



STARS 4 Water

Policy synthesis report: a blueprint for strengthening EU water policies and actions

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Summary

This policy synthesis report translates the findings from river-basin and pan-European risk assessments into recommendations for strengthening European Union (EU) water policies and actions. It serves as a practical blueprint for enhancing water resilience across Europe and provides a transferable framework that can be adopted by other river basins facing similar challenges.

Drawing on evidence from seven European river basin hubs, the report examines the major water-related risks affecting Europe, including water scarcity and droughts, flooding, and declining water quality, all of which are being exacerbated by climate change. It assesses how existing EU water legislation and the broader policy objectives of the European Green Deal address these challenges and identifies opportunities to further strengthen resilience.

The report also evaluates the contributions of STARS4Water to the objectives of the European Water Resilience Strategy. It highlights the value of advanced data services, integrated modelling frameworks, and stakeholder-driven assessment approaches that improve understanding of current and future water risks. These innovations support evidence-based decision-making and enable more adaptive, resilient, and sustainable management of freshwater resources across Europe.

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1. Introduction

1.1. The STARS4Water project

The STARS4Water project “Supporting STakeholders for Addaptive, Resilient and Sustainable Water Management” is a four-year collaborative Horizon Europe project comprised of 21 institutional partners from 10 countries. The project started in October 2022 and aims to improve understanding of climate change impacts on water resource availability and the vulnerabilities of ecosystems, society, and the economy at the river basin scale, providing actionable knowledge, tools, and guidance to support policy and practice. It includes two distinctive elements:

- the need for an international stakeholder community to address their specific needs and requirements;
- the development and application of innovative data services, models, and tools.

The specific project objectives are:

1. to provide stakeholders with new generation data services and data-driven models tailored to their needs and requirements;
2. to improve the accuracy and resolution of regional-scale projections of water resources availability;
3. to enhance the knowledge base and the scientific underpinning of climate risks and impacts, in various scenarios and time horizons;
4. to support decision-making through the development of dashboards: co-designed and co-developed information systems;
5. to promote uptake and transferability of the data services and tools through guidance documents and capacity building activities.

The STARS4Water project covers seven diverse river basin hubs across Europe (Figure 1), ranging from the relatively small Messara Basin in Crete (Greece), to large national river basins such as the Drammen, East Anglia, and Seine, and extending to major international basins including the Danube, Duero, and Rhine. This diversity in basin size, hydrological characteristics, climate conditions, topography, and land use enhances the relevance and transferability of the project's findings across a wide range of European settings.

The river basin hubs also represent a broad spectrum of water management challenges and governance contexts. They encompass key areas of water resources management, including reservoir operations, ecosystem and river ecology management, groundwater recharge, and water demand management. By addressing these varied conditions and management needs, STARS4Water generates knowledge, tools, and approaches that can support water resilience planning and decision-making across different river basins in Europe.



Figure 1. The seven river basin hubs represent a diverse portfolio of climate vulnerabilities and adaptation needs across sectors and include Danube, Drammen, Duero, East Anglia, Messara, Rhine and Seine.

The project has developed and delivered new data services and data-driven models to support better decision-making in planning actions for the adaptive, resilient, and sustainable management of freshwater resources, co-designed with stakeholders to meet their needs and ensure their relevance and uptake beyond the project's lifetime. Following a co-creation process across seven river basin hubs, the project aimed to provide stakeholders with next-generation river basin tools and to build a strong community of practice.

The new services and models were developed in close consultation and collaboration with stakeholders from seven river basin hubs to meet their needs and promote the uptake of data services beyond the project's lifetime. The river basin hubs served as living labs for co-creating data services and tools with stakeholder communities and as accelerators for further upscaling these services and tools to other river basins across Europe.

Geophysical, hydro-meteorological, and various other spatial data play an important role in the project. Many datasets were already used by river basin authorities to manage their systems. However, the STARS4Water project team believes that the utilization of global data can be improved. A vast amount of data is produced continuously, and river basin authorities often lack the capacity to keep track of all new data sources and developments. Some available datasets remain unknown to river basin authorities and are difficult to access or apply at the river basin scale.

Existing data sets and data services from earth observation initiatives (Copernicus, GEOSS), JRC activities, and earlier EU research projects are underexploited by public and private stakeholders in water resources planning. Earth observation and other data sources have the potential to improve the accuracy and spatial resolution of models and decision support tools currently used in water resources management and climate change adaptation. Moreover, data science techniques like machine learning have resulted in new modelling approaches and ways to combine data and generate new insights. The STARS4Water project built on these new technologies to develop and improve data services and data-driven models, particularly regarding water use by economic sectors and the impacts on water resource availability for ecosystems and on water quality.

The project assessed water-related challenges across a range of European river basins, with findings that are scalable and relevant at the pan-European level. It addressed the three principal categories of water-related risks: water deficits and scarcity, destructive excess water events such as floods, and declining water quality. These interconnected challenges were examined through an assessment framework, recognising that climate change is intensifying the frequency, severity, and complexity of all three and increasing pressures on water resources, ecosystems, and society across Europe.

In the project, the category of stakeholders is understood broadly as those holding stake in freshwater: policy makers in administration (national, provincial, regional, local); sectoral administration (of water, agriculture, energy, transport, environment); river basin organisations and river basin communities; education and research; as well as civil society (NGOs); media; and broad public with interest in water.

The structure of the project is presented in Figure 2.

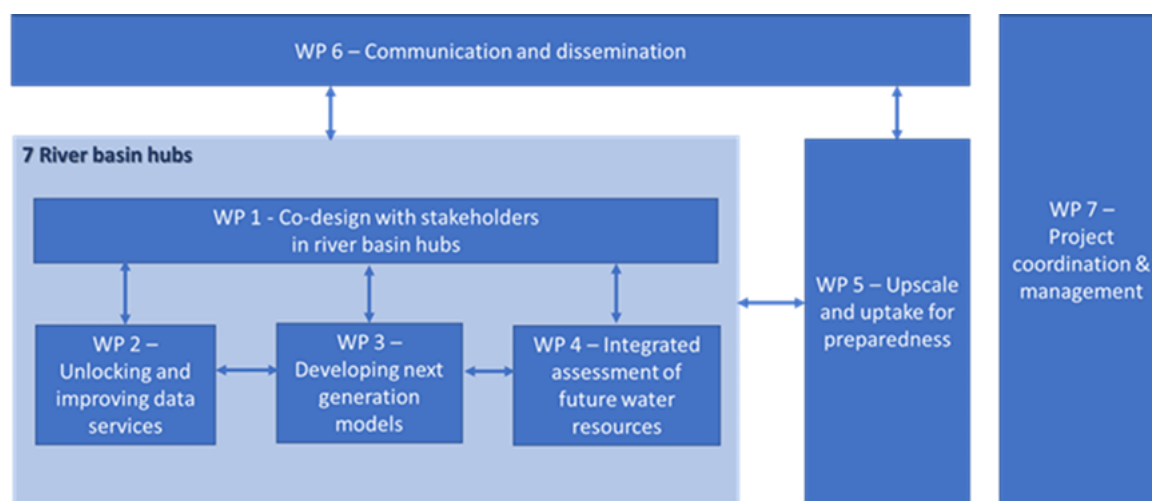


Figure 2. Work package structure of the STARS4Water project: the development of the next generation models (WP3) through a co-creation approach (WP1), benefiting from data sources available (WP2) and calibration and validation activities in WP4 to explore future water resources availability in European river basins (WP4).

1.2. Upscaling and uptake for preparedness

The Work Package 5 (WP5) “Upscale and uptake for preparedness” was intended to synthesize the results from risk assessments at river basin and pan-European level and promote uptake and upscaling to support river basin managers and EU member states in preparing for climate change impacts with respect to water resources management. The specific objectives of this WP are:

- to develop a synthesis report for guidance to practitioners' climate risk assessments (Task 5.1);
- to upscale from the seven river basin hubs to other river basins inside and outside the EU, supported by a multidimensional analysis (Task 5.2);
- to develop technical guidance on data and model innovations to river basin practitioners for capacity building purposes (Task 5.3);
- to create a Story Map website for International Networking, capturing main insights and recommendations for adaptation in co-design with stakeholders (Task 5.4); and
- to support the EU Green Deal and the EU water policies and prepare a 'blueprint' with recommendations for strengthening EU policies and actions (Task 5.5).

The present project deliverable, D5.6, "Policy synthesis report: a blueprint for strengthening EU water policies and actions," is an outcome of Task 5.5. The aim of this deliverable is to serve as a 'blueprint' containing recommendations for strengthening European Union (EU) policies and actions, based on the results of risk assessment at the river basin level and at the pan-European scale in relation to the EU Green Deal and the EU water policies. The expected audience for this report includes policymakers at various levels and individuals involved in implementing water policies.

1.3. Content of this report

The present deliverable consists of seven chapters. After the present introductory chapter, a brief presentation of Europe's water challenges, organized around problems of water quantity, then water quality, and ecosystem degradation, is provided in Chapter 2. In Chapter 3, responses to challenges and solutions of freshwater problems in Europe are tackled in the order corresponding to the challenges presented in the earlier chapter. Then, EU water policies and the water context of the EU Green Deal are examined in Chapter 4. Among the reviewed policies are - Water Resilience Strategy; EU Governing Missions ("Restore our ocean and waters" and "Adaptation to climate change"); EU water-related directives; and EIT Water. In Chapter 5, STARS4Water's contribution to water resilience is examined, focusing on how STARS4Water can facilitate the EU Water Resilience Strategy. A synthesis of findings is organized around building resilience through integrated data, modelling, and decision support. Project's contribution towards the interface between scientists and stakeholders – co-creation and uptake; data and modelling tools; and living labs at river basin hubs is analysed next. Finally, recommendations for enhancing the knowledge base to support the EU Water Resilience Strategy and related water policies are presented in Chapter 7.

2. Europe's freshwater challenges

2.1. Introduction

Europe's freshwater resources are under considerable and growing pressure, facing a range of serious challenges. These challenges also apply to the various river basin hubs assessed in the project. Many parts of Europe face water resources challenges related to scarcity, floods and pollution, which can lead to ecosystem and habitat degradation. There are many more challenges, among which aging infrastructure (sewage and water treatment plants, piping, and structural flood defenses) and investment gaps are most prominent. Advanced pollutant removal is increasingly costly; for example, micropollutant removal alone considerably increases household wastewater treatment costs.

Freshwater challenges and pressures can interact in a complex way, leading to a compound (cascading) risk. For example, water pollution exacerbates water scarcity, and scarcity worsens pollution; flooding impairs water quality, droughts adversely affect ecosystems, and floods damage infrastructure. Dilution is not a solution to pollution, but during low flows, the likelihood of a major environmental incident due to pollution increases even with a “usual” influx of contaminants. “Usual” influx of salty waters from the mining area to the river was undoubtedly one of the reasons for the Odra (Oder) ecological disaster in the summer of 2022 (Free et al., 2023), when golden algae (*Prymnesium parvum*) bloom killed around 1000 tons of fish. Similarly, floods may increase the risk of pollution. Intense rainfall flushes fertilizers and pesticides from fields, and the inundation of sewage treatment plants directly releases contaminants into rivers.

Climate change exacerbates freshwater challenges in Europe. In a warming climate, many extreme weather events are increasing in frequency, intensity, and duration. Heatwaves, prolonged droughts, and devastating floods damage ecosystems and human health and cause major disruptions to economic activities. Since many of Europe's rivers and lakes are international surface waters, shared by multiple countries, cross-border water management is essential.

The EU Member Countries report that the main pressures on their surface waters are linked to water quality - pollution from diffuse sources (e.g., atmospheric deposition and agriculture) and point sources, such as from wastewater discharges; and water quantity (high abstractions, as water demand is high compared to water availability) (EEA, 2024). Also, changes to the physical features and natural flow of rivers, lakes, transitional and coastal waters are a recognized pressure.

Three overarching challenges facing future European water management, as identified in (EEA, 2024), are:

1. protecting and restoring aquatic ecosystems;
2. achieving zero-pollution ambition;
3. adapting to water scarcity, drought and flood risks.

2.2. Water quantity challenges

The slogan “global water bankruptcy”¹ does not hold for most of Europe that has, on average, relatively abundant freshwater resources. However, the severity of problems related to freshwater availability in Europe is on the rise. Water resources may be insufficient in some regions during specific seasons; thus, the uneven distribution of freshwater resources, both spatially and temporally, is a major water management challenge. Some countries (e.g. Iceland, Norway) are water-rich, while southern and eastern regions face chronic water shortages. In contrast, in Malta and Cyprus, renewable per capita freshwater resources are below the water scarcity threshold of 500 m³/cap/year, whereas in the Czech Republic and Poland, below the water stress threshold of 1700 m³/cap/year (Kundzewicz et al., 2021).

On average, water stress affects 20% of Europe's territory and 30% of the population every year (EEA, 2024), and the severity of the problem is likely to increase in the future due to climate change. Water stress is linked to water use, and currently, we already have many areas with overexploitation of water resources, including groundwater, mainly for agricultural purposes. In Mediterranean and southeastern river basins, human withdrawals regularly exceed sustainable levels. The Water Exploitation Index Plus (WEI+)² attains its highest values in Cyprus and Malta, where water stress is chronic, but high stress also occurs in Romania, Spain, Italy and Greece. This refers to the overextraction of both surface water and groundwater.

Groundwater is a very important resource, because it supplies about two-thirds of the EU's drinking water and supports aquatic ecosystems. In 2021, 91% of the groundwater area was reported as being in good quantitative status (EEA, 2024).

Agriculture is by far the largest net water consumer in Europe, and without changes in practices, demand from irrigated agriculture is likely to increase drastically as the climate changes. In some countries, such as Poland, the transition from rain-fed to irrigated agriculture is likely to have a considerable impact on water availability. In STARS4Water hubs, we have reservoir management issues too, related to hydropower and conflicting uses (Drammen), as well as sustaining droughts and downstream users (Seine).

Intense rainfall has already increased in parts of Europe and is projected to intensify further under a warmer climate. Under Clausius Clapeyron law, there is more room for water vapor in the warmer atmosphere, hence the risk of heavy rainfall, its intensity and frequency, that may lead to flash floods and urban floods, is on the rise (Kundzewicz and Pińskwar, 2022).

Also, droughts are projected to become more frequent, more intense, and longer lasting due to climate change³. In many parts of Europe (particularly in the south, but increasingly in Central Europe as well), the climatic water balance during the vegetation period is negative, reflecting lower precipitation than evapotranspiration. Thus, precipitation levels are below the vegetation water demand.

Floods and droughts compromise water security, thereby affecting food, human, and environmental health, ultimately undermining social cohesion and stability and incurring high economic costs.

¹ <https://news.un.org/en/story/2026/01/1166800>

² https://ec.europa.eu/eurostat/databrowser/product/page/sdg_06_60

³ <https://water.europa.eu/freshwater/europe-freshwater/freshwater-themes/drought>

Financial losses caused by drought and flood events can be significant. For instance, the continent-wide drought and heat event in 2022 cost up to €40 billion, while the 2021 flood event in Germany, Belgium, and the Netherlands cost €44 billion (EEA, 2024).

The adverse impact of low flows on navigation is of increasing concern, e.g., for two project river basin hubs - the Rhine and Danube.

2.3. Water quality challenges

Europe's water continues to be impacted by chemicals. In 2021, only 37% of surface water bodies in Europe were in good or high ecological status and only 29% were in good chemical status (EEA, 2024). Failing even one water quality parameter means that an overall good status cannot be achieved.

The 2015 deadline originally set by the Water Framework Directive (WFD) (Section 4.4.4), for European waters to reach good quality status, was not met. Unfortunately, the situation has hardly improved since 2015.

The lack of significant progress in chemical status in Europe's surface waters can be partly attributed to long-lived pollutants that are particularly challenging to remediate, such as mercury and brominated flame retardants. Without considering these substances, the statistics look much better, with good chemical status achieved in 80% of surface waters (and 14% in unknown status).

About 77% of the EU's groundwater area is in good chemical status. Nutrients and pesticides are a particular threat to groundwater, with 14% of groundwater areas failing due to nutrients and 10% due to pesticides (EEA, 2024). However, average nitrate concentrations in groundwater have not declined during 2000-2021.

The main water pollutants include diffuse (non-point source) pollution mainly due to chemicals used in agriculture (fertilizers, pesticides, and herbicides) and diffuse atmospheric pollutants from coal-powered energy generation; point-source pollution by heavy metals, industrial chemicals (e.g., ammonia, chloride), and emerging contaminants (e.g., microplastics, per- and polyfluoroalkyl substances - PFAS). Pharmaceuticals, including antibiotics, as well as antibiotic-resistant bacteria in water, are another source of concern from human and environmental health perspectives. Persistent harmful substances called "forever chemicals" (such as PFAS) are of particular concern, because they stay in waters for very long. Their breakout is very slow and their long-term effect on life is not well understood yet.

2.4. Ecosystem degradation

Inadequate quantity and quality of surface water and groundwater may cause degradation of aquatic ecosystems such as wetlands, floodplains, rivers, lakes and ponds. The natural flow and physical features of surface water bodies are altered by many human activities, including urban development, hydropower, irrigation, navigation, structural flood protection and withdrawal of water for industry, energy, drinking, and households. Such changes already affect or destroy natural habitats and affect species dependent on the original habitat (e.g., prohibit the spawning of migratory fish).

The majority of protected aquatic habitats and species in the EU are assessed as having a poor or bad conservation status, showing little to no recovery (EEA, 2024). Reporting under the Water Framework Directive (see 4.4.3) shows that the status of some aquatic plants has improved, but this rarely translates into attaining an overall good ecological status.

Failure to achieve a good ecological status shows that European aquatic ecosystems are seriously degraded. Complementary evidence reported under the Habitats Directive shows that only 17% of protected river, lake, alluvial and riparian habitats in 2013-2018 were in good conservation status (EEA, 2024). About 89% of protected wetland habitats had poor or bad conservation status and were still suffering from multiple pressures, including land drainage, habitat conversion and agricultural intensification. Most protected fish and amphibian species were in poor or bad conservation status and were at risk of becoming locally extinct and need restorative action.

3. Responses to challenges and solutions of freshwater problems in Europe

In the present chapter, a range of technical responses are reviewed. A range of institutional responses from the EU (Water Resilience Strategy, Mission Oceans and Water, Mission on Climate Adaptation, water-related directives, EIT-Water) are discussed in Chapter 4.

3.1. Water quantity

Reducing water use and improving water efficiency are essential in abating water stress. Water efficiency can be enhanced by reducing water loss, enhancing water reuse, increasing use of water efficient devices, smarter sharing of water among competing users, smarter management of water reservoirs, using sensors for real-time monitoring, and applications of artificial intelligence (AI) solutions. A key part of managing water demand is to improve water efficiency in industry and in households, to save water by using it sparingly, to reduce leakage and to increase water reuse. In the agricultural sector, smart irrigation and precision agriculture should be enhanced, over-abstraction should be reduced, more water-efficient and drought-resistant crops should be developed and water storage in soils should be increased. Adopting more sustainable farming models, assisted by innovative technological solutions, giving incentives for water reuse practices, and reducing pollution and water demand should be pursued. Water pricing can also be an important driver of water use reduction and efficiency improvements, while providing a mechanism to fund water investments. Target setting, focused on saving water or managing (reducing) demand, could drive action and facilitate the monitoring of progress towards greater water resilience. Demand management means, in fact, striving for negaliters (negative liters) of saved water instead of megaliters of provided water. Notions of the water footprint and virtual water trade are also important measures of water efficiency.

Disaster preparedness should be improved to enhance resilience to climate change. Managing flood risk affordably and sustainably becomes increasingly important in the warmer climate. The two overarching strategies indicate possible directions that can be difficult, if not impossible, to implement in a particular case:

- (i) Keep destructive waters away from people and wealth; and
- (ii) Keep people and wealth away from destructive waters.

Disaster risk reduction (DRR) includes the participation of users in decision-making (e.g. Early Warnings for All, EW4All initiative⁴). Hence, ‘living with waters’, ‘living with floods’ and ‘not being surprised by floods’ can be more actionable than keeping people and waters away. We haven’t explicitly dealt with DRR in STARS4Water, but water managers and infrastructure operators should indeed be better informed about potential disasters and how to act and prepare for future (intensified) hazards.

Nature-based solutions, including blue-green infrastructure (e.g. the concept of “sponge city”), lend themselves well to reducing flood risk in urban areas. In addition, they provide environmental and social co-benefits. Urban wetlands, rain gardens, permeable pavements, and green roofs catch and

⁴ <https://earlywarningsforall.org/site/early-warnings-all>

store rainwater, thereby slowing it, with positive impacts on habitats for plants and wildlife, as well as benefits for heatwave management and air quality.

A stronger knowledge base on freshwater is needed to enable more equitable and sustainable allocation of water among competing uses, including environmental uses. Access to relevant, reliable, and up-to-date information is also needed to help improve risk management. Floods can develop in hours, so early warning systems are essential for saving lives. Water management needs to adapt to abstraction and cope with extreme conditions such as drought, and to prevent or reduce the severity of catastrophic events, such as the ecological disaster that occurred in the River Odra in the summer of 2022 (cf. Free et al., 2023). Remote sensing data offers new opportunities. Digital innovation, e.g., AI/ML models and possibly “high resolution digital twins,” has the potential to improve the timeliness of information for predicting and responding to water-related risks.

3.2. Water quality

To prevent harm to people and the environment, pollution must be prevented in line with the long-term objectives of the EU zero pollution action plan. In the short term, there is a need to reduce the use of harmful substances and nutrients to improve the overall status of water. The existing EU laws to tackle water pollution (multiple EU directives, therein: the Water Framework Directive, the Drinking Water Directive, the Nitrates Directive, and the Sustainable Use of Pesticides Directive), need to be upgraded and updated, as well as better implemented and enforced.

By establishing targets in the zero-pollution action plan to reduce nutrient losses by 50% and reduce the use and risk of pesticides by 50% by 2030, the urgency of tackling excessive emissions of nutrients and pesticides has been addressed. However, this policy target aims to address existing challenges at the continental/EU level, but not necessarily at local or regional levels.

European agriculture needs to increase its use of more sustainable organic and agroecological practices. However, it requires more water-efficient practices; otherwise, it may have little impact on water management issues such as water scarcity and competing users during low-water and drought periods.

Diffuse atmospheric pollution remains a major pressure on surface waters, so that action should be taken to further reduce atmospheric emissions of substances which later return to the earth's surface with rainfall, including those arising from the burning of fossil fuels. Wastewater treatment can also benefit from advanced treatment processes that enable higher rates of water reuse in both urban and rural areas.

3.3. Ecosystems

Restoring natural features to improve aquatic ecosystems can generate co-benefits such as drinking water purification, improved carbon storage, flood protection and recreation. However, it requires careful planning with the affected sectors. In recent years, there has been emphasis on removing river barriers and improving the conditions for fish migration. A record 602 river barriers (dams, weirs, sluices and culverts that had previously fragmented waterways and prevented rivers from functioning naturally) were removed across Europe during 2025⁵. As a result, approximately 3,740 kilometers of

⁵ <https://www.naturalworldfund.org.uk/river-barrier-removal-europe-2025/>

rivers were reconnected. However, further efforts are needed across Europe to achieve the goals of the EU Nature Restoration Law and the biodiversity strategy for 2030, to restore the natural flow and functions of rivers and floodplains.

The use of nature-based solutions should be expanded on a larger scale to enhance water retention and slow down the flow of heavy rain, mitigating flooding. These include blue-green infrastructure in cities, agroforestry practices, development and restoration of wetlands, and reforestation. Major pressures include changes to physical features and natural river flow, e.g., via dams and channelization, which degrade natural habitats. Achieving free-flowing rivers and restored wetlands and peatlands, as well as reconnecting rivers and their floodplains, is essential to restore healthy, biodiverse, freshwater ecosystems and to secure the delivery of essential ecosystem services, such as the supply of good quality water, nutrient retention and recycling, water retention and carbon storage. One could state the following rule: go green where possible and go grey (resorting to structural measures) where necessary.

Chapter 5 of this deliverable demonstrates how a range of Project STARS4Water outcomes addresses Europe's water challenges identified in the present chapter.

4. EU water policies and missions

4.1. Introduction to EU legal act typology

The EU legal act typology embraces several categories (regulations, directives, decisions, recommendations, opinions, and policy communications) – see box 1⁶. They may be binding or not binding and either apply to all EU Member States or to just a few Member States (regions, companies) or even one State (region, company).

The present chapter discusses EU water policies and initiatives, including water-related directives, EU governing missions and EIT Water, as well as the EU New Deal. It starts with the EU Water Resilience Strategy.

Box 1: EU Legal act typology

A "**regulation**" is a binding legislative act that must be applied in its entirety across the whole EU. A "**directive**" (e.g. water-related directives dealt with in this chapter) is a legislative act that sets out a goal that EU Member States must achieve. However, it is up to the individual EU Member States to decide how to reach these goals. An EU "**decision**" is binding on the addressees (e.g. an EU Member State or an individual company) and is directly applicable. A "**recommendation**" is not binding and does not impose a legal obligation on those to whom it is addressed. An "**opinion**" is a non-binding instrument that allows institutions to make a statement from a regional, economic, and social viewpoint, without imposing any legal obligation on the addressees. An opinion can be issued by EU institutions such as the European Commission, the Council, or the European Parliament, as well as by the Committee of the Regions and the European Economic and Social Committee. Finally, a non-binding "policy communication", such as the EU Water Resilience Strategy, does not create new direct legal obligations or enforceable penalties but serves as an interpretive and operational framework.

4.2. European Water Resilience Strategy

Freshwater is essential to people's lives, well-being, and livelihood, to human and environmental health, but also central to the economy, competitiveness, and adaptation to climate change. A range of water-related directives have been issued by the European Commission, but certainly this is not enough because the severity, frequency and duration of water-related problems do not seem to decrease. In 2025, the European Water Resilience Strategy (EWRS) was adopted by the European Commission (EC, 2025a), to address water-related challenges by reducing water-related risks and boosting water resilience (see box 2). Although the European Water Resilience Strategy had not yet been published when the STARS4Water project was started, it has become a key reference framework throughout the project and plays a prominent role in this report.

⁶ <https://www.wareg.org/articles/5-european-water-resilience-strategy-2025/>

From the legal point of view, the European Water Resilience Strategy is a non-binding policy communication rather than a new standalone law. It is a soft law, implementation bridge⁷ and integration catalyst⁸.

The European Water Resilience Strategy (EWRS) is central to this chapter, as the overarching water strategy should guide the water policies and water-dependent sectoral policies (e.g., agriculture, environment, energy).

Box 2: Examples of actions envisaged in the European Water Resilience Strategy (EC, 2025a).

- Restoring and protecting the water cycle;
- Building a water-smart economy that leaves no one behind, supports EU competitiveness and attracts investors;
- Securing clean and affordable water for all, empowering consumers and other users;
- Financing, investments and infrastructure to achieve a stable water supply;
- Security and preparedness to boost collective resilience;
- Research and innovation, water industry and skills to strengthen competitiveness;
- Digitalization and artificial intelligence;
- Acting globally – providing the leadership to the world by example, commitment and initiatives of EU.

A range of actions are foreseen under the implementation of the Water Resilience Strategy that can be informed by improved scientific understanding, including via the findings of STARS4Water (see Section 5.1). It is necessary to take stock of progress made in enhancing water resilience across all levels of government, business and civil society; to monitor implementation of the EWRS; as well as to evaluate the uptake of the Recommendation on Water Efficiency First - a core operational pillar of the broader EWRS (EC, 2025b), and in consequence, to update or revise the EWRS, wherever appropriate.

In 2029, the EC will evaluate progress, including national actions taken in line with the Recommendation on Water Efficiency First (EC, 2025b). The Commission will also identify any further actions needed to address emerging concerns and, as appropriate, review the identified targets and actions to enhance water resilience across all sectors of society. These targets require scientific underpinning and findings, an area to which STARS4Water can contribute.

On 8 December 2025, the EC, together with the European Committee of the Regions and the European Economic and Social Committee, convened the first-ever EU Water Resilience Forum. It was a high-level gathering of policymakers, scientists, industry leaders, and civil society stakeholders to accelerate joint action on Europe's growing water challenges. The Forum was regarded as a milestone for European water security. It responded to mounting pressures on Europe's water resources, including unsustainable land use, pollution, climate change impacts, and increasing water demand. It aimed to translate the EU Water Resilience Strategy into concrete actions across three core objectives: restoring the water cycle, building a water-smart economy, and ensuring universal access to clean and affordable water and sanitation (see first three lines of Box 2). Challenges and pathways related to water efficiency, urban water resilience, industrial water use, financing, digital transformation in water management and capacity-building for stakeholders were explored at the Forum in solution-

⁷ <https://www.wareg.org/articles/5-european-water-resilience-strategy-2025/>

⁸ <https://www.wbgu.de/en/publications/publication/eu-wasserpolitik>

oriented panel sessions. The Forum also launched the Water Resilience Stakeholder Platform — an expert group designed to bring together public authorities, civil society, industry and regional actors to support delivery of the Strategy’s priority actions.

As a project working on water sustainability, governance and resilience, STARS4Water welcomed the Forum as a major, relevant, EU-level initiative. In particular, the Forum’s commitment aligns closely with the goals of STARS4Water. The new stakeholder platform and the collaborative spirit promoted by the Forum are expected to enhance opportunities for engagement, innovation and knowledge exchange across Europe — benefiting the STARS4Water hubs, partners and outreach activities.

As part of WP6, a policy brief titled “Climate change impacts: water challenges of European river basins” was published (STARS4Water, 2025). This policy brief identified six guiding principles, rooted in a stakeholder-driven approach, to enhance water resilience at the river-basin level. These guidance principles, designed to support adaptive, resilient, sustainable and inclusive water resources management in the face of climate change, are listed in Box 3. This is the new aspect we introduce in this document for policymakers who are aware of the existing directives and policy acts. References to bullet points in Box 3, relevant to STARS4Water, are contained in chapters 5 and 7.

Box 3: Six guiding principles for enhancing water resilience (STARS4Water, 2025).

1. Understanding our freshwater systems;
2. Building a water-resilient Europe through science-stakeholder partnerships;
3. Being better prepared for the future flow regimes and water resources availability;
4. Identifying the Safe-Operating-Space (SOS) for resilient water resources management;
5. Exploring management options to enhance water resilience;
6. Raising awareness and information sharing.

The European Water Resilience Strategy features the European Water Academy⁹ (EUWA) as its flagship initiative. The EUWA is an innovative research and technology infrastructure designed to address the pressing challenges of water management in Europe. It also includes an innovative collaboration and public-private-partnership between the European Commission, key water stakeholders, academic institutions and other key sectors.

The primary objective of EUWA is to become the leading EU platform for water resilience and governance training, providing tailored solutions in training, capacity building, networking, and technology transfer to a diverse community of water professionals.

The EUWA is structured as a network of networks, unified by three core principles that guide all its activities:

- Lab-to-Fab¹⁰ Principle: Develop scalable, market-ready solutions to address water issues;
- Living Labs Principle: Real-world sites for testing and training;
- Hands-on Training: courses held in local languages, customer discovery, and public engagement for broad acceptance.

In the context of EUWA, the STARS4Water Academy could be mentioned, with its experience feeding into this platform.

⁹ https://knowledge4policy.ec.europa.eu/water-academy_en

¹⁰ from a small-scale research laboratory to a large-scale commercial manufacturing in a fabrication plant

4.3. EU Governing Missions

The EU introduced the concept of missions in response to the fragmentation and siloed nature of traditional R&D (research and development) policy, which was focused on “market failure”. The EU governing missions are large-scale research and innovation (R&I) initiatives within the Horizon Europe program. They set clear, time-bound (2021-2030), public goals that drive focused efforts towards grand challenges. The EU missions mobilize science, policy, industry, civil society, and finance, pooling the resources to deliver concrete solutions to specific societal challenges.

Five EU Governing Missions were formally adopted by the European Commission. They are governed through mission boards, mission work programs, and multi-level implementation structures. The specific governing missions are listed in Table 1, along with their stated goals and focus areas.

Two out of five missions (cf. Table 1) explicitly deal with water (“Restore our ocean and waters” and “Adaptation to climate change”, described respectively in further detail in sections 4.2.1 and 4.2.2. Two further missions are indirectly related to water (“Climate-Neutral and Smart Cities” and “A Soil Deal for Europe”). Indeed, smart cities must be resilient to increased water stress due to climate change, and a greater prevalence of healthy soils will increase water storage. All Missions have quantitative goals to be met by a predefined deadline (2030 in one case, 2050).

Mazzucato (2019) identified five criteria for selecting EU missions. She suggested that missions should be bold, inspirational, measurable, and time-bound, with a clear target and societal relevance. They should generate ambitious but realistic actions and bottom-up solutions. The innovations should be cross-disciplinary, cross-sectoral, and cross-actor.

The core idea is that missions are not just R&D (research and development) programs, but system-level transformations, combining science, regulation, finance, citizen participation, and cross-sector coordination to achieve outcomes that really matter to European citizens.

Special features of missions are intended to be:

- strengthening Europe’s competitiveness through purpose-driven innovations;
- unleashing innovation across sectors; mobilizing citizens, not just experts;
- reducing uncertainty to increase private investment; and creating spillovers beyond the missions themselves.

Missions are run, based on citizen engagement, in a co creation mode, rather than being imposed from above. The three stages of citizen engagement are: co design (citizens help define mission goals); co implementation (citizen science and user led innovation); and co assessment (citizens help monitor progress). It is crucial for the success of missions to build legitimacy and trust.

Table 1. Governing Missions of the EU: goal and focus.

Mission	Goal	Focus
Adaptation to climate change	Help at least 150 regions and communities become climate-resilient by 2030 by improving understanding of climate risks, developing preparedness pathways, and implementing innovative solutions.	Extreme weather, resilience planning, nature-based solutions, risk modelling, citizen observatories.
Cancer	Improve the lives of at least 3 million people by 2030 through prevention, early detection, treatment, and quality-of-life improvements.	Screening, personalized medicine, data platforms, patient engagement.
Restore our ocean and waters	Protect and restore ocean and freshwater ecosystems through innovation and action by 2030 .	Pollution reduction, circular economy, blue innovation, marine biodiversity, and river basin restoration.
Climate-neutral and smart cities	Deliver 100 climate-neutral and smart cities by 2030 and ensure that these cities act as experimentation and innovation hubs to enable all European cities to follow by 2050 .	Mobility, energy systems, buildings, citizen participation, urban innovation.
A soil deal for Europe	Establish 100 living labs and lighthouses to ensure that 75% of soils are healthy by 2030 .	Sustainable farming, land restoration, carbon farming, soil monitoring, living labs.

Missions require that:

- silos across ministries are removed;
- flexible structures are created;
- risk-taking (and learning from failure) is encouraged;
- procurement is used strategically to create markets; and
- regulations are designed in a way that enables innovation, rather than blocks it.

The missions should be evaluated dynamically. They need coordinated, patient, long-term finance across the entire innovation chain, including crowdfunding and philanthropy for bottom-up initiatives. All in all, missions are regarded as a major cultural shift: from risk-averse bureaucracy to entrepreneurial state. In this report, more details are provided on the two missions directly related to water.

4.3.1. Mission: Restore our ocean and waters

This Mission tackles the pressing challenge of restoring the health of the oceans, seas, and inland waters by 2030. Although oceans and seas are not explicitly addressed in STARS4Water, inland waters (rivers, lakes, and groundwater) are often hydrologically connected to coastal and marine environments. Most rivers ultimately discharge into seas or oceans, linking inland and marine water systems. However, there are exceptions, including large endorheic basins, which are closed drainage

systems with no outlet to the World's oceans. Examples of such systems include the Caspian and the Aral Sea.

Through research and innovation, public engagement, and targeted “blue” investments, this Mission takes a systemic approach to:

- protect and restore marine and freshwater ecosystems and biodiversity, in line with the EU Biodiversity Strategy 2030¹¹;
- prevent and eliminate pollution of our ocean, seas and waters, in line with the EU Action Plan Towards Zero Pollution for Air, Water and Soil¹²;
- make the sustainable blue economy carbon-neutral and circular, in line with the proposed European Climate Law (see 4.5) and the comprehensive vision outlined in the Sustainable Blue Economy Strategy¹³.

To ensure implementation across Europe, and beyond, this Mission operates through “lighthouses” in major sea and river basins: Atlantic-Arctic, Mediterranean Sea, Baltic-North Sea, and Danube-Black Sea. These four lighthouses are living labs for demonstrating, deploying and scaling up solutions. The water quality of seas and oceans depends on the contaminants transported by rivers and groundwater influx. The lighthouse's name explicitly mentions one river (the Danube, flowing to the Black Sea), but inland waters are implicitly included in all sea basins. For instance, contaminants transported by many rivers (unnamed in the lighthouse title) to the Baltic Sea degrade the coastal zone's seawater quality and contribute to algal blooms (driven by nutrients generated inland). Bathing and swimming are adversely affected, and at times, beaches on the southern shore of the Baltic Sea are closed.

Mission Charter invites EU Member States, regions, cities, and stakeholders to pledge concrete actions to support the Mission's objectives (more than 1,000 pledges have already been recorded). A mission portal¹⁴ enables progress tracking, knowledge sharing, and access to funding and partnership opportunities.

Supporting the digital transition, this Mission is also developing a Digital Twin Ocean¹⁵, an innovative, virtual replica of the ocean, designed to integrate a vast array of data, simulate the effects of different actions on marine and freshwater ecosystems, and project future scenarios. This cutting-edge tool is intended to enable real-time monitoring, predictive analysis, and better-informed decision-making for sustainable management of marine and freshwater ecosystems across Europe.

This Mission engages and empowers a broad range of stakeholders, public and private organisations, national, regional, and local actors, coastal, riparian, island communities, businesses, and citizens in general to actively participate in shaping the future of Europe's marine and freshwater ecosystems.

This Mission is anchored in the European Ocean Pact¹⁶ and the European Water Resilience Strategy (see 4.1). The objectives and targets of this Mission in the time horizon of 2030 are:

¹¹ https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

¹² https://environment.ec.europa.eu/strategy/zero-pollution-action-plan_en

¹³ https://oceans-and-fisheries.ec.europa.eu/blue-economy/sustainable-blue-economy_en

¹⁴ <https://projects.research-and-innovation.ec.europa.eu/en/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters/mission-ocean-and-waters-service-portal>

¹⁵ https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/restore-our-ocean-and-waters/european-digital-twin-ocean_en

¹⁶ https://oceans-and-fisheries.ec.europa.eu/european-ocean-pact_en

- Protecting and restoring marine and freshwater ecosystems and biodiversity, with the following defined targets:
 - protecting a minimum of 30% of the EU's sea area and integrating ecological corridors;
 - strictly protecting at least 10% of the EU's sea area;
 - restoring at least 25 000 km of the flowing rivers;
 - contributing to relevant upcoming marine nature restoration targets – seabed habitats and coastal ecosystems);
- Preventing and eliminating pollution for our oceans, seas, and waters with the following defined targets:
 - reducing by at least 50% plastic litter at sea;
 - reducing by at least 30% microplastics released into the environment;
 - reducing by at least 50% nutrient losses, the use and risk of chemical pesticides.
- Making the blue economy sustainable, carbon-neutral, and circular with the defined target of eliminating greenhouse gas emissions from maritime economic activities in the EU and sequestering those emissions that cannot be avoided (so-called net-zero maritime emissions).

This Mission is implemented in two phases: (1) development and piloting phase (2021-2025) focused on research, innovation and testing of new solutions; (2) deployment and upscaling phase (2026-2030) expanding proven approaches to achieve the 2030 targets across Europe's basins.

4.3.2. Mission: Adaptation to climate change

A large portion of adaptation to climate change is linked to water, for instance, adaptation to water-related extremes (droughts and floods) getting more extreme, i.e., more intense, more frequent, and more long-lasting in the changing climate. Also, adaptation to rising temperatures (e.g., heat waves) includes water-related elements, such as blue-green infrastructure, particularly in urban areas. Vegetation provides shade and a local cooling effect (due to the high latent heat of water evaporation). So do surface water bodies, including small ponds, canals and fountains.

The Mission "Adaptation to climate change" is crucial, as climate change affects various regions, economic sectors, and societal groups differently, necessitating a spatially distributed, tailor-made approach. Climate change mitigation aims to reduce greenhouse gas emissions and achieve carbon neutrality, a goal that remains central to international climate policy. However, even the most ambitious mitigation efforts cannot halt warming in the short- to medium-term. Hence, it is crucial to enhance preparedness and resilience to the impacts of climate change and adapt our way of life. This Mission also contributes to the delivery of the European Green Deal (Section 4.6).

This Mission¹⁷ aims to support at least 150 European regions and communities towards climate resilience by 2030. It is intended to help these regions and local authorities to:

- Understand climate risks by identifying current and future climate-related challenges specific to their areas;
- Develop adaptation pathways by creating strategic plans to prepare for and manage the impacts of a changing climate;

¹⁷ https://mission-adaptation-portal.ec.europa.eu/index_en

- Implement innovative solutions by deploying practical measures and technologies to enhance resilience on the ground.

This Mission is addressed to all stakeholders committed to building climate resilience, including policymakers shaping adaptation strategies, regional or local authorities implementing solutions on the ground, research institutions developing innovative approaches, and businesses contributing expertise and resources. The Mission fosters a strong, united approach to tackling climate risks, providing a collaborative framework to accelerate adaptation efforts via its strong mission community, with 326 regions and local authorities from 25 (of the total of 27) EU Member States and five associated countries, signing the Mission Charter.

A Mission projects catalog¹⁸ lists concrete solutions for climate adaptation challenges, providing key information on each of the 65 projects – highlighting their objectives, achievements, the climate risks they address, and the local and regional authorities involved.

4.4. EU water-related directives

4.4.1. EU Water Framework Directive

The aim of the EU Water Framework Directive (WFD, 2000) is to protect all water bodies in Europe. It established a program and timetable for EU Member States to achieve a "good status" of all waters in the EU by 2015. Its objectives are to prevent deterioration of the water bodies, enhance the status of aquatic ecosystems, reduce pollution, promote sustainable water use, and support the mitigation of the effects of floods and droughts. Although the aim was not fully achieved by 2015, the WFD triggered a considerable improvement in water quality across the EU, especially with respect to point-source pollution.

4.4.2. EU Groundwater Directive

The EU Groundwater Directive (GWD, 2006) addressed issues relevant to protecting groundwater from pollution and deterioration. It establishes specific measures as provided for in the WFD (2000), to prevent and control groundwater pollution.

In October 2022, the EC published a proposal for amendment of the Water Framework Directive as well as the Groundwater Directive, and the 2008 Environmental Quality Standards Directive (EQSD, 2013), aligning these directives with the European Green Deal (Section 4.6), by updating lists of pollutants (a permanent activity¹⁹) and quality standards, improving assessment of combination effects and ensuring that the legal framework of the directives can align with scientific findings.

¹⁸https://mission-adaptation-portal.ec.europa.eu/document/download/e0a14c50-10ec-40e7-b6bc-79b588539118_en?filename=EU-Missions-Mission-Projects-Catalogue-2026.pdf

¹⁹https://commission.europa.eu/news-and-media/news/new-eu-law-better-protect-water-enters-force-2026-05-13_en

4.4.3. EU Floods Directive

In 2007, the European Parliament and the European Council issued a directive on the assessment and management of flood risks, the EU Floods Directive (FD, 2007), which prescribed the following three-step procedure:

1. Preliminary Flood Risk Assessment, which considers the impacts on human health and life, the environment, cultural heritage and economic activity, with a completion date of December 2011;
2. Risk Assessment, including the identification of areas at significant risk via models to produce flood hazard and flood risk maps, to be in place by December 2013. The assessment should contain details on the flood extent, depth and level for three flow scenarios of high, medium and low probability;
3. Flood Risk Management Plans whose purpose is to inform policy makers, developers, and the public of the nature of the risk and the measures proposed to manage it. This step was to be completed by December 2015.

The Floods Directive prescribed an active involvement of stakeholders in the process. The management plans focus on prevention, protection and preparedness, while taking into account the relevant environmental objectives of Article 4 of WFD (2000). Regular updating of Flood Risk Management Plans is obligatory for EU Member States.

4.4.4. Drought policies

Droughts have been on the rise across Europe in recent decades, and with global warming, the risk of droughts is likely to increase in large parts of the EU. There is no EU drought directive as such, but a lot has been going on regarding EU and Member States' drought policies.

The current drought situation in Europe, using a combined drought indicator, warm spell intensity, and river low-flow conditions, is reviewed by the European Drought Observatory, EDO²⁰.

Schmidt et al. (2023) presented a stock-taking analysis of drought policies, planning and management in EU Member States and an outlook of planned work at the Member States and EU levels. Currently, in over two-thirds (19 out of 27) of the EU Member States, the way to deal with drought is regulated by legislation. The report by Schmidt et al. (2023), providing information on effective options (best practices) for dealing with drought risk, is an input to the EU-wide discussion on a harmonized EU approach. It helped establish a better understanding of drought impacts and risks across different sectors of society and raised awareness among water stakeholders about the increased drought risk due to climate change. However, even if many EU Member States have drought policies in place, some of them have no ranking what to do.

Water scarcity and droughts are recognized as priorities in the European Green Deal (see 4.6). They are reflected in such major European strategies as the EU Strategy on Adaptation to Climate Change (2021), the 2020 Circular Economy Action Plan, and the Biodiversity Strategy for 2030²¹.

²⁰ https://joint-research-centre.ec.europa.eu/european-and-global-drought-observatories/current-drought-situation-europe_en

²¹ https://environment.ec.europa.eu/topics/water/water-scarcity-and-droughts_en

4.5. EIT Water

In November 2025, the European Institute of Innovation and Technology (EIT) launched EIT Water, a Knowledge and Innovation Community dedicated to the water, marine, and maritime sectors and ecosystems²², by selecting the winning consortium to lead Europe's response to pressing water challenges. The EIT Water challenges include water scarcity, drought, and flooding; ecosystem degradation in oceans, lakes, and rivers; and the shift to a circular and blue economy. To meet these challenges, EIT Water is expected to deliver entrepreneurial education, create and accelerate startups, and support innovation-driven research. By uniting education, research, and business, it is expected to build a strong European innovation ecosystem and to align with key EU partnerships and missions, pioneering an integrated approach across water, marine, and maritime sectors.

EIT Water receives startup funding through 2026. After two years, the funding will gradually decrease as EIT Water is planned to move towards financial sustainability, in line with the EIT's unique model of building financially sustainable innovation communities.

Eight local offices of EIT Water are established, located in Denmark (headquarters), the United Kingdom and Ireland, Germany, Belgium, Austria, Croatia, Spain, and Bulgaria. EIT Water brings together many dozens of partners from across Europe.

4.6. EU Green Deal

The European Commission has been committed to transforming the EU into a clean, resource-efficient, and competitive economy, in line with the goals of the Paris Agreement adopted at the COP-21 (Conference of the Parties) of the United Nations Framework Convention on Climate Change (UNFCCC), held in Paris in December 2015. The Paris Climate Agreement set the long-term goal of the global climate policy: to reduce effective greenhouse gas (GHG) emissions so that global temperature increase in the 21st century is constrained to at most 2°C (preferably 1.5°C) above the pre-industrial level (UNFCCC, 2015). However, a recent study (Foster and Rahmstorf, 2026) convincingly demonstrated a statistically significant acceleration of global warming. In 2024, for the first time ever, the annual global temperature was (according to some databases) more than 1.5°C higher than the pre-industrial level. It already surpassed the more stringent guardrail set by the Paris Agreement in a single year (Kundzewicz and Huang, 2026).

Clearly, climate change mitigation at the global level has not lived up to the ambitions of the Paris Agreement. Atmospheric CO₂ concentrations continue to increase despite the EU's worldwide leadership in emissions reduction. So, there is a risk of breaching the targets defined in the Paris Agreement. Friedlingstein et al. (2026) estimate that the remaining CO₂ budget for a 50% probability to restrict warming to 1.5°C is nearly exhausted. If the level of the 2025 emissions continues, there are only around four years left. So, exceeding the 1.5°C level on a regular basis (not in a single year) is virtually certain to happen within the next few years (Kundzewicz and Huang, 2026).

However, 2025 was the first year ever with more power generated, globally, from renewable energy sources than from coal, prompting Thorp (2025) to declare that the 'Rise of the Renewables' was the 'Breakthrough of the Year'.

²² https://www.eit.europa.eu/sites/default/files/2025-11/Water%20Factsheet_winning%20consortia.pdf

The European Green Deal²³, launched by EU President Ursula von der Leyen in 2019, aims to ensure that EU Member States achieve net-zero greenhouse gas emissions by 2050. The Green Deal sets out a plan to transform Europe's economy, energy, transport, and industries towards a more sustainable future. The transition to clean energies and technologies is meant to enhance economic growth and innovation. Furthermore, the Russian Federation's invasion of Ukraine has underscored the Union's need to reduce dependence on unreliable trade partners and to boost its own energy autonomy by enhancing energy efficiency and expanding renewable energy sources. In 2021, the EU adopted its first European Climate Law that set in stone the EU's goal to become climate-neutral by 2050, by achieving the following targets:

- 55% emission reduction by 2030 vs 1990.
- 90% emission reduction by 2040 below the 1990 level, a very ambitious, intermediate target which was added later.

The European Green Deal is not a single legal act but rather an overarching policy framework and growth strategy, codified and enforced through legally binding EU regulations, directives, and specific framework legislation²⁴. The political ambition of the Green Deal was turned into a legal obligation through the European Climate Law, which sets legally binding targets for the entire EU to achieve net-zero greenhouse gas emissions by 2050, along with interim reduction targets.

There is a range of technical issues in which climate change mitigation, as the core of the European Green Deal, can benefit from the outcomes of the Project STARS4Water. Water availability plays a key role in the energy system, e.g., through hydropower and power plant cooling. Output of nuclear plants in a range of European countries was reduced, or plants were shut down in the summer of 2015 (in France, Switzerland, Germany, and Sweden) and in the summer of 2018 (France, Sweden, Germany), and 2026 (Hungary, Romania) due to low water availability. Some nuclear reactors were shut down to avoid thermal pollution from cooling-related exceedances of legal limits on maximum river water temperatures. An important facet of mitigation is CO₂ sequestration by vegetation, particularly by forests. Seasonal Carbon sequestration rate is largely dependent on climate conditions. In a dry year, sequestration can be much lower than in an average year (Kundzewicz et al., 2023). Water availability plays a crucial role in adaptation to climate change across all sectors, but above all in agriculture, social and environmental health, navigation and water transport, and the water supply of industry, commerce, and households.

Beyond setting tangible targets, the European Green Deal creates the enabling environment, putting people at the core of the transition. The clean transition, centered on decarbonization, is meant to be just and fair by supporting people who are more vulnerable in the clean transition and most affected by the climate change impacts. Implementation of the European Green Deal should help Europeans enjoy cleaner air and a more enjoyable climate, as well as more energy-efficient products and homes.

The Emission Trading System ETS is the world's first carbon market (launched in 2005), operating in all EU countries, as well as in Iceland, Liechtenstein and Norway. Since 2020, it has also been linked to the Swiss ETS. The system is based on the "polluter pays" principle, requiring emitters to pay for their GHG emissions, thereby reducing overall EU emissions and generating revenues to finance the green transition.

²³ https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

²⁴ <https://www.consilium.europa.eu/en/policies/european-green-deal/>

The EC has made stakeholder engagement a priority. For instance, many clean transition dialogues with key industrial sectors have been launched, including the strategic dialogue on the future of EU agriculture. In line with this EC priority, dialogue with stakeholders has been an essential part of STARS4Water. The future of EU agriculture is largely dependent on availability of freshwater. Also here, the findings of the Project STARS4Water have a role to play in projecting future irrigation demands.

European Green Deal also takes care of ecological risk reduction, i.e. protecting biodiversity and ecosystems. In line with the Kunming-Montreal Global Biodiversity Framework (Stephens, 2023), the aim is to restore biodiversity, address pollution, and make efficient use of resources.

In May 2021, the EC adopted the EU Action Plan: “Towards a zero pollution for air, water and soil”²⁵, as a key deliverable of the European Green Deal.

²⁵ https://environment.ec.europa.eu/strategy/zero-pollution-action-plan_en

5. Can outcomes of STARS4Water facilitate the implementation of the EU Water Resilience Strategy at river basin scale?

5.1. Building resilience through integrated data, modelling, and decision support

The increasing frequency and severity of floods, droughts, water scarcity, ecosystem degradation and competing water demands highlight the need for more resilient water management systems. Water resilience, in a broad sense, is the ability of river basins, institutions, and communities to anticipate, withstand, adapt to, and recover from hydrological, climatic, and socio-economic pressures while maintaining essential functions and ecosystem services.

The STARS4Water project contributes to this objective through an integrated portfolio of data services, modelling frameworks, machine learning applications and decision-support tools. While developed across diverse river basin contexts, the project demonstrates several common pathways through which digital innovation can strengthen water resilience.

Resilience through improved knowledge and situational awareness

High-quality data are a prerequisite for resilient water management. The STARS4Water project has improved access to harmonized climate, hydrological, and socio-economic data through common indicators, data services, and metadata infrastructure. These resources support a shared understanding of current conditions, emerging risks and long-term trends, enabling more informed decision-making across scales.

The combination of global and local datasets also supports resilience by helping identify areas where local knowledge, monitoring or management interventions are most needed.

Resilience through integrated system understanding

Many water challenges arise from interactions between hydrology, infrastructure, ecosystems and human water use. The modelling frameworks developed within STARS4Water demonstrate the value of integrated approaches that link water availability, allocation, reservoir operations, environmental flows and sectoral demands. Rickards and Keller (2024) showed how improved modelling frameworks allow better understanding of water resources at the river basin scale, expanding the upscaling possibilities.

By supporting the exploration of future scenarios and management trade-offs, these frameworks help decision-makers identify robust adaptation strategies under changing climatic and socio-economic conditions (Ramos et al., 2026).

Resilience through innovation and adaptive capacity

Machine learning and data-driven approaches offer new opportunities to address knowledge gaps, particularly where observations are sparse or processes are difficult to monitor directly. For example, applications developed within STARS4Water support the estimation of snow resources, groundwater dynamics, water quality risks, and water storage conditions (Baron & Keller, 2026; Avila et al., 2026).

These tools increase adaptive capacity by providing rapid, scalable, and flexible information that can complement traditional process-based approaches, e.g., by merging models with observations and support early identification of emerging risks.

Resilience through stakeholder engagement and co-creation

Technical solutions alone do not create resilience. Across the project, stakeholder engagement proved essential for ensuring relevance, usability and trust between scientists and stakeholders. River basin organisations, water managers, and local stakeholders contributed to identifying challenges, developing scenarios, and interpreting results.

This co-creation process strengthens institutional resilience by improving ownership, encouraging knowledge exchange and supporting the integration of scientific evidence into planning and decision-making. A tangible example from East Anglia is the creation of a groundwater pollution map that exploits the results of the SOS work (Ramos et al., 2026).

Resilience through accessible decision support tools

STARS4Water dashboards, Story Maps, and visualization tools translate complex analyses into formats that are accessible to decision-makers and non-technical stakeholders. By improving communication, transparency and understanding of risks, these tools help bridge the gap between scientific knowledge and practical action (Hermawan et al., 2026; Klösch et al., 2026).

Their greatest contribution lies in supporting timely, evidence-based, responses to future water challenges.

Concluding message: The STARS4Water project demonstrates that water resilience emerges from a combination of reliable information, integrated system understanding, adaptive decision-making, stakeholder engagement and sustained institutional commitment. The project therefore provides both practical tools and transferable lessons that can support more resilient river basin management across Europe and beyond.

5.2. Interface between scientists and stakeholders – Co-creation and uptake

The stakeholder community represents a spectrum of interests, with different needs and preferences regarding involvement in and information about STARS4Water project (Hegdahl et al., 2023). For example, hydropower companies with modeling expertise are likely to be more interested in data and models, whereas municipalities are interested in easily accessible water resource information, processed data, and storylines of water resources under climate change. Hegdahl et al. (2023) based the concept of information strategy on the classification of stakeholder engagement, measured by their influence on decisions and by their interest in general or specific STARS4Water products, therein deliverables.

The STARS4Water project follows a stakeholder-driven approach, strengthening the interface between scientists and stakeholders through co-creation, as well as upscaling and uptake for preparedness. This closely matches building a water-resilient Europe through science-stakeholder partnerships, one of the guiding principles of the European Water Resilience Strategy (see Box 3).

The co-creation process addressed the main points in the hub's water resources information system, where new data, indicators, and modeling tools were evaluated to improve the effectiveness and timeliness of water management decisions for climate-resilient water resources planning. Co-creation, co-development, co-evaluation, and co-assessment were also implemented. Specific objectives included, among others:

- Mapping the stakeholders' data needs and requirements for assessing water resources availability and water use;
- Making local data concerning the river basin hubs available through the river basin communities;
- Co-design and co-development of a dashboard for informed decision making; and
- Co-design of qualitative narratives with stakeholders to explore future water scenarios in the river basin hubs.

These objectives closely match several guiding principles of the Water Resilience Strategy (Box 3).

STARS4Water has stakeholders embedded in its consortium; hence, the stakeholder co-creation strategy was already designed with their involvement. To guarantee the success of a more local approach, while also in line with a more continental/EU wide view of stakeholder's challenges, the strategy was first discussed among project scientists, ensuring that the hub focal points would assess local aspects in their meetings/workshops but with an enlarged vision (and with, more or less, the same target/goal, despite the local differences encountered in the different river basin hubs).

The project began by identifying, with the river basin hubs, gaps in existing decision-support systems and data needs (as part of WP1) to inform the development of new tools and datasets to address them. As a result, a suite of practical resources was developed, including:

- enhanced modelling frameworks;
- Earth Observation data integration;
- Interactive, tailor-made, dashboards;
- future regional, socioeconomic, climate, and what-if, scenarios;
- data portals;
- training materials to ensure the longevity and shareability of the data and tools developed.

The message was simple: "Good science becomes valuable when it is developed together with those who will ultimately use it." However, this message does not cover all the situations encountered. Several of the stakeholders who helped develop the science might not use it, but they still provided vital information about the system. Local knowledge ensured that the tools and model development captured the properties of the system being modelled. For example, this was clearly visible when future scenarios were developed.

The Project STARS4Water developed and delivered new data services and models for better supporting the decision making for adaptive, resilient and sustainable (ARS in STARS4Water) management of freshwater resources (Blind, 2025). Interactions of shared science (research community stance) and shared perception (stakeholder community stance), with feedback loops, were the key, cf. Figure 3. A common understanding between stakeholders and researchers was forged, so that data services, modelling approaches, and risk assessments – products created by the research community – were used by the stakeholder community. The project ensured that scientists, policymakers, and managers "see the same thing".

The aim of WP5 (Section 1.3) aligns well with the guiding principle of the Water Resilience Strategy (Box 3) - being better prepared for the future flow regimes and water resources availability.

The RHB approach provided a space to bring together key regional stakeholders to test ideas and techniques and to learn from each other. For instance, this was facilitated at online workshops. In some river basin hubs, it was for the first time ever that stakeholders got together, prompted by an invitation to take part in the STARS4Water project's activities.

Up-to-date and timely information on water quantity and quality is critical to Europe's ability to understand its freshwater systems (Box 3) and to manage its water. A more robust knowledge base is also needed to enable more equitable and sustainable water allocation among competing uses, including environmental uses. An important activity in the stakeholder-driven process was the preparation and dissemination of custom-made video tutorials within the framework of STARS4Water Academy (Blind, 2025).

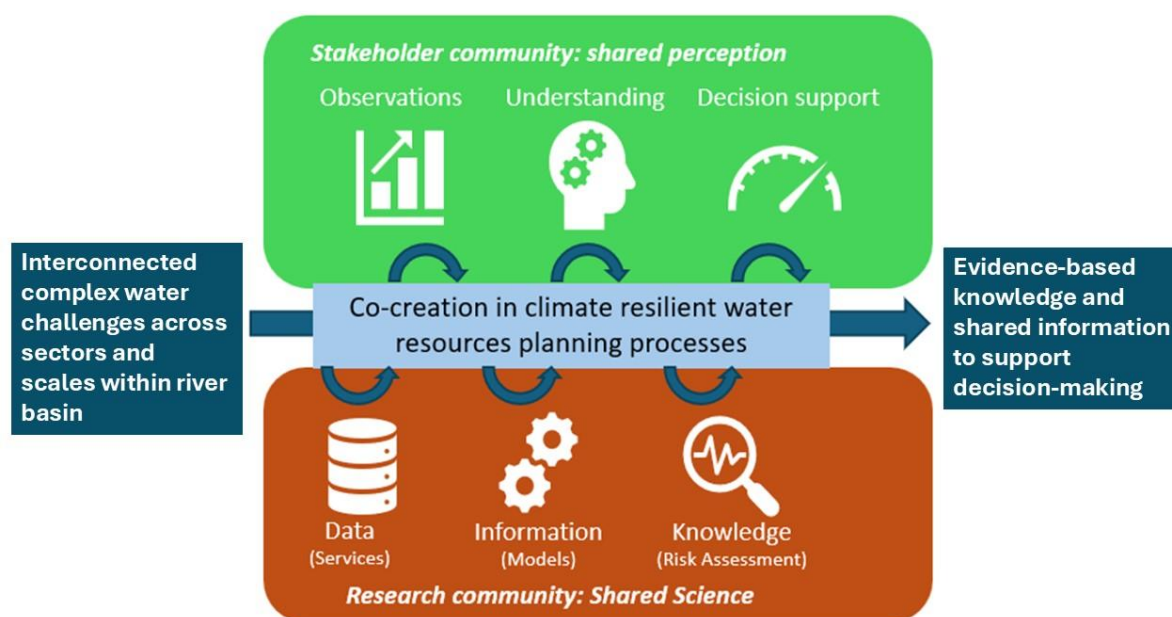


Figure 3. Basic underlying layout structure of the STARS4Water project, with strong focus on co-creation.

5.3. Data and modelling tools

Accurate and comprehensive data collection forms the foundation of effective risk assessment at both the river-basin and pan-European scales. Gathering relevant data sets in the STARS4Water is important for evaluating climate-change impacts on water resources, as well as the vulnerabilities facing society, economy and ecosystems, in much of Europe. Modelling based on gathered data ensured that recommendations regarding EU policies were based on robust evidence, allowing stakeholders to make informed decisions. An intercomparison of multiple large-scale models (Leandro & Kollet, 2026), including ParFlow-CLM, CLM3.5, TSMP, LISFLOOD, and PCR-GLOBWB, was conducted to identify the strengths and limitations of numerical models previously developed by different project partners in estimating hydrological variables, with an emphasis on seven river hubs. In some cases, numerical models were also used as input data to develop machine learning models. However, even if a large-scale picture were provided by global models, efficient linking a global- and local-scale picture based on local hub analyses remains an unsolved issue.

In its first policy brief, STARS4Water recommended unlocking global water data and enhancing its use by river-basin stakeholders to develop tailor-made water management strategies (Kossida and Blind, 2025). The main data challenges identified by the river basin stakeholder communities are: (1) findability, availability and quality of (meta) data, (2) accessibility and usability, and (3) application for decision-making.

It was found that existing global data are underutilized. At times, data sources were unknown or not findable by end-users and basin stakeholders. Even when global and supra-regional datasets are available, river basin managers often struggle to identify relevant datasets and assess their usability in terms of variable relevance and temporal and spatial resolution. Furthermore, inconsistent methodologies across data providers and a lack of quality metadata hinder mutual comparability and integration. Data silos and fragmented ownership of available data, split over different sources, limit access to data. Licensing restrictions and administrative barriers prevent data sharing between agencies.

Even if data are obtained, preprocessing and assessing their added value can be challenging and time-consuming, as stakeholders frequently lack the technical capacity to process and interpret large raw datasets effectively. This refers, for example, to a wide range of remote-sensing data - accessing and utilizing such datasets in a way that meets operational needs is not straightforward. More user-friendly interfaces and standardized formats that enable easy access for decision-makers are required. Therefore, existing datasets are often underutilized. They are not designed for nor easily integrated into policy and planning applications. A gap exists between the multitude of raw and available data and the aggregated, actionable information at the basin scale that stakeholders require.

Kossida and Blind (2025) concluded that European datasets alongside global and supra-regional datasets offer complementary benefits, particularly where local monitoring is sparse or inconsistent. Untapped potential was found in global datasets, especially when combined with data-driven modeling.

Global data is of great value to fill in gaps or to complement local hydrological data:

- to develop data services for a better understanding of hydrological processes;
- to provide standardized, high-resolution, tailor-made water and climate data that assure a sound knowledge base for enhancing scenario planning, forecasting and developing water management strategies;
- to support transboundary water management by harmonized datasets across multiple jurisdictions (e.g., in different states);
- to enable long-term trend analysis, to support strategic decision-making for climate adaptation;
- to foster the development of innovative machine learning (ML) models for improved water availability assessments and use projections.

All newly derived datasets were uploaded to Zenodo and the metadata concerning the datasets was captured in the STARS4Water searchable Metadata Portal, housing some 450 datasets, global and continental (for various continents). Additionally, the tier-1 indicators were published on a web dashboard. The new datasets were discussed with stakeholders from the river basins.

Among the datasets in the STARS4Water Metadata Portal are hydrology-related climate impact indicators from 1970 to 2100, derived from bias-adjusted European climate projections. This dataset provides water variables and indicators based on hydrological impact modelling, forced by bias-adjusted regional climate simulations from the European Coordinated Regional Climate

Downscaling Experiment (EURO-CORDEX). The Metadata Portal also includes PCRGLOB Human Water Consumption data that was used to derive the results reported in (Wada et al., 2013), demonstrating that human water consumption intensifies hydrological drought worldwide. Another exemplary dataset includes values of the Soil Moisture Anomaly (SMA) indicator, computed every decade (10-day intervals) as anomalies of the soil moisture index derived from the JRC's in-house LISFLOOD hydrological model²⁶.

In the STARS4Water project, a set of indicators was developed for assessing climate risks and impacts on integrated water resources systems. The indicators were developed in a three-tiered approach. The indicators from the first two tiers were described in (Beckers et al., 2025). The first tier of indicators was derived directly from readily available datasets, e.g., the Copernicus Climate Data Store. The existing raster data was aggregated to the river basins (subbasins) to make it more practical and bring it a step closer to use by river basin managers. The second-tier indicators were derived by combining available global data with auxiliary data from various sources to produce indicators more directly related to water resources management. Local data lends itself well to bias-correcting global data. The third-tier indicators follow from modelling activities.

The calculation methods for all indicators, including assumptions and limitations, as well as the main results for the seven river basins, are described in (Beckers et al., 2025).

Available data should adhere to the FAIR principle: Findable – Accessible – Interoperable – Reusable. The portal included datasets that abide by the FAIR principles.

The stance of STARS4Water project aligns with the statement by Professor Celeste Saulo, WMO Secretary-General: “Let us ensure that Earth information is not only collected — but also understood, accessible, and actionable for all.”

The project developed and delivered new data services and data-driven models to better support decision-making on planning actions for adaptive, resilient, and sustainable management of freshwater resources. Spatio-temporal data plays a particularly important role in the project (Beckers et al., 2025) that aimed, among other things:

- to provide stakeholders with new generation data services and data-driven models tailored to their information needs and requirements;
- to improve the accuracy and the spatial-temporal resolution of regional-scale projections of water resources availability and to get a more complete picture of the water resources system, including the impacts on ecosystems, society and economic sectors, at grids from 1 km² to 10 km² (the high-resolution modelling on the Rhine hub goes down to grids smaller than 1 km²);
- to enhance the knowledge base and the scientific underpinning of climate risks and impacts, in various scenarios and time horizons;
- to improve decision-making by stakeholders through the development of co-designed ‘dashboards’.

A comparison of existing models and benchmarking of models currently used against stakeholder requirements was undertaken in the STARS4Water project (Rickards et al., 2023). The modelling needs, categorized across a range of topics, were identified and prioritized. An inventory of models, operationally in use across the river basin hubs for water resources management purposes, was created. Based on stakeholder modelling requirements, a review of these was conducted and benchmarked against the needs of the river basin hubs. Potential models, modelling approaches and

²⁶ <http://data.europa.eu/89h/a47c68f3-818f-4c41-92cc-1b94bdefcb6f>

improvements in process representation were identified to meet stakeholder needs. Information on stakeholders' priority needs was gathered at local workshops. A gap analysis of existing modelling tools was carried out. Improving the modelling framework for better understanding of water resources at the river basin level was carried out, based on improved driving data. Existing models were upgraded, based on enhanced process understanding, and new process-based models were developed (Rickards and Keller, 2024). New data can inform process representation in process-based models and enable more accurate model application using more up-to-date data, as was the case in the Messara river basin hub.

In STARS4Water, specific modelling tools were proposed and selected, based on the requirements of the stakeholders and modelling gaps. These tools covered a range of water resource-related issues, including the estimation and forecasting of key water sources, such as reservoirs and groundwater stores (and inflows), at a range of spatial and temporal scales; predictive spatial mapping of groundwater quality; and estimation of irrigated areas (Rickards and Keller, 2024). Process-based modelling via the environmental flows tool, STARS4Water ERFA, provides a first-tier assessment of ecological risk due to river flow alteration.

Baron & Keller (2026) described the data-driven modelling tools that have been developed to help address the needs of the seven STARS4Water river basin hubs. Data-driven methods have been used to leverage the increasing volumes of hydrological, environmental, and socio-economic data available, both observed and modelled, to provide valuable information on water resources availability and related topics. These methods are well-suited to solve complex problems, since they can capture non-linear patterns while assuming no prior knowledge, and can do so in a computationally efficient manner. Thus, these tools perfectly complement the development of existing process-based modelling tools and frameworks. Even if some ML (machine learning)-based models were exploratory and not directly used in the hubs, and their usability was not fully discussed with stakeholders, they offered valuable perspectives for the future.

A key requirement for the data-driven tools developed in Project STARS4Water is that they should not remain restricted to the seven river basin hubs but should be applicable to other river basins in Europe and beyond. This requirement was explicitly tested in Deliverable D4.4 (Avila et al., 2026a) and Deliverable D5.3 (Avila et al., 2026b), by upscaling and transferring the ML models from their original basin-scale training domains to larger spatial domains and hydro-climatically distinct regions.

At the European scale (D4.4), Convolutional Long Short-Term Memory (ConvLSTM) models trained at the river basin scale for daily Snow Water Equivalent (SWE) and daily Water Table Depth (WTD) were shown to generalize across Norway, the European Alps, and the pan-European domain, retaining performance levels broadly comparable to the reference physically based simulations. Similarly, the MLMapper predictive mapping tool for groundwater quality generalized effectively to a different European aquifer system (East Anglia) and ensemble-tree models for monthly reservoir storage forecasting were transferred to the Seine basin, demonstrating that local retraining consistently improves forecast skill.

Beyond Europe, the transferability of these models was evaluated in four case studies (Leandro et al, 2026):

- ConvLSTM SWE model transferred from its European training domain to the Rocky Mountains (US);
- ConvLSTM WTD model transferred from Europe to the contiguous United States using ParFlow-CONUS1 simulations as a reference benchmark;
- MLMapper model applied to identify groundwater-dependent ecosystems in Chile and Madagascar;
- Ensemble-tree reservoir storage model, originally developed for European reservoirs, and extended to tropical reservoirs in Thailand.

Promising results were demonstrated for each of these tools in at least one of the river basin hubs, and with continued collaboration with basin stakeholders, they have the potential to be deployed operationally to support water management decisions and extended to other regions. For some applications, including STARS4Water ERFA (Laize & Crapper, 2026) and the groundwater mapping ML method (Baron & Keller, 2026), the latter has already been achieved by applying these solutions to several river basin hubs.

Bridging the gap between data availability and information needs is essential and requires a targeted approach that processes and combines datasets with other data and model outputs to meet stakeholder demands. End-user requirements must be systematically gathered through structured co-design processes, ensuring that data producers align their outputs with real-world operational needs. This, *inter alia*, means that links to policy and regulations must be considered and established. This structured approach enables the development of dedicated, requested information services and dashboards, and informs European and global data strategies and service providers, ensuring that future data production initiatives are guided by local realities and emerging challenges. The use of the asked-for services requires capacity building in using data services and decision support tools. Training programs and initiatives related to capacity-building on data processing, scenario modelling, and impact assessment were successfully undertaken in the Project STARS4Water, serving as effective models.

Generally, whilst developing data-driven models, no explicit assumption of process knowledge is made, even if many modelers tend to select predictors based on process-based assumptions and physical process knowledge. Machine learning models learn from data, harnessing its increasing availability. The project shows that operational deployment of such data-driven modelling tools in water management is promising and that co-development is key to aligning technologies and system understanding.

In general, stakeholder knowledge of the system and its processes is key to success, as illustrated by the groundwater case developed in East Anglia.

Further development of models was carried out via multi-model integration and multi-scale modelling as well as using data-driven techniques.

The STARS4Water project improved the understanding of climate-change impacts on water resources availability and the vulnerabilities for ecosystems, society and economic sectors at the river basin scale, providing actionable information to stakeholders. New data services and data-driven models were developed and delivered to better support decision-making in planning actions for adaptive, resilient, and sustainable management of freshwater resources. Advanced modelling can help understand trade-offs between hydropower, agriculture, biodiversity, groundwater, ecosystem health

and climate adaptation, while explicitly accounting for uncertainty. The goal in the project was not simply to produce better models, but to create decision-support frameworks that help policymakers navigate increasingly complex choices. Different modelling priorities exist across the seven river basin hubs (Rickards et al., 2023). In several river basin hubs identified modelling needs were related to environmental flows and water allocation. In contrast, in one hub, namely the Drammen, snow modelling was identified as an area needing improvement. Comparing various hubs, one finds out that the most priority modelling schemes were identified for Drammen (seven out of the total of eight topical areas considered).

Stakeholders expect robust findings that scientists cannot always provide. However, even if the degree of uncertainty in climate impact science is high, especially with regard to the projections for the future (Kundzewicz et al., 2018), there have been robust findings that hold across different regions, time horizons, scenarios of greenhouse gas emissions, and socio-economic pathways, as well as climate and impact models. The most robust general finding in climate change science and climate change impact science, holding for both past observations and future projections, is the ubiquitous increase in temperature across all spatial and temporal scales of concern in the project.

Even if uncertainty in water-related projections is typically higher than in temperature-related indices, robust increases are projected in a set of water demand components for basin hubs analysed in STARS4Water, based on data from global models. Domestic water demand (Figure 4) and industrial water demand (Beckers et al. (2025), Figure 8) are projected to increase monotonically until 2050, marking the end of the analysis period, for all hubs. Also, irrigation water demand is projected to increase in the future (2031-2060) compared with the past (1985-2014) for all seven river basin hubs of concern in the project (Beckers et al., 2025). However, even if irrigation water demand is projected to increase in all river basin hubs (Beckers et al., 2025), the rate of relative increase differs across river basin hubs, at times in a counterintuitive manner. The relative increase in irrigation water demand is highest for Drammen (Norway), more than doubling between 1985-2014 and 2031-2060. The climate of Drammen at present is moderate, wetter than in other catchments, and is projected to become even wetter in the future, yet the increase in irrigation water demand is projected to be higher, in relative terms, than in all other river basins analysed in the project. The Messara (Crete, Greece) hub analyses showed significant water deficits even at the current stage. However, based on model-based projections of the future, the increase in irrigation water demand for the dry river basin of Messara (Crete, Greece) is relatively minor, even though the projections show rising temperatures and declining precipitation.

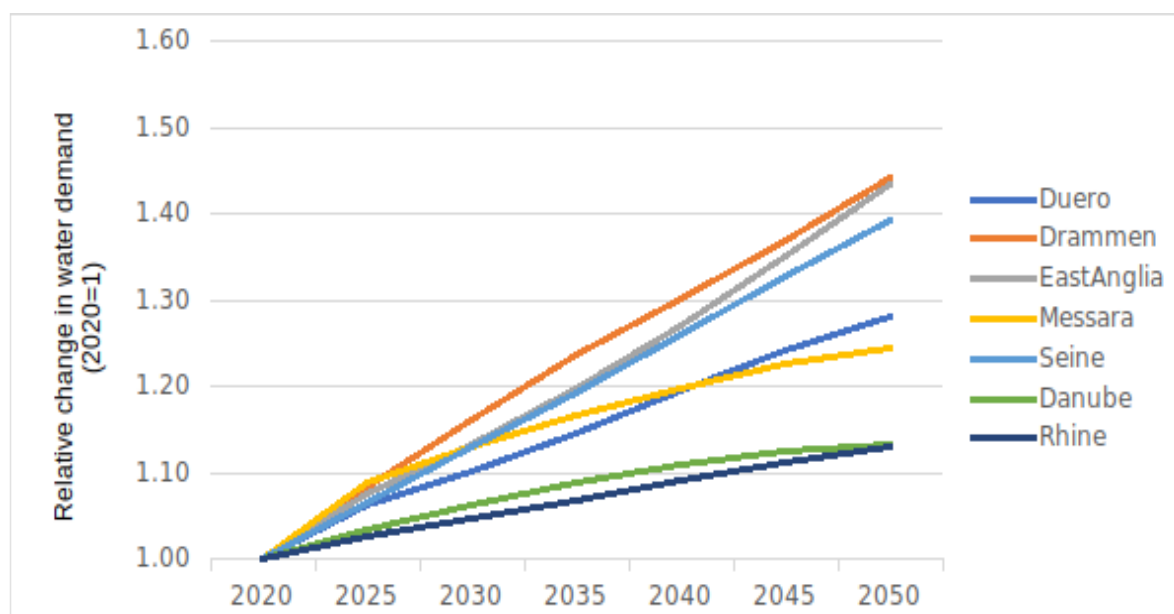


Figure 4. Expected relative change in domestic water demand for the seven basins under SSP2. (Source: Beckers et al. (2025), Figure 7).

5.4. Living labs at river basin hubs

The seven river basin hubs in the Project STARS4Water are living labs where data and tools are co-created with stakeholders and then scaled up. Practical use of the STARS4Water data services was demonstrated for these basins that have a diverse range of needs, climate vulnerabilities, and adaptation needs. They can serve as accelerators for further upscaling of these services and tools to other river basins worldwide (Kossida and Blind, 2025). Co-design of stakeholder data needs could complement local data with global data and data originating from data-driven models.

The stakeholder-driven approach adopted in STARS4Water and its relevance to EU policies is illustrated here through a few examples.

In the Duero river basin hub, an effective and efficient dialogue among science, policy, and local users was established, leading first to the co-design of activities and later to the co-creation of solutions. A new index (Groundwater Availability Index, GWAi) was created, as a management indicator that assesses the availability of groundwater resources by relating renewable groundwater resources to current groundwater demand and environmental requirements. It provides a simple, quantitative measure of groundwater pressure and sustainability. More advanced methods with a solid scientific basis were used at pilot river basins. Models and local knowledge were combined to predict groundwater quality (nitrate concentration) maps, with the help of NDVI, and spatio-temporal machine-learning (ML) models for groundwater storage change estimations. Finally, an assessment of the Safe-Operating-Space framework applied at Duero basin scale has highlighted some windows for proactive management decisions, not previously recorded under the Water Framework Directive analysis.

In the Seine river basin hub, an adaptive management approach has long been used to manage upstream reservoirs. Impacts of climate change were noticed by stakeholders, mostly as increasing air and water temperatures. Also changes in low flows were observed, with a tendency of having low flow periods that start earlier and last longer in a year, while also getting more severe. Aware of climate impacts, stakeholders have put efforts into developing more robust river basin modelling frameworks, which they can use for anticipated planning of reservoir operations, reducing vulnerability and enhancing adaptive capacity. The modelling and Safe-Operating-Space (SOS) frameworks developed and tested in STARS4Water highlighted how the revision of the current strategy for reservoir operation might occur more often in the future, and how the risk of underfilling the reservoirs in June (for releases in July-October) might pose critical challenges in terms of sustaining low flow levels for ecological purposes and downstream water uses.

In the Danube river basin hub, one of the principal challenges is water allocation focused on low flows. In a warm climate, with shrinking mountain glaciers, hydropower is likely to decline, as will the water needed for nuclear power plant cooling, and there will be problems with the provision of drinking and irrigation water. On the ecology side, connectivity is an increasing problem, when side arms are not connected to the main channel of the river. For navigation, the increasing number of days with fairway depth below 2.5 meters is an issue. The project has been carried out in dialogue with the International Danube Secretariat.

The East Anglia river basin hub is the flattest and most arid part of Great Britain, low-lying and fast-growing. It is becoming even more arid under climate change, with a decreasing precipitation-to-potential-evapotranspiration ratio. Predictive maps of groundwater nitrate pollution have been developed, using different techniques, including regression and machine learning. Groundwater pollution is a complex issue, integrating spatial and temporal factors, and being expensive and very time-consuming to treat. While existing use of groundwater models to explore the issue in practice is limited, physically informed statistical and machine-learning models are promising. In new techniques to explore environmental flow requirements, the use of SOS (Safe-Operating-Space) concept augurs well.

In line with one of the guiding principles for Water Resilience Strategy (see Box 3), the concept of SOS was considered and implemented across the seven river basin hubs according to their specific concerns on water-related risks of climate change, stakeholder knowledge, and needs for additional information related to local water management and system operation (Ramos et al., 2026). By disseminating some of the SOS findings via Story Maps, STARS4Water has raised awareness of river basin stakeholders (another guiding principle for Water Resilience Strategy, see Box 3) to climate change risks, and to improve their preparedness for climate change and future extreme hydrological events.

This process enabled the integration of management scenarios alongside climate (RCP - Representative Concentration Pathways) and socioeconomic (SSP - Shared Socioeconomic Pathways) scenarios when assessing indicators and thresholds for safe vs. at-risk operations.

By embedding operational flexibility into climate risk and adaptation analyses, the SOS framework can support the development of more robust and locally grounded adaptation strategies. Climate change can threaten water resources management. It has the potential to intensify socioeconomic and environmental risks and challenge best practices in water management. Scenario analyses already reveal critical situations regarding water sharing and tensions among different users, and these pressures are likely to be further exacerbated in the future.

There is an 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 neighboring basins linked through surface and groundwater interdependencies, or across regions linked by shared services (e.g., hydropower grids in the energy sector). The SOS framework offers a valuable tool for evaluating the robustness and resilience of water systems and their management. However, disaggregating the somewhat abstract global SOS concept and applying it to river basin management is far from straightforward.

The STARS4Water project has demonstrated the applicability of the Safe-Operating-Space framework at the scale of river basins. This requires consolidation of knowledge, refining indicators and thresholds, strengthening the translation of modelling outputs into actionable local and regional management strategies, and communicating these insights more effectively to decision makers and stakeholders. The integration of results across river basins should support the upscaling of these outcomes to the European scale, while also providing guidance for their uptake by other river basins.

In a joint policy event, organized by two EU Horizon Europe projects, namely STARS4Water and SOS-Water (Safe-Operating-Space for Water) entitled “*Navigating Europe’s Water Challenges: Building Resilience through Science and Policy*”, it was recognized that water is a very local and regional issue, so that we should not expect one European directive to solve every water problem. Hence, water resilience is ultimately local (built locally). Whether addressing groundwater depletion in Mediterranean basins, changing snow regimes in Scandinavia, flood risks in Central Europe, or transboundary governance in major international river basins, every region faces its own combination of challenges. European strategies provide a common direction and scientific research provides evidence. But implementation depends on local knowledge, stakeholder engagement and governance that reflects the realities of each river basin. There was a sentiment expressed at this joint policy event that research and policy support should not be too uniform. It must allow for the diversity of governance systems, hydrological conditions, risk profiles and sectoral trade-offs across Europe.

6. Is science the bottleneck?

A joint policy event, “Navigating Europe’s Water Challenges: Building Resilience through Science and Policy,” convened by the Horizon Europe projects STARS4Water and SOS-Water investigated how the global-scale Save Operating Space (SOS) concept (Rockström et al., 2009) can be translated into practical decision-making at the river basin level^{27,28}. Both projects started under the same call and have collaborated since the beginning. The joint policy event mentioned here is an example of collaboration between the two “twin” projects.

The policy event concluded that the interconnection between science and the people who need to make decisions is still very weak. “Many excellent research results never reach the politicians and water managers who need them most”. Indeed, the research-to-operations transfer is still an important bottleneck, and the challenge lies in transforming research outputs into practical guidance for decision-makers. River basin organisations frequently collaborate with Horizon Europe projects and highly value these partnerships. Yet, they also described the reality of limited staff capacity, overlapping project requests and the difficulty of maintaining sophisticated tools once the project funding ends.

There was a sentiment that the issue is how to ensure that scientific knowledge reaches “the right people, at the right time, in a form that enables informed decision-making”. Participants of the event repeatedly stressed that successful implementation depends on translating scientific findings into accessible language, practical guidance and operational tools that can support day-to-day river basin management.

Continuity is key because, while some Horizon Europe projects generate impressive scientific advances, the know-how is often shelved once projects end. Stronger coordination between projects and longer-term maintenance of digital platforms and decision-support tools, as well as more sustained collaboration between researchers and practitioners, is therefore needed. It was stated that Europe should think beyond individual projects and instead build enduring scientific communities capable of supporting long-term implementation.

There are still many recognized gaps in knowledge and understanding of how climate change is altering the hydrological cycles at river basin level, as well as related water quality and ecological challenges. For comprehensive listings of such challenges, see (Kundzewicz & Gerten, 2015; Blöschl et al., 2019). We could find many further needs for scientific advances. So, on top of “research-to-operations challenges,” we can indeed identify pure “research challenges.”

The STARS4Water project demonstrated a need for more science on several aspects. For instance, water withdrawal data are hard to get from direct observations (or national databases of declarations of water use). It is even harder to obtain information at the right resolution needed for hydrological models. Further, science is needed to develop statistical techniques to estimate and disaggregate data at the right scales with uncertainty estimates. Science advances are much needed for tackling cascading events, compound events and multi-hazard assessments that are just starting to be

²⁷<https://stars4water.eu/stars4water-and-sos-water-joint-policy-event-highlights-the-role-of-science-policy-partnerships-in-building-europes-water-resilience/>

²⁸<https://www.sos-water.eu/news-press/navigating-europes-water-challenges-turning-scientific-knowledge-into-water-resilience>

investigated in hydrology and have still to be assessed and implemented in joint modelling and management frameworks at river basins.

There are remaining hydrological science bottlenecks (e.g., transfer from global to local scales, or groundwater-surface water interaction in modelling tools), but there are also user/service bottlenecks related to translating science into services. National governments do not adequately fund these transfer and operational services, and researchers are not equipped to devote time to them. The EU invested in Copernicus services at the continental scale, but their uptake is still complex at local (non-calibrated) scales. Apparently, the question of who ensures the link between Copernicus products and the local/regional services (in a continuous and ever-evolving way) remains.

7. Recommendations for enhancing the knowledge base to support EU Water Resilience Strategy and water related policies

Climate change and its impact were clearly sensed in Europe in the summer of 2026, when extreme weather events hit the continent hard, putting lives, agriculture, ecosystems and essential infrastructure under severe pressure and incurring substantial economic, societal, and ecological costs. There is an interim estimate that economic losses from extreme weather and climate events in the summer of 2026 could reduce EU GDP for 2026 by about 1% (i.e. 180 billion €), effectively wiping out the planned growth^{29,30}. This estimate is much greater than the four-year average (2021-2024) of economic losses from all extreme weather and climate events in Europe, reaching about EUR 54 billion (in constant 2024 prices), which is around 0.3% of Europe's GDP³¹. The economic and societal costs included elevated heat-related mortality and morbidity that put pressure on healthcare systems; reduced labor productivity; severe wildfire damage; decreased agricultural output; increased food prices; constrained energy production and increased electricity prices; transport disruption; and increased transportation costs.

In the summer of 2026, compound risk occurred in many European countries (e.g., Spain, France, Greece, and Croatia). A heatwave coincided with a drought and a massive wildfire. Water played a role in all three components of this triad. The year 2026 has been announced as the worst low-water year on record for many rivers in Europe, including the Rhine and the Danube, causing significant economic, societal, and ecological impacts. Under the European Good Navigation Status standards for the River Danube, the fairway must provide a depth allowing a draught of 2.50 m for at least 94% of the days (approximately 343 days) in a year. By 23 September 2026, the Danube had 152 low-water days (previous 30-year high until 23 September was 76 in 1998), while the Rhine had 134 low-water days (previous high: 91 in 2022)³². Low water disrupted navigation and transport (reducing freight and passenger traffic) and energy production (cutting hydroelectric and nuclear plant outputs) and agriculture across much of Europe. The droughts, low-water episodes, and related reductions in groundwater recharge had a dramatic impact on groundwater-dependent ecosystems, as well as on aquatic and wetland ecosystems. Prioritizing different water uses, such as ecology (e-flow), agriculture, energy, navigation in the time of low water becomes a critically difficult issue.

A broad category of drivers of Europe's water-management challenges is collectively termed anthropopressure, including pollution of water, land and air from urban, industrial, and agricultural sources; land-use change and land-cover change (urbanization, degradation of wetlands, and hydromorphological change, including river regulation), as well as water over-exploitation. Anthropopressure can lead to ecological degradation. On the top of direct anthropopressure effects, there are adverse climate change impacts driven by increasing anthropogenic emissions of greenhouse gases to the atmosphere, therein increasing problems with freshwater availability and water-related extremes (droughts and floods) that get more extreme and more frequent. The past

²⁹ <https://www.triodos.com/en/articles/2026/hot-summer-economics>

³⁰ <https://www.triodos.com/en/press-releases/2026/europes-extreme-heat-could-wipe-out-eu-growth-in-2026>

³¹ <https://www.abnamro.com/research/en/our-research/the-economic-impact-of-a-hotter-europe>

³² <https://www.riverwaterwatch.com/low-water-2026>

climate extremes may become a new normal. “Cracks have become canyons” says Mr António Guterres, UN Secretary General³³

The main outcomes of the STARS4Water project can be distilled into a short set of key messages for stakeholders that inform water policy on emerging issues that challenge reaching water policy goals:

- Even if, on average, Europe has relatively abundant freshwater resources, severity of problems related to freshwater availability is on the rise. Water resources may be insufficient in some regions during specific seasons; thus, the uneven distribution of freshwater resources, both spatially and temporally, is a major water management challenge.
- Climate change has been ongoing in Europe and is projected to intensify in the future, with consequences to freshwater availability as well as social, economic, and ecological, vulnerability in European river basins. Recent findings from beyond the STARS4Water project (C3S/ECMWF and WMO, 2026) demonstrate that over the last 30 years (1996-2025), Europe was the fastest-warming continent (+0.56°C/decade) and the Arctic – the fastest-warming region (+0.75°C/decade), globally.
- Since the projected rate of temperature- and circulation-conditioned rise of evapotranspiration often outweighs the precipitation rise (if any, because for some areas of Europe precipitation is projected to decrease in absolute terms), the risk of drought is on the rise in many European river basins. Europe is becoming a drought hotspot.
- Water demand in all categories (domestic, industrial, irrigation) is projected to increase in the future in European river basins.
- Even if the STARS4Water project has not explicitly dealt with floods, it is worthy of mentioning that there is more room for precipitable water in the warming atmosphere. Hence, potential for heavy precipitation events has increased with the warming, and is projected to increase further, augmenting flood (and in particular flash and urban flood) risk in European river basins.

Figure 5 summarizes the STARS4Water pathways to water resilience, linking project outputs to the European Water Resilience Strategy objectives.

It is expected that the legacy of the Project STARS4Water will extend beyond the datasets, models, and tools produced by the project. It will also be the partnerships strengthened between scientists, policymakers and river basin organisations that will remain essential as Europe works towards a more resilient water future. The STARS4Water project identified six guiding principles, rooted in a stakeholder-driven approach, for enhancing water resilience at the river basin level, listed in Box 3. To enhance water resilience, it is necessary to: improve our understanding of the freshwater system and be better prepared for future flow regimes and water resource availability. We should build a water-resilient Europe through science-stakeholder partnerships, raising awareness, and sharing information. It is crucial to identify the Safe-Operating-Space (SOS) for resilient water resources management and to explore management options to enhance water resilience.

³³ <https://news.un.org/en/story/2026/09/1168392> Guterres: ‘Cracks have become canyons’ says UN Secretary General.

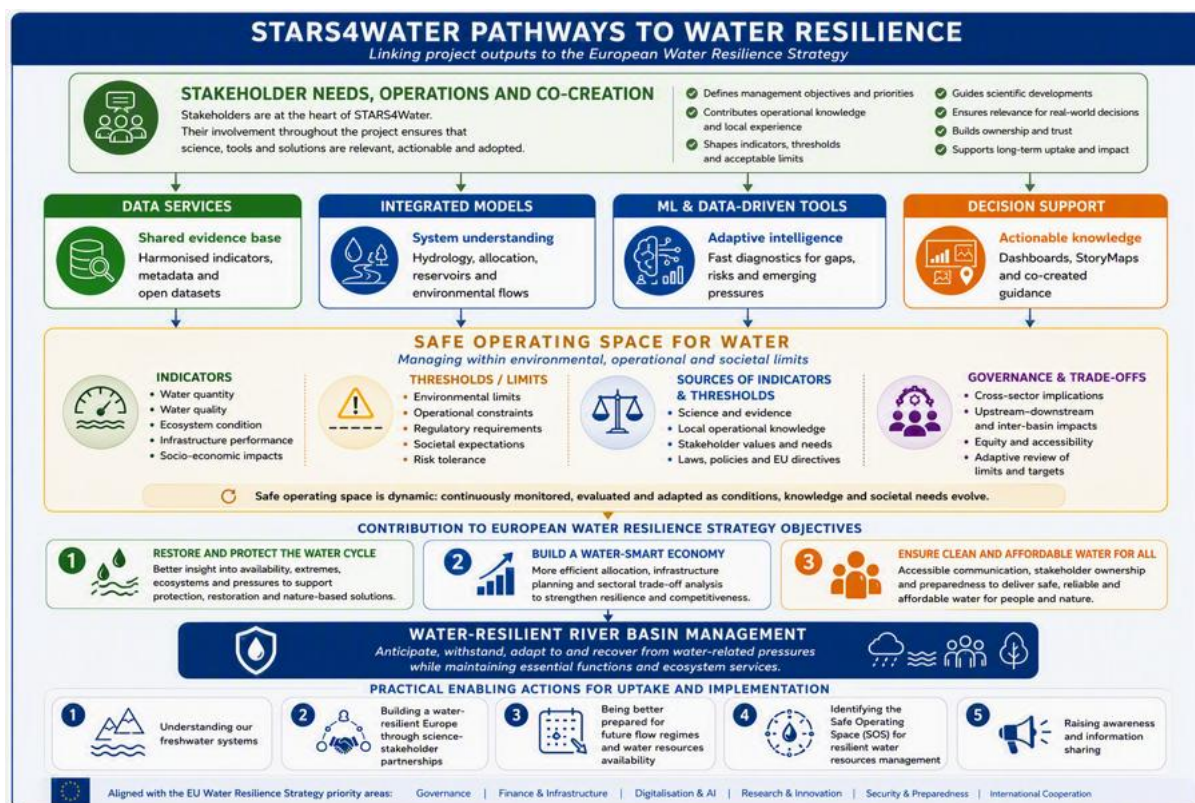


Figure 5. STARS4Water pathways to water resilience (Hegdahl – design assistance copilot).

Understanding our freshwater systems

To enhance water resilience and support sustainable water resource governance in the face of climate change, it is essential to understand the full catchment hydrological processes from source to sea. This includes recognizing the role of various water bodies (reservoirs, aquifers) and land ecosystems that may impact processes such as groundwater recharge, evapotranspiration, and streamflow. This understanding encompasses the impacts of societal pressures and water use priorities on catchment processes. New datasets and models offer improved understanding and enhanced projections of water resources availability. Within STARS4Water, new data services and global-to-local data collection were developed alongside the generation of new and improved models and frameworks, both process-based and data-driven. It is important to note that global, continental, national, and regional datasets, although created to serve different purposes, are complementary. New projections for water demand and water availability were released. The STARS4water project also developed sophisticated hydrological, water allocation, and reservoir models, which are supported by these new data services. Process modelling and data-driven models are two distinct approaches that can complement each other. Within STARS4Water, we identified that machine learning techniques are particularly suited to estimate snow water equivalent, groundwater storage changes, groundwater contamination risk, irrigated areas and reservoir storage. They are particularly useful to exploit heterogeneous datasets due to their computational efficiency and flexibility.

The new insights into the links between water, nature, and society need a broader set of indicators to inform decision-making on water management. These novel datasets, models, and indicators are not yet fully integrated into current river basin management information tools and decision-making processes.

Building a water-resilient Europe through science-stakeholder partnerships

To strengthen water resilience across Europe, technical innovations alone are not sufficient. Strengthening water resilience across Europe requires robust partnerships between science and stakeholders, ensuring that scientific advances in modelling tools, knowledge systems, and data services are translated into decision-relevant information and actionable solutions. Equally, these partnerships improve the relevance of research by embedding stakeholder knowledge, experience, and priorities into the development process. The STARS4Water project demonstrated that technical innovation alone is insufficient for uptake; the most effective outputs were those developed through continuous dialogue with stakeholders and tailored to clearly identified needs. Co-creation is essential to drive innovation by leveraging the combined expertise of stakeholders and scientists.

The project team has worked with river basin organisations and river basin communities as key implementation factors through a co-creation, living-lab, approach called river basin hubs. Across these river basin hubs, stakeholder engagement helped define relevant indicators, appropriate spatial and temporal scales, and meaningful future scenarios, while fostering shared ownership of knowledge related to both current and emerging water challenges.

The new services and models have been co-designed with stakeholders to meet their needs on data and information, ensuring relevance and uptake for use beyond the lifetime of the project and across other basins in Europe. Among the tangible stakeholder-related outcomes of the project are: metadata portal, river basin datasets, improved modelling tools (including data-driven models), operationalization of the concept of Safe-Operating-Space (SOS), Story Maps, dashboards and the STARS4Water academy. The project enhanced knowledge of climate and operational risks related to freshwater resources. The STARS4Water project follows a stakeholder-driven approach and a science-(data-)driven approach in the application of novel data and modelling tools. This collaborative approach not only increased the usability and adoption of project outputs but also strengthened collective capacity to implement effective water management strategies and enhance long-term resilience.

Being better prepared for the future flow regimes and water resources availability

Future climate change is expected to substantially alter hydrological regimes and freshwater availability across European river basins, and rising socio-economic water demands may further intensify pressure on water resources if mitigation measures are not adequately implemented. It is essential that scientists and stakeholders have a common understanding of the potential future pressures on the system. Strengthening water resilience requires participatory and robust scenario-based approaches that integrate local concerns with regional, national and European pathways. These scenarios will enable the assessment of vulnerabilities, explore future water availability, and identify adaptation opportunities for ecosystems and society as well as sustainable prosperity.

The general characteristic of projected climate change in Europe is wetter in the north and drier in the south. However, STARS4Water demonstrated that even in wetter north (for instance, in the Drammen and East Anglia basin hubs), the irrigation water demand can grow more strongly in relative terms, due to temperature increase and longer growing season, than in other river basin hubs studied in the project, including those in the drier south. The STARS4Water results show that regions of Europe face very different challenges, so recommendations cannot be identical for every country. For Central Europe (Rhine, Danube), and for East Anglia and the Seine, recommendations must address the management of low water levels (including reservoir operation) and related threats to power plant cooling and navigation. For Southern Europe (Duero, Messara), recommendations must emphasize

combating the critical level of groundwater overexploitation by agriculture (via restriction systems and efficient irrigation). Throughout most of Europe, there is a need to adapt infrastructure to heavy rainfall, which is causing flash and urban flooding with increasing frequency. In Northern Europe (Drammen), earlier snowmelt, reduced winter snow, and shifts in seasonality must also be considered.

Identification of the Safe-Operating-Space for resilient water resources management

The European Water Resilience Strategy focuses on reducing the impacts of hydrological extremes, improving water efficiency, and lowering water consumption to support a water-smart economy. Defining sustainable water-use limits and environmental flow requirements is essential for establishing a Safe-Operating-Space (SOS) that ensures resilient water management and secures long-term water availability for both people and ecosystems.

The STARS4Water SOS Framework demonstrates that climate change is likely to increase pressures on water resources, creating growing competition among water users and challenging existing water management practices. To support policymakers, the framework provides an integrated, stakeholder-informed approach that combines climate, socio-economic, and operational information to identify risk thresholds, evaluate system resilience, and guide evidence-based decisions for sustainable and adaptive river basin management. The findings highlight the urgent need for data and tools that support an integrated modelling approach, and the identification of relevant indicators. In STARS4Water project, we provided data and tools and made progress in transferring from science to practice. Applying the SOS concept is challenging and relies upon a shared understanding of the concept and how it relates to existing approaches, thus incorporating the perspective of water managers is crucial. This framework, combined with the system knowledge and current operational practice, provides the means to explore management options to enhance water resilience. A range of management strategies and adaptation measures can help mitigate the impacts of climate change on water resources. To build water resilience, these interventions should be tailored to local basin conditions and implemented within a Safe-Operating-Space that supports the sustainable and equitable allocation of water resources, thereby contributing to long-term societal prosperity.

The concept of SOS was considered and implemented in STARS4Water across river basin hubs according to their specific concerns on water-related risks of climate change, stakeholder knowledge, and needs for additional information related to local water management and system operation. By embedding operational flexibility into climate risk and adaptation analyses, the SOS framework can support the development of more robust and locally grounded adaptation strategies.

There are two crucial things behind the SOS concept:

- “operations” are important and need to be considered in risk analysis (co-creation is not only about gathering needs and requirements from stakeholders but using their way to operate/manage water today to innovate climate adaptation); and
- “safe space” is relevant for the society: what are our limits/thresholds and how the thresholds of one sector impact the other(s).

Indicators and thresholds are intrinsically related to governance as, in many real cases, they are defined by laws. We need to question ourselves about these indicators and thresholds as well: should they come from science, from the environment (impacts), from operators (and their local knowledge), or from governments and EU directives (higher-level guidance)?

Raising awareness and sharing information

The STARS4Water project plays a role in the development of evidence-based awareness, preparedness, and capacity building. It paves the way from evidence to implementation. It makes a step towards strengthening science-based decision making through targeted policy guidance and towards fostering long-term partnerships between science and river basin management.

By disseminating SOS findings via Story Maps, the STARS4Water project has raised awareness of river basin stakeholders to climate change risks and improved their preparedness for future extreme hydrological events.

The STARS4Water project unlocked datasets and facilitated their use in water management and enhanced integration of water management operations, practices and ‘what ifs’ in scenario assessments.

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