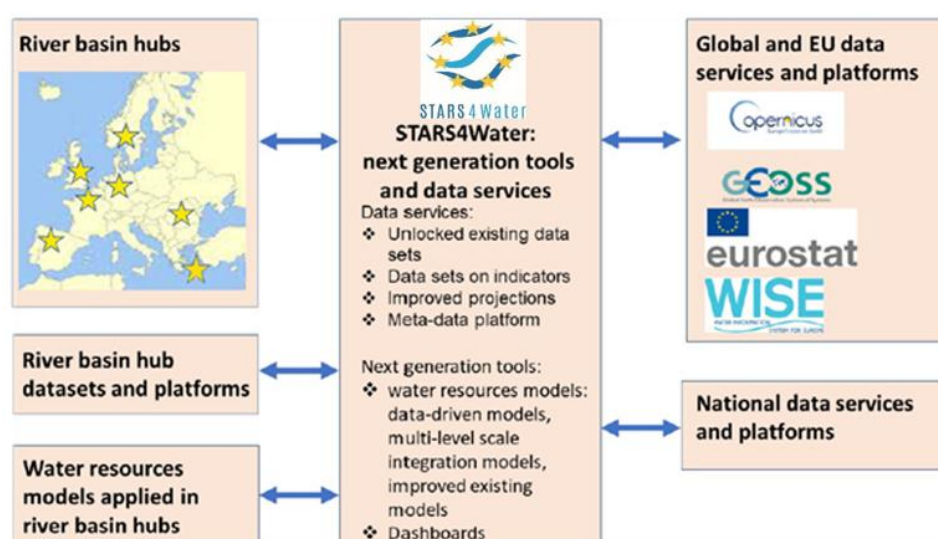


Figure 1.1. Selected European river basins that serve as living labs (river basin hubs) for innovation.

1.2. Upscale and uptake for preparedness

This report forms part of the activities aimed at facilitating the upscaling and uptake of innovations developed within STARS4Water to support the assessment of future water resources and flow regimes under WP5. Figure 1.2 illustrates the role of WP5 within the overall STARS4Water framework. WP5 builds on the outcomes of the other work packages of the project. Its activities are guided by the stakeholder co-design process undertaken in WP1, draw on the data services developed in WP2 and the modelling innovations developed in WP3, and are informed by the integrated assessments of future water resources conducted in the river basin hubs under WP4. Together, these components provide the knowledge base needed to support the wider adoption and application of STARS4Water innovations.

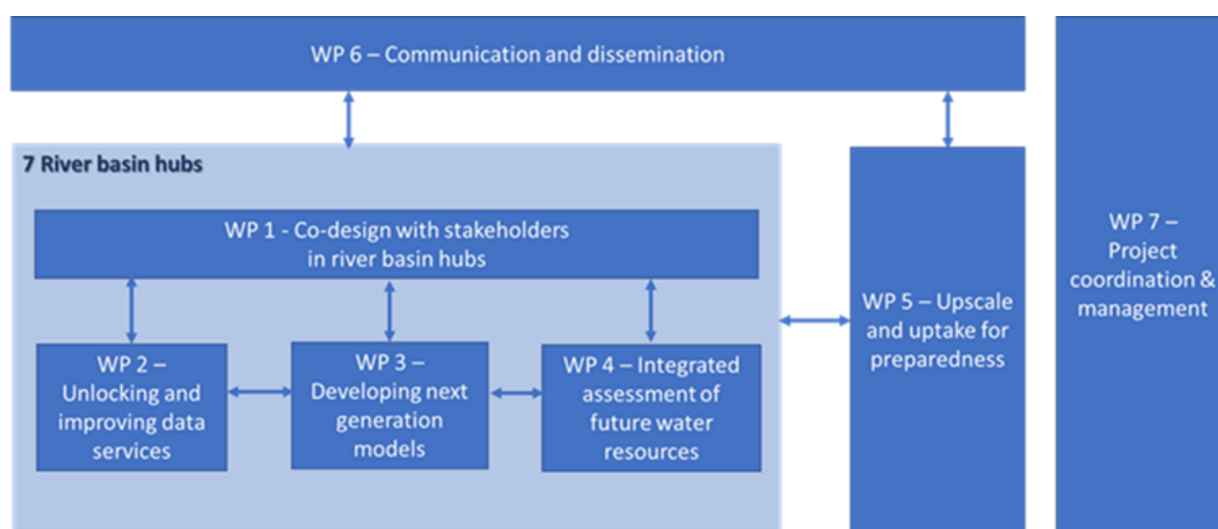


Figure 1.2. Work package structure of the STARS4Water project, illustrating how the uptake and scaling of STARS4Water innovations build on the co-creation process (WP1), available data sources and services (WP2), next-generation modelling developments (WP3), and assessments of future water resources availability in selected European river basins (WP4).

WP5 consisted of the following tasks:

- Task 5.1: Synthesis report for guidance to practitioners to perform climate risk assessments.
- Task 5.2: Upscaling of the data-driven tools to other river basins inside and outside the EU.
- Task 5.3: Technical guidance on data and model innovations to river basin practitioners for capacity building purposes.
- Task 5.4: Create a story-map website for international networking on policy level.
- Task 5.5: Supporting EU policies by preparing a ‘blueprint’ containing recommendations for strengthening EU policies and actions based on the results of integrated climate risks assessments at river basin level.

This report presents the results of task 5.1.

1.3. Synthesis of STARS4Water insights on co-creation with basin stakeholders

The selected river basins reflect a wide range of climate-related vulnerabilities and water management challenges across Europe, providing valuable insights for scaling integrated climate risk assessments to other basins. This report introduces the STARS4Water guiding principles for building water resilience at river basin level through a co-creation approach and presents the key findings from stakeholder engagement activities conducted across the project's river basin hubs.

By combining stakeholder perspectives with the results of water resource assessments supported by STARS4Water data, services, and modelling tools, the report provides an integrated view of current and future climate risks, their implications for water resources availability, Safe-Operating-Space assessment and potential adaptation pathways. The framework was designed to help river basin stakeholders strengthen preparedness for water-related challenges from source to sea, while promoting shared understanding and evidence-based decision-making.

The report also highlights practical experiences and good practices of co-creation with basin stakeholders from across the river basin hubs to support the uptake of STARS4Water results among diverse stakeholder groups. To further facilitate the use of STARS4Water tools, services, methods, and approaches, the STARS4Water Academy offers a series of training webinars aimed at building capacity among practitioners, decisionmakers, and other target audiences [The STARS4Water Academy – STARS4Water](#). The Academy is built around the STARS4Water approach, which combines a shared scientific knowledge base with a shared understanding of stakeholder perspectives. As a result, it provides learning opportunities covering different elements of the science-to-decision support chain and tailored to varying levels of expertise and user needs.

Detailed technical guidance on the project's data and modelling innovations for river basin practitioners is provided separately in Deliverable D5.4 (ter Maat, 2026) and is therefore not covered in this report.

1.4. The structure of this report

This report is structured as follows:

Chapter 2 presents the key lessons and insights from the STARS4Water science-stakeholder engagement process, highlighting how collaboration has strengthened understanding of current and future water resource challenges.

Chapter 3 synthesises the climate risk assessments conducted across the river basin hubs, providing an integrated European perspective on the implications of climate change and evolving water demands for future water availability.

Chapter 4 introduces the STARS4Water guiding principles to design an impactful and meaningful science-stakeholder engagement process. These principles support collaborative actions to foster shared understanding on current and future water challenges and co-design pathways to strengthening water resilience at the river basin scale.

Finally, chapter 5 addresses final remarks and conclusions.

2. The STARS4Water science-stakeholder engagement processes

2.1. Introduction

Water is fundamental to the functioning of ecosystems, societies, and economies. For centuries, water systems have been managed to provide essential services and support human development. However, increasing pressures from freshwater overexploitation, water pollution, and growing demands have placed many water systems under significant stress. Climate change is further amplifying these pressures by altering hydrological cycles, affecting water availability, and increasing the frequency and severity of floods, droughts, and water scarcity. As a result, river basins, aquifers, and reservoirs across Europe are becoming increasingly vulnerable to water-related climate risks.

Addressing these challenges requires forward-looking planning processes that enable stakeholders to identify risks, evaluate response options, and develop adaptation strategies that strengthen water resilience. In recent years, a range of innovative frameworks and approaches have emerged to support climate risk assessment, water security planning, adaptive governance, and resilience building. These approaches include methodological frameworks for assessing climate risks and impacts on water security, such as Strategic Water Systems Planning Framework (Van Beek et al., 2022), Climate risk Informed Decision Analysis (Mendoza et al., 2018), National Water Security Framework (Panella et al., 2020), and Water security sectoral guide (Green Climate Fund, 2022). Novel approaches on water governance and institutional frameworks include EPIC Response (Browder et al., 2021) and Principles for Water Governance (OECD, 2018). Innovative approaches for strategic planning under climate uncertainty and building water resilience include Dynamic Adaptive Policy Pathways (Haasnoot et al., 2013) and the Water Resilience Tracker (Idrees et al., 2025). Together, these approaches reflect a growing recognition that managing future water challenges requires both robust scientific evidence and inclusive decision-making processes.

A common feature across these approaches is the active involvement of stakeholders. Meaningful stakeholder participation is widely recognized as a critical element in assessing water-related climate risks and impacts on ecosystems, society, and economic sectors. The ambition of STARS4Water is to improve understanding of the impacts of climate change on water resources and the associated vulnerabilities of ecosystems, society, and economic sectors at the river basin scale. To achieve this ambition, the project has adopted a stakeholder-driven co-creation approach involving river basin organizations and key actors across seven European river basins: the Danube, Drammen, Duero, East Anglia, Messara, Rhine, and Seine. By fostering trust, shared ownership, and consensus, participatory processes enhance the legitimacy, relevance, and acceptance of the data services, tools, and approaches developed through collaboration between research organizations and basin stakeholders. Co-creation also provides opportunities to integrate local knowledge, practical experience, and basin-specific perspectives with scientific evidence, resulting in more robust and actionable solutions. The effectiveness of stakeholder engagement depends on the diversity, interests, capacities, and needs of the groups involved, as well as on the level of participation facilitated throughout the process. Recognizing these different levels of participation is essential for designing collaborative processes that support informed decision-making and strengthen resilience to current and future water resource challenges.

2.2. The STARS4Water stakeholder engagement approach

The STARS4Water stakeholder engagement approach is founded on close collaboration between the scientific community and river basin stakeholders to improve the understanding of water-related climate risks and their implications for water management. The approach is built on two basic principles (Figure 2.1.): creating shared perception (understanding) and fostering shared science (knowledge base).

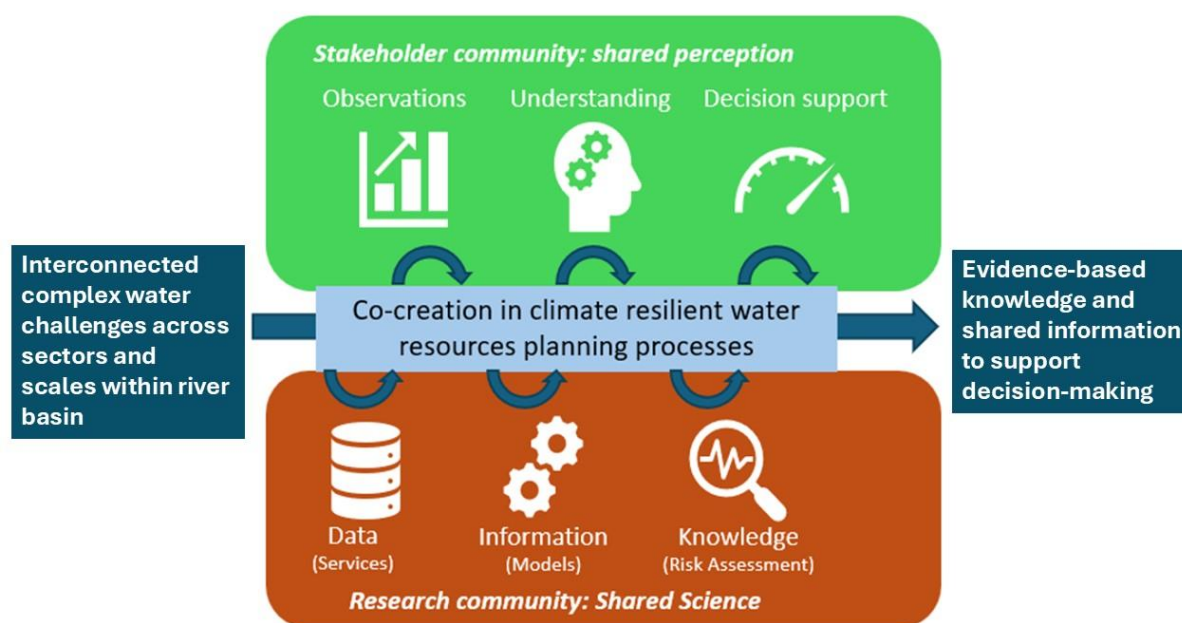


Figure 2.1. The two basic principles of the STARS4Water science-stakeholder partnership approach: shared perception and shared science.

Through a process of co-creation, STARS4Water has strengthened the connection between scientific knowledge and information needed to support decision-making, creating a more effective science-to-policy and science-to-practice interface. Co-creation is a collaborative approach that brings together stakeholders, water users, experts and scientists, to jointly define problems and information needs, generate ideas and design solutions. This collaborative approach supports the development of a shared knowledge base and a shared understanding of current and future water challenges, enabling stakeholders to make more informed and resilient decisions. The shared knowledge base (shared science) refers to joint development and use of models, data services and risk assessment methodologies, whereas the shared perception refers to building a common understanding between stakeholders and researchers of what the water-related climate risks are, how they are observed and impact society, economy and ecosystems, and what actionable solutions could be.

For each of the selected seven STARS4Water river basins, a river basin organisation participated as a direct project beneficiary and a core member of the science-stakeholder team responsible for guiding the co-creation processes (Hegdahl et al., 2023). These stakeholders are the STARS4Water stakeholder champions. The stakeholder champions are key players in the stakeholder engagement processes and activities because of their high interest and strong stakeholder network in the river basin. The stakeholder champions were teamed up with one or more research organisations that are responsible

for organising the scientific activities and serve as focal point for the research partners within STARS4Water (see table 2.1).

Table 2.1. The STARS4water science-stakeholder partnerships for the selected river basins.

River basin	Basin stakeholders (stakeholder champions)	Research organisations (research focal points)
Danube	- International Commission for the Protection of the Danube River (ICPDR) - Lower Danube River Administration (AFDJ)	- University of Life Science Vienna (BOKU) - Romanian Research-Development Institute for Marine Geology and Geoecology (GeoEcoMar)
Rhine	- International commission for the hydrology of the Rhine basin (CHR) - International Commission for the Protection of the Rhine River (ICPR) - Central Commission for the Navigation of the Rhine (CCNR)	- Deltares - Rijkswaterstaat (RWS) - Bundesanstalt für Gewässerkunde (BfG)
Seine	- EPTB Seine Grands Lacs	- French National Research Institute for Agriculture, Food and Environment (INRAE)
Duero	- Confederación Hidrográfica del Duero (CHD)	- Geological and Mining Institute of Spain (IGME-CSIC)
Messara	- Region of Crete - Hellenic Ministry of Environment and Energy (HMEE)	- SEVEN
East Anglia	- Anglian Water Services Ltd (AWS)	- UK Centre for Ecology and Hydrology (UKCEH)
Drammen	- Norwegian Water Resources and Energy Directorate (NVE)	- Norwegian Water Resources and Energy Directorate (NVE)

To ensure effective stakeholder engagement and foster shared ownership of project outcomes, the river basin organisations played a leading role in establishing and coordinating basin-specific stakeholder communities. These communities provided a platform for collaboration throughout the project, supporting the identification of user needs and information requirements, the co-design of data services and modelling tools, and the co-development, testing, and validation of new data-driven solutions. The stakeholder champions are the primary end users of the project's products, services, and knowledge outputs, while the benefits of the STARS4Water results extend to a broader range of stakeholders.

In addition to river basin organisations, the stakeholder communities brought together a diverse range of actors with responsibilities, interests, or expertise related to water management. These included public authorities, water utilities, civil society organisations, environmental and nature conservation groups, research institutions, and private sector representatives, such as the energy sector and agricultural organisations. By engaging this broad range of stakeholders, STARS4Water ensured that the developed solutions address real-world challenges and support informed decision-making for climate-resilient water resources management.

2.3. Stakeholder engagement in the STARS4Water river basins

2.3.1. Co-creation with stakeholders

This section presents the stakeholder engagement processes implemented across the seven STARS4Water river basin hubs. Governance structures, institutional arrangements, and approaches to integrated river basin management differ considerably among the basins. These differences extend beyond the organisation of water management responsibilities to the composition of stakeholder communities, reflecting the diverse range of water users, economic sectors, environmental organisations, research institutions, and governmental authorities operating at local, regional, national, and international levels. This diversity required a flexible and adaptive engagement strategy. The varying governance contexts, decision-making processes, and stakeholder needs called for different levels and forms of support from the STARS4Water research partners to establish effective collaboration and meaningful stakeholder participation. While these differences sometimes posed challenges for aligning scientific activities with formal planning and water management processes, they also provided valuable opportunities to test, refine, and demonstrate innovative approaches across a broad range of institutional and governance settings.

Within STARS4Water, co-creation and stakeholder engagement were a continuous process during the lifetime of the project and include activities, such as collecting river basin data sets to support the development of data services and data-driven tools, defining information needs and indicators, building narratives and scenarios, developing data-driven models and improving modelling frameworks, modelling future water resources availability, assessing safe-operating-space, developing dashboard to support decision-making, designing story maps to support information sharing, exchanging knowledge and experiences, and identifying needs for capacity building and training.

2.3.2. Rhine river basin

Stakeholder champions on the Rhine river basin hub included the three principal Rhine basin commissions: the International Commission for the Hydrology of the Rhine Basin (CHR), the International Commission for the Protection of the Rhine (ICPR), and the Central Commission for the Navigation of the Rhine (CCNR). The stakeholder champions teamed up with the research focal points from Rijkswaterstaat (RWS), the German Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde, BfG) and Deltares.

Early stakeholder consultations and bilateral discussions identified a strong demand for model-based scenario assessments to evaluate the impacts of climate change and socio-economic developments on water availability, water shortages, and low-flow conditions in the basin. To support this effort, socio-economic and water-use data were collected from the Rhine countries, while future transboundary socio-economic scenarios were co-developed with basin stakeholders and combined with regional climate change scenarios. This new data input enhanced the model performance and improved the assessment of future low flows and water balances. A comprehensive modelling framework, combining the wflow hydrological model with the RIBASIM basin management model, was developed and validated, and applied to explore future water management challenges (Ter Maat et al., 2025). The

framework builds on earlier initiatives and projects addressing climate change impacts in the Rhine basin and incorporates the latest regional climate change scenarios (KNMI'23 scenarios¹).

Throughout the project, regular exchanges were organised with the three Rhine commissions and their scientific officers and expert working group to share progress, obtain feedback, and jointly identify opportunities for model refinement and assessments. In addition, model results and key insights were presented at several international events, including the ICPR Climate Adaptation Conference in Arnhem, the Water Europe Assembly in Warsaw, and the INBO General Assembly in Bordeaux. The Rhine was also presented as a good example of using new technologies for transboundary water governance on conference of the UN-ECE Water convention and the official OSCE platform conferences. These events provided valuable platforms for discussing data sharing and exchange, new modelling technologies, future water availability and demand, water storage and building drought resilience. In March 2025, the ICPR and CHR presented its work on drought management to the EU Working Group on Droughts and Water Scarcity. Recently, the ICPR Expert Group on Low Water discussed in detail how the STARS4Water outputs need to be incorporated in their report on the status of water availability in the basin as background report for the Climate Adaptation Strategy development. STARS4Water outputs are already feeding the update of the ICPR Climate Change Adaptation Strategy and the preparation of the ICPR Work Program 2028 – 2033. The science-stakeholder collaborations strengthened the scientific foundation of drought-related policymaking and further enhanced the connection between Global agenda initiatives, European-level initiatives and integrated water management practices across the Rhine river basin. It also provided necessary information in preparation of the Ministers' conference of the Rhine riparian countries in 2027.

2.3.3. Danube river basin

Stakeholder champions within the Danube River Basin included the International Commission for the Protection of the Danube River (ICPDR) and the Lower Danube River Administration in Romania. The stakeholder network was further strengthened through the involvement of the Danube Commission, WWF Danube-Carpathian Programme, and the International Association for Danube Research (IAD). In addition, broader engagement activities brought together a diverse range of stakeholders representing key sectors and interests across the basin, including water management, navigation, environmental protection, hydropower, agriculture, and scientific research. This broad stakeholder participation ensured that multiple perspectives were incorporated into the assessment of low-flow risks and climate change impacts, helping to identify sector-specific vulnerabilities, build consensus around adaptation priorities, and enhance the relevance and applicability of the resulting tools and recommendations.

Early stakeholder consultations highlighted a pressing need for improved understanding of current and future low-flow conditions and their implications for water-dependent sectors and ecosystems. As no dedicated low-flow model was available, a new modelling framework, including water abstractions, was developed for the Danube Basin in close collaboration with stakeholders. A series of stakeholder meetings was organised to discuss the model framework, the key functionalities and output indicators, to validate model outputs, and to explore a range of future “what-if” scenarios.

The Safe-Operating-Space concept was applied to assess the impacts of low-flow conditions on water supply, hydropower generation, navigation, aquatic ecosystems, and riverbed incision. Particular

¹ <https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-23-klimaatscenario-s>.

attention was given to the long-term effects of glacier retreat, which is expected to contribute to lower summer water levels in the Danube.

In 2025, the Marchfeldkanal Betriebsgesellschaft, which manages several irrigation channels connected to the Danube, joined the stakeholder community. Its expertise and feedback were incorporated into the model development and validation process. The RIBASIM model and its analytical capabilities were also presented to the wider river basin management community during the 61st RBM Expert Group Meeting in May 2025.

The final modelling framework provides a valuable tool for assessing low-flow risks and supports stakeholder-informed decision-making aimed at strengthening the resilience of the Danube river basin to future droughts and water scarcity. Through the science-stakeholder partnership, the International Commission for the Protection of the Danube River gained a broader understanding of low-flow vulnerabilities across the basin, incorporating a multi-sector perspective from upstream reach to the delta. This collaborative approach enabled the integration of scientific analyses with basin-specific knowledge and management experience, resulting in a more comprehensive assessment of risks of climate change and water allocation plans for irrigation.

2.3.4. Messara river basin

Stakeholder champions in the Messara basin included the Region of Crete and the Directorate for the Protection and Management of Aquatic Environments of the Hellenic Ministry of Environment and Energy (HMEE). The stakeholder community comprised organisations responsible for irrigation management and infrastructure (namely the Local Land Reclamation Organisation TOEV), water supply, water resource protection, and regional agricultural development.

As part of the co-creation process and the planned stakeholder engagement activities, numerous bilateral meetings and two multi-stakeholder workshops were conducted. The Messara Basin is subject to severe water stress and faces significant pressure from the overexploitation of water resources for agricultural use. To explore the future water resources availability and risks, the workshops focused on discussing data services, modelling approaches, dashboard indicators, the co-design of future scenario narratives, and the definition of the Safe-Operating-Space under the Messara context.

Stakeholders played a key role in validating model outputs, including abstraction rates, irrigation extend, water demand, and unmet demand. They also agreed on scenario quantification metrics and proposed several enhancements, such as conducting an irrigation sensitivity analysis for olive cultivation and upgrading the model to the latest version of RIBASIM (v8). In response to this feedback, the Messara basin model was revised and migrated to RIBASIM v8 at a disaggregated sub-basin level (9 general districts). The results of the final RIBASIM model were subsequently presented and discussed with stakeholders, together with the application of the Safe-Operating-Space concept to support sustainable water resource management in the basin.

As the Messara basin is already highly water-stressed, and pressures are expected to intensify due to climate change and increasing water demands, basin stakeholders recognise there is a clear need to strengthen water governance and restructure water allocation practices. Such measures are essential to improve the reliability of water supplies for irrigation, reduce vulnerability to water scarcity, and enhance the basin's overall resilience to future climate and socio-economic pressures.

2.3.5. Duero river basin

The Duero River Basin Authority (Confederación Hidrográfica del Duero, CHD) was acting as stakeholder champion for the Duero river basin hub. The stakeholder community included organisations responsible for urban water supply, energy companies, as well as several agricultural irrigation associations, reflecting the basin's diverse water management interests. The Duero river basin benefits from a long tradition of hydrological planning and a well-established institutional framework for water management. Nevertheless, stakeholders identified the need for stronger integration of hydrological planning with climate change adaptation strategies and rural development policies to ensure the effective implementation of future measures.

To support this process, a series of stakeholder meetings was organised with representatives from key sectors to discuss water availability, climate change, and potential impacts on water resources. These discussions were complemented by a basin-wide survey distributed to approximately 800 stakeholders, which generated more than 100 responses. The survey results provided valuable insights into stakeholder concerns, priorities, and expectations regarding future water management challenges. A subsequent workshop, attended by 23 participants representing nearly all major stakeholder groups, was dedicated to discussing the survey findings and exploring future development pathways for the basin. Based on the results of the exploratory survey, participants identified and prioritised a range of socio-economic and environmental drivers likely to shape future water management. The most influential factors were ranked as: (1) climate variables, (2) water quality, (3) European Union agricultural policies under the Common Agricultural Policy (CAP), (4) demographic developments, and (5) European Union environmental policies. These discussions formed the basis for the co-development of three socio-economic scenarios for the Duero Basin.

A third stakeholder workshop focused on the application of the Safe-Operating-Space (SOS) concept within the context of the Water Framework Directive. Participants explored how the SOS framework could support sustainable water resources management and help identify acceptable operational boundaries for balancing environmental objectives with socio-economic water demands.

2.3.6. Seine river basin

In the Seine River Basin, EPTB Seine Grands Lacs served as the stakeholder champion within STARS4Water. EPTB Seine Grands Lacs is a public interregional authority responsible for the design, operation, and management of key water infrastructure that supports flood protection, low-flow management, and broader water resources management objectives. As the operator of the four major upstream reservoirs on the Seine, EPTB Seine Grands Lacs plays a central role in regulating river flows to balance water supply, flood risk reduction, and environmental needs.

Stakeholder discussions highlighted growing concerns about increasingly severe low-flow conditions, prolonged drought episodes, and the risk that the existing reservoirs may not fully refill during winter, thereby reducing resilience to dry summer conditions. To address these priorities, a modelling framework was co-developed that explicitly incorporates the operational rules of the four regulated reservoirs. Following calibration and validation against historical observations from river gauging stations, the framework was applied to investigate a range of stakeholder-defined what-if scenarios. These scenarios included simulations without reservoir regulation, alternative reservoir operating strategies, and future climate conditions derived from the national Explore2 climate projection database (CMIP5 contrasted climate scenarios over France). The analyses considered contrasting

climate change pathways and assessed their implications for water availability, flow regulation, and drought management throughout the twenty-first century.

A series of workshops, technical meetings, and bilateral exchanges were organised throughout the project to support model development, discuss calibration results, and jointly define the Safe-Operating-Space framework. Stakeholders contributed to the formulation of scenarios and indicators used to evaluate future water resource challenges and management options. During the STARS4Water Annual Meeting in Norway in September 2025, representatives from the Seine River Basin reflected on the practical value of the project results, particularly for situations where reservoir filling remains incomplete after dry winters or where late-season flood events challenge existing reservoir management practices. In October 2025, STARS4Water results were presented to a wider stakeholder audience during one of the biannual technical committees organised by EPTB Seine Grands Lacs. This consultation brought together more than fifteen representatives from water utilities, navigation authorities, hydropower operators, flood forecasting services, and other water users, providing an opportunity to discuss the relevance and applicability of the project findings across sectors and a wider range of stakeholders.

In addition to the hydrological assessments, an environmental flow (e-flow) analysis was undertaken with support from UKCEH. The assessment covered all gauged stations within the Seine River Basin and evaluated ecological flow conditions under historical, current, and projected future climates, both with and without reservoir operations. Dedicated meetings were organised to gather stakeholder feedback on the ecological indicators used, discuss the interpretation and usability of results, and explore opportunities for wider uptake, transferability, and dissemination of project outcomes through scientific publications and practical applications in river basin management.

The collaborations established through the project will continue beyond its completion, with discussions already underway on further enhancing the modelling framework, co-developing new water demand scenarios based on the lessons learned, and updating the Safe-Operating-Space risk assessment. These activities will build on the project's achievements and help ensure that the tools, knowledge, and partnerships developed through the collaboration continue to support evidence-based decision-making and climate-resilient water management in the Seine River basin.

2.3.7. East Anglia

Anglian Water Services Ltd (AWS) served as the stakeholder champion for the East Anglia Basin. The stakeholder community included organisations and authorities involved in water resources planning, flood risk management, navigation, agricultural water use, environmental flow management, and ecosystem health. Building on stakeholder needs and priorities identified through a series of workshops and bilateral meetings, the project developed several data-driven modelling and process-based applications. These included tools for reservoir storage forecasting, groundwater quality mapping, and ecological flow assessment. All models were co-developed in close collaboration with stakeholders, and their results were presented and discussed during dedicated online stakeholder meetings.

A team from the Universidad Complutense de Madrid (UCM), responsible for the development of the MLMapper tool, worked closely with Anglian Water and the UK Centre for Ecology & Hydrology (UKCEH) to develop a dedicated MLMapper application for predicting nitrate concentrations in the East Anglian Chalk aquifers. This collaborative effort involved weekly online meetings, two in-person workshops, and a field visit, ensuring that the modelling approach reflected both scientific knowledge and stakeholder expertise.

In parallel, UKCEH collaborated with Anglian Water to develop a range of future “what-if” scenarios that addressed the priorities and concerns expressed by stakeholders during the early stages of the project. These scenarios were used to explore potential future challenges related to water availability, water quality, and ecosystem resilience under changing climatic and socio-economic conditions. The scenarios were used to drive an exploratory study to investigate the potential impacts of climate change and socio-economic change on environmental flows using STARS4Water ERFA. The results from this study were discussed with Anglian Water and a co-created story-map showcasing these were published.

Stakeholders in East Anglia emphasised strengthening stakeholder relationships within the region through new international partnerships and cross-basin learning. Through collaboration with partners from other European river basins, stakeholders explored innovative methods for assessing ecological flow requirements and addressing groundwater nitrate pollution and gained access to a broader range of tools and knowledge. The combined use of these techniques supported a more comprehensive and inclusive approach to water resource risk assessment and management.

2.3.8. Drammen basin

In the Drammen River Basin, the Norwegian Water Resources and Energy Directorate (NVE) had a dual role as the stakeholder champion and research organization. NVE coordinated all stakeholder engagement activities, including establishing the STARS4Water stakeholder community for the Drammen river basin. The stakeholder community included representatives from the hydropower sector through the Regulatory Cooperation for Hydropower Companies and Associations in the Drammen basin (RSD), river basin district authorities, sub-district boards at municipality level (indirectly representing agricultural and forestry), water supply company Glitrevannverket, and municipalities.

A series of stakeholder workshops was organised to identify key water management challenges, assess water-related climate risks, and prioritise stakeholder needs for data services, modelling tools, and decision-support products. These discussions also informed the design of the services and tools developed within STARS4Water, ensuring that they addressed basin-specific requirements and management priorities.

To support assessments of future water resources, updated climate projections for Norway developed by the Norwegian Centre for Climate Services, in which NVE is a partner, were incorporated into the project. The analysis included three combinations of global and regional climate models under both medium- and high-emission scenarios, based on the latest CMIP6 climate projections.

In response to stakeholder concerns regarding future climate risks, a set of “what-if” scenarios and accompanying narratives was co-developed, focusing on two key risk areas: extreme flooding and extreme drought. The hydrological models developed within STARS4Water were calibrated, validated, and applied to assess the implications of these scenarios for future water availability and flow regimes in the Drammen River Basin.

Stakeholder workshops were subsequently used to review and discuss the assessment results and to support the identification of indicators for sustainable water resources management. Dedicated engagement sessions were also organised with representatives from the hydropower sector to explore the implications of future hydrological changes for energy production and related sectoral narratives. In addition, stakeholders contributed to the design of a tailored dashboard aimed at improving access

to information on current and future water-related climate risks and their impacts across sectors. During the STARS4Water All-Partners Meeting held in Drammen, Norway, in September 2025, a dedicated stakeholder event provided an opportunity to present and discuss the preliminary assessment results and the Safe-Operating-Space (SOS) framework adopted within the project, further strengthening the dialogue between science and practice.

Although the Drammen River Basin is a highly regulated hydropower-dominated water system, multiple stakeholders manage different parts of the basin at varying spatial scales and for different purposes. As climate change alters the temporal and spatial distribution of water resources across the basin and through the regulated system, the science-stakeholder partnership established a transparent and collaborative process that integrates data, modelling tools, and stakeholder knowledge to support future water management decisions.

By bringing together hydropower operators, water district managers, water supply companies and municipalities, the co-creation process facilitated a shared understanding of emerging challenges and potential trade-offs associated with changing flow regimes. This collaborative approach enhanced the credibility, relevance, and usability of the developed modelling framework, strengthening the basin's capacity to adapt to future climatic and hydrological changes.

2.4. From stakeholder engagement to shared ownership

The stakeholder engagement process highlighted substantial variation among the seven STARS4Water river basins in the organisation and implementation of integrated river basin management. Despite these differences, experiences from the river basin hubs demonstrate that science-stakeholder collaboration can be successfully tailored to different governance contexts and institutional arrangements while maintaining a shared objective: enhancing the knowledge base and decision-support capacity needed to address current and future water resource challenges.

Through its basin-specific and stakeholder-driven approach, STARS4Water successfully integrated local knowledge, management priorities, and scientific expertise into the co-development of data services, modelling frameworks, scenarios, and decision-support tools. The project's flexibility enabled the application and evaluation of innovative data sources, modelling approaches, scenario analyses, and upscaling methods in ways that were tailored to the needs of individual river basins while maintaining a coherent European framework.

Most importantly, the strong and sustained engagement of stakeholders throughout the project has demonstrated the value of the STARS4Water science-policy-practice interface. The collaborative process fostered trust, transparency, and mutual learning between researchers and basin stakeholders. By actively involving stakeholders in the design, development, validation, and interpretation of project outputs, STARS4Water has strengthened ownership of the co-created tools and services, thereby increasing their relevance, credibility, and likelihood of long-term uptake.

The experiences gained across the pilot basins confirm that stakeholder-driven water management research is essential for supporting evidence-based decision-making and enhancing the capacity of river basin organisations to address future challenges related to water scarcity, droughts, ecosystem protection, climate change adaptation, enhancing water resilience and sustainable water resource management across Europe.

The STARS4Water stakeholder engagement process has significantly enhanced stakeholders' understanding of how river basins function under current and future climatic conditions, and how water management decisions influence water availability, ecosystem health, and water-related risks. Through participation in workshops, scenario development exercises, model evaluations, and discussions on future pathways, stakeholders gained valuable insights into the interactions between hydrological processes, water demand, operational management, and climate change impacts. This increased awareness has reinforced the understanding that operational decisions related to water allocation, reservoir management, drought mitigation, and water distribution can have far-reaching consequences across entire river basins.

The experiences gained across the STARS4Water river basins demonstrate that effective climate adaptation and water resource management require a demand-driven co-creation approach. By engaging stakeholders from the outset, the process helps identify the most pressing water challenges and the specific information needs of different user groups. This collaborative understanding provides a stronger basis for assessing current water-related risks and anticipating how climate change may affect water availability, droughts, floods, and other extreme events in the future.

A key lesson is that stakeholder information needs should guide innovation. Aligning scientific research with practical management challenges ensures that the development of modelling frameworks, data services, and decision-support tools is directly relevant to water managers, policymakers, and other end users. This not only increases the usability and acceptance of the resulting products but also strengthens their capacity to support informed decision-making.

Another key outcome of the engagement process has been the recognition that narratives and what-if scenarios provide a powerful mechanism for exploring uncertainties, identifying vulnerabilities, and discussing alternative futures. This is also underlined by Baulenas et al. (2023) and Van der Hurk (2022). By connecting long-term climate and socio-economic developments with present-day management challenges, stakeholders were able to translate future risks into concrete considerations for current planning and operational decision-making. This collaborative exploration of possible futures has strengthened the capacity of river basin communities to anticipate change and prepare adaptive responses.

The stakeholder dialogues consistently highlighted that future water availability and water-related risks are shaped by a complex interplay of climatic, socio-economic, and biophysical factors. In highly regulated river basins, management and operational choices can be equally important in either mitigating risks or contributing to water shortages and system failures. Population growth, economic development, land-use change, environmental objectives, and evolving water demands interact with hydrological and climatic pressures, creating challenges that require integrated and cross-sectoral solutions. At the same time, stakeholders recognised that access to knowledge alone is not sufficient. Effective adaptation depends on the availability of institutional, legal, financial, technical, and operational capacities to translate knowledge into action.

The project also demonstrated the importance of explicitly incorporating operational water management into modelling frameworks and scenario assessments. This approach helped bridge the gap between strategic planning and day-to-day decision-making, providing stakeholders with a more realistic understanding of how management interventions influence system's performance under changing conditions. The introduction of the Safe-Operating-Space framework further stimulated discussion on acceptable limits, trade-offs, and adaptation pathways. For many stakeholders, the concept represented a new perspective for assessing risks and resilience at the river basin scale, and the resulting dialogue proved valuable for identifying both constraints and opportunities for

sustainable water management. Also, the SOS framework applied provides an early warning system to identify water bodies at risk which has not yet been identified as such by the WFD. This allows more proactive actions before the worsening of the condition happens.

A central lesson emerging from STARS4Water is that there are rarely simple or immediate solutions to the challenges of floods, droughts, water scarcity, and ecosystem degradation. Building resilience requires well-monitored data records over the long term, long-term commitment, adaptive management, continuous learning, and cooperation across sectors, administrative boundaries, and governance levels. It also requires a thorough understanding of existing operational practices and the flexibility of water managers to adapt these practices under both current and future conditions. These conditions are not only climate but can also be economically driven water demand conditions.

Ultimately, the project has shown that strong, inclusive, and continuous stakeholder engagement is fundamental to effective river basin management and climate adaptation. By bringing together water managers, policymakers, water users, researchers, environmental organisations, and economic sectors, STARS4Water fostered mutual learning, knowledge exchange, and shared ownership of the generated knowledge and tools. This collaborative approach not only strengthened trust and transparency but also created a foundation for collective action, supporting more informed, resilient, and sustainable water management decisions across Europe's river basins.

3. Integrated perspective on water related climate risks in Europe

3.1. Introduction

Europe's climate is changing rapidly, with significant variations in climate-related risk drivers across regions (Figure 3.1). As the fastest-warming continent in the world, Europe is already experiencing the consequences of rising temperatures, changing precipitation patterns, and more frequent and intense extreme weather events. These changes pose growing risks to water resources, ecosystems, food and energy production, infrastructure, economic stability, and human health.

Land regions	Northern Europe			Western Europe			Central-eastern Europe			Southern Europe			European regional seas		
	Past	Future		Past	Future		Past	Future		Past	Future			Past	Future
		Low	High		Low	High		Low	High		Low	High			
Mean temperature	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	Sea surface temperature	↗	↗
Heatwave days	☐(*)	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗			
Total precipitation	↗	↗	↗	↗	↗	↘	↗	↗	↗	↘	↘	↘	Sea level	↗	↗
Heavy precipitation	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗			
Drought	↗	↘	↘	↗	↗	↗	↗	↗	↗	↗	↗	↗			

Figure 3.1. Observed and projected trends in key climatic risk drivers in different European regions (EEA, 2024).

Water is at the centre of many of these climate risks. Climate change is altering the hydrological cycle, affecting the timing, magnitude, and distribution of precipitation, river flows, groundwater recharge, and evapotranspiration. As a result, many European river basins are facing increasing challenges related to floods, droughts, water scarcity, declining water quality, and ecosystem degradation. These developments have the potential to intensify existing socio-economic and environmental pressures and to challenge established approaches to water resources management. Despite advances in climate and hydrological science, substantial uncertainties remain regarding how climate change will affect river basin hydrology, flow regimes, groundwater systems, and water availability at local and regional scales. Equally important, the cascading impacts on society, economic sectors, and ecosystems are not yet fully understood. Understanding these complex interactions has become increasingly important for supporting effective adaptation planning and sustainable water management.

In recent years, drought risk management has become an emerging topic in Europe and beyond (Duel et., 2022). In 2026, the drought events across Europe have once again highlighted the urgency of strengthening water resilience. Prolonged periods of low rainfall and exceptionally high temperatures have led to record-low water levels in several European rivers, disrupting inland navigation, constraining cooling water availability for energy production, reducing agricultural yields through irrigation shortages, and increasing pressure on drinking water supplies and freshwater ecosystems. At the same time, declining river flows and elevated water temperatures have adversely affected biodiversity and ecosystem services across many river basins. The economic consequences of these events are substantial. Recent estimates suggest that the 2026 drought conditions in the EU may have imposed economic losses amounting to 180 billion euros, equivalent to 1% of the EU's GDP². In

² Stegeman, H., J. de Wilde & E. Hobma. Hot summer economics. Tridos Bank. Online article 8 September 2026. <https://www.tridos.com/en/articles/2026/hot-summer-economics>

addition, heatwaves and drought conditions have contributed to some of the most severe wildfire seasons on record, over 630,000 ha of land burned across the EU³.

Climate change is also increasing the frequency and severity of flood events across Europe, including catastrophic flash floods triggered by extreme rainfall and cloudburst events. Since 2000, Europe has recorded an average of over 40 flood events per year (Krichene et al., 2026). The severity of the extreme flood events has increased dramatically. In 2021, exceptionally heavy rainfall over a two-day period caused devastating floods in the Rhineland region of Germany, Wallonia in Belgium, and Limburg in the Netherlands. The disaster claimed more than 220 lives and resulted in economic losses exceeding €40 billion. More recently, in 2024, extreme rainfall led to severe flooding in parts of the Spanish regions of Valencia, Castilla-La Mancha, and Andalusia. The event became one of the deadliest natural disasters in Spain's recent history, causing around 240 fatalities and widespread disruption to communities, infrastructure, and economic activities. The associated economic losses were estimated to amount to approximately 0.65% of Spain's national GDP⁴. In June and September 2024, floods across Central Europe affected populations and caused significant economic damage (Krichene et al., 2026).

These events highlight the growing vulnerability of European societies and economies to climate-related flood hazards and underscore the need for enhanced preparedness, adaptive water management, and climate-resilient planning strategies. Future water resources availability will depend not only on climatic changes but also on socio-economic development, land-use change, demographic trends, ecosystem conditions, and operational water management decisions. Building resilience therefore requires a combination of improved scientific knowledge, innovative modelling and forecasting tools, adaptive governance frameworks, and strong stakeholder engagement to support informed decision-making under increasing uncertainty.

Against this backdrop, STARS4Water sought to advance understanding of current and future climate-related water risks across Europe's river basins, supporting the development of science-based, stakeholder-informed strategies for sustainable and climate-resilient water management. Reflecting the priorities identified by river basin stakeholders, the project placed particular emphasis on understanding changes in hydrological flow regimes, the increasing frequency and severity of droughts, and growing pressures related to water scarcity. By combining innovative data sources, modelling approaches, scenario analyses, and stakeholder knowledge, STARS4Water strengthened the evidence base for managing water resources under a changing climate and to support the identification of effective adaptation pathways at the river basin scale.

³ [Current wildfire situation in Europe - Joint Research Centre](#)

⁴ <https://www.zurich.com/commercial-insurance/sustainability-and-insights/commercial-insurance-risk-insights/valencia-floods-lessons-in-claims-and-recovery-one-year-on>

3.2. European rivers under stress: cases across Europe

3.2.1. Introduction

The STARS4Water river basins collectively demonstrate that climate change is driving European water systems towards greater variability, more frequent droughts and floods, and increasing competition for water resources. We already observe:

- Reduced summer flows and increasing drought frequency (Rhine, Danube, Seine, Duero, Messara, East Anglia).
- Increased glacier melt, earlier snowmelt and changing runoff patterns in snow- and glacier dominated catchments (Drammen, Rhine, Danube).
- Increased frequency and intensity of rainfall-driven floods (Drammen, Rhine, East Anglia, Danube, Seine).
- Greater interannual variability, resulting in more extreme drought and flood events. Recent drought events and record-breaking low river flows in many of European rivers demonstrate that extreme events will become more extreme.
- Increased pressure on ecological flows in all river basin hubs due to changes in the flow regimes, highlighting the urgent need for stronger integration of hydrology and ecology through robust ecological flow indicators and assessment methods.
- Significant shifts in seasonal hydrological patterns affecting water retention, storage and availability within river basins.

While the specific challenges differ between river basins, a common conclusion is that future water resilience will depend on reducing vulnerability through integrated water management, improved water-use efficiency, ecosystem restoration, adaptive infrastructure operation, and long-term planning under uncertainty. The results of the climate risk assessments for the individual river basins are presented by Ramos et al. (2026). This section provides a summary of the key findings for each basin and highlights how these assessments have enhanced river basin stakeholders' understanding of climate change impacts, associated risks, vulnerabilities and potential adaptation strategies.

3.2.2. Rhine

The Rhine river basin is one of Europe's largest and most economically important river systems, spanning nine countries and covering approximately 185,000 km². Its hydrological regime is shaped by a combination of alpine snowmelt, glacier runoff, and precipitation, with strong spatial variability in climatic conditions. Annual precipitation exceeds 2,000 mm in the Alpine headwaters, decreases to around 700-900 mm in the downstream maritime lowlands of the Netherlands, and can be as low as 500 mm in the rain-shadow regions of the low mountain ranges. Consequently, the southern parts of the basin are characterized by peak flows in early summer driven by snow and glacier melt, whereas northern catchments typically experience maximum runoff during late winter and minimum flows in autumn.

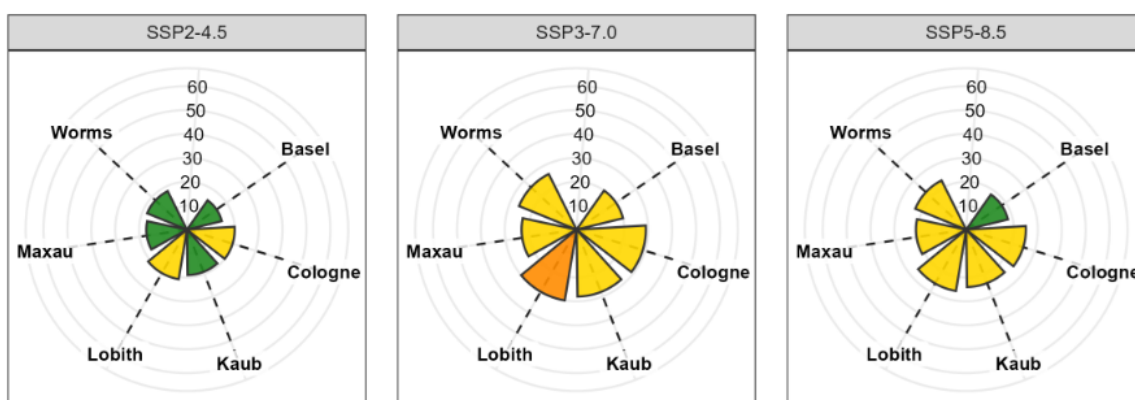
The basin is highly urbanized, industrialized, and densely populated, reflecting centuries of economic development and settlement. Water resources support a wide range of sectors and ecosystem services, including agriculture, public and industrial water supply, hydropower generation, inland navigation, and environmental functions. Agriculture is particularly important in some regions of Germany, France,

and the Netherlands, where both surface water and groundwater are used extensively and irrigation demands are increasing during hotter and drier summer periods.

Climate change is fundamentally altering the Rhine's hydrology. Rapid glacier retreat, reduced winter snowfall, changing precipitation patterns, and rising temperatures are accelerating the transition from a glacier-influenced to a predominantly rainfall-driven river system. These changes are modifying seasonal flow dynamics and producing more high and low water extreme events. The decline of glacier contributions is already affecting hydropower production in the Alpine region and placing additional stress on mountain river ecosystems and habitats.

Projections developed within the STARS4Water initiative indicate that average summer flows in the middle and lower Rhine could decline by approximately 10% over the coming decades as a result of climate change and growing water demand. More frequent and severe low-flow conditions are expected to constrain inland navigation (Figure 3.2), leading to economic impacts on freight transport and supply chains. Reduced river flows also threaten aquatic ecosystems, riparian wetlands, drinking water supplies, and water abstractions for agriculture and industry. In the Rhine delta, sea-level rise combined with lower river discharges is likely to intensify saltwater intrusion, further complicating freshwater management.

CMIP6 Projections (2050)



CMIP6 Projections (2080)

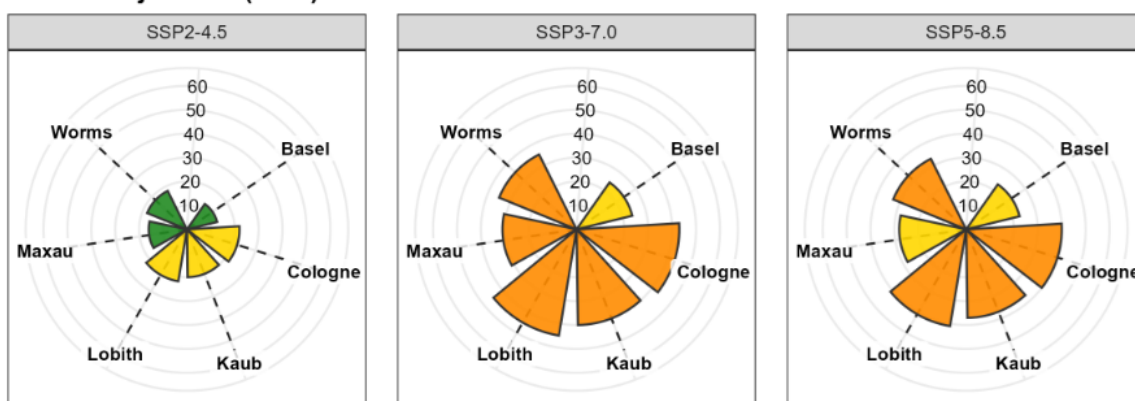


Figure 3.2. Radial charts showing navigation risk based on the CMIP6 ensemble mean for the selected SSP scenarios for 2050 and 2080. Each bar represents the average number of days per year during which discharge falls below the GIQ threshold at six Rhine locations: Basel, Cologne, Kaub, Lobith, Maxau, and Worms. Colours indicate navigation risk levels: green = no risk (< 20 days), yellow = low risk (20–25 days), orange = medium risk (25–30 days), and red = high risk (> 30 days). Source: D.4.2: Rhine (Taner et al., 2026).

Water-related risks are not evenly distributed throughout the basin. Downstream locations, such as Kaub and Maxau, are projected to experience substantially greater hydrological changes than upstream areas such as Basel. Moreover, the Rhine exhibits pronounced seasonal and interannual flow variability. While long-term averages suggest moderate overall impacts, model simulations reveal that extreme low-flow years may involve more than 80 days below critical navigation thresholds. Such extremes are often obscured by multi-year averaging yet represent significant operational and economic risks. Overall, the evidence suggests that the Rhine River Basin will face increasingly complex water-management challenges throughout the century, with a growing probability of conditions exceeding the limits of its current safe operating space.

As river basin stakeholders identified the need for a better understanding of current and future low-flow conditions, droughts, and water scarcity issues at the outset of the project, the collaboration provided river basin commissions with new insights into future water availability across the basins, projected water demands, and potential water deficits. It also revealed important data and modelling gaps and challenges, particularly in relation to transboundary water demand assessment and forecasting. The collaboration with CHR, the low water working group of the ICPR, and CCNR will continue beyond the lifetime of the project focusing on addressing the identified gaps and challenges while further exploring solutions to strengthen water resilience. This includes evaluating the potential of nature-based solutions, alongside other adaptation measures, to enhance water availability and improve the resilience of water resources during dry periods.

3.2.2. Danube

The Danube River Basin is Europe's second-largest river basin, covering approximately 800,000 km² across 19 countries and supporting a population of around 80 million people. Stretching from the Black Forest in Germany to the Black Sea, the basin encompasses a wide range of climatic, geographic, and socio-economic conditions, from Alpine and mountainous headwaters to extensive lowland plains and wetlands. The Danube is a vital resource for drinking water supply, agriculture, industry, hydropower generation, navigation, and biodiversity, including internationally important ecosystems such as the Danube Delta. Climate change is expected to alter the basin's hydrology through rising temperatures, changing precipitation patterns, and more frequent extreme events. Southern and eastern parts of the basin are projected to experience increasing water scarcity and drought risk, while northern and mountainous regions may face higher flood risks due to more intense rainfall and earlier snowmelt. These pressures are likely to affect water availability, ecosystem health, agricultural production, hydropower generation, and navigation, highlighting the need for integrated and adaptive water resources management across the transboundary basin.

The retreat of alpine glaciers and shifts in precipitation patterns are altering flow regimes and seasonal water availability in the Danube River basin, mirroring similar trends and risks projected in the Rhine River basin. These changes are expected to intensify low-flow conditions, creating growing bottlenecks for inland water transport along the Danube River, reducing the hydrological conditions for river ecosystems and riparian wetlands and limiting the abstraction of water (Figure 3.3). As major rivers in Central and Western Europe, hydrological changes in the Danube and Rhine have widespread impacts on water-dependent sectors, such as agriculture, hydropower, industry, and inland navigation, as well as on ecosystems and water supply.

The project outcomes provide a strong foundation for developing a shared evidence base on low flows, water allocation, and water scarcity issues across the Danube riparian countries. By integrating modelling outputs with hydrological monitoring data, water allocation records, water demand

information, and operational management data, stakeholders can develop a more comprehensive understanding of current and future water-related risks and vulnerabilities. Such an integrated approach is essential for evaluating the benefits, trade-offs, and potential impacts of different management options, enabling more informed decision-making that balances water allocation needs, ecological requirements, and wider societal values. This shared knowledge base will support enhanced transboundary cooperation and more resilient water resources management throughout the Danube river basin.

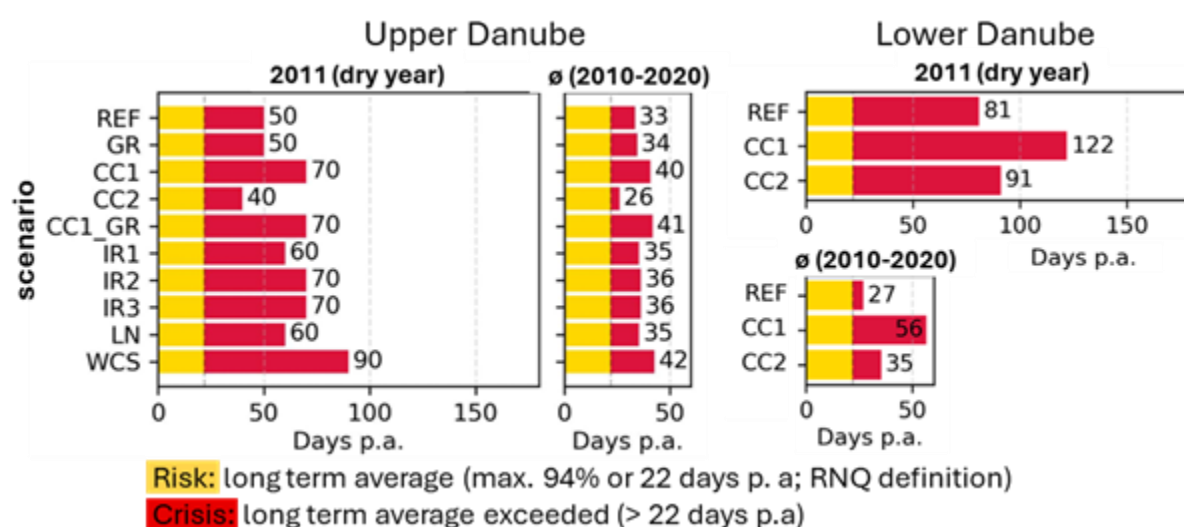


Figure 3.3. Safe-Operating-Space for navigation in the Danube using the indicator ‘number of days per year with discharge at critical stages for navigation’. Left and middle chart shows all considered scenarios and combinations for the Upper Danube. Right column shows the same for the Lower Danube. Results for the average (ø) conditions or for the dry year (2011) are shown. Source: D.4.2.: Danube (Glas et al. 2026).

3.2.3. Messara

Across the Mediterranean region, water scarcity is projected to intensify as declining precipitation, rising temperatures, and unsustainable water use reduce the availability of freshwater resources. Agriculture remains the dominant water-consuming sector and is a key driver of increasing pressure on already stressed water systems. The Messara Basin, located in southern Crete, exemplifies these challenges. The basin is characterized by a semi-arid Mediterranean climate, with long, dry summers and mild, wet winters. Annual precipitation ranges from approximately 400 to 700 mm, decreasing from north to south, while high evapotranspiration rates, particularly during summer, further limit effective water availability.

As the principal agricultural region of Crete, the Messara Basin already experiences substantial water deficits, defined as the gap between water demand and available supply. These deficits are expected to increase under climate change and growing water demands. Simulations with the RIBASIM model under what-if scenarios of increased drought conditions resulted in 9% to 20% increases of the water deficit across the Messara sub-basins (Figure 3.4). Irrigation requirements frequently exceed annual rainfall, resulting in the overexploitation of groundwater resources and the progressive depletion of aquifers. The impacts of water scarcity extend beyond water resources themselves, contributing to environmental degradation, reduced ecosystem resilience, and increasing socio-economic vulnerability.

The persistent imbalance between water supply and demand highlights the urgent need for coordinated and adaptive water management strategies. Strengthening water resilience in the Messara Basin will require a combination of demand-side and supply-side measures, with particular emphasis on reducing agricultural water consumption, improving irrigation efficiency, enhancing groundwater sustainability, and accelerating the transition toward climate-smart and water-efficient farming practices. Such measures are essential to safeguard water security, maintain agricultural productivity, and support long-term environmental sustainability in the basin.

The most valuable outcome of the project for stakeholders in the Messara Basin was the development of a much deeper, evidence-based understanding of current and future water challenges. Through close collaboration between scientists and stakeholders, the project provided a clearer picture of the spatial distribution of water-related risks and water supply vulnerability, how these may evolve under climate change and increasing water demands, and which interventions are most effective for strengthening long-term resilience and supporting sustainable water management. The Region of Crete has expressed to take the next step by upscaling the application of the newly developed tools, models, and data services from the Messara Basin to the entire island. This represents a major opportunity to support more integrated, evidence-based, and proactive water resources planning and management across Crete. By extending these capabilities to the island scale, the Region of Crete will be better equipped to address growing pressures from climate change, water scarcity, and increasing demand, while helping to secure reliable drinking water supplies and sustainable irrigation resources for future generations and strengthening the long-term resilience of Crete's water systems.

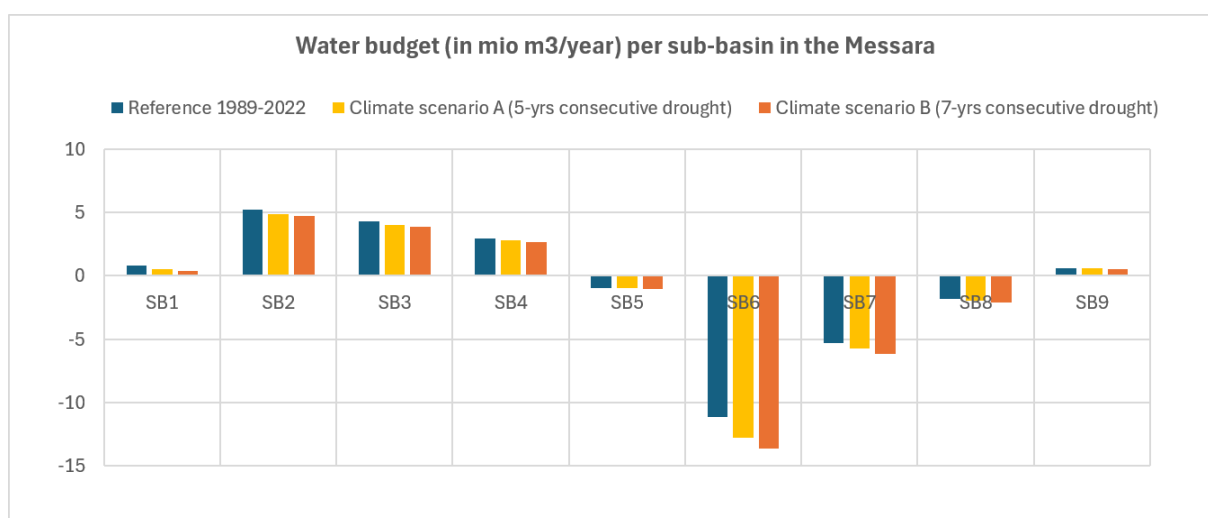


Figure 3.4. Changes in the water budget in the nine sub-basins of Messara under future what-if scenarios of increased drought conditions.

3.2.4. Duero

The Duero River Basin, shared between Spain and Portugal, is the largest river basin on the Iberian Peninsula, covering approximately 98,000 km², of which about 79,000 km² lies within Spain. The basin is characterized by a continental semi-arid climate with marked seasonal variability. Despite these climatic conditions, it benefits from relatively abundant surface water and groundwater resources and maintains a comparatively low population density. Its water system is supported by an extensive regional aquifer underlying the central plateau and connected recharge zones, with 67 identified groundwater bodies. Agriculture is the dominant water user, accounting for around 90% of total water

consumption, while a network of large reservoirs, primarily located on the northern tributaries, provides flood protection, irrigation water, and hydropower generation.

Climate change is expected to substantially affect the hydrology of the Duero Basin. Projections indicate significant reductions in both surface runoff and groundwater recharge, driven by rising temperatures, changing precipitation patterns, and increasing interannual climate variability. At the same time, droughts are projected to become more frequent and severe, increasing pressure on already stressed water resources and groundwater aquifers (Figure 3.5). These changes are likely to reduce water availability for irrigation, particularly in lowland agricultural areas, while placing additional stress on groundwater-dependent ecosystems and other vulnerable freshwater habitats.

The increasing risk of drought highlights the need for a transition towards more climate-resilient water and land management practices. Strengthening the basin's resilience will require improving water-use efficiency in agriculture, promoting climate-smart farming systems, and enhancing the protection of groundwater resources and water-dependent ecosystems. In addition, optimizing reservoir storage and operational rules will be essential to balance competing water demands, improve drought preparedness, and maintain ecosystem functions under increasingly variable hydrological conditions. Together, these measures can help reduce the vulnerability of the Duero Basin to future climate and water-related risks.

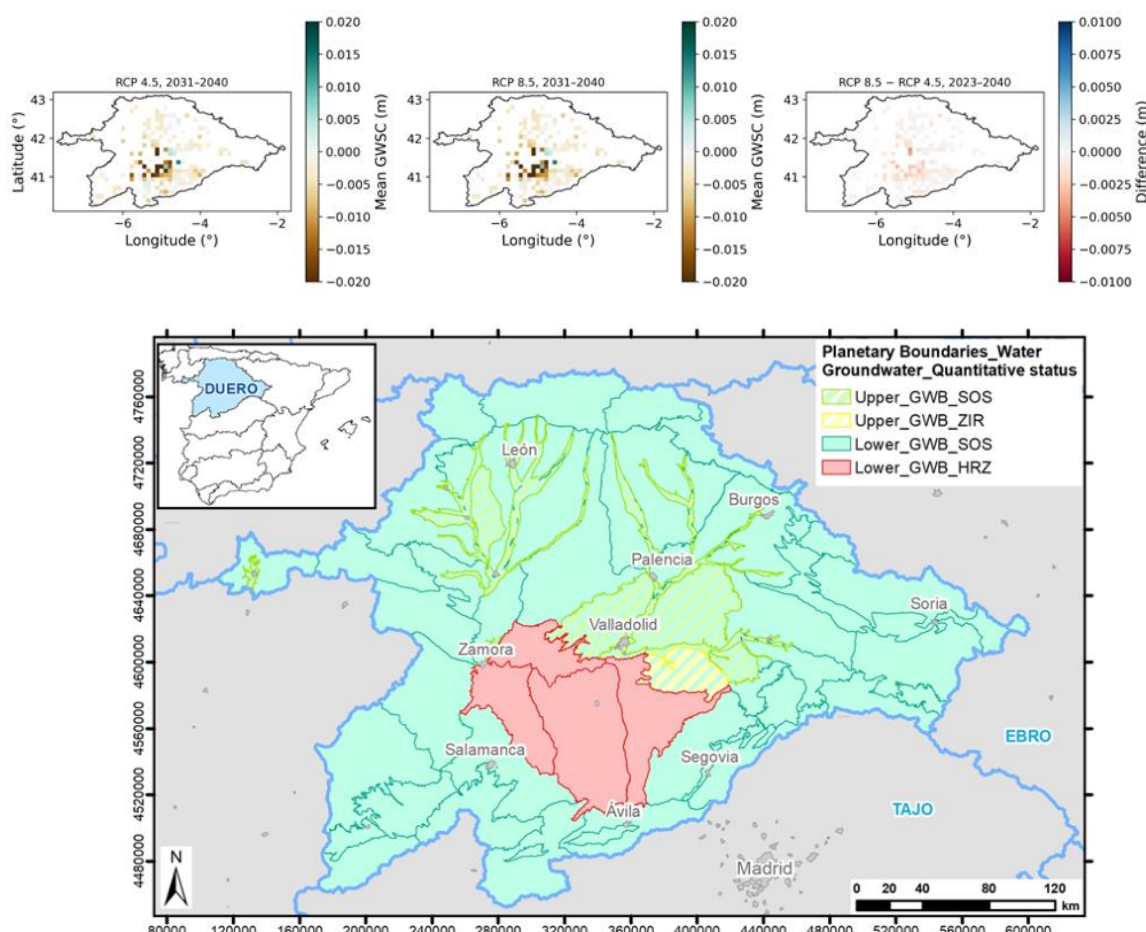


Figure 3.5. Map of the groundwater quantitative status in the SOS framework of the Duero, indicating the risk zones of Safe-Operating-Space (SOS, in green), increasing risk (ZIR, in yellow), and high risk (ZHR or HZR, in red). Source D4.2: Duero. (García Menéndez et al., 2026).

3.2.5. Seine

The Seine river basin presents a unique challenge for water managers, as it is situated at the transitional boundary between two contrasting European climate zones: the drying southern regions and the increasingly wetter northern areas. This geographical position makes the basin particularly sensitive to climate variability and creates substantial uncertainty regarding future water availability, drought occurrence, and flood risks. Water management in the basin benefits from a system of four major upstream reservoirs with a combined storage capacity of approximately 810 million m³. Managed by EPTB Seine Grands Lacs in collaboration with governmental authorities and the Seine-Normandie Water Agency, these reservoirs serve multiple purposes, including flood mitigation, low-flow support, water supply, and the protection of aquatic ecosystems.

Climate projections consistently indicate a worsening of summer low-flow conditions in the Seine Basin due to rising temperatures, higher evapotranspiration rates, and declining summer precipitation. These trends are expected to reduce water availability during critical periods and increase pressure on water-dependent sectors and ecosystems. In contrast, future changes in annual precipitation and flood regimes remain highly uncertain, with climate models showing divergent results. This combination of robust drying signals during summer and uncertainty regarding high-flow conditions highlights the need for adaptive and flexible water management approaches.

Strengthening the resilience of the Seine Basin will require greater emphasis on reservoir operations to maintain downstream environmental flows and secure water availability during prolonged dry periods (Figure 3.6). At the same time, basin management strategies must be designed to cope with a wide range of possible climate futures, balancing drought preparedness, flood risk management, ecosystem protection, and socio-economic water demands. Such adaptive planning will be essential to ensuring long-term water security and resilience under increasing climatic uncertainty.

The comprehensive modelling framework developed during the STARS4Water project will continue to be further enhanced. Discussions with EPTB Seine Grands Lacs are ongoing to support the inclusion of water withdrawals (agriculture, water supply, industry, energy) and other water infrastructure operations (navigation) in the modelling framework. A 3-year study is planned to start in 2027 to co-develop water demand scenarios and analyse their joint effect with climate scenarios on the safe-operating- space risk assessment.

3.2.6. East Anglia

East Anglia is one of the most water-stressed regions in England, characterized by relatively low annual rainfall and high-water demand from agriculture, the energy sector, and public water supply. This combination of limited water availability and intensive water use makes the region particularly vulnerable to climate change. Future climate projections indicate hotter, drier summers and wetter winters, increasing the likelihood of both droughts and flooding while placing additional pressure on already constrained water resources.

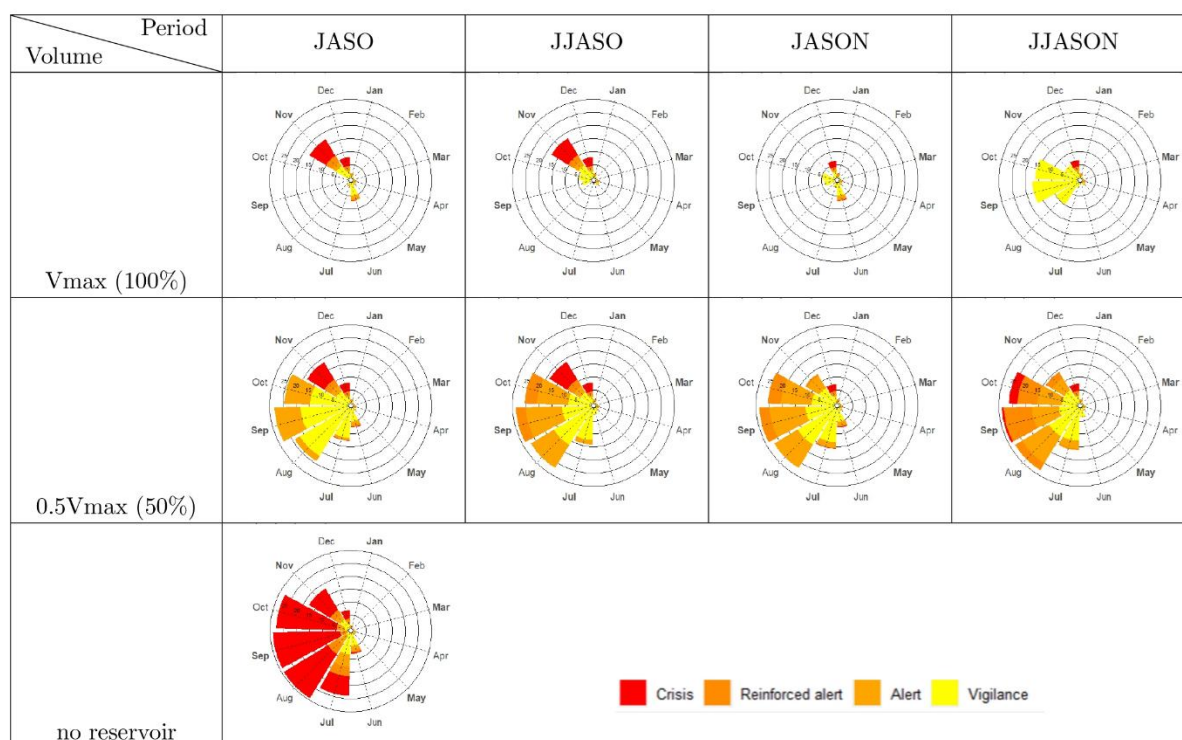


Figure 3.6. Average number of days per month (between 0 and 30 days) below each threshold for the station of Paris in the Sein Reiver basin, considering the projected driest climate scenario ICHEC-MOHC (2070-2098) and the management scenarios JASO, JJASO, JASON, JJASON. The first row shows the scenarios for which we start the release period with the reservoirs fully filled. The second row shows the scenarios for which we start the release period with only 50% of the reservoir capacity filled. Each column shows the management scenarios with different lengths of the release period from June (J) to November (N). Source: D4.2. Seine (Collignan et al., 2026).

The region's freshwater ecosystems, including its internationally important chalk rivers and streams, wetlands, peatlands, and other sensitive aquatic environments, are already experiencing significant ecological stress. Declining river flows, groundwater depletion, and water abstractions, compounded by the impacts of climate change, have contributed to the deterioration of ecosystem health across many catchments. Assessments of future ecological flow regimes indicate a medium to high risk of further environmental degradation, suggesting that without effective adaptation measures, the resilience of East Anglia's water-dependent ecosystems is likely to decline further in the coming decades.

Stakeholders in East Anglia highlighted the value of cross-basin learning and international partnerships in broadening and deepening their understanding of current and future climate risks. Through these collaborations, they gained access to a range of innovative approaches, including regression-based and machine learning techniques, to support the assessment of hydrological change and water-related risks. Furthermore, the application of environmental flow assessment methods and the Safe-Operating-Space concept offers a more holistic and inclusive framework than current modelling and management practices, enabling water managers to better balance the needs of ecosystems, water users, and climate resilience within future water resources planning.

3.2.7. Drammen

The Drammen River Basin in Norway is characterized by a snow-dominated hydrological regime that is highly sensitive to climate change. Rising temperatures and increasing precipitation are expected to substantially alter flow patterns across the basin. Observations already indicate earlier spring snowmelt and a reduction in the magnitude and frequency of traditional snowmelt-driven floods. At the same time, rainfall-induced flooding has become more common and is projected to intensify further as precipitation amounts and rainfall extremes increase over the coming decades.

Climate change is also expected to influence low-flow conditions. Although annual water availability may increase, projections suggest a longer duration of summer low-flow periods driven by higher temperatures, an extended growing season, and increased evapotranspiration. These changes are likely to affect water availability, ecosystem functioning, and the management of water-dependent sectors.

Like many Norwegian river systems, the Drammen River is an important source of hydropower generation. Increased precipitation may create opportunities for enhanced hydropower production (Figure 3.7). However, realizing these benefits will require adaptations in reservoir operation and water management practices. More flexible operating rules will be needed to accommodate higher and more variable flows, while balancing energy production, flood protection, ecological requirements, and water security. Such adaptations are essential to reduce the risks associated with both floods and droughts, strengthen climate resilience, and safeguard freshwater ecosystems and habitats under future climate conditions.



Figure 3.7. Annual mean hydropower production in light blue, and water loss (bypass and flood-loss) in light red the lower part of Krøderen subbasin: “less wet-scenario” RCP45 (left) and “warm-wet-scenario” SSP370 (right). Source: D4.2: Drammen (Hegdahl & Hisdal, 2026).

3.3. What have river basin stakeholders learned?

Stakeholders across the STARS4Water river basins perceived the partnership as a highly effective mechanism for bridging the gap between science and water management practice. The co-creation approach enabled researchers, water managers, policymakers, and other stakeholders to work together in identifying key water challenges, defining information needs, and evaluating potential adaptation measures. This collaborative process strengthened trust in the modelling results and ensured that the tools and services developed were directly relevant to management and decision-making.

The partnership significantly increased stakeholders' understanding of climate-related water risks by combining scientific expertise, modelling capabilities, monitoring data, and local knowledge. Through co-creation approach, stakeholders gained deeper insights into the drivers of droughts, low flows, water scarcity, floods, and ecosystem vulnerability, as well as how these risks may evolve under future climate and socio-economic conditions. The collaborative assessments helped identify risk hotspots, understand current operational limits, discuss thresholds and uncertainties, assess risks and vulnerabilities for society and ecosystems, and explore adaptation pathways.

An additional benefit highlighted by stakeholders was the opportunity for cross-basin learning and international knowledge exchange. By sharing experiences, methodologies, and innovative approaches across different European river basins, stakeholders were exposed to new techniques and perspectives that enhanced their capacity to assess climate risks and support more resilient and adaptive water resources management.

A key lesson from STARS4Water is that historical hydrological conditions can no longer be relied upon as a basis for future water resources management. Preparing for future climate challenges requires a shift from managing water systems based on past conditions to managing for an increasingly uncertain and changing climate.

Across the STARS4Water river basins, stakeholders observed growing pressures on water resources driven by the combined impacts of climate change and increasing water demands. While water scarcity has long been recognized as a major challenge in the Mediterranean region, the project demonstrated that it is becoming an increasingly significant concern in many river basins across Western and Central Europe as well. At the same time, the frequency and severity of hydrological extremes, including both droughts and floods, are expected to increase, placing additional pressures on water management systems.

Building water resilience therefore requires a holistic understanding of how hydrological systems are changing, including shifts in seasonal flow regimes, water availability, groundwater recharge, and the occurrence of extreme events. The climate risk assessments undertaken within STARS4Water highlighted that annual or multi-year averages can mask critical vulnerabilities and underestimate the impacts of hydrological extremes. For example, extreme low-flow years in the Rhine and Danube can cause prolonged disruptions to inland navigation, water supply, ecosystems, and economic activities, despite relatively moderate projected changes in long-term average river discharge. Recent low-flow conditions in these river basins further underscore the importance of assessing risks through the lens of extremes rather than averages.

Groundwater emerged as a critical source of climate resilience across many of the case-study basins, providing an important buffer against increasing climate variability and drought. However, declining aquifer recharge in semi-arid regions and continued over-abstraction threaten long-term water security. Protecting groundwater resources, improving monitoring and modelling, and enhancing natural and managed aquifer recharge should therefore be key priorities within future adaptation strategies.

Many river basins also reported deteriorating ecological conditions associated with altered flow regimes, increasing water temperatures, and excessive water abstractions. These findings demonstrate that healthy aquatic ecosystems are not only environmental assets but also a prerequisite for long-term water resilience. Environmental flows should therefore be treated as essential water demands rather than residual allocations after other needs have been met. They should be connected to hydrological modelling of water resources availability. In addition, nature-based solutions should continue to be encouraged and incorporated in the pathways for climate change adaptation, as they can play a vital role by delivering multiple benefits, including enhanced water retention, improved biodiversity, reduced climate risks, and increased ecosystem resilience.

Together, these findings highlight the need for adaptive, risk-based and integrated water management approaches that account for uncertainty, balance ecological and societal water needs, and evaluate future conditions across a range of plausible climate and socio-economic scenarios. Strengthening water resilience will require not only improved data, models, and monitoring systems, but also collaborative governance approaches that support informed decision-making and timely adaptation across sectors and scales.

4. Guiding principles for water resilience at basin level

Building water resilience requires a fundamental shift from reactive crisis response to proactive risk management that is informed by climate projections, scenario analysis, and long-term planning. Experiences from STARS4Water have demonstrated the value of this approach by fostering science-stakeholder partnerships that create a shared understanding of water risks and opportunities through a process of shared science (Figure 4.1). By bringing together scientific evidence, practical expertise, and stakeholder perspectives, STARS4Water provides a foundation for assessing water-related climate risks, exploring future scenarios on water resources availability, and identifying vulnerabilities for society, economy and ecosystems. The next step would be to co-design interventions and make decision about adaptive pathways for building water resilience. This chapter presents a guidance framework for building on these insights to support river basin managers, policymakers, and stakeholders in developing climate-resilient water management strategies that can adapt to increasing uncertainty and strengthen basin-wide resilience.

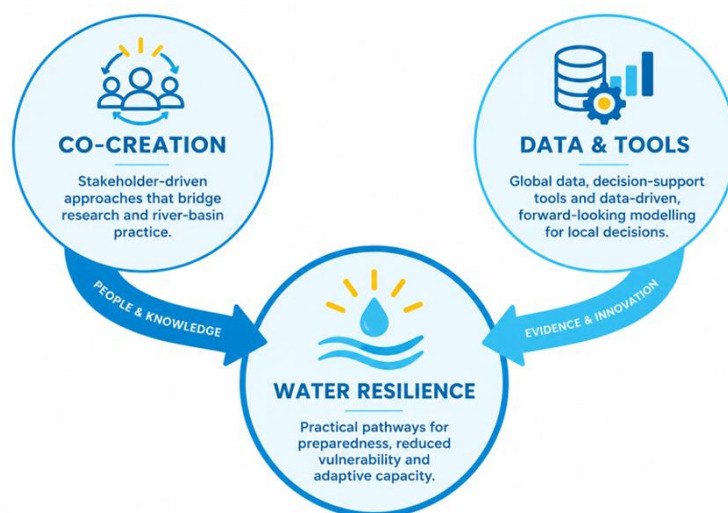


Figure 4.1. A stakeholder-centred co-creation approach for building water resilience at river basin level.

Guiding principles for understanding and managing climate change impacts on water availability, extreme events, and related vulnerabilities across river basins (Figure 4.2):

- Build strong science-stakeholder partnerships.** Place stakeholders at the centre of the assessment process and engage river basin stakeholders from the outset. Foster continuous collaboration throughout the project lifecycle to identify key water management challenges, define information needs, and jointly develop knowledge, scenarios, data services, and decision-support tools. A co-creation approach ensures that scientific research is aligned with real-world management and policy needs, enhances stakeholder ownership of the outcomes, and builds trust in the evidence generated. By actively involving stakeholders throughout the assessment process, the resulting tools, models, and services are more likely to be relevant, actionable, and adopted in practice, thereby strengthening the effectiveness of climate adaptation and water resilience strategies across the river basin.

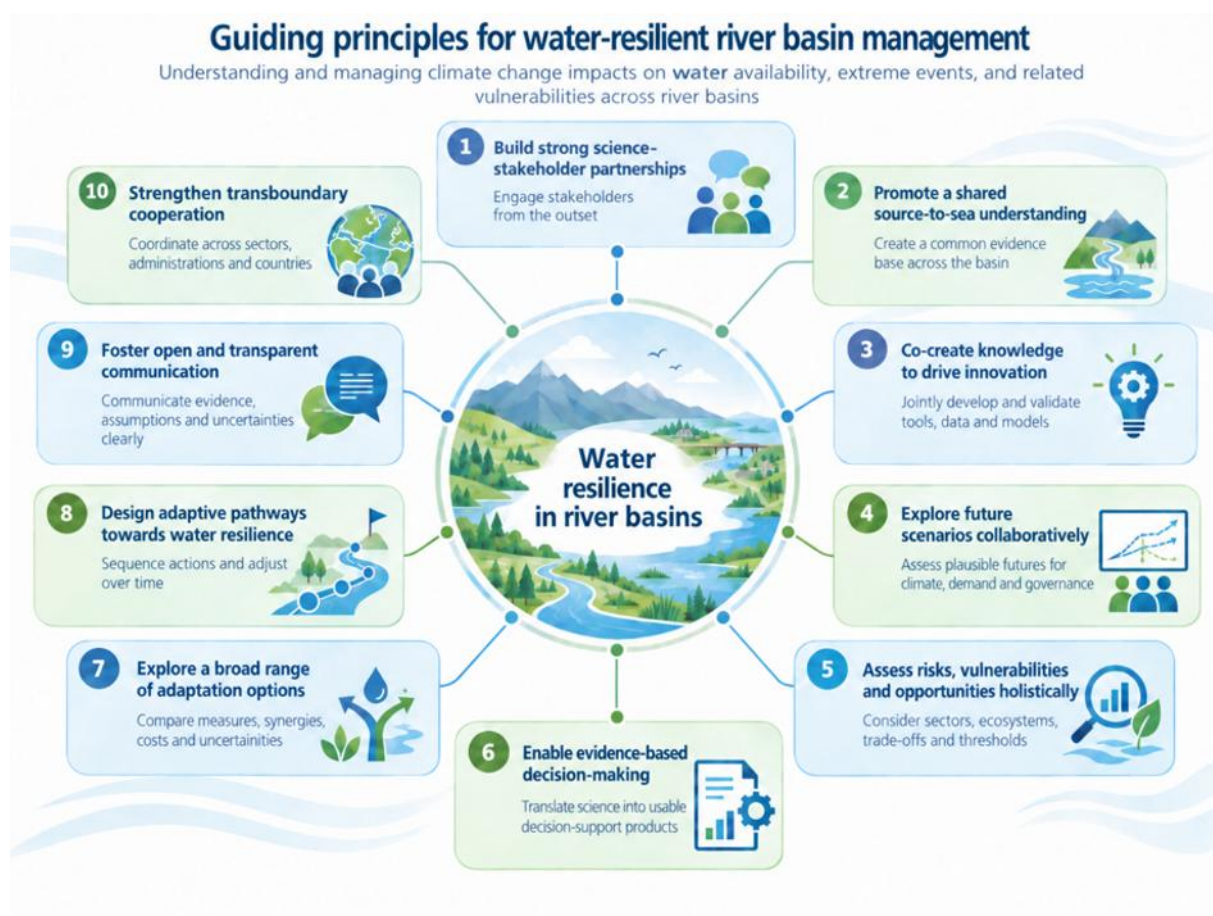


Figure 4.2. Guiding principles for water-resilient river basin management

- **Promote a shared source-to-sea understanding and data-wise river basin management.** Foster a shared, transparent and evidence-based understanding of current and future water-related climate challenges across the entire river basin. Different stakeholder groups face distinct challenges, operate at different spatial and temporal scales, and require different types of information to support decision-making. Establishing a common evidence base, built on transparent and shared data, indicators, monitoring information, and model outputs, is essential for facilitating stakeholder dialogue, strengthening transparency, and supporting coherent decisions on water management operations, planning, and long-term adaptation strategies. Include all water components of the hydrological cycles, including groundwater, soil moisture, glaciers, snowpacks. Combine climate projections, hydrological modelling, and data analytics with stakeholder experience and basin-specific expertise to improve the relevance and credibility of assessments.
- **Co-create knowledge to drive innovation.** Leverage the combined expertise of stakeholders and scientists to co-create next-generation data services and modelling tools to deepen understanding of river basin systems, generate new knowledge, and accelerate innovation in water management. Co-develop tools, co-design future scenarios, and jointly validate data, models, and results to ensure that scientific advances are robust, credible, and relevant to stakeholder needs. By integrating scientific knowledge, local expertise, monitoring data, and advanced modelling

capabilities, stakeholders can develop a more comprehensive understanding of climate risks, vulnerabilities, system behaviour, and potential adaptation pathways. The collaborative approach supports innovation, strengthens confidence in decision-support tools, and enables the identification of effective and resilient solutions for sustainable water management under changing climate conditions.

- **Explore future scenarios collaboratively.** Develop and assess plausible futures through the joint design of narratives and scenarios, addressing trends in domestic water use and water demands by economic sectors. Integrating climate change projections, trends in water use or demand, infrastructure developments, governance strategies, and ecosystem requirements enable stakeholders to identify emerging challenges, evaluate adaptation options, and understand the implications of different development trajectories.
- **Assess risks, vulnerabilities, and opportunities holistically.** Evaluate current and future water management actions and adaptation strategies to understand their implications for river basin resilience. Assess how climate change may affect water availability, droughts, floods, water quality, and other extreme events, providing information that supports practical adaptation and management decisions. Evaluate climate risks from a multi-sector perspective, considering impacts on water-dependent ecosystems, agriculture, energy production, navigation, industry, public water supply, and communities. Scenario assessments support proactive decision-making by revealing future challenges, vulnerabilities, opportunities, trade-offs and operational boundaries, thereby strengthening the resilience and sustainability of river basin management under future climate conditions. Identify conditions that may push water systems towards critical thresholds.
- **Enable evidence-based decision-making.** Apply the Safe-Operating-Space concept to support climate-resilient and sustainable water management. Identify the conditions and pressures that may push water systems towards critical ecological, hydrological, or socio-economic thresholds, and assess how these thresholds may be affected by climate change, increasing water demands, and management interventions. The Safe-Operating-Space concept provides a valuable framework for understanding system limits, evaluating risks, and defining operational boundaries within which water resources can be managed sustainably. To maximize its value for decision-making, scientific information on risks, thresholds, vulnerabilities, and adaptation options should be translated into actionable and accessible decision-support products that are understandable, transparent, and usable by stakeholders. These may include interactive dashboards, visualizations, story maps, risk indicators, operational forecasting tools, and policy briefs tailored to different stakeholder groups. By providing clear and evidence-based information, the Safe-Operating-Space concept can support strategic planning, guide investments, strengthen adaptive management, and enhance the long-term resilience of water resources systems under a changing climate.
- **Explore a broad range of adaptation options.** Systematically identify, assess, and compare potential measures, strategies, and innovations to address water-related climate risks. Consider trade-offs, synergies, costs, benefits, and uncertainties to support resilient and sustainable river basin management.
- **Design adaptive pathways towards water resilience.** Use climate impact assessments and evaluation of adaptation options to develop flexible and robust pathways that enable stakeholders to respond to changing climate, socio-economic, and environmental conditions over time. Sequence actions strategically, identify decision points, and maintain the capacity to adjust course as new knowledge and conditions emerge.

- **Foster open and transparent communication.** Promote continuous, inclusive, and accessible dialogue among stakeholders, scientists, policymakers, and communities. Ensure that information, assumptions, uncertainties, and decisions are communicated clearly to build trust, understanding, and shared ownership.
- **Strengthen transboundary cooperation.** Encourage collaboration across administrative, sectoral, and national boundaries to address shared water-related challenges. Build common understanding, align objectives where possible, and support coordinated action to enhance resilience across the entire river basin.

5. Final remarks and conclusions

To be better prepared for future water-related challenges, our findings underscore the urgent need for data and tools that support an integrated modelling approach to water management, where physical factors, socio-economic dimensions and management operations come together. This is not only a key issue at the local or river basin scale, but also at regional scales, across neighbouring basins linked through surface and groundwater interdependencies, or across regions linked by shared services, such as those offered by hydropower grids in the energy sector.

The European Water Resilience Strategy acknowledges that well-functioning water cycles from source to sea are essential for water resilience. River basin organisations and basin stakeholders are essential for mainstreaming actions and water resilience solutions. The European Water Resilience Strategy faces critical implementation gap risks in understanding the changes in hydrological cycles at river basin scale, evolving flow regimes in catchments and aquifers, and the complex human-water interactions that shape water availability. To tackle this, an agile multi-level governance approach is required, with each governance level having clearly defined roles and responsibilities. This includes the specific role of river basin organisations in mainstreaming actions and solutions that support the restoration of hydrological cycles from source-to-sea. While the strategy does not create new formal roles for river basin organisations, it strongly reinforces their importance at the operational level where climate change impacts are already being felt. Many river basin organisations face systemic, institutional, financial, and technical challenges that can significantly hinder implementation.

River basin water management involves multiple sectors, such as agriculture, energy, industry, and urban planning, often with competing water uses. Fragmented governance is recognised as a major barrier to effective water management. In transboundary river basins, the additional governance challenge is the coordination across countries, as it is usually politically sensitive. Water resilience is inherently cross-sectoral. This also implies that agricultural practices, land use planning, water infrastructure development, and hydropower production need to integrate with river basin management objectives regarding water resilience. Achieving water resilience relies upon the active involvement of basin stakeholders representing economic sectors and societal organisations. Thus, we need to ‘mainstream’ working with all sectors of society to deliver water resilience solutions.

The STARS4Water Safe-Operating-Space framework is a valuable tool to enhance the understanding of future water resources availability at the river basin scale under changing climate and socio-economic developments and to identify risks of the current operations. It is inclusive, adaptative and flexible enough to incorporate new stakeholder needs and indicators, additional data services, and enhanced modelling tools. Applying the Safe-Operating-Space concept in river basin management is not straightforward. Effective stakeholder engagement is crucial to build a shared understanding of the concept and to clarify how it complements existing approaches, such as risk assessments and scenario-based analyses used in climate impact assessments and adaptation planning.

Setting clear limits on water abstraction from groundwater, rivers, and lakes is fundamental to safeguarding a sufficient, reliable, and sustainable water supply for both human use and ecosystems, under current conditions and future pressures related to climate change, population growth, and economic development. These limits should be grounded in robust assessments of ecological and hydrological needs to prevent overexploitation.

Across European river basins in STARS4Water, responses to water scarcity and drought vary in their level of coordination. While some countries have established national frameworks to prioritise water use during low-flow periods, recent dialogues and discourse highlight the need for stronger mechanisms to enable fair and sustainable water allocation. Overall, significant challenges remain in transitioning societies and economic sectors towards more sustainable and climate-resilient water-sharing approaches, particularly in regions facing higher levels of water scarcity or drought vulnerability.

Many river basin organisations have limited expertise and capacity to address the system complexity and climate uncertainty required to support decision making on cross-sectoral trade-offs and implement effective water resilience solutions. Data, tools and knowledge limitations at river basin organisations constitute a significant gap in the understanding of basin dynamics and how climate change and future water use will impact the availability of water resources.

The experiences gained through STARS4Water demonstrate the value of bringing science and practice together to address complex water management challenges. By fostering strong partnerships among researchers and river basin stakeholders, the project helped create a shared understanding of current and future water resource challenges. This process of co-creation not only strengthened the scientific evidence base for decision-making but also built trust, stakeholder ownership, and collective capacity to address increasingly complex climate-related water risks.

Future research and innovation initiatives should adopt and maintain stakeholder-driven co-creation processes throughout the project lifecycle. Early and continuous engagement with stakeholders is essential to identify emerging challenges, define information requirements, and ensure that modelling and data service developments respond to real management needs. Such an approach will enhance the relevance, uptake, and impact of scientific innovations while supporting more resilient and adaptive water management under changing climatic conditions.

In addition, STARS4Water promoted cross-learning and knowledge exchange among the seven river basin hubs by facilitating the sharing of approaches, tools, experiences, and best practices. This was achieved through a series of stakeholder workshops, joint learning activities, and exchanges on data services, modelling innovations, and assessment results. These interactions enabled river basin partners to learn from one another's experiences and to explore the transferability of methods and tools across different hydro-climatic and governance contexts. A notable outcome of this collaborative approach was the application of ecological flow assessments using the STARS4Water E-flow tool in all seven river basin hubs. In addition, several other modelling tools and assessment approaches developed within the project were adopted and applied across multiple basins, demonstrating their flexibility and relevance under diverse environmental and institutional conditions (Baron & Keller, 2026; Avila & Kollet, 2026). These experiences highlight the potential of collaborative learning and co-development processes to accelerate the uptake of scientific innovations and strengthen the capacity of river basin authorities to prepare for and respond to future water resource challenges.

A key lesson from STARS4Water is that effective adaptation is not achieved through technical solutions alone. Resilience emerges from collaborative processes that integrate scientific knowledge, local expertise, and stakeholder perspectives. Co-designing interventions within a shared framework allows river basin actors to identify feasible and widely supported measures that are both locally relevant and scientifically robust. The guidance framework presented in this report builds on these lessons. It provides a framework for using scientific evidence, practical insights, and stakeholder engagement to support climate-resilient river basin management. By applying these principles, river basin authorities and their partners can better prepare for future uncertainties, strengthen adaptive capacity, and

develop resilient water systems that continue to deliver environmental, social, and economic benefits under changing climatic conditions.

Building water resilience in river basins requires a transition from reactive crisis management to proactive and adaptive risk management. As climate change increases hydrological uncertainty and the frequency of extreme events, water governance must be guided by future-oriented approaches that combine climate projections, scenario analysis, and long-term planning. Such approaches enable decision-makers to anticipate risks, evaluate trade-offs, and identify robust pathways towards resilient basin management.

Improving the understanding of vulnerability therefore provides a more tractable and actionable pathway for enhancing climate resilience than attempting to directly influence the occurrence of hazards. In the water sector, vulnerability assessments can be strengthened through detailed analyses of hydrogeological and hydrogeochemical processes, including aquifer-wetland interactions, recharge-discharge dynamics, groundwater dependency, and hydroperiod variability. Such knowledge helps identify critical thresholds, vulnerable ecosystem components, and management options that can reduce the impacts of droughts, floods, and other climate-related pressures. Accordingly, advancing vulnerability assessment should be considered a central pillar of climate adaptation strategies. By improving understanding of the factors that determine system resilience and adaptive capacity, water managers and policymakers can design more targeted and effective interventions. Since vulnerability is the component of risk most directly influenced by management actions, strengthening its assessment offers one of the most promising avenues for building long-term climate resilience in river basins and water-dependent ecosystems.

Ultimately, achieving water resilience is an ongoing process rather than a fixed endpoint. Continued collaboration, learning, and adaptation will be essential to ensure that river basins remain resilient in the face of evolving challenges. The STARS4Water approach offers a practical foundation for this journey, demonstrating how shared understanding and co-designed action can support sustainable and climate-resilient water futures.

References

- Avila, L. & Kollet, S. (2026). *Multi-scale model integration: Improving existing models based on multi-scale model integration*. Deliverable 3.3. Version 1.2. STARS4Water Project. Horizon Europe Grant Agreement No 101059372.
- Baulenas, E., G. Versteeg, M. Terrado, J. Mindlin & D. Bojovic, 2023. Assembling the climate story: the use of storyline approaches in climate-related science. *Global Challenges*. <https://doi.org/10.1002/gch2.202200183>.
- Baron, H. & V. Keller, 2026. Data-driven water resources modelling tools. STARS4Water. Deliverable D3.4.
- Beckers, J., 2025. *Next generation data services*. STARS4Water Deliverable D2.4.
- Beek, E. van, A.J. Nolte, J. ter Maat, M. Faneca-Sachez, N. Asselman & H. Gehrels, 2022. *Strategic water system planning. A framework for achieving sustainable, resilient and adaptive management*. Deltares, Delft.
- Blind, M., 2025. *Workshop report on capacity building for using the models, services and dashboards*. STARS4Water. Deliverable D5.1.
- Browder, G., A. Nunez-Sachez, B. Jongman, N. Engle, E. van Beek, M.C. Errea & S. Hodgson, 2021. *An EPIC response: Innovative Governance for Floods and Drought Risk Management*. The World Bank, GFDRR, GWSP, Deltares. Washington D.C.
- Collignan, J., A. de Lavenne, M.-H. Ramos, 2026. *Seine*. Ramos, M.H. (eds.), 2026. Improved projections on water resources availability and risks in selected river basins. STARS4Water Deliverable D4.2., p. 65-70.
- Duel, H., H. Wolters, I. Timboe, J. ter Maat & J. Matthews, 2022. *HELP Guiding Principles for Drought Risk Management under a Changing Climate. Catalysing actions for enhancing climate resilience*. High-level Experts and Leaders Panel on Water and Disasters (HELP).
- EEA, 2024. *European Climate Risk Assessment*. European Environment Agency. Report 01/2024.
- García Menéndez, O., H. Aguilera, Á. De la Hera-Portillo, P. Martínez-Santos, V. Gómez-Escalonilla, L. Moreno Merino, 2026. *Duero*. In: Ramos, M.H. (eds.), 2026. *Improved projections on water resources availability and risks in selected river basins*. STARS4Water Deliverable D4.2, p. 29-38.
- Glas, M., T. Graf, F. Monji, M. Klösch, M. Preiml, A. Scricciu, A. Toma, J. ter Maat & H. Habersack, 2026. *Danube*. In: Ramos, M.H. (eds.), 2026. *Improved projections on water resources availability and risks in selected river basins*. STARS4Water Deliverable D4.2., p. 15-20.
- Green Climate Fund, 2022. *Water security sectoral guide*. Sectoral Guide Series. Korea.
- Haasnoot, M., J.H. Kwakkel, W.E. Walker & J. ter Maat, 2013. Dynamic policy pathways: a method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change* 23 (2): 485 – 498.
- Habersack, H., M. Glas, T. Graf, M. Klösch & M. Prieml, 2026. *Added value of next generation modelling frameworks*. STARS4Water. Deliverable 4.1.
- Hegdahl, T.J., J. ter Maat, J. Kruijshoop & H. Hisdal, 2023. *Stakeholder engagement plan*. STARS4Water Deliverable D1.1.

- Hegdahl, T.J. et al., 2023. *Assessment and needs on data services and modelling tools for stakeholders in selected European river basins*. STARS4Water. Deliverable D1.2.
- Hegdahl, T.J., & H. Hisdal, 2026. *Drammen*. In: Ramos, M.H. (eds.), 2026. Improved projections on water resources availability and risks in selected river basins. STARS4Water Deliverable D4.2., p. 21-28.
- Hurk, B. van der, 2022. Impact oriented climate information selection. In: Kondrup et al. (eds): *Climate Change Adaptation Modelling*. Springer.
- Krichene, H., M. Aichinger, K. Wenigmann, R. Papaoiannou & K. Uthermöhl, 2026. Europe under water: The macroeconomic cost of flooding and the economic case for adaptation. Allianz Research. Report.
- Maat, J. ter, T. Edler, D. Purnamasari & E. Mes, 2026. *Water resources modelling framework for the Rhine basin*. In: Preiml, M., Klösch, M., Glas, M., Graf, T. & Habersack, H. (2026): Added value of next generation tools. Deliverable 4.1 (D4.1). Horizon Europe project STARS4Water, p. 9-12.
- Maat, J. ter, 2026. *Guidance on new data services and modelling tools*. STARS4Water Deliverable D5.4.
- Malyar, I., J.H. Matthews, D. Ravindranath, H. Duel & M. Shouler, 2025. *Global Trends in climate-water resilience 2025: Navigating the Policy, Finance, and Climate Landscape*. Water Resilience Tracker.
- Mendoza, G., A. Jeuken, J. Matthews, E. Shakiv, J. Kucharski & K. Kilroy, 2018. *Climate risk informed decision analysis (CRIDA). Collaborative water resources planning for an uncertain future*. UNESCO & ICIWaRM. Paris, France and Washington, USA.
- Mes, E. & T. Edler, 2024. *Dashboard to support decision making on water resources management at river basin level: prototype*. STARS4Water. Deliverable D1.4.
- OECD, 2018. *Implementing the OECD principles on water governance: Indicator Framework and Evolving Practices*. OECD Regional Development Policy Committee. Paris. <http://dx.doi.org/10.1787/9789264292659-en>.
- Panella, T., et al., 2020. *Asian water development outlook 2020: advancing water security across Asia and the Pacific*. Asian Development Bank. <http://dx.doi.org/10.22617/SGP200412-2>.
- Ramos, M.H. (eds.), 2026. *Improved projections on water resources availability and risks in selected river basins*. STARS4Water Deliverable D4.2.
- Rickards, N., S. Kollet & V. Keller, 2023. *Gap analysis of existing tools in the river basins*. STARS4Water Deliverable D3.1.
- Rickards, N. & V. Keller, 2026. *Improved water resources modelling frameworks*. STARS4Water. Deliverable D3.2.
- Taner, U., D. Purnamasari & J. ter Maat, 2026. *Rhine*. In: Ramos, M.H. (eds.), 2026. Improved projections on water resources availability and risks in selected river basins. STARS4Water Deliverable D4.2., p. 57-64.