STARS4Water

Improved projections on water resources availability and risks in selected river basins

Deliverable 4.2

Version 1.0

Lead beneficiary	INRAE
Lead author	Maria-Helena Ramos
Work Package	4: Integrated assessment of future water resources
Due date	31 December 2025, extended for updated results
Submission date	17 May 2026
Contributors	Chapter authors are indicated in the text

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

Version log			
Version	Date	Released by	Nature of Change
0.0	06.10.2025	Maria-Helena Ramos	Outline
0.1	10.12.2025	All contributors	Partner contributions added
0.2	24.12.2025	Maria-Helena Ramos	First version for review
0.3	31.01.2026	Maria-Helena Ramos	Feedback from first review incorporated
0.4	16.02.2026	Harm Duel	Review of draft report
0.5	15.04.2026	All contributors	Review assessment and updating
0.6	13.05.2026	Maria-Helena Ramos	Final version for coordinator
1.0	22.05.2026	Harm Duel	Final version submitted

Citation

Ramos, M.H. et al. (2026): Improved projections on water resources availability and risks in selected river basins - Deliverable 4.2 (D4.2). Horizon Europe project STARS4Water.

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

Summary

This report presents the results of the **assessment of water resources availability and risks under climate change** across seven river basins: Danube, Drammen, Duero, East Anglia, Messara, Rhine, and Seine. It describes the future scenarios of climate change, water demand and/or management strategies co-established with stakeholders to assess water availability and risks. It highlights the data services and modelling tools developed and used for the evaluation of the main impacted sectors or ecosystem functions, following stakeholder's concerns in each river basin. These comprise sectors related to agriculture, hydropower, navigation, water supply, environment or aquatic ecosystems through ecological flows ("eflows"), as well as risks for hydrological extremes (floods, droughts) and water reservoir filling/release conditions. The assessments are the result of an intensive co-construction process with stakeholders. Results have been presented in scientific conferences (e.g. European Geosciences Union General Assemblies in 2025 and 2026) and peer-reviewed publications. Additional peer-reviewed publications (e.g. special issue in the International Journal of River Basin Management) are under preparation with the respective generated datasets at river basin scale published/in preparation to be published in Zenodo or national permanent open data repositories.

As part of the STARS4Water project, the assessment of water resources availability and risks under climate change relied on a common understanding of the **Safe Operating Space (SOS) concept** and its operationalisation at the scale of river basins. The SOS concept is an approach to translate the complex information on the variations of the hydrological regime and water resources availability due to climate change, and the uncertainties related to this, into information understandable for river basin managers and sectors to allow them to develop actionable strategies for future operations and water management. The STARS4Water SOS concept was extensively discussed among partners and river basin stakeholders along the process to ensure the successful implementation of the **STARS4Water SOS Framework**. The emerging framework for water resources management at river basin level is supported by the following guiding principles:

- It builds on a **bottom-up approach and on science-stakeholder partnerships** in the river basin hubs, anchored to the realities and needs of local stakeholders, as assessed through workshops, bilateral meetings, and by the validation of the results at different phases of the risk assessment.
- Its implementation at the **river basin scale** implies **contextualization** to tackle the local meanings (e.g. values) and specificities of local contexts, and to define data and indicators that can inform on future impacts of water management operations and strategies.
- It leverages opportunities in **new generation data services and modelling tools** to enhance **understanding of the water system** in the river basins, foster new knowledge, and boost innovation in water management.
- It strongly relies on co-designed **scenarios** about the future, delivered though the co-construction of **relevant narratives and trajectories** for water use and socio-ecological management, integrating aspects related to climate, water demand and infrastructure in order to assess current water use and boundaries of water-related operations under future changing conditions.
- It takes into account **actions and strategies in river basin water management** (current and future adaptation strategies) to assess the landscape of "safe operations" and draw attention to situations that might put the water systems at risk or close to boundary conditions at the river basin scale.

- Finally, it provides **actionable information on SOS** for the planning of water resources management and to support decisions, with the help of visualization tools, dashboards, story maps, and policy briefs, among others.

With the implementation of the STARS4Water SOS Framework in seven river basins in Europe, we showed that **climate change can be a threat to water resources management**, with 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 could be further exacerbated in the future.

In this report, projections refer to any estimate of a future situation concerning water resources availability and risks to operations that are crucial to water resources management in the river basins. Projections can be related to climate, hydrology (river flow or groundwater) and management (operation or water allocation) scenarios. The STARS4Water SOS framework focuses on bringing together these projections at the river basin scale to shed light on the risks of the current operations and inform stakeholders on the what-if scenarios that were co-built with them since the start of the project.

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

Identifying relevant indicators to distinguish safe from at-risk operational conditions is essential for this integrative approach and for drawing robust conclusions about complex system interdependencies. Tailormade visualisations and dashboards can facilitate information sharing and guide coordinated action on future water management strategies, improving preparedness for joint responses across different water users. Incorporating operational and management practices adds flexibility to the continuous assessment of climate risks and helps identify effective actions today for tomorrow's challenges. The SOS framework offers a valuable tool for evaluating the robustness and resilience of water systems and their management.

Our results showed that applying the SOS concept in river basin management is far from straightforward. Early in the process, a key challenge was to establish a shared understanding of the concept itself, including clarifying how it relates to existing approaches in integrated river basin management or complements them, such as risk assessment analyses and scenario-based evaluations used in climate change impact assessments and adaptation planning.

Incorporating the perspectives of water managers and stakeholders proved essential for shaping the contours of the project's SOS framework. Their input enabled us to integrate a management and operational dimension into the physical, social, and ecological components of risk analysis, thereby strengthening and adding value to the inhouse expertise within water management organisations and public services.

Climate and water risk analyses are therefore enriched, as risk becomes not only the intersection of hazard, vulnerability, and exposure, but also more explicitly incorporates existing knowledge about how water systems operate within the river basin. This operational knowledge, reflected in current practices such as water quantity and quality monitoring, reservoir management and control, and the prioritisation of water uses, can be integrated alongside ongoing or planned adaptation actions. Within such a framework, the operations of water systems can be better understood in relation to climate risks. They may emerge as a strong and flexible tool for mitigating climate related impacts, or they can be adapted themselves to ensure they do not become amplifiers of future risks.

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1. Introduction

1.1. STARS4Water project

STARS4Water (Supporting Stakeholders for Adaptive, Resilient, and Sustainable Water Management) is a four-year (2022-2026) Horizon Europe research project focused on improving water resources understanding to support the European Green Deal and EU water policies.

The project's ambitions include to:

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

STARS4Water collaborates with seven River Basin Hubs (RBHs) — Danube, Drammen, Duero, East Anglia, Messara, Rhine, and Seine — using a co-creation, living lab approach to ensure stakeholder-driven solutions. It also integrates new datasets and models into existing water management tools, improving projections and decision-making for more resilient water policies (Figure 1.1).

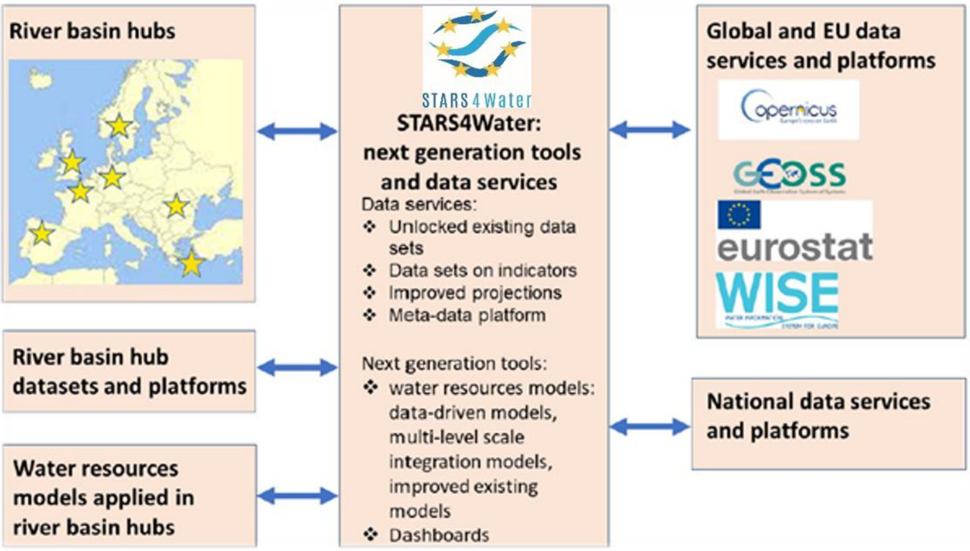

Figure 1.1. Overview of STARS4Water activities within the context of stakeholders and data providers.

1.2. Assessment of water resources availability under climate change risk

One of the objectives of the STARS4Water project is to improve the understanding of climate change impacts on water resources availability and the vulnerabilities for ecosystems, society and economic sectors at river basin scale. The project explores the use of novel data services and modelling tools, co-developed and validated with stakeholders, to assess future water resources and risks in selected River Basin Hubs (RBHs) in Europe under future conditions.

Work Package 4 (WP4) of the project is dedicated to the integrated assessment of future water resources. The main activities in this work package are to:

- Calibrate and validate the next generation models in the 7 RBHs (Task 4.1).
- Assess and report of water resources availability under risk by climate change in the seven RBHs, by interacting with stakeholders (Task 4.2).
- Provide story maps on climate change and socio-economic developments within the seven RBHs (Task 4.3).
- Upscale basin-wide assessment of climate change risks and impacts to EU-level (Task 4.4).

The interrelation of Work Package 4 in the STARS4Water Framework is displayed in Figure 1.2. Its activities are strongly supported by stakeholders codesign (WP1) and rely on data (WP2) and models (WP3) developed along the process of assessing future water resources for increased preparedness in river basin water resources management in Europe (WP5).

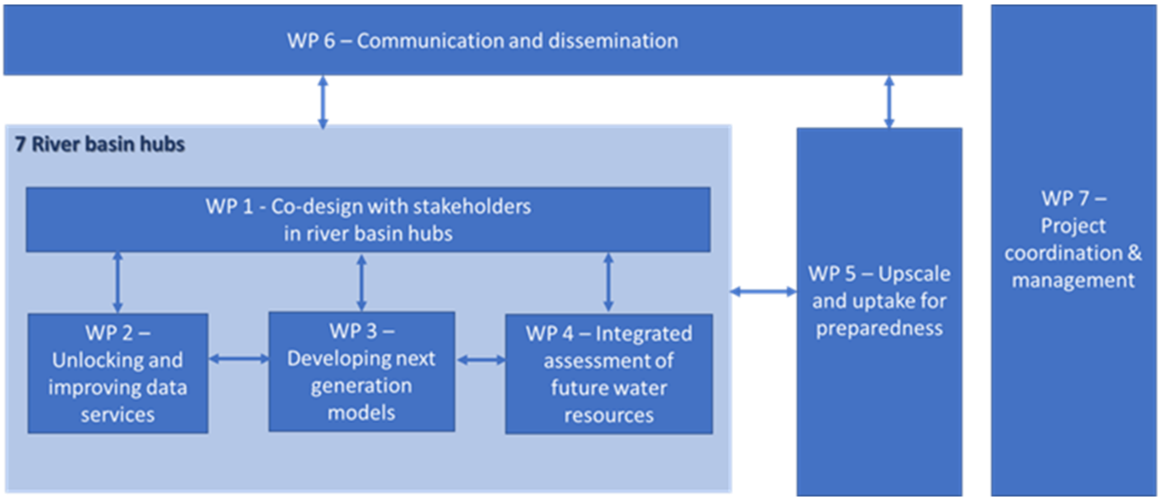

Figure 1.2. Work package structure of the STARS4Water project: the development of the next generation models (WP3) through a co-creation approach (WP1), benefitting from data sources available (WP2) and calibration and validation activities in WP4 to explore future water resources availability in European river basins (WP4).

1.3. Content of this report

In this report, projections refer to any estimate of a future situation concerning water resources availability and risks to operations that are crucial to water resources management in the river basins. Projections can be related to climate, hydrology (river flow or groundwater) and management (operation or water allocation) scenarios. The STARS4Water SOS framework focuses on bringing together these projections at the river basin scale to shed light on the risks of the current operations and inform stakeholders on the what-if scenarios that were co-built with them since the start of the project.

Supported by state-of-the-art regional, national or global datasets (WP2: Beckers et al, 2023; Piniewski et al., 2024) and modelling tools (WP3: Rickards et al., 2023; 2024; Baron et al., 2025, and WP4: Preiml et al., 2024), as well as stakeholders' narratives and what-if scenarios (WP1: Hegdahl et al., 2023; Okruszko et al., 2024), this report presents the following for each river basin:

- Future scenarios of climate change (including, when relevant, related hydrologic scenarios).
- Future scenarios or strategies of infrastructure or water management/allocation.
- State of water resources availability and risks (assessment results).
- Lessons learnt and perspectives.

Firstly, it presents the processes of defining the project’s Safe operating space (SOS) framework for water resources management at river basin level. Secondly, it reports on the assessment of water resources availability and risks under climate change in each river basin hub of the project. This report has thus a strong component of integration of previous achievements of the project.

2. STARS4Water Safe Operating Space (SOS) Framework

2.1. The SOS concept within the Planetary Boundaries framework

In 2009, Rockström et al. proposed an approach to global sustainability, where the concept of **Planetary Boundary (PB)** was introduced. Planetary boundaries are those “within which we expect that humanity can operate safely.” Planetary boundaries are interdependent (the shift of one may affect other(s)) and may or may not be associated with a threshold or “tipping point”. Originally, the authors had identified nine planetary boundaries, with quantification proposed for seven of them. For instance,

- the safe limit for the climate change Planetary Boundary was quantified as: CO2 concentration in the atmosphere below 350 ppm and/or a maximum change of +1 W/m^2 in radiative forcing;
- the safe limit for the Planetary Boundary on the rate at which biological diversity is lost was quantified as: an annual rate of less than 10 extinctions per million species;
- the safe limit for the Planetary Boundary on Global freshwater use (later renamed to “freshwater change”, see Wang-Erlandsson et al., 2022) was quantified as: less than 4000 km^3/year of consumptive use of runoff resources.

The idea was that transgressing one or more planetary boundaries “may be deleterious or even catastrophic due to the **risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems**.” With that in mind, the authors estimated that humanity has already transgressed the first two planetary boundaries mentioned here above, as well as the planetary boundary on the global nitrogen cycle. Wang-Erlandsson et al. (2022) introduced the green water Planetary Boundary, identifying root-zone soil moisture as control variable, and its assessment indicated that this planetary boundary is also already transgressed. Finally, updates of the framework in 2023 suggested further transgressions resulting in earth beyond six of nine planetary boundaries (Richardson et al., 2023).

While acknowledging uncertainties and knowledge gaps, Rockström et al. (2009) highlighted the added value of the approach as an **integration at the global (Earth system) scale**, as it “lays the groundwork for shifting our approach to governance and management, away from the essentially sectoral analyses of limits to growth aimed at minimizing negative externalities, toward the estimation of the safe space for human development.”

Moreover, one may keep in mind the relationship between the Planetary Boundary concept and the **tipping points approach for social-ecological systems**, used to describe rapid, non-linear changes. In their review on tipping points and similar concepts (e.g., regime shifts, critical transitions), Milkoreit et al. (2018) draw attention to the needs to “map and interpret the use of the term tipping point”, in particular as the term “has been picked up by policy makers and diplomats dealing with climate change and sustainable development.” From their analyses of minimum conditions to define a tipping point, they suggest that “tipping points in general can be defined as the point or threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible. This new state can be distinguished from the original by its fundamentally altered (positive and negative) state-stabilizing feedbacks.”

It is interesting to note that the authors evaluate that **climatic tipping points** were popularized in the 2000s, pointing out in particular to the publication by Lenton et al. (2008), where the "idea of tipping elements in the climate system, defined as subsystems of the climate system that can experience abrupt change, 'triggering a transition to a new state'" is introduced. The authors differentiate the common definition of the term **"tipping point"** (a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system) from their definition of the term **"tipping element"** to describe "subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point—in forcing and a feature of the system—at which the future state of the system is qualitatively altered."

Back to the Planetary Boundary framework, a question may arise: **are planetary boundaries and tipping points two terms for the same thing?** In response to criticisms to the Planetary Boundary framework (in particular related to the Biosphere Planetary Boundary), Rockström and colleagues[1] explain that the theoretical framework of the "planetary boundary as originally defined is not equivalent to a global threshold or tipping point." (citation from Steffen et al., 2015). It is argued however that "even in the recent critical discussions over whether or not there are tipping points in the Earth System, most agree that there is strong scientific evidence of tipping points in the climate system"[2].

In their 2009 paper, Rockström et al. mention the climatic "tipping elements" and suggest that the Planetary Boundary concept "deal with such cross-scale complexity by proposing planetary boundaries to avoid all known sub-Earth System thresholds in the foreseeable future." The Planetary Boundary concept would then reflect environmental processes that "are known to contribute to regulating the Earth System," with **some of these processes exhibiting a threshold or "tipping point" behaviour, but not necessarily all of them**. The authors add that: "Even in the few cases where the scientific evidence supports threshold behavior, the identified planetary boundaries are not placed at the estimated point (for a control variable) of a threshold. The existence (or otherwise) of thresholds and/or "tipping point" behaviour in the processes included is thus not a pre-assumption or requirement to the framework of planetary boundaries."[1]

The distinction between Earth and climate systems appears to be crucial, as well as the **scale issue**, as also highlighted by the authors: "if operationalised, planetary boundaries need to translate to the relevant scale where both the environmental and governance processes occur." [2] Finally, they also highlight that the conceptual framework for planetary boundaries "is first and foremost designed to **advance Earth System science**", and not for policy, although it "could indeed become a useful **policy tool** with further development." They add that it "was a scientific effort to identify the ample evidence that Earth not only is a coupled self-regulating system, but also a system with finite limits."

Further aspects of the Planetary Boundary framework can be found in the latest review by Rockström, et al. (2024). Here, for the purposes of establishing an **SOS concept for the STARS4Water project**, we will retain the following **key aspects** of particular interest:

- a scale (planetary for the Planetary Boundary) is defined;
- integration (opposed to a siloed analysis) is an important feature;

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[1] https://www.stockholmresilience.org/research/research-news/2017-11-20-a-fundamental-misrepresentation-of-the-planetary-boundaries-framework.html

[2] https://www.stockholmresilience.org/research/research-news/2012-07-02-addressing-some-key-misconceptions.html

- thresholds and/or “tipping point” behaviour may or may not exist in the evaluated processes (i.e., there is a need to define what is desirable and undesirable changes);
- boundaries included in the framework reflect processes that may bring undesirable (or catastrophic) changes due to the risk of crossing (known or unknown) thresholds;
- it is up to societies to choose where the boundary positions are placed (i.e., at the system level, how much deviation do we allow from the acceptable targets?)

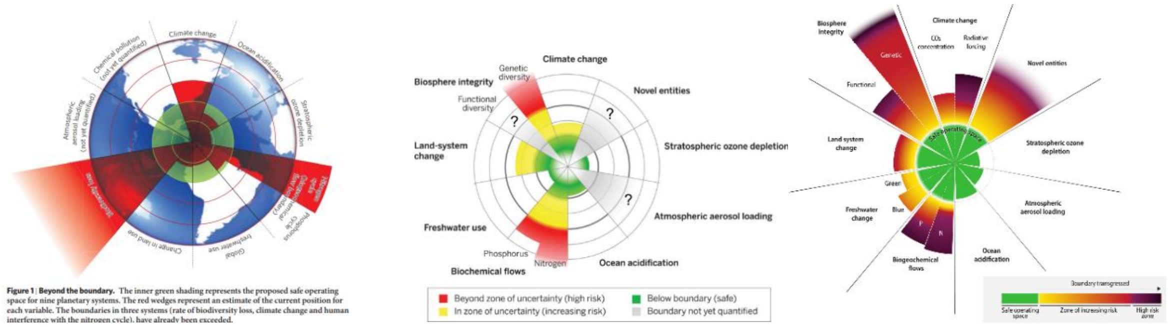

Figure 1 | Beyond the boundary. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded.

Figure 2.1: Illustrations of the evolution of the SOS Safe Operating Space within the Planetary Boundaries framework from the literature (Source: left, Rockström et al., 2009; middle, Steffen et al., 2015; right, Rockström et al., 2023).

2.2. Localization and contextualization: towards the case of water management

Freshwater (indicator for freshwater availability) was already defined as a Planetary Boundary in the first proposals of the framework in terms of consumptive use of runoff resources. Subsequent main criticisms have pointed out to the fact that this definition neglects spatial variations of water availability and uses a control variable that neglects the complexity of global hydrogeological processes. From 2020, additional publications have proposed new considerations for freshwater and water management within the Planetary Boundary framework:

- Gleeson et al. (2020) proposed a framework for defining water planetary sub-boundaries (based on five water stores: atmospheric water, surface water, soil moisture, groundwater, and frozen water) into local water management approaches to account for a variety of changes to the water cycle.
- Zipper et al. (2020) proposed an integration of the water planetary boundary with water management from local to global scales, defining “a local safe operating space, in which interactions between water stores and Earth System components are used to define local boundaries required for sustaining the local water system in stable conditions (…)”.
- Bunsen et al. (2021) proposed a review on the planetary boundaries for water, noting that in some “reviewed studies, a link to the water planetary boundary remains rather vague as these studies merely investigate water availability in comparison to consumption”.
- Wang-Erlandsson et al. (2022) proposed to change from the "freshwater use" planetary boundary to "freshwater change" to include both "blue water" (groundwater/surface water) and "green water" (root-zone soil moisture).

From Zipper et al. (2020), in particular, we retain the following aspects:

- It is crucial to recognize the real-world complexity in SOS for water and water management. Multidimensional parameter spaces representing multiple interconnected can be a challenge.
- Defining control and response variables and boundary values for local safe operating space requires identifying if/how the degradation of the local water system would lead to outsize impacts at the global scale (potential local-global interactions).
- Considering existing management and governance approaches is essential. Local applications of the water planetary boundary can complement existing water management approaches. Their integration with the water planetary boundary can provide a consistent approach for interregional comparisons and quantification of the impact of water management solutions.

From their literature review, Rieutor et al. (2025) note that "maintaining consistency between the global and local scales is highlighted in 44% of the publications" related to the PB concept; and that "the low level of commitment among local stakeholders (difficulty of adapting the concept to local contexts lack of legitimacy) is highlighted in 59% of publications". The authors raise the crucial question: *What is hindering the effective operationalization of the Planetary Boundary concept?*

Methodological aspects of localization are identified, referring to, for instance, issues related to:

- Scaling: how to produce localized representations while maintaining global relevance?
- Data and methods: what processes and which indicators to prioritize, and should methods be adapted to local specificities or be standardized methods?
- Values: should experts dominate (technocratic approach), or should local stakeholders guide its implementation (participatory approach)?
- Time continuity: how to integrate future developments?

Barriers for better local operationalization are suggested: insufficient stakeholder engagement; uniqueness of context (local variability); perceived lack of relevance to the territory; need to rethink the governance and organization of local institutions to effectively integrate the Planetary Boundary concept into local public policies and strategies; lack of clear and appropriate goals, and of strategies to maintain the approach over time; doubts about the validity (uncertainties) and impartiality of the process.

Recognizing that localization is a prerequisite, the authors also caution that "technical sophistication increases the precision of results but reduces accessibility to the method." To improve the local operationalization of the Planetary Boundary concept, they emphasize the need for contextualization: "rebuilding the entire [Planetary Boundary] framework with local stakeholders to better integrate specific territorial characteristics and strengthen the uptake of the concept at the local scale." This implies adopting flexible, context-specific transformation pathways that align with territorial realities and consider the actual operational capacity of stakeholders.

2.3. The STARS4Water SOS framework and its guiding principles

The numerous reflections from the literature pointed out to some key aspects for consideration when designing the STARS4Water SOS concept and applying it to a river basin hub:

- What **impacts** are to be considered (which can be translated by the "what-if" questions previously co-defined with stakeholders during the narrative processes in Work-package 1)?
- What are the **drivers** of impact(s)? This requires knowledge co-created with stakeholders as well, during the first phases of the project.
- What are the **pressures**? (e.g. a change in regime, change in climate, change in water demand). This also relies on stakeholder co-creation, as well as climate projections and socio-economic scenarios.
- What is **the response variable** and what is **the control variable**, and how are they related? (e.g. in the case proposed in Zipper et al. (2020), 'Biosphere integrity' is defined as the response variable and 'water salinity' as the control variable, with water salinity being influenced by three local hydrological mechanisms at different scales).
- Can the **status of the control variable** be measured, tracked in time, and monitored?
- What are the (control variable) **indicators and thresholds** that will define safe/at-risk operations? Thresholds may not exist and could be inferred from operational practices or acceptance/aversion towards risky situations.
- Is the **outcome understandable** to non-scientific audience, consistent with the stakeholder's perceptions of impacts, and can it be potentially operationalized?

Finally, it was agreed that the **STARS4Water SOS Framework** for water resources management at river basin level would be supported by the following guiding principles:

- It builds on a **bottom-up approach and on science-stakeholder partnerships** in the river basin hubs, anchored to the realities and needs of local stakeholders, as assessed through workshops, bilateral meetings, and by the validation of the results at different phases of the risk assessment.
- Its implementation at the **river basin scale** implies **contextualization** in order to tackle the local meanings (e.g. values) and specificities of local contexts, and to define data and indicators that can inform on future impacts of water management operations and strategies.
- It leverages opportunities in **new generation data services and modelling tools** to enhance **understanding of the water system** in the river basins, foster new knowledge and boost innovation in water management.
- It strongly relies on co-designed **scenarios** about the future, delivered though the co-construction of **relevant narratives and trajectories** for water use and socio-ecological management, integrating aspects related to climate, water demand and infrastructure in order to assess current water use and boundaries of water-related operations under future changing conditions.
- It takes into account **actions and strategies in river basin water management** (current and future adaptation strategies) to assess the landscape of "safe operations" and draw attention to situations that might put the water systems at risk or close to boundary conditions at the river basin scale.
- It provides **actionable information on SOS** for the planning of water resources management and to support decisions, with the help of visualization tools, dashboards, story maps, and policy briefs, among others.

A key aspect to keep in mind is that the implementation of the STARS4Water SOS Framework in the project's river basin hubs has searched to incorporate the perspectives of water managers and stakeholders through their operational practices. This proved essential for enabling us to integrate a management and operational dimension into the physical, social, and ecological components of risk analysis, thereby strengthening and adding value to the in-house expertise within water management organisations and public services.

In the next sections, we present the results of implementation of the STARS4Water SOS framework in the river basins of the project (Danube, Drammen, Duero, East Anglia, Messara, Rhine and Seine). It is important to note that each assessment is the result of an integrated effort to implement the framework at the river basin scale in order to support local concerns of stakeholders on water availability and management. The work builds on achievements from several of the project's work packages, for which the results were reported in previous deliverables of the project: stakeholder co-creation of narratives and what-if scenarios of local interest (deliverable D1.2 and D1.5; Hegdahl et al., 2022 and Okruszko et al., 2024), indicators and model developments (deliverables D2.1, D3.1 and D3.2; Beckers et al., 2023, Rickards et al., 2023 and 2024) and model calibration/validation (deliverable D4.1; Preiml et al., 2025). All reports are available in the project's website[3].

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[3] https://stars4water.eu/output/public-deliverables/

3. Danube River basin: low-flow projections and risks

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During the needs assessment with stakeholders in the Danube basin, which included consultations with the International Commission for the Protection of the Danube River (ICPDR), the development of a modelling approach to support an evidence-based estimation of water availability in the river basin was highlighted as a key challenge. The need for this modelling approach was particularly identified to establish or improve low-flow modelling, and to gain information on available water at any specific location of interest in the basin.

The RIBASIM model was developed in collaboration among partners BOKU, Deltares and GeoEcoMar as a tool to simulate water resource management in the Danube River basin. The model setup is linked to a hydrological model (wflow_sbm model[4]), developed as part of the European research project H2020 DOORS Black Sea[5], which forms the basis for simulating natural flows in the river basin. Within this modelling framework, RIBASIM incorporates demand nodes and links to represent water use and distribution across the Danube basin. In STARS4Water, the focus is on assessing the Danube River during low-flow conditions under future 'what-if' scenarios, compared against the Danube RIBASIM model run for 2010–2020 (scenario of reference, REF). The REF scenario was developed within the STARS4Water project through model development and calibration (Graf et al., in prep.).

3.1. Future scenarios of climate change

In the Danube River basin, literature review and stakeholder consultations led to the definition of future discharge scenarios under climate change for use as RIBASIM model inputs: one scenario based on glacier retreat (scenario GR) and two scenarios based on climate change projections under RCP8.5 (scenarios CC1 and CC2).

Future what-if scenario of glacier retreat (scenario GR): Glacier retreat due to climate change is inevitable; however, studies differ on the timing of complete melt. Based on different projections in the literature, which vary with the climate scenario considered (e.g., APCC, 2025 and Weber et al., 2010), the worst-case scenario was used for the analysis. Water availability under GR was calculated in several steps. The basis for the glacier runoff is Weber et al. (2010), which provides the proportion of ice melt runoff at the gauge Achleiten in Austria, peaking in August. These percentages and their projections were used to calculate the ice-melt runoff component of the median discharge in the model's reference period (scenario REF), then extrapolated to 2050. The glacial area distribution across sub-basins contributing to the Achleiten was computed, and the Achleiten ice melt runoff was distributed to sub-basins in RIBASIM according to the glacial area fraction of each sub-basin. The remaining discharge, given by the calculated ice melt runoff subtracted from the median discharge, served as input to assess hydrological conditions under glacier retreat.

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[4] https://wflow.readthedocs.io/en/latest/wflow_sbm.html. The development of wflow_sbm, the model structure, equations and functionalities are described in detail, including example applications of wflow_sbm, in van Verseveld et al. (2024): https://gmd.copernicus.org/articles/17/3199/2024/gmd-17-3199-2024.pdf

[5] https://www.doorsblacksea.eu/ (last access: December 2025)

Future scenario on climate change (scenario CC1 and CC2): The scenarios were derived from a compilation and analysis of literature available for the Danube River basin. The main indicators of variations in discharge due to climate change are reported in Table 1. Focus was put on the most extreme concentration pathway RCP8.5, with effects on annual and seasonal low-flow changes at the project's time horizon of 2050. Intercomparison across studies is challenging because reference and projection periods differ. A common trend emerges particularly for the winter season in the Upper Danube, with projected increases in discharge, but the three studies often diverge otherwise. Whereas Probst and Mauser (2023) indicate mostly increasing seasonal discharges, Stagl and Hatterman (2016) project decreases over the whole basin. The study of Stanzel and Kling (2018), conducted only in the upper Danube, showed decreasing discharges in summer, whereas other seasons showed increases. The study from Stagl and Hatterman (2016) was selected to estimate the highest risk on discharge reductions, as they indicated negative changes in all Danube regions due to climate change forming the basis for CC1 scenario. Probst and Mauser's (2023) study results were chosen to implement a moderate climate change scenario for the CC2 scenario. Mean seasonal changes for RCP8.5 (2031-2060) compared to 1971-2010 were adapted to the scenario configuration, by using interpolation to estimate reduced changes between the model´s reference period (2010-2020) and the near future period (2031-2060). These reduced seasonal discharge changes were then used to build the scenarios CC1 and CC2 in the RIBASIM model.

Future combined scenario on climate change and glacier retreat (CC1_GR): Since Stagl and Hatterman (2016) do not mention any consideration of using a glacier model in their modelling framework, this scenario combines the scenarios CC1 and GR. The combined scenario is anticipated to further exacerbate the risks associated with navigation, ecology and hydropower in the upper Danube, where the glacier-melt and climate-change effects converge.

Table 3.1: Overview of main literature for the annual and seasonal effects of climate change projections on discharge (ΔQ) at different stations in the Upper, Middle and Lower Danube River basin for the near future and RCP8.5. Green values indicate positive changes and red values, negative changes, with colour shades darker as change values increase. DJF = December, January, February; MAM = March, April, May, JJA = June, July, August, SON = September, October, November.

	Reference Period	Emission Scenario			Upper Danube		Middle Danube	Lower Danube
Authors			Season	Gauge	Achleiten	-	Bezdan	Ceatal Izmail
Probst and Mauser (2023)	1971-2000	RCP8.5 (2031–2060)	Annual		7.2		8.1	3.1
			DJF		22.5		21.1	12.1
			MAM		4.4		6.2	6
			JJA		2.8		4.7	-1.5
			SON		0.2		0	-4.4
Stanzel and Kling (2018)	1961-1990	RCP8.5 (2021-2050)	Season	Gauge	-	Vienna	-	-
			Annual			1.3		
			DJF			17.1		
			MAM			4.3		
			JJA			-9.6		
			SON			-0.8		
Stagl and Hatterman (2016)	1971-2000	RCP8.5 (2031–2060)	Season	Gauge	Passau (Inn)	Bratislava	Iron Gate, SRB	Before Delta
			Annual		-2	-9	-37	-18
			DJF		24	10	-22	-8
			MAM		-5	-16	-42	-18
			JJA		-13	-16	-37	-23
			SON		-2	-9	-38	-25

3.2. Future scenarios on water allocation

Future scenario on water allocation (IR1, IR2, IR3 and LN): In the RIBASIM model, future irrigation demands using surface water abstraction scenarios from the river were considered. Scenario IR1, considers an abstraction of 15 m³/s of the Danube surface water pumped to a dry region in the Upper Danube. Scenario IR2 assumes increased surface-water abstraction in a flat, agriculturally intensive region of the Upper Danube. Currently, irrigation demand is mainly covered by pumping groundwater at the fields, which resulted in depletion of groundwater resources. To reduce this pressure, a channel was constructed to enable direct surface-water abstraction for agriculture. Until recently, surface water abstraction from the channel has been minimal. However, future surface water demand may increase to the consented maximum level of 15 m³/s. By reducing the average discharge of around 4 m³/s in the channel, a future demand of 11 m³/s for surface water irrigation in the Marchfeld was assumed for scenario IR2. The future scenario IR3 combines IR1 and IR2. The final allocation scenario LN considers future water abstraction from the Danube to fill a shallow endorheic lake in the Upper Danube. According to stakeholders, up to 4 m³/s are in discussion. Finally, the worst-case scenario (WCS) is defined as a combination of climate and water allocation scenarios (GR, CC1, IR3, and LN).

3.3. Impacts of low-flow conditions under different scenarios

The analysis of water resource availability in the Danube, under a range of scenarios and risk conditions (Safe Operating Space), examined impacts across three main areas: navigation, ecological systems, and hydropower production.

Navigation: the risk of low-flow conditions on navigation is assessed based on a low-flow occurrence indicator (Beckers et al., 2023) and RIBASIM model output. The indicator describes the risk of fairway conditions at bottlenecks critical for navigation and is defined as the number of days per year with water depths in the fairway critical for navigation. Safe/at-risk thresholds are based on the legally prescribed critical water depth of 2.5 m by the Danube Commission (2013). The associated discharge (low-water discharge, RNQ, Danube Commission, 2023) corresponds to a 94% exceedance probability, evaluated from a 30-year (1991-2020) daily series. The associated characteristic low-water level (RNW or ENR) is the reference water level defining the water depth in the fairway. This classification is a simplification based on modelled discharges and does not account for actual riverbed levels, morphological changes and maintenance dredging. For the safe operating space (SOS) assessment, two classes of risk were defined. The class at “Risk” is defined by a threshold at up to 22 days per year. It represents the exceedance above the 94% quantile (i.e., the definition for RNQ). The class “Crisis” indicates the risk of exceeding 22 days per year. To illustrate the SOS assessment for navigation in the Danube, one site was selected in of the Upper and one in the Lower Danube. At these sites, critical status was e.g. reported in 2015 (FAIRway Danube, 2016-2020), when a drought in Europe caused low water levels in several European rivers (Lahaa et al., 2017).

In the reference model (REF), indicators based on observed and modelled discharges at the critical section in the Upper Danube were compared. Exceptionally dry years, such as 2011, 2015 and 2018, were modelled sufficiently well with the RIBASIM model. Moreover, the considered free flowing section in the Upper Danube is threatened by riverbed incision caused by the channelization and by the sediment deficit related to the upstream chain of reservoirs. Remaining sediments accumulate in the sections critical for navigation. Dredging activities are undertaken by the waterway authorities to ensure navigation. The considered critical section is among the sections comprising the highest dredging volumes in the Upper Danube (FAIRway Danube, 2016-2020). These measures are also being accompanied by other sediment management and ecological measures including, among others, dumping material from the reservoirs upstream, optimizing in-stream measures and riverbank restoration. This highlights the challenges of representing local management practices in model-based risk assessments.

For the reference model (REF), especially dry years (2011, 2015 and 2018) were discernible, leading to critical navigation conditions in the sections in both regions. The highest critical situations obtained using the selected indicator were found for scenarios CC1, IR3 and their combination WCS. In the Upper Danube, the indicator for those scenarios is increasing up to +9 more days for the average (ø) between 2010-2020 and up to +30 days for the dry year 2011, when compared to the reference (REF). Under CC1, the effect is even stronger in the Lower Danube section. The scenario CC1 doubles the days where navigation will be critical with reference to the average (ø) between 2010-2020 (scenario REF). In Upper Danube, the combination of both irrigation scenarios (IR3) slightly increases critical conditions in the bottleneck section compared with REF (+3 days for the average (ø) between 2010-2020), while scenario LN increases them by +2 days on average. Scenario glacier retreat (GR) increases critical situation by only +1 day on average in the Upper Danube, due to seasonal contribution of glaciers (summer). Finally, the worst-case scenario (WCS) shows the largest increase relative to REF: +40 days in the dry year 2011, leading to 90 days per year with critical navigation conditions in the Upper Danube section.

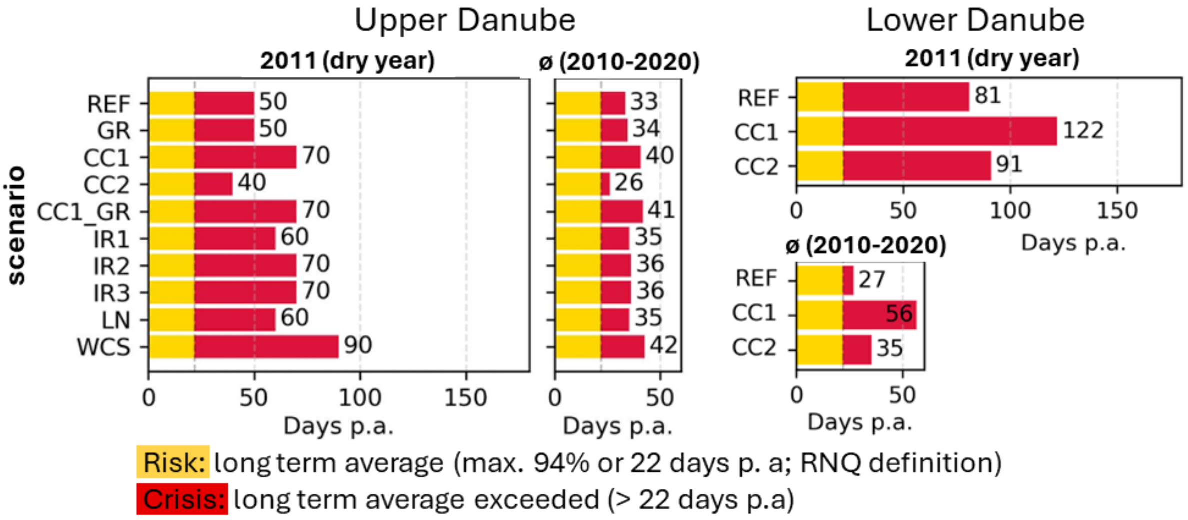

Figure 3.1: Safe operating space for navigation in the Danube using the indicator 'number of days per year with discharge at critical stages for navigation'. Left and middle chart shows all considered scenarios and combinations for the Upper Danube. Right column shows the same for the Lower Danube. Results for the average (ø) conditions or for the dry year (2011) are shown.

Ecology: Ecological risk of changes in flow regime is assessed based on an indicator describing the hydrological connectivity of a side channel: the number of days per year with a side channel not connected to the main stem. Threshold discharges for an Upper Danube side-channel, firstly reconnected in the 1990s, were estimated from hydrodynamic modelling (Tritthart et al., 2021) and viadonau (2025). The model evaluation found a connectivity of around 150 days per year (or 215 crisis days per year) for the actual state (scenario REF), which was comparable with viadonau (2025). The largest change in SOS was identified for scenario CC1, increasing the crisis by 21 days (Figure 3.2), but also glacier retreat (GR) and water allocation (IR1, IR2 and IR3) was increasing crisis by up to 4 days. A future planned side-channel reconnection measure (Tritthart et al., 2021; viadonau, 2025) increases ecosystem connectivity to 332 days per year for scenario REF, corresponding to 33 crisis days per year.

Climate and water allocation may increase crisis by up to 9 days per year under scenario WCS. On top of this, SOS is eventually decreasing due to riverbed incision and sedimentation of the inlet channel.

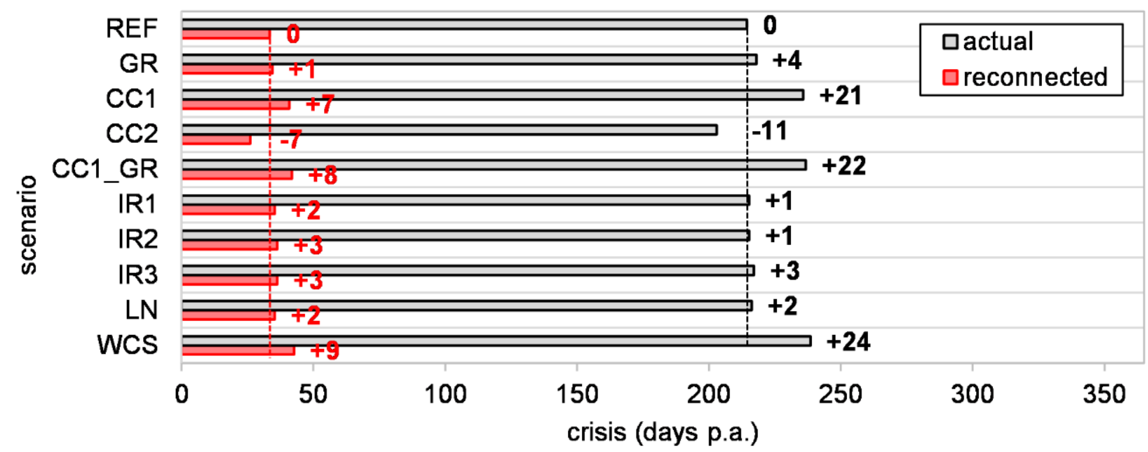

Figure 3.2: Safe operating space for ecology in the Danube using connectivity of the side-channel in a free-flowing section of the Upper Danube as indicator, considering the actual situation ('actual') and a future reconnection measure ('reconnected'). The indicator shows the number of days per year with not connected side channel (indicating a crisis) based on the average year (2010-2020).

Hydropower: the changes in water resources availability on hydropower is assessed based on an indicator describing the annual average energy output (MWh/year) of a hydropower plant. In the absence of a well-defined threshold, we considered the losses in energy output under the scenarios. For a selected hydropower plant (HPP) in the Upper Danube, the SOS indicator (not shown) projects an average 4.8% reduction of energy output (MWh/year) under scenario WCS relative to REF (2010–2020). Almost all scenarios reduce annual average energy output, with the main contribution to the energy loss coming from the climate scenario CC1. Conversely, the more optimistic scenario CC2 would increase energy output by 2% at the considered HPP in the Upper Danube.

3.4. Lessons learnt and perspectives

Our SOS assessment in the Danube River basin showed that climate change has the potential to increase the risk of critical situations for of navigation, ecology and hydropower. The most pessimistic effects on low flows from Stagl and Hatterman (2016) were considered (scenario CC1) to capture worst-case effects. However, other hydrological modelling studies are less pessimistic in terms of seasonal changes, which was also captured with a what-if scenario. For the upper Danube (Vienna), for instance, Stanzel and Kling (2018) report on projections of increasing discharges in the winter season (+17%) and decreasing discharges in the summer season (-10%) in the period 2021-2050, with reference to the period 1961-1990. In the study by Probst and Mauser (2023), captured by scenario CC2, conditions are even less critical in the future, due to increases in future discharges of up to 8% (except for the autumn season in the lower Danube, with a decrease of -4.4%) for the period 2031-2060 (with reference to 1971-2000). Bisselink et al. (2018) also found increasing seasonal discharges in the upper Danube for the +2°C scenario. In general, the projected rising winter discharges in the Upper Danube, found within all considered studies in the literature, has the potential to reduce the risks for navigation and hydropower in this region during the winter season. The what-if scenario of glacier retreat (GR) until 2050 considered in our SOS assessment also showed an effect in water use, but only in the Upper Danube. Water allocation scenarios at the local scale in the Upper Danube, considering increased irrigation demand from surface water abstraction, also showed increased risk for navigation, ecology and hydropower. Overall, the assessment carried out highlights the relevance of considering future irrigation demand in combination with climate change scenarios in an integrated modelling approach.

Future work could extend the RIBASIM model to estimate the range of water-allocation effects under climate change in the Danube basin. Assessments with coupled hydrological-allocation models (wflow or other models such as the Community Water Model CWatM) are expected to enhance our understanding of climate change impacts on water management systems. Model improvements could include additional local coupling of groundwater simulation models, to account for future irrigation demands and their impacts. Additional indicators may be incorporated (e.g., sediment transport and morphology, reduction in groundwater levels). Other low-flow relevant indicators could include water abstractions for drinking water, industry, and cooling, moving towards a modelling tool for the Danube basin that covers all sectors relevant for local water management.

4. Drammen River basin: hydrological projections for hydropower reservoir operations

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During stakeholder meetings, several concerns were identified in the Drammen River basin. This led to targeted improvements in the local needs assessment (identification and prioritization) and in the hydrological modelling for the Drammen River basin. During floods, water management is coordinated by a regulatory body representing all hydropower companies. Concerns were raised about the need for implementing a better flow of information and coordinated efforts, particularly regarding municipal flood emergency preparedness. On the other hand, the dry summer of 2022, with record low water levels, prompted reflections on water use prioritization, as energy producers had to make choices between maintaining environmental flows and conserving water for the future, notably for winter energy production. The Drammen River supports diverse species, including salmon, trout, and endangered fauna, such as the freshwater pearl mussel. During the 2022 drought, the river suffered a mass die-off of these mussels due to rapidly falling water levels. While the basin’s multi-year water reservoirs can typically handle one or two dry years, longer droughts threaten water uses, such as hydropower, water supply, and biodiversity, and represent an additional pressure when dealing with the complexity of their interdependencies.

Discussions with the stakeholders at workshops allowed us to determine the main indicators to assess changes under critical conditions for the what-if scenarios of interest, with focus on water prioritization in space and time under conditions of water use restrictions. The need for improved information sharing prompted the co-development of a dashboard for the Drammen River basin (Edler and Mes, 2024). Feedback loops with stakeholders were key in the co-design process to target relevant scenarios, indicators and visualisation tools and to prepare the ground for the implementation of the project’s safe operation space framework in the river basin. There was a focus on finding a balance between energy production and ecological impacts, under flow alterations in the river basin.

An overview of the modelling approach used to assess the impact of climate change and energy demand on hydrological regimes, ecology and energy production is presented Figure 4.1 (see also Rickards et al., 2024; Preiml et al., 2025).

Two locally calibrated and validated hydrological models, HBV (Beldring et al., 2003; Huang et al., 2019; Erlandsen et al., 2021) and Lisflood (JRC, 2024) were used. In addition, the energy market model (EOPS available at NVE; Sintef, 2024) was used to include hydropower operations in a market situation, and the Ecological Risk by Flow Alteration approach (ERFA, Laize et al. 2014) was used to analyse changes in the hydrological regime affecting ecology.

4.1. Future scenarios of climate change

To assess future water availability, the most recent updated, downscaled and bias-adjusted climate projections and hydrological projections were used as input for the modelling activities. These projections are described in the new climate assessment report for Norway “CiN-2025” (Dyrrdal et al., 2025). A commonly used modelling chain for hydrological climate impact studies was used, i.e., selecting emission scenarios and a suite of GCMs and RCMs, followed by statistical downscaling and bias correction of the projections before they are used as forcing in hydrological modelling (see Huang et al., 2025 for details). For the CiN-2025 report, two RCPs used in CMIP5 were selected, representing pathways of low (RCP2.6) and moderate emissions (RCP4.5). The shared socioeconomic pathway SSP3-

7.0 used in CMIP6 projections was selected to represent the high-emission scenario. In the analyses in the Drammen River basin, projections from three GCM-RCM combinations under two different emission scenarios (RCP4.5 and SSP3-7.0) were selected. The selection was based on temperature and precipitation changes, with a focus on representing both warm/less-warm and wet/less-wet scenarios.

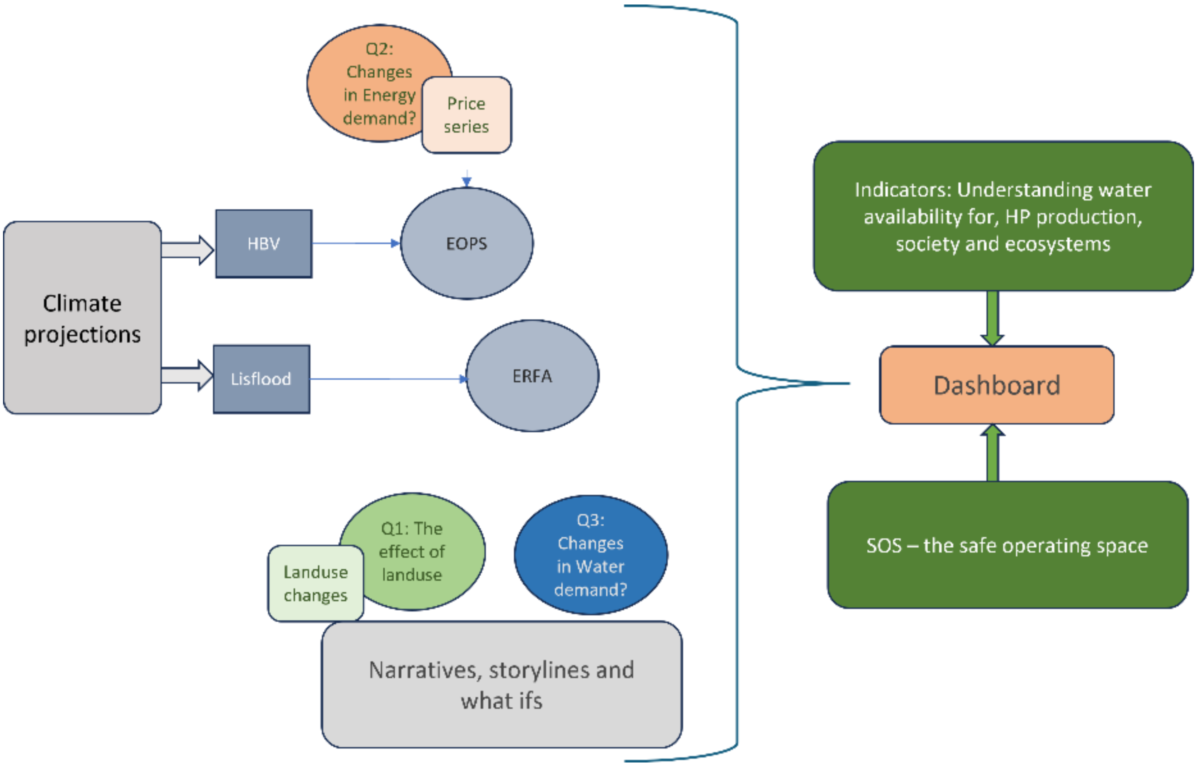


Figure 4.1 Overview of the modelling approach used to assess water management in the Drammen River basin. The different models produce indicators presented in the Drammen River basin dashboard The safe operating space was explored for energy production and ecology.

Bias correction is crucial for hydrological modelling in Norway due to its complex topography, with more than 90% of the landscape consisting of mountains and snow accumulation, and snowmelt being an important process in the hydrological regime. Bias correction was applied to temperature and precipitation variables to improve the accuracy of their projected changes (Huang et al., 2025).

The hydrological projections (average annual changes in runoff) for the near future (2041-2071) and the far future (2071-2100) under RCP4.5 are presented in Figure 4.2.

Table 4.1 presents the changes in precipitation (PR), evapotranspiration (ET), and snow water equivalents (SWE) for two selected projections representing wet-warm conditions (61-from the SSP370-scenarios) and a less-wet alternative (52-from the RCP45-scenarios).

The results indicate an overall increase in runoff, except in some lower elevation areas in the southeast. In the near future, annual runoff is projected to increase by 3% and, in the far future, by 6%. The seasonal variability assessment shows an increase in runoff in winter, as precipitation also increases, with higher amounts occurring as rain. Spring snowmelts occur earlier and lead to less runoff in high western areas during summer. In spring, these areas display more runoff, while a decrease in runoff is projected in lower elevated areas within the catchment. In autumn, runoff in the catchment is projected to slightly increase or to remain unchanged.

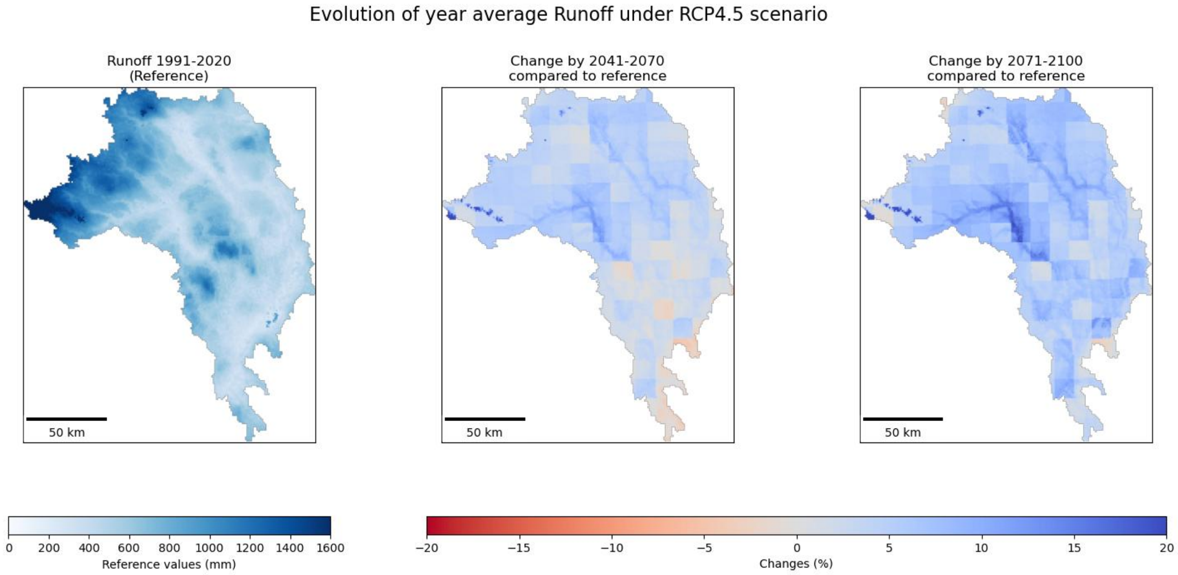


Figure 4.2: Changes in average annual runoff compared to the reference runoff for the period 1991-2020 (left) for the Drammen River basin for the RCP4.5 scenario and the future periods 2041-2070 (middle) and 2071-2100 (right). Results come from using the climate assessment report for Norway and models recalibrated for the Drammen River basin in the STARS4Water project.

Table 4.1: Percentage changes in precipitation (PR), snow water equivalents (SWE) and evapotranspiration (ET) for the near (NF) and far future (FF) based on and two climate projections wet-warm (SSP370-61) and less-wet (RCP45-52) using the Lisflood-Drammen model. The reference period is 1991-2020.

	PR-61	PR-52	SWE-61	SWE-52	ET-61	ET-52
NF (2041-2070)	10.6	2.5	-55.0	-21.9	6.8	6.7
FF (2071-2100)	24.5	4.7	-69.0	-40.0	10.3	8.3

4.2. Future scenarios on water management

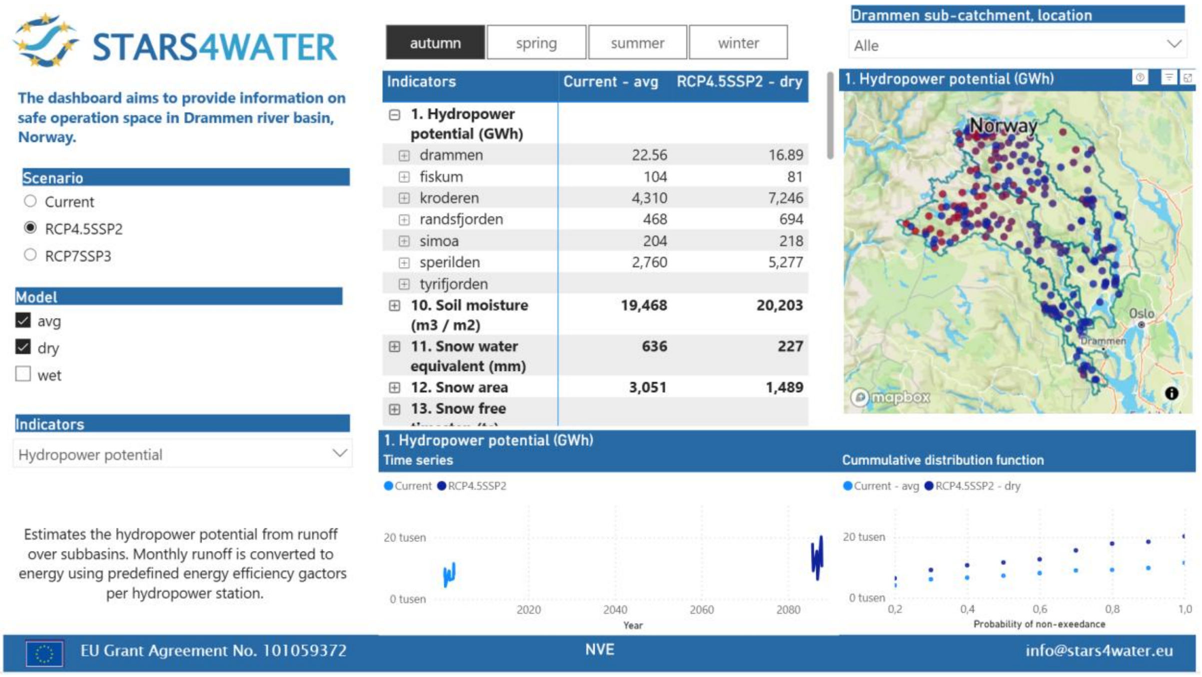
Climate projections for the Drammen River basin show increases in temperature, precipitation, and runoff due to climate change. Socio-economic influences are less significant. Findings based on global trends indicate that slight population growth and expanded irrigation can be expected in the future, according to the regional narratives for the Drammen basin (Okruszko et al. 2024). Discussions with stakeholders highlighted the following key priorities for future management: (i) preventing flood damage; (ii) managing droughts, and (iii) incorporating climate change effects on runoff regimes in reservoir operation rules, in order to support adaptation and to mitigate potential conflicts between energy production, ecological status, and other water uses.

Currently, an established indicator of the licensing requirements for reservoir operation rules is related to minimum flow requirements. This indicator serves as the basis for the analysis of the risks of hydropower companies not being able to release sufficient water under various climate change projections and energy demand scenarios.

Hydropower production with reservoir operations is a complex matter, not only driven by availability of water and reservoir capacity, but further by electricity prices. To show the effect of energy demand, driven by market prices, we have introduced two price scenarios to reflect different pathways for production operations. The NVE price series was generated by stacking the existing 30-year data and using RCP 8.5 scenario inflows in the model to estimate annual prices (Koestler et al., 2019). The alternative HydroConnect price series assumes baseline Norwegian hydropower and transmission capacity, and increased electricity demand in Norway under RCP4.5, and was provided by the HydroConnect project (https://www.sintef.no/en/projects/2021/hydroconnect/).

We applied the method of Laizé et al. (2014) to assess Ecological Risk due to Flow Alteration (ERFA). Alterations to flow-regimes are suggested to indicate risk to eco systems that are adapted to the existing flow regimes. The approach gives an overview of areas where changes are expected. It is also important to further evaluate known vulnerable areas and areas of large changes, to get a better overview of actual consequences and impacts. Significant changes can be a user defined threshold. We have chosen 30% change to be classified as significant, and the cumulative number of altered indicators is used to assign an ecological risk class using a colour coded system. The analyses were made using the Lisflood modelled discharge timeseries, calibrated for the Drammen River, with a simple reservoir management scheme.

The Drammen River basin dashboard (Figure 4.3) presents examples of indicators derived from climate projections for the Drammen River basin. Selected years are provided for parameters such as energy potential, soil moisture and snow water equivalent. The dashboard is in its first prototype version, and indicators will be continuously reviewed and refined in consultation with stakeholders until its release at the end of the project. The aim is to use the indicators to guide information sharing and action on future water management strategies for better preparedness and for lower water-related risks in the river basin, establishing a regionally tailored safe operating space at the river basin scale.



The dashboard aims to provide information on safe operation space in Drammen river basin, Norway.

Scenario
○ Current
● RCP4.5SSP2
○ RCP7SSP3

Model
☑ avg
☑ dry
☐ wet

Indicators
Hydropower potential

Estimates the hydropower potential from runoff over subbasins. Monthly runoff is converted to energy using predefined energy efficiency gactors per hydropower station.

Indicators	Current - avg	RCP4.5SSP2 - dry
1. Hydropower potential (GWh)		
drammen	22.56	16.89
fiskum	104	81
kroderen	4,310	7,246
randsfjorden	468	694
simoa	204	218
sperilden	2,760	5,277
tyrifjorden		
10. Soil moisture (m3 / m2)	**19,468**	**20,203**
11. Snow water equivalent (mm)	**636**	**227**
12. Snow area	**3,051**	**1,489**
13. Snow free		

Drammen sub-catchment, location
Alle

1. Hydropower potential (GWh)

1. Hydropower potential (GWh)
Time series
Cummulative distribution function

EU Grant Agreement No. 101059372 NVE info@stars4water.eu

Figure 4.3: Screenshot with an example of outline of the dashboard for the Drammen River basin.

4.3. Projected water resources availability and risks

Two large concerns on water resources and risks in the Drammen River basin are related to hydropower and ecological impacts. Hydropower generation plays a key role in national energy security, with energy demand — measured by market prices — driving production. Water use conflicts may arise, especially during periods of excess or insufficient water availability, and are also linked to energy production patterns, ramping, and insufficient minimum flow requirements that can have ecological impacts.

Projected changes in river flow seasonality and increases in floods and droughts are expected to affect reservoir management strategies. A growing population and more frequent extreme events could put additional pressure on water supplies even if annual river flow is expected to increase. Higher temperatures can boost agricultural productivity and lead to an earlier growing season but also result in reduced spring snowmelt and more severe summer droughts. This may change agricultural irrigation needs, which currently are minimal, but are expected to increase in the future. In the RCP45 SSP2 narrative explored for Drammen (Okruszko et al. 2024) only small changes in land use and in hydropower infrastructure were expected.

Hydropower production in the Drammen River basin: It is expected that hydropower licenses may need to be more frequently updated to reflect climate conditions that have already shifted since many of these licenses were first granted. This is especially important for the changes in snow water equivalent and seasonality of available water. Figure 4.4 shows that, for the drier CMIP5-RCP45 climate projection (left), both the production and the water losses (caused by flood losses and HP production bypass, for example, to maintain low flow) are reduced. The wetter scenario (right) shows a clear increase in the production, even if the water loss increases. This reflects loss in power production, unless reservoir management adapts to the expected increased runoff.

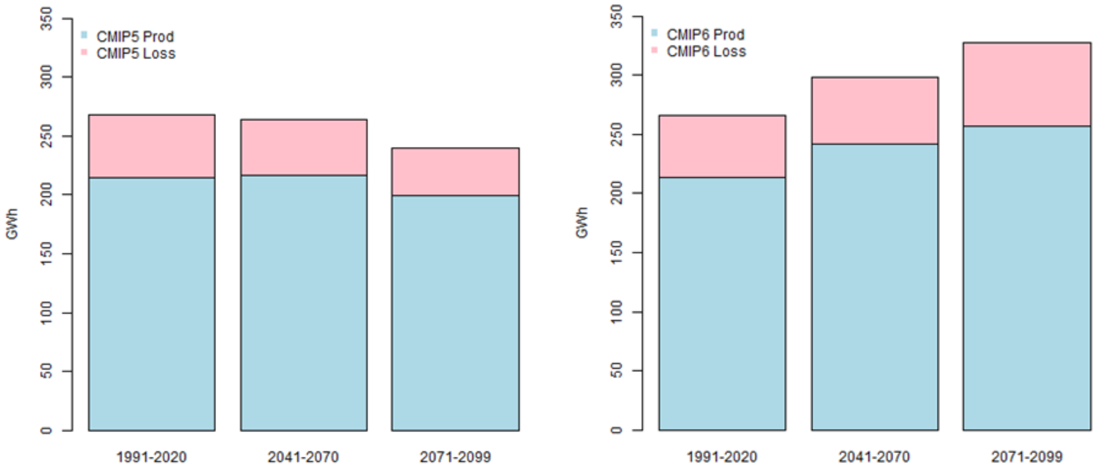


Figure 4.4: Selected "less wet-scenario" RCP45 (left) and "warm-wet-scenario" SSP370 (right). Annual mean HP production in light blue, and water loss (bypass and flood-loss) in light red. The figures represent the production in the lower part of Krøderen subbasin.

Effect of electricity pricing on hydropower production, water loss and reservoir storage: The changes in hydropower production and water losses (bypass and flood losses) caused by pricing varied depending on climate projections, future periods, and time of the year, as exemplified in Figure 4.5 for the two price-series. All numbers for the energy analysis are presented in GWh.

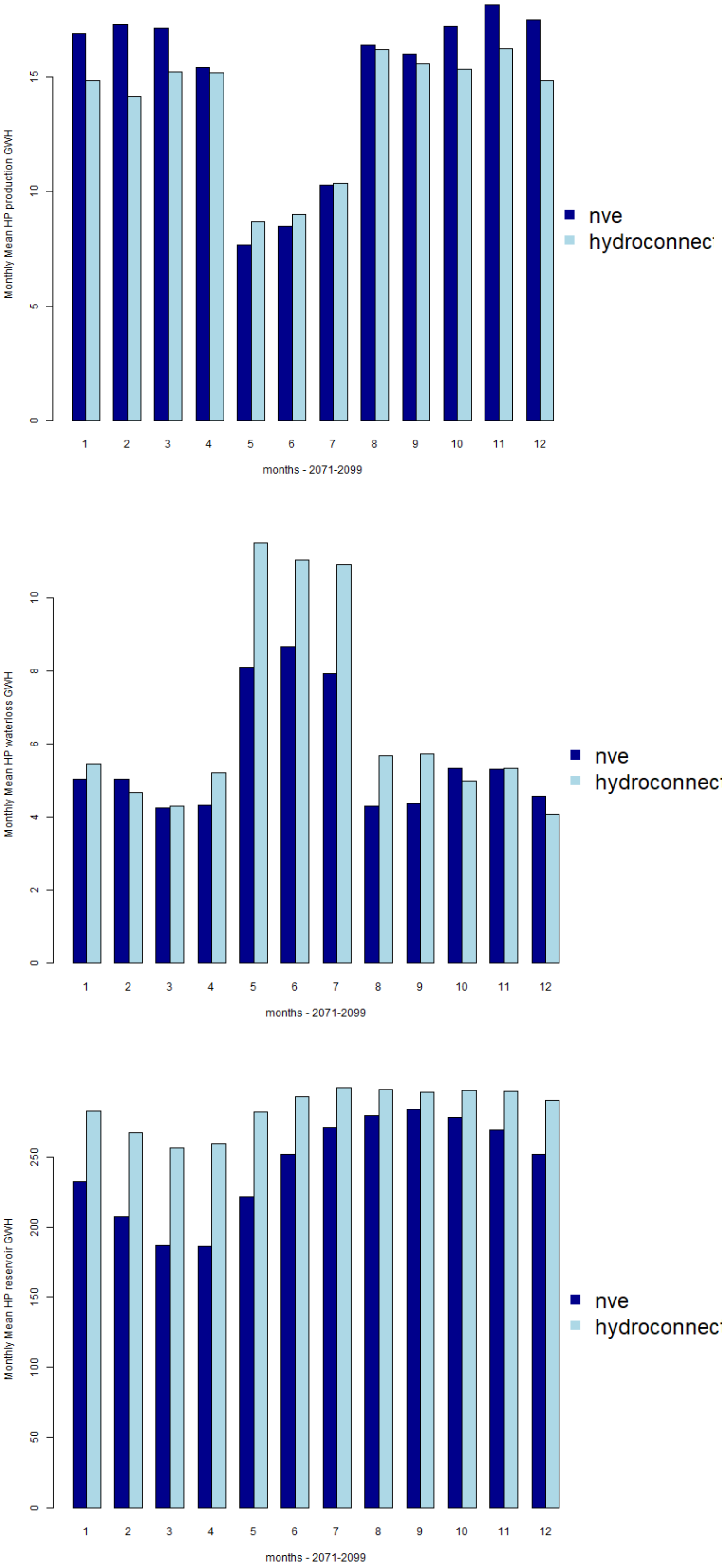


Figure 4.5: Mean monthly hydropower production (top), water loss (bypass and flood loss; middle) and reservoir storage (bottom) for the outlet of the Krøderen sub-basin. Two price series are used to represent different market situations: the NVE (dark blue) and HydroConnect (light blue). All data are presented for the far future and the SSP370 warm-wet scenario.

Table 4.2 summarizes some of the findings: positive numbers show that the NVE price series gives a higher percentage change in HP production and water losses, and negative numbers show that Hydroconnect prices give a higher percentage change in HP production and loss compared to the reference period. The HP production change is more pronounced for the winter season (WP). Mostly, the HydroConnect prices result in larger water losses and less production compared to the NVE price series. This shows that the market pricing has an effect both on the overall hydropower production, and loss of production due to bypassing and flood losses.

Table 4.2: Percentage point change in production for Winter (WP- week 39-18), Hydropower production (Prod) and Water losses (Loss), in the near future (NF), far future (FF) for the three selected RCP45 and SSP370 projections, including two bias correction methods.

Percent	WP NF	WP FF	Prod NF	Prod FF	Loss NF	Loss FF
RCP45	-0.3 to +1.8	-1 to +0.5	-0.3 to +0.3	-0.9 to +0.6	-7 to -0	-10 to +1
SSP370	-0 to +1.5	-4 to +0.5	-0.4 to +0.1	-0.6 to -0.3	-2 to +0.1	-6 to -1

Flow regimes changes and possible ecological effects (ERFA) are presented for one of the RCP45 projections. The ecological impacts are assessed for two different sub-basins representing the upper and the lower part of the Drammen River basin (Figure 4.6). The doughnut plots present the changes in the following indicator groups; rate of flow changes (RFC), high flows (HF), low flows (LF), monthly flow (MF), and Overall risk (Overall). Green lines define low risk, yellow a moderate risk, and red a high risk. We find that only the low flow (LF) indicator in Fiskum reaches the high-risk line. There is a moderate risk for more indicators, and moreover the overall risk is assumed moderate for both subbasins, for both future periods for this specific projection.

4.4. Lessons learnt and perspectives

Stakeholder meetings and feedback were crucial to co-design scenarios and to set up the framework and the tools to assess water resources availability. The scenarios were collaboratively developed with stakeholders in the Drammen River basin, who expressed concerns regarding extreme floods and droughts. Flood events tend to be *ad hoc* and are addressed through well-established licensing guidelines and reservoir operation rules, whereas droughts have longer duration and present broader challenges in terms of modeling and management.

The stakeholder co-development process revealed that many of the existing indicators that were presented are challenging for the stakeholders to interpret. Climate change projections can also present challenges to assess risks in operational water management. Making a reference to previous years and extreme events revealed to be an efficient way to make risk analysis more informative, by introducing comparisons to events such as, in our case, the “Hans storm” that hit southern Norway over 3 days from August 7 to 9, 2023, and the European 2018 summer drought.

Figure 4.6: Results of the ERFA analysis for the upper (top) and lower (bottom) part of the Drammen River basin for the RCP4.5 emission scenario for 2041-2070 (left) and 2071-2100 (right).

Consequently, for the implementation of the safe operating space, it was chosen to examine more closely the potential effects of a wet and dry climate scenario, selecting two climate projections for the Drammen River basin. To account for the effect of hydropower operations, two driving price scenarios were introduced.

Future work will further follow up with what-if scenarios based on historical data to enforce additional stress on the system for the purposes of the analysis. Using historical events as a basis for what-if scenarios, the stakeholders found that it was easier to understand the impact and consequences. Moreover, further investigations of the safe operating space aim to assess multi-sectoral impacts, by examining the combined effect of multiple indicators across six targeted regions in the Drammen River basin. Focus areas will include stakeholder feedback on how to best present risk and impacts on hydropower production and ecology, and how we further could include agriculture irrigation demand and water supply.

5. Duero River basin: projections of future groundwater resources

Authors: Olga García Menéndez, Héctor Aguilera, África De la Hera-Portillo, Pedro Martínez-Santos, Víctor Gómez-Escalonilla, Luis Moreno Merino (IGME-CSIC & UCM)

The Duero River basin, shared by Spain and Portugal, is the largest river basin on the Iberian Peninsula, covering approximately 98,000 km^2, of which around 79,000 km² lie within Spanish territory (Gómez-Escalonilla and Martínez-Santos, 2024). The basin is characterised by a continental, semiarid climate with pronounced seasonal contrasts. Despite its semiarid nature, the basin is relatively well endowed with both surface water and groundwater resources and is sparsely populated (approximately 25 inhabitants/km^2 versus 109 inhabitants/km^2 across the EU), which, to date, has limited direct conflicts among water users.

The basin's water system is underpinned by a large regional aquifer occupying its central portion, together with surrounding recharge areas. In total, 67 groundwater bodies (GWBs) have been identified. The most important water user is agriculture, which accounts for approximately 90% of the total water consumption, followed by urban supply (7%) and other uses such as industry and recreation (3%). Major reservoirs are concentrated along the northern tributaries, particularly the Esla (Ricobayo, Riaño), Órbigo (Barrios de Luna), Pisuerga (Aguilar de Campoo) and Tormes (Santa Teresa), serving flood control, irrigation and hydropower generation. The hydroelectric complex at Los Arribes, shared with Portugal, includes the Ricobayo, Villalcampo, Castro, Almendra and several transboundary dams.

Within the STARS4Water project, the Duero River basin is represented by the Instituto Geológico y Minero de España (IGME-CSIC) as the Research Focal Point and the Confederación Hidrográfica del Duero (CHD) as the River Basin Organisation and stakeholder champion. The stakeholder community also includes water supply companies (Aguas de Castilla y León), energy producers (Naturgy, Iberdrola), irrigation communities (Canal de Villagonzalo) and groundwater user associations (groundwater users communities). Through a questionnaire distributed to approximately 800 contacts via the CHD mailing list (103 responses received) and a dedicated stakeholder workshop held in Arévalo in March 2024, climate change and climate-related variables emerged as the single most pressing concern, followed by water quality and agricultural policy. Stakeholders specifically highlighted risks associated with groundwater overexploitation, nitrate contamination, the resilience of irrigation systems, and the effects of demographic change in the basin.

Demographics are a critical issue: the basin's population has declined steadily from 2.6 million in the 1980s to 2.3 million in 2023, a trend expected to continue. The farming population is ageing, and the replacement rate appears insufficient to maintain the current workforce. As retired farmers sell their holdings, cheap land could attract large agricultural businesses, potentially driving water demand in unforeseen ways. Agricultural policy is equally important, as most of the basin's production is subsidised, favouring water-intensive crops such as sugar beet and maize despite the semiarid climate. EU trade agreements with third countries could drive European farmers out of the market, while environmental regulations limiting fertiliser inputs add further pressure. Due to the slow groundwater flow and long residence times characteristic of the basin's regional aquifers, pollution issues — notably nitrates and naturally-occurring arsenic mobilised by pumping — are likely to persist for decades regardless of mitigation measures.

5.1. Future scenarios of climate change

Climate projections for the Iberian Peninsula indicate a consistent pattern of rising temperatures and declining precipitation, with amplified impacts under higher emission pathways. For the Duero, the recent study by Paredes-Beltrán et al. (2024) provides state-of-the-art high-resolution estimates of water availability for the Iberian Peninsula, based on several EURO-CORDEX models (GFDL-ESM2NM, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M) and for two representative concentration scenarios (RCP4.5 and RCP8.5). Climate models suggest an increase in mean annual temperature by 1.5°C to 3°C by 2050 accompanied by a significant reduction in specific runoff under RCP4.5 and RCP8.5 scenarios. Table 5.1 presents the mean annual flow and specific runoff for the control period (1960–1999) and the short-term (2020–2059) and long-term (2060–2099) future periods.

The analysis by Paredes-Beltrán et al. (2024) projects a reduction in the mean annual flow of the Duero, ranging from -13% to -36%, depending on the scenario and time horizon. Among the catchments studied (Guadiana, Guadalquivir, Segura, Ebro, Miño and Duero), the Duero exhibited the highest mean annual flow for all scenarios and the lowest relative impact in terms of reduced mean potential water availability. Although not completely unaffected by climate change, the Duero demonstrated a comparatively resilient hydrological response, suggesting a distinct level of adaptation is needed. This finding is consistent with the study by Yeste et al. (2021), which showed annual streamflow reductions of up to 40% in various parts of the Duero for the period 2071–2100 under RCP8.5. Yeste et al. (2021) attributed these reductions to the combined effect of precipitation decreases in the southern sub-catchments and evapotranspiration increases in the north.

Table 5.1: Mean annual flow (km^3/year) and specific runoff (mm/year) for the Duero River basin, for the control historic period (1960–1999), the short-term future period ST (2020–2059) and the long-term future period LT (2060–2099) (source: Paredes-Beltrán et al., 2024).

	Mean annual flow	**Specific runoff**
Period:		
Control	15.30	157
RCP4.5-ST	12.74	131
RCP8.5-ST	12.92	133
RCP4.5-LT	13.32	137
RCP8.5-LT	9.79	101

Given the importance of groundwater resources in the Duero and the concerns raised by stakeholders regarding aquifer recharge under climate change, a dedicated effort was undertaken within STARS4Water to project groundwater storage change (GWSC) under future climate scenarios.

As described in Baron et al. (2025), a spatiotemporal Transformer (STT) deep learning model was developed and trained on 120 months of geospatial data from 2013 to 2022 across the Duero basin, integrating dynamic environmental features (precipitation, potential evapotranspiration and maximum temperature) with static landscape characteristics (land use, soil properties, geological features). The STT model employs multi-head self-attention mechanisms to capture complex spatial and temporal dependencies, using 48 months of historical observations to forecast the next 12 months of groundwater conditions. The training pipeline incorporates uncertainty estimates derived from corrections of Terrestrial Systems Modelling Platform (TSMP) total water storage products using in-situ groundwater level observations from the CHD monitoring network.

To run the STT model in climate projection mode, an autoregressive (AR) enhancement was implemented in which the model's own GWSC predictions are fed back as input for successive forecasting steps. For the observational period (2013–2022), the historical GWSC buffer is populated with real observations; from 2023 onward, the buffer is progressively filled with model predictions, creating a fully autonomous simulation through to 2040. The exogenous climate drivers for the projection period are drawn from regionalised simulations of three EURO-CORDEX ensemble members sharing the same GCM (ICHEC-EC-EARTH) but different RCMs: CLMcom-CCLM4-8-17, SMHI-RCA4 and KNMI-RACMO22E. The three models were averaged to produce ensemble-mean monthly time series of precipitation, maximum temperature and potential evapotranspiration under both RCP4.5 and RCP8.5 concentration pathways, covering the period 2013–2040. Longer-term periods were not considered as they do not influence the safe operating space operational framework from the stakeholder's point of view, which requires seasonal and short-term groundwater storage predictions.

Figure 5.1 presents the results of the climate scenarios at the basin-wide scale. The upper panel shows the spatial mean of predicted GWSC (±1σ uncertainty envelope, σ equals to the standard deviation) for both RCP4.5 and RCP8.5, with the green dashed line marking the end of the observational period (December 2022).

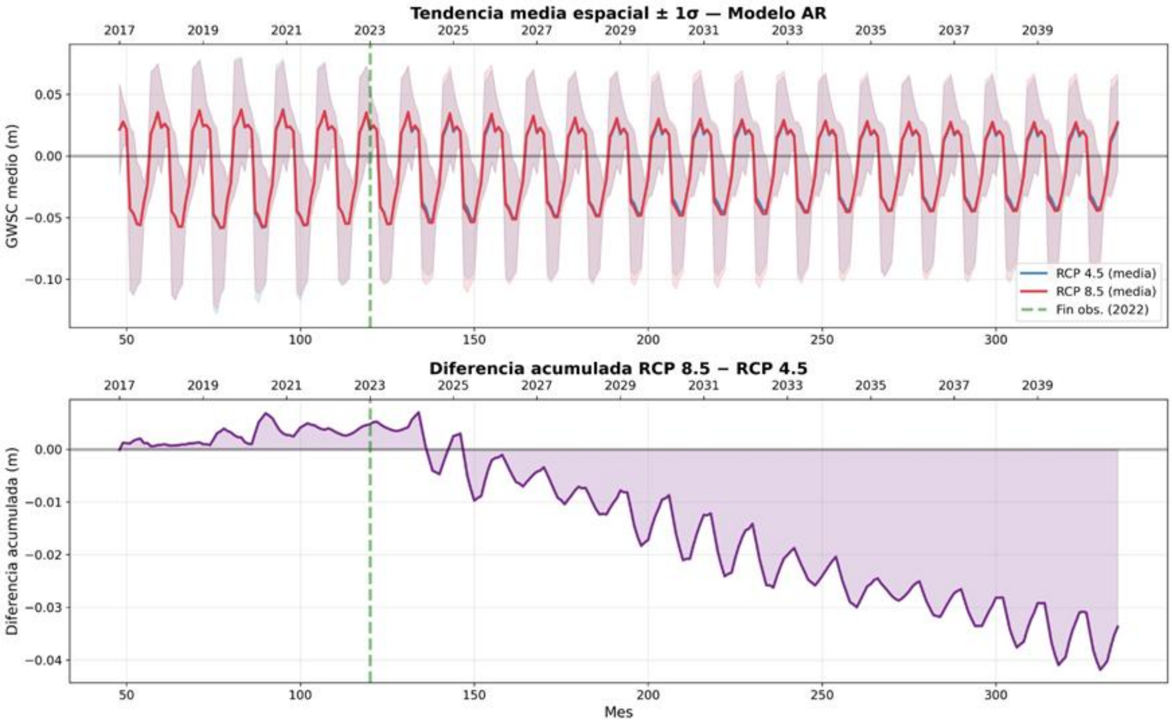


Figure 5.1: Spatial mean GWSC (±1σ) predicted by the autoregressive spatiotemporal Transformer model under RCP4.5 (blue) and RCP8.5 (red) for the Duero basin, 2017–2040 (upper panel). The green dashed line marks the end of the observational period (2022). The lower panel shows the cumulative difference (RCP8.5 − RCP4.5) in meters, highlighting the progressive divergence under a high-emission pathway.

During the historical window, the model closely tracks the observed seasonal oscillations, providing confidence in the autoregressive feedback mechanism. In the projection period (2023–2040), both scenarios maintain the characteristic seasonal cycle, with summer drawdowns and winter recharge pulses. However, RCP8.5 progressively diverges from RCP4.5, showing slightly deeper summer minima and a tendency toward more negative average GWSC values. The lower panel displays the cumulative difference between RCP8.5 and RCP4.5, which remains near zero during the observational period but becomes increasingly negative after 2024, reaching approximately −0.04 m by 2040. This growing divergence indicates that, under a high-emission trajectory, the Duero's groundwater system would experience a sustained, albeit gradual, additional depletion relative to a moderate-emission pathway.

Figure 5.2 provides a pixel-level view of the same projections for five representative grid cells spanning the central and western Duero basin. Each panel corresponds to a pixel identified by its longitude and latitude coordinates. The shaded area between the RCP4.5 and the RCP8.5 curves highlights the local divergence between the two scenarios. Several features stand out from the pixel-level analysis. First, the amplitude of the seasonal GWSC cycle varies substantially across pixels, from approximately ±0.1 m in the northernmost pixel to ±0.2 m in the southernmost pixels, reflecting heterogeneity in aquifer properties, land use and recharge conditions. Second, the difference between RCP4.5 and RCP8.5 is generally small in the early projection years but increases progressively, with the RCP8.5 trajectory consistently showing deeper summer drawdowns. Third, the autoregressive model maintains realistic and stable seasonal dynamics throughout the entire simulation period, with no evidence of drift or amplification artifacts, suggesting that the feedback loop remains well conditioned even beyond the observational training window.

Taken together, these results suggest that climate change will affect groundwater storage in the Duero basin through a gradual intensification of the seasonal cycle and a progressive reduction in mean storage levels, with the magnitude of the impact sensitive to the emission pathway. Under RCP4.5, the changes remain modest and largely within the range of natural interannual variability. Under RCP8.5, the accumulated deficit of roughly 0.04 m by 2040, while not catastrophic at the basin-wide scale, could translate into significant localised impacts in areas already experiencing quantitative stress, such as the Los Arenales and Tordesillas–Toro aquifer systems, identified in the SOS framework assessment (see Section 5.3).

5.2. Future water management scenarios

In the Duero River basin, stakeholders identified climate change as a central future driver while also stressing the importance of demographic shifts, agricultural policy and land-use change as mediating factors. Several co-designed what-if scenarios were developed through the iterative engagement process described above, combining stakeholder concerns with the scientific expertise of the research team. These scenarios allow us to explore the combined effects of climatic and socio-economic drivers on the basin's water resources, and are formulated as follows:

- DUE1: How would rising evapotranspiration (ET) and increased crop water demand due to climate change together with more frequent extreme weather events affect groundwater (aquifer) recharge? This scenario is directly linked to the climate projections presented in Section 5.1 and was selected as the priority scenario for exploration within the SOS framework, given stakeholders' emphasis on groundwater quantitative status.
- DUE2: How would groundwater nitrate levels be affected if European environmental policies promoted a stronger reduction of fertilizer inputs? This scenario addresses the widespread nitrate contamination observed across the basin's central aquifers, where concentrations systematically exceed the 50 mg/L threshold at many monitoring wells. The slow groundwater flow and long residence times mean that even under stricter regulations, water quality improvements would lag significantly behind policy implementation.

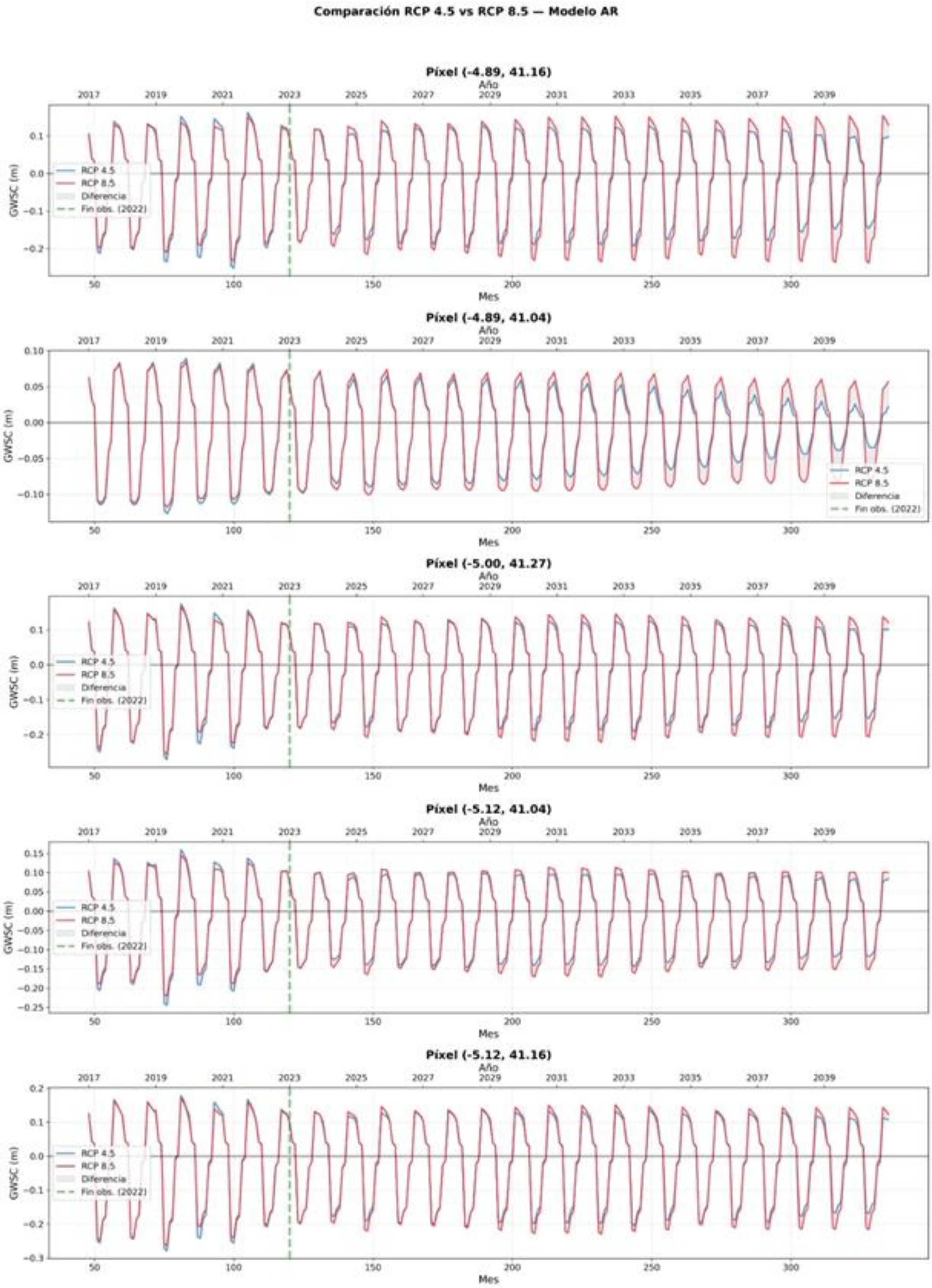


Figure 5.2: Pixel-level comparison of GWSC projections under RCP4.5 (blue) and RCP8.5 (red) from the autoregressive spatiotemporal Transformer model for five representative grid cells in the Duero basin. The shaded area indicates the difference between scenarios. The green dashed line marks the end of the observational period (December 2022).

- DUE3: How would the use and availability of groundwater and its quality be affected due to the gradual abandoning of the existing agricultural land combined with a massive implementation of new energy acquisition technologies (e.g., photovoltaic, solar thermal)? This scenario reflects the ongoing demographic transition in the basin, where an ageing farming population and insufficient replacement rates could lead to large-scale land-use change, with uncertain consequences for water demand and quality.
- DUE4: How would reducing or removing agricultural subsidies influence crop choices and overall agricultural water use? Given that most of the basin's agricultural production is policy-driven and subsidised — explaining the presence of water-intensive crops despite the semiarid climate — a shift in EU agricultural policy could fundamentally alter crop patterns and associated water demands.

The what-if scenario DUE1, which explores the impact on aquifer recharge of rising evapotranspiration and crop water demand combined with more frequent extreme events, was selected as the priority scenario for the first application of the STARS4Water SOS framework. This choice was motivated by the fact that climate change and its effects on groundwater were consistently identified as the single most important concern during the stakeholder survey and workshops. The scenario also presents an interesting scientific question given the semiarid nature of the climate, where recharge tends to occur preferentially during humid years and is relatively small in dry years, it is unclear whether net recharge would increase or decrease under a warmer climate with fewer but more intense precipitation events.

Each scenario frames a plausible shift in management or socio-economic drivers and assesses its effect on water supply and quality. They allow us to test how changes in climate and human management may push water systems toward or beyond their safe operating limits, serving as the basis for the implementation of the project's SOS framework.

5.3. Risks related to changes in water resources availability and quality

The risk assessments carried out in the Duero River basin build upon the main concerns expressed by stakeholders during dedicated workshops, where future water availability and management under climate uncertainty were prioritized. Stakeholders highlighted risks associated with groundwater overexploitation, nitrate contamination, and the resilience of irrigation systems.

In the Duero, focus is placed on two sub-processes: surface water and groundwater. Moreover, the assessment considers the integration of the STARS4Water SOS framework into existing risk assessment frameworks related to the freshwater change process of the Planetary Boundary approach. In this context, the SOS implementation seeks to align the assessment of water resources availability and risks with the EU Water Framework Directive (WFD) and national hydrological plans.

Each water process (surface water and groundwater) is evaluated by two control variables. For surface water, the controls are ecological status and chemical status, relying on WFD biological/hydro-morphological indicators and pollutant thresholds. For groundwater, the controls are quantitative status and chemical status. Figure 5.3 illustrates these sub-processes and variables, as co-defined with stakeholders. The indicators and their thresholds define two SOS boundaries delineating three zones: the 'safe operating zone' (SOS), the zone of increasing risk (ZIR), and the zone of high risk (ZHR).

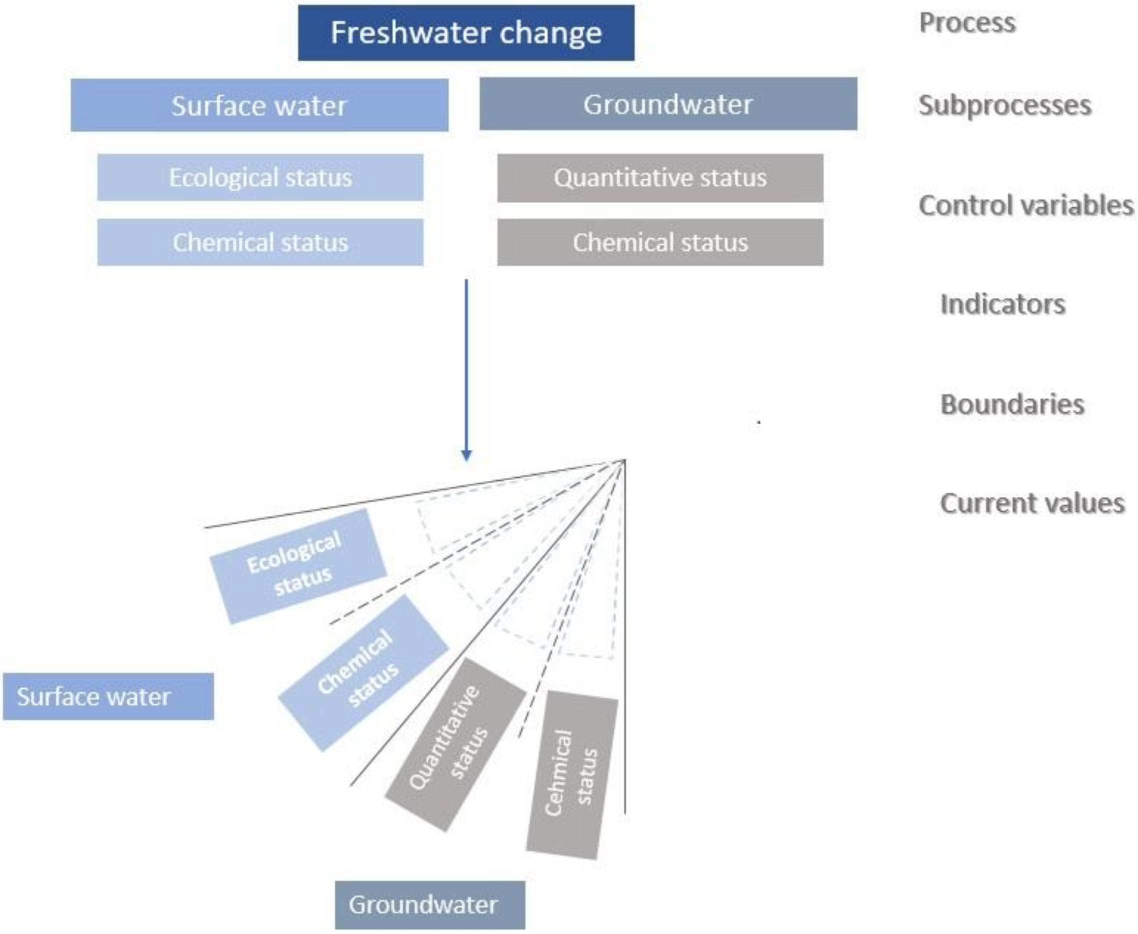


Figure 5.3: Sub-processes and control variables of the freshwater change process in its application to the Duero River basin.

To quantify 'what-if scenarios', a regional modelling framework for basin-scale planning is needed, which faces typical challenges, such as downscaling global climate model projections to capture local hydrological dynamics. Precipitation data in the river basin show observed trends toward a reduction of 10% to 15%, with increased seasonal variability. These trends already affect hydrological processes, including blue water (surface runoff) and green water (soil moisture). In this context, the data-driven tools developed in the project (Baron et al., 2025) offer complementary capabilities: the multi-reservoir Extra Trees model provides 1- and 3-month ahead reservoir storage predictions (with performance metric of NSE of 0.83–0.97 at 1 month and 0.23–0.92 at 3 months across 15 Duero reservoirs; with NSE = 1 being the best model performance), while the spatiotemporal Transformer model captures basin-wide groundwater dynamics at monthly resolution.

The SOS application focuses on groundwater assessment. The groundwater quantitative status indicator uses the observed long-term piezometric trends and an exploitation index (EI), defined by the ratio between the amount of water withdrawal and the amount of water available for recharge (EI = withdrawal/available recharge). Depending on the observed trend, thresholds are applied to delineate the three SOS zones. If the long-term trend is increasing or undefined, the values of 0.8 and 1 are set as the thresholds for the SOS-ZIR and the ZIR-ZHR boundaries, respectively. If the trend is decreasing, stricter values are applied at 0.5 and 0.75 (Figure 5.4).

Quantitative status	Long-term piezometric trend + Exploitation Index	Trend: increasing or undefined	
		0,8	1
		Trend: decreasing	
		0,5	0,75

Quantitative status Trend: decreasing	EI-Boundaries
SOS	<0.50
ZIR	0,5-0.75
ZHR	>0.75

Figure 5.4: Indicator and thresholds for the application of the SOS framework to groundwater in the Duero (table on the left). The indicator is related to the quantitative status of groundwater and relies on long-term piezometric trends and the exploitation index (EI = withdrawal/available recharge); the thresholds define the boundaries and colours to be applied (e.g., the case of decreasing long-term piezometric trend is shown on the table on the right).

The application of the SOS framework for groundwater revealed several insights to the Duero's current risk profile. **Groundwater quantitative status** shows localized stress: four aquifers (administrative groundwater bodies) were found in the ZHR, specifically the Tordesillas–Toro aquifer and multiple Los Arenales aquifers, where exploitation indices are high and water levels are falling. One additional groundwater body is in the ZIR, and the remaining 59 of 64 aquifers are in the SOS (Figure 5.5). In terms of **groundwater chemical status**, approximately 44% (28 of 64) of groundwater bodies fall in the SOS zone, 31% (20) in the ZIR, and 25% (16) in the ZHR (Figure 5.5). Nitrate, ammonium and arsenic are the main contributors to the chemical status of the groundwater bodies in the ZHR.

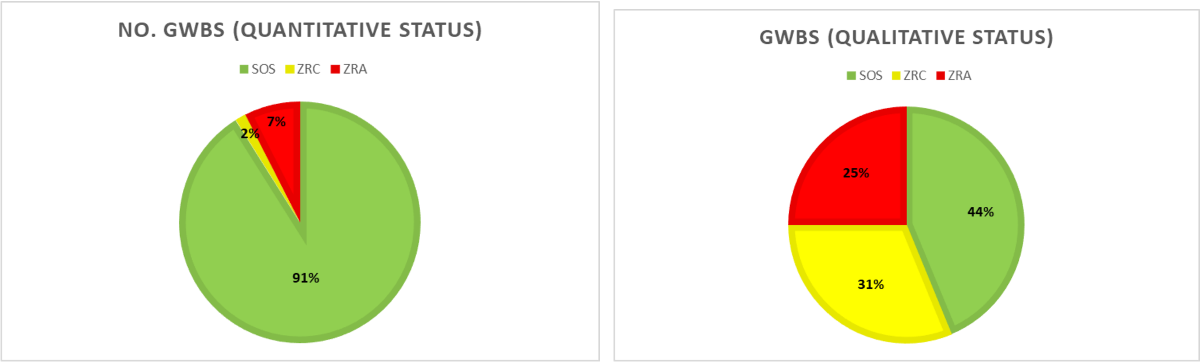


Figure 5.5: Distribution of the number of groundwater bodies (GWBS) in the Duero (out of a total of 64 GWBS) in the SOS framework for quantitative (left) and chemical status (right) control variables. Numbers indicate the percentages of GWBS that are located in the zones of safe operating space (SOS, in green), increasing risk (ZIR or ZRC, in Spanish, in yellow), and high risk (ZHR or ZRA, in Spanish, in red).

While most surface waters maintain good ecological and chemical status, groundwater bodies show localized risks, particularly in terms of chemical status. Groundwater vulnerability in the Duero River basin can be spatially assessed through maps of quantitative status (Figures 5.6 and 5.7), which allows us to visualize the distribution of groundwater bodies across the SOS, ZIR and ZHR-zones. This spatial representation underscores critical areas such as Los Arenales and Tordesillas-Toro, where exploitation indices and piezometric trends indicate significant stress.

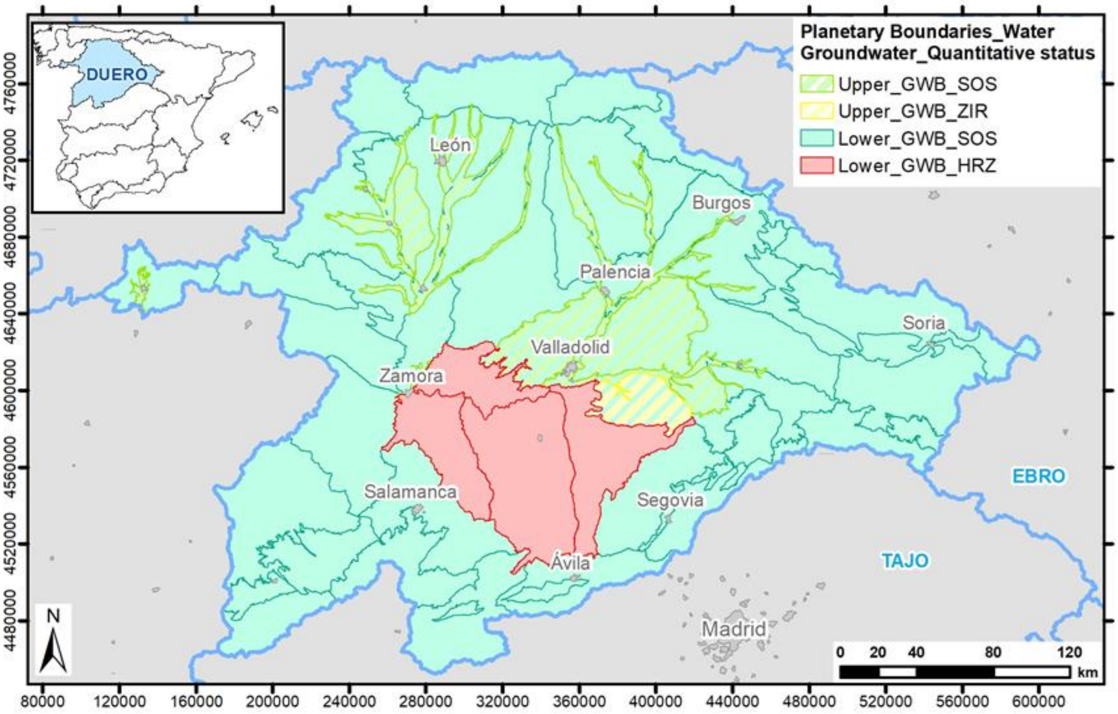


Figure 5.6: Map of the groundwater quantitative status in the SOS framework of the Duero, indicating the risk zones of safe operating space (SOS, in green), increasing risk (ZIR, in yellow), and high risk (ZHR or HZR, in red).

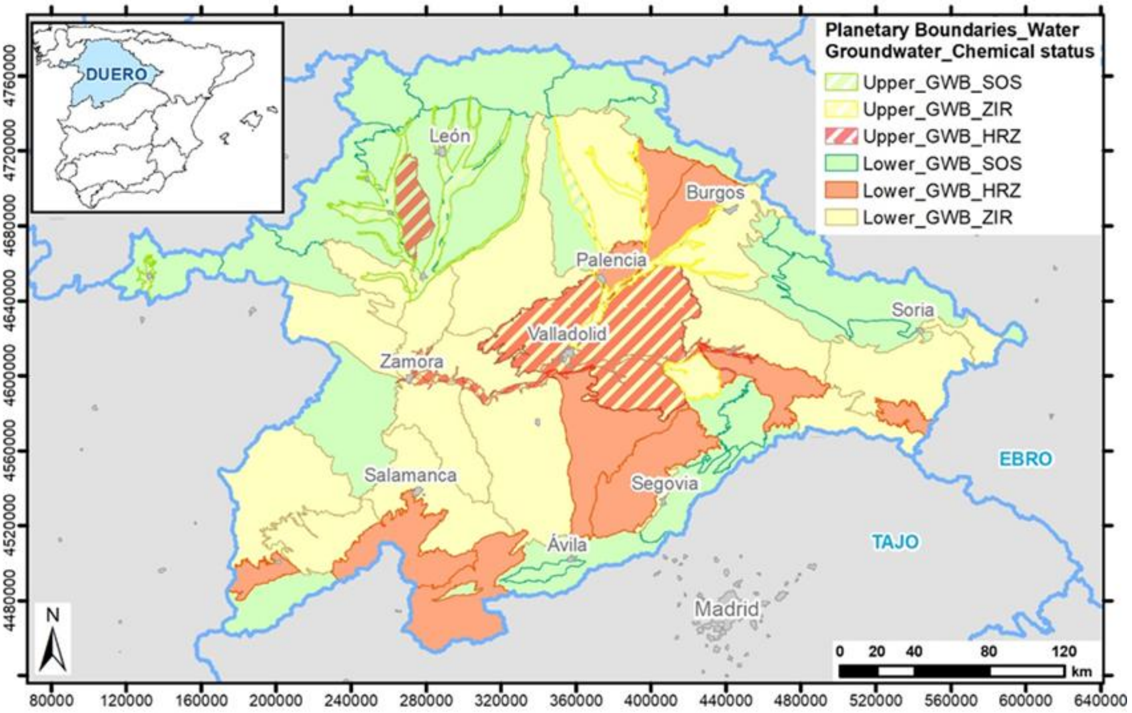


Figure 5.7: Map of the groundwater chemical status in the SOS framework of the Duero, indicating the risk zones of safe operating space (SOS, in green), increasing risk (ZIR, in yellow), and high risk (ZHR or HZR, in red).

When combined with the climate projections presented in Section 5.1, these findings raise important concerns. The GWSC simulations under RCP8.5 indicate a progressive reduction in groundwater storage that, while modest at the basin-wide scale (approximately −0.04 m cumulative deficit by 2040), could significantly worsen conditions in the already-stressed aquifers identified in the ZHR. The Tordesillas–Toro and Los Arenales systems, where exploitation indices are already high and piezometric trends are declining, are particularly vulnerable to additional climate-driven reductions in recharge. Under these conditions, the current SOS–ZIR–ZHR classification could shift, with some groundwater bodies that are currently in the SOS zone potentially moving into the ZIR zone by mid-century, and those already in the ZIR potentially crossing into the ZHR zone.

5.4. Lessons learnt and perspectives

Overall, the Duero remains largely within safe limits for most water metrics, but localized hot spots of risk exist, mainly in overexploited or polluted aquifers. The development and application of the STARS4Water SOS framework tailored to the Duero River basin highlighted where water withdrawals or pollution levels approach unsustainable thresholds. In practical terms, maintaining current reservoir operations and irrigation practices within the Duero is necessary to avoid further encroachment into zones of increasing or high risk in the river basin’s key aquifer systems.

The integration of deep learning tools developed in the project (Baron et al., 2025), including the spatiotemporal Transformer for GWSC estimation and the multi-reservoir Extra Trees model for reservoir storage prediction, has provided new capabilities for assessing climate change impacts at a resolution and temporal frequency previously unavailable in the basin. The autoregressive extension of the STT model, driven by regionalised EURO-CORDEX climate projections (ICHEC-EC-EARTH combined with three RCMs: CLMcom-CCLM4-8-17, SMHI-RCA4 and KNMI-RACMO22E), demonstrated that the trained model can produce physically plausible GWSC trajectories through 2040 under both RCP4.5 and RCP8.5, maintaining stable seasonal dynamics without drift artifacts. This represents a significant advance in the toolkit available to the stakeholders for forward-looking water management.

The Duero River basin SOS assessment shows that global sustainability concepts can be meaningfully integrated with local water management frameworks, in harmony with EU and national water legislations. However, this requires careful adaptation and strong stakeholder involvement. A key insight is that model and data resolution are critical: global climate and hydrology models must be downscaled for basin relevance, and monitoring networks must be sufficiently dense to evaluate control variables. The spatiotemporal Transformer model addresses part of this gap by leveraging the basin’s piezometric network to correct and downscale water storage outputs from land surface models, but further development is needed to couple these predictions with process-based groundwater flow models for fully integrated scenario assessment.

Stakeholder co-design has been essential. For the Duero, stakeholders specifically prioritized groundwater depletion and nitrate pollution, which directed the SOS analysis toward these issues. The what-if scenarios (DUE1–DUE4) constitute an initial framework that requires the quantification of changes and the selection of specific impact indicators before full modelling can be performed. These scenarios must be translated into numerical values (e.g., percentage increase in evapotranspiration, amount of fertilizer reduction, extent of land-use change) for use in simulation models. The ongoing demographic transition, which could lead to either reduced water demand through agricultural abandonment or increased demand through the arrival of large agri-businesses, represents a particularly challenging source of uncertainty that cannot be resolved through climate modelling alone but requires continued dialogue with stakeholders and monitoring of socio-economic trends.

Future assessments could refine the thresholds used and consider multi-sector interactions (agriculture, energy, ecology) under combined climate and management scenarios, ensuring that the Duero water management stays within its safe operating space. Promising avenues include the development of adaptive monitoring systems informed by the STT model's spatial predictions, the extension of autoregressive climate projections to longer horizons with additional EURO-CORDEX ensemble members, and the creation of digital twin frameworks that integrate real-time data with predictive models for the dynamic tracking of safe operating space indicators. Such tools would enhance the basin's resilience and support the CHD's mandate to achieve and maintain good status for all water bodies under the EU Water framework Directive.

6. East Anglia: ecological flow projections

Authors: Cedric Laize, Nathan Rickards, Helen Baron and Virginie Keller (UKCEH)

The East Anglia region, located in the east of the UK, receives only two-thirds of the average national rainfall, making it the driest part of the country. Public water supply, agriculture and the energy sector are all large water users, with part of the country hosting over 60% of all extraction licences in England. Future water demand across all sectors is predicted to increase, driven by a growing population, increased irrigation requirements, and greater demand for cooling water for power stations in order to meet the UK government targets for greenhouse gas emissions.

Many of East Anglia's chalk rivers and streams, wetland areas, peatlands and sensitive water environments are already seen to be in poor health due to over-abstraction and the impact of a warming climate. During the project, discussions with stakeholders highlighted concerns over how increases in future drought risk and heightened sectoral water demand could further impact the ecological health of riverine environments. Such pressures are likely to affect environmental flows (see Rickards et al., 2024) and the hydrological characteristics required to sustain a healthy river ecosystem; planning around how to best manage these changes going forward is therefore key.

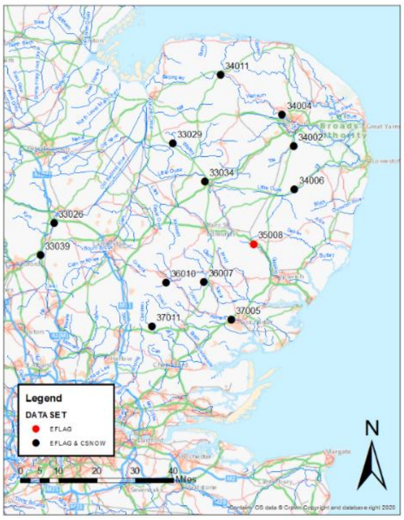
As a result of these concerns, stakeholders highlighted two priority what-if scenarios to explore further in relation to environmental flows and the health of riverine ecosystems in the region: (i) What if droughts become more frequent in the future? (ii) What if future water demand is significantly higher than current predictions? Stakeholders expressed concerns for both the short to mid-term future periods, and the extent of change that may be seen in environmental flows due to both climatic and anthropogenic drivers.

6.1. Future scenarios of climate change

Within the UK, a set of projections, namely UKCP18 are publicly available for use and underpin many future water resources assessments (Murphy et al., 2018). The UKCP18 dataset provides a set of 12 projected climatic time series for the period Dec 1980 - Nov2080 at a high resolution (12 km). These climate projections were derived using the Hadley Centre global climate model (HadGEM3-GC3.05) and a regional climate model (HadREM3-GA705) using a high-emissions scenario (RCP8.5).

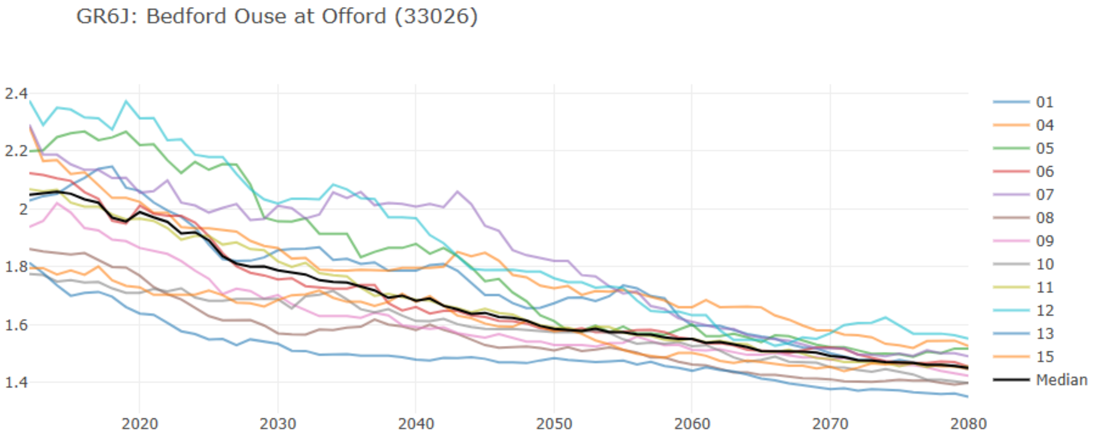
River flow future projections were readily available for most of the UKCP18 climatic projections. The enhanced future 'FLows and Groundwater' (eFLaG) dataset contains estimates of river flows consistent with the UKCP18 for 200 river catchments across the UK, including several in East Anglia (Hannaford et al., 2023). Figure 6.1 shows the location of the gauging stations used in our analysis, their names and identifier codes. River flow future estimates were available for a range of hydrological models, including GR6J (Genie Rural, 6-parameter daily hydrological model developed at INRAE; Pushpalatha et al., 2011), which is a model in use amongst UK water companies to establish future water resources management plans. For the purposes of this analysis, whilst analysing the what-if scenario related to drought, we focussed on those derived using the GR6J model forced by the driest ensemble members of the eFLaG dataset.

Figure 6.2 illustrates the impact of climate change in low flows, here represented by the Q90 (flow exceeded 90% of the time), for two river catchments in East Anglia (33026 and 36010, Figure 6.1), over the period 2000-2080. For these catchments, for instance, ensemble members 13 and 08 produced the lowest Q90. Low flows are more pronounced for the far future (2050-2079). It is important to note that, within the eFLaG dataset, artificial influences are not explicitly modelled; therefore, in the future estimates, the artificial influences are considered similar to those in the current period.



STATION	RIVER	NAME
33018	Tove	Cappenham Bridge
33026	Bedford Ouse	Offord
33029	Stringside	Whitebridge
33034	Little Ouse	Abbey Heath
33039	Bedford Ouse	Roxton
34002	Tas	Shotesham
34004	Wensum	Costessey Mill
34006	Waveney	Needham Mill
34011	Wensum	Fakenham
*35008**	*Gipping*	*Stowmarket*
36007	Belchamp Brook	Bardfield Bridge
36010	Bumpstead Brook	Broad Green
37005	Colne	Lexden
37011	Chelmer	Churchend

*Figure 6.1: Location of the gauging stations analysed in East Anglia (left), and their names and identifier codes (right). *eFLaG data only (future drought assessment).*


GR6J: Bedford Ouse at Offord (33026)

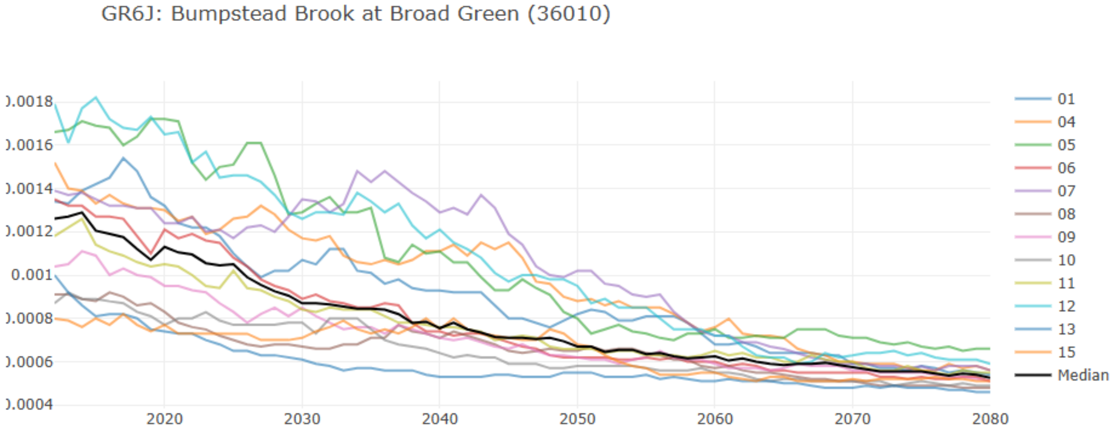

GR6J: Bumpstead Brook at Broad Green (36010)

Figure 6.2: Estimates of Q90 (flow exceeded 90% of the time) using the GR6J model under different UKCP18 climates in two catchments in East Anglia (see Figure 6.1 for their location). Source: Enhanced Future Flows and Groundwater (eFLaG) Portal, https://hydroprojections.ceh.ac.uk/eflag/transient.

6.2. Future water management scenarios

Future population increases in East Anglia are likely to exert additional pressures in the water resources. It is therefore important to quantify the potential impact of changes in water demand and, therefore, the impact of water abstractions and discharges on water resources availability. Recently, UKCEH published a set of future projections of river flows for the period 1980 to 2080, where artificial influences are explicitly modelled (Bell et al., 2024). This dataset was developed in line with the eFLag methodology and the climate projections from UKCP18, but introduces novel aspects. It uses the distributed grid-based hydrological model Grid-to-Grid (Bell et al., 2009). Artificial influences were considered by estimating three water demand scenarios, namely the following socio-economic scenarios: Sustainability (SUS), Business as Usual (BAU) and Economic Growth (EG) (Baron et al., 2023). These scenarios were specifically designed to be in line with existing demand projections.

To investigate the impact of management scenarios related to water demand, we focussed on those artificially influenced flow projections for all three water demand scenarios, using two UKCP18 ensemble members, namely 13 and 07. Unlike for the exploration of the drought-what-if scenario, it was important to select an extreme ensemble member (13) and a less extreme, milder one (07) for our analysis. The use of a less extreme climate projection allows for a more pronounced impact of changes in water demands.

Figure 6.3 illustrates the impact of climate change on the low flows, here represented by the Q90 (flow exceeded 90% of the time), for the same river catchments in East Anglia presented in Figure 6.2, over the period 2000-2080. For both catchments, it is clear that the influence of climate overrides the management (water demand) signal. When the signal from the water demand is visible (station Bedford Ouse at Offord, 33026), there is little difference between the three socio-economic scenarios (SUS, BAU, EG). This difference increases in the far future (2050-2079).

6.3. Ecological risks related to changes in water resources availability

In East Anglia, the main concern of stakeholders was the ecological impact of alterations in the flow regimes of the river basin due to climate change. For the implementation of the STARS4Water SOS framework, we therefore focus on the ecological assessment, which is carried out by applying the Ecological Risk due to Flow Alteration (EFRA) approach (Laize et al. 2014). This approach relies on indicators of hydrological variability, considered as important determinants of the ecological functioning of the rivers. We focused on assessing the ecological risk to rivers in East Anglia under two distinct sets of future scenarios: (i) Abstraction scenario (based on UK Climate Services for a Net Zero Resilient World, CS-N0W, data); and (ii) Future drought scenario (based on eFLaG data). A set of fourteen East Anglian gauging stations were used for the future drought (climate) assessment, and thirteen for the abstraction (management) assessment (one station was not available in the CS-NOW dataset; see Figure 6.1).

Abstraction assessment: we used modelled data from the CS-N0W datasets (Rameshwaran et al., 2025), which includes gridded future projections of natural and artificially influenced river flows for 1980 to 2080, with climate projections consisting of an ensemble of bias-corrected UKCP18 Regional Climate Model (RCM) output (catalogue available https://catalogue.ceda.ac.uk[6]). We downloaded the modelled observed mean daily flow time series (“Mean Obs”), under the three socio-economic future abstractions scenarios (SUS, BAU and EG), all including artificial influences. For the purpose of the ERFA

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[6] https://catalogue.ceda.ac.uk/uuid/cf66055440344d7eb9b6f834e81736c6/

analysis, the dataset was split as: (i) Baseline (mean daily flows for the period 1989-2018); (ii) Scenarios: BAU, SUS, and EG for the periods 2040-2059 ("near future", NF) and 2060-2079 ("far future", FF). We selected RCM07 and RCM13 runs, as mentioned previously. RCM13 runs are the most extreme in terms of low flows, while RCM07 runs project milder future conditions. With regard to the ERFA analysis, we compared the baseline mean observed flows with the scenarios, for both RCM07 and RCM13, i.e. there are two distinct ERFA analyses. For each station analysed, we obtained six sets of ERFA ecological risk classes (NF/FF x BAU/EG/SUS) under RCM07, and another set of six under RCM13.

Figure 6.4 and Figure 6.5 illustrate the SOS framework ERFA class results obtained for one station (36010) in East Anglia, considering the RCM07 and RCM13, respectively. All scenarios BAU, SUS, and EG for the near and far future periods are presented. On these plots, ERFA risk classes are represented as: yellow, low risk (code 1); amber, medium risk (code 2), red high risk (code 3). Going clockwise, the sectors are the risk classes for "All Indicators", high flow indicators, monthly flow indicators, low flow indicators, rate of flow change indicators, and intermittent flow indicators.

This example suggests that patterns are driven primarily by the choice of RCM (07 or 13) and of future period (NF/FF), with the different abstraction scenarios, given by the BAU, SUS, and EG scenarios, causing more limited changes. These plots are useful to highlight which aspect of the flow regime puts ecology at risk the most. At this station in East Anglia, the overall ERFA risk is medium (sector "1-All Indicators" in the radius plot) and it is the low flows that are most severely impacted (sector "4-Low Flows" in red), while high flows and rate of flow change are the least impacted indicators.

In Table 6.1, we present the results for all the stations together and for the ERFA 'All-Indicators' class. For RCM13, almost all stations are assigned the medium risk class. For RCM07, near future (NF) runs are most frequently indicating low risk, followed by medium. Nearly all far future (FF) runs indicate medium risk. The water abstraction socio-economic scenarios BAU, EG, and SUS are secondary drivers only, as also illustrated in Figures 6.4 and 6.5 for the station Bumpstead Brook at Broad Green, although they can play an important role when looking at individual stations (e.g., NF SUS has 6 stations with medium class against NF EG, with 4 stations).

Future drought: for this assessment, we used the eFLaG dataset (Hannaford et al., 2022; dataset in the catalogue https://catalogue.ceh.ac.uk/[8]). We downloaded the GR6J modelled observed flows ("simobs" files) for the fourteen gauging stations in East Anglia and their GR6J future projections under RCM08 and RCM13 ("simrcm" files). RCM13 is the worst scenario for all stations in terms of proportion of time under drought, and RCM08 is the second worst. We used the same baseline and future periods as in the abstraction assessment. Table 6.2 shows breakdown results for the number of stations in each ERFA class ('All Indicators' and the other specific flow indicators). Most stations are at medium risk. The 'Low flows' indicator group has the largest number of stations in the high-risk class, compared to the other indicator groups. In this this assessment, there is overall consistency in potential ecological risk across all scenarios, with site-specific differences driven by the choice of RCM/scenario period.

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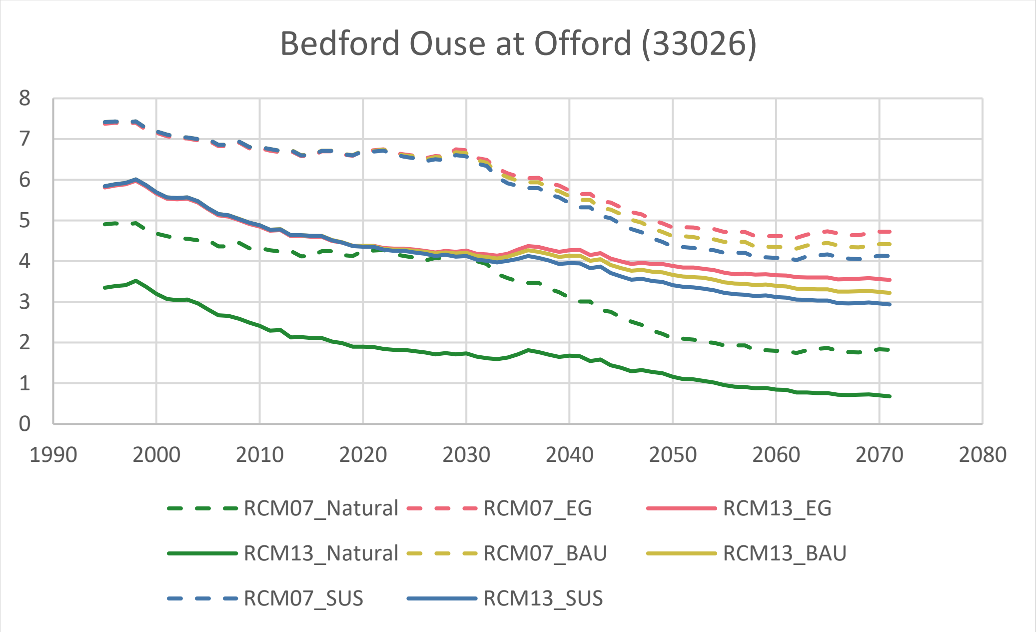
[7] https://catalogue.ceh.ac.uk/documents/1bb90673-ad37-4679-90b9-0126109639a9

[8] https://catalogue.ceh.ac.uk/documents/1bb90673-ad37-4679-90b9-0126109639a9



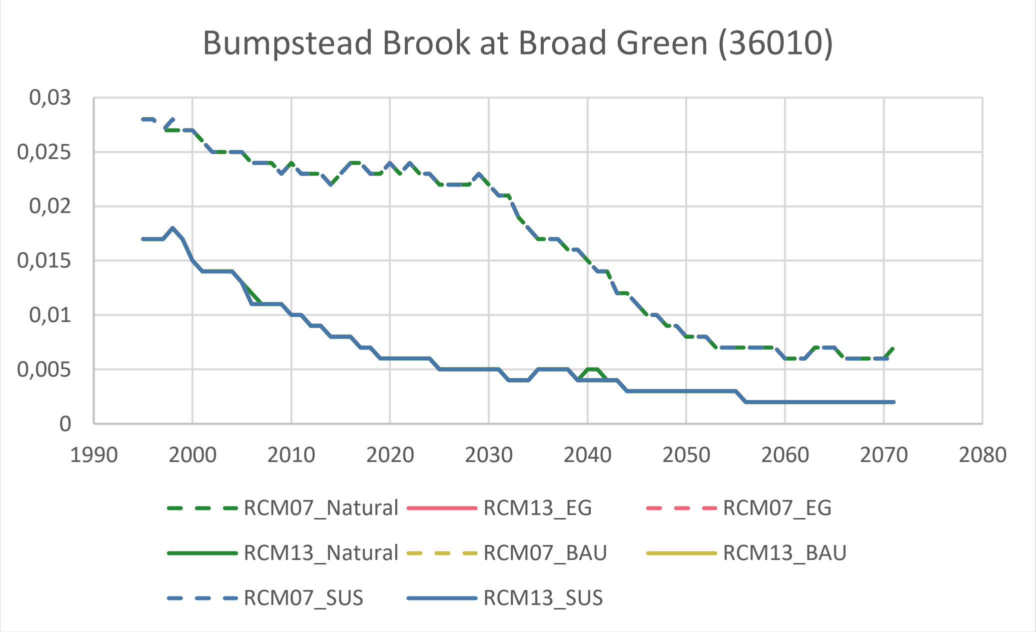
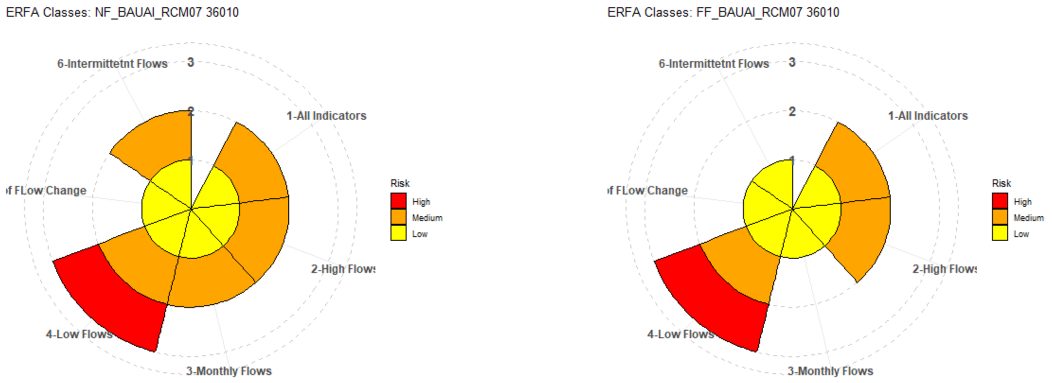


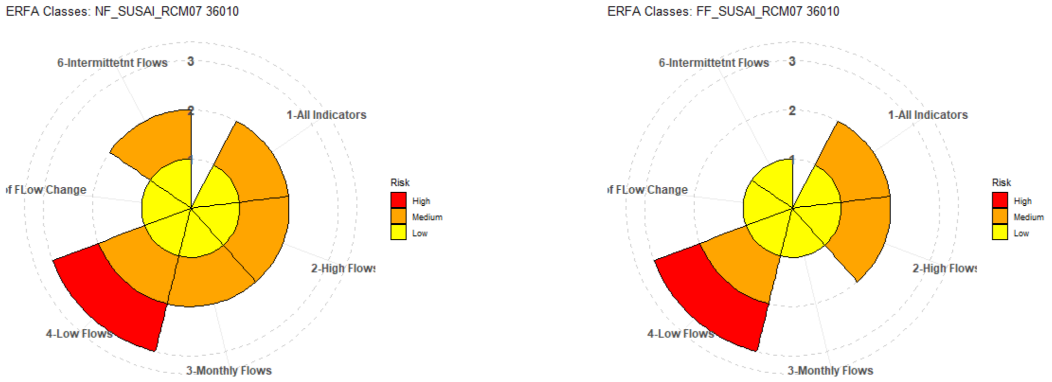
Figure 6.3: Estimates of Q90 (flow exceeded 90% of the time) using the Grid-to-Grid model under two UKCP18 climate scenarios (RCM13: extreme low flow; RCM07, mild scenario) and three socio-economic scenarios (Sustainability, SUS; Business as Usual, BAU; Economic Growth, EG), for two catchments in East Anglia (see Figure 6.1 for their location).

RCM07 NF RCM07 FF

BAU scenario:



SUS scenario:



EG scenario:

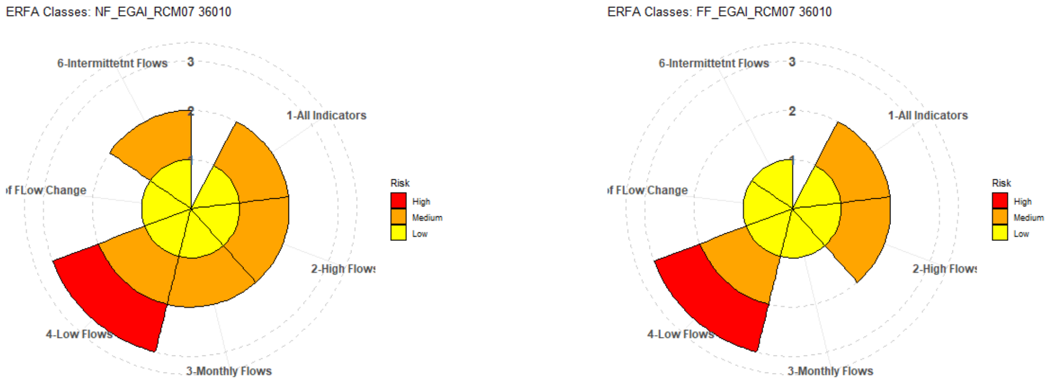
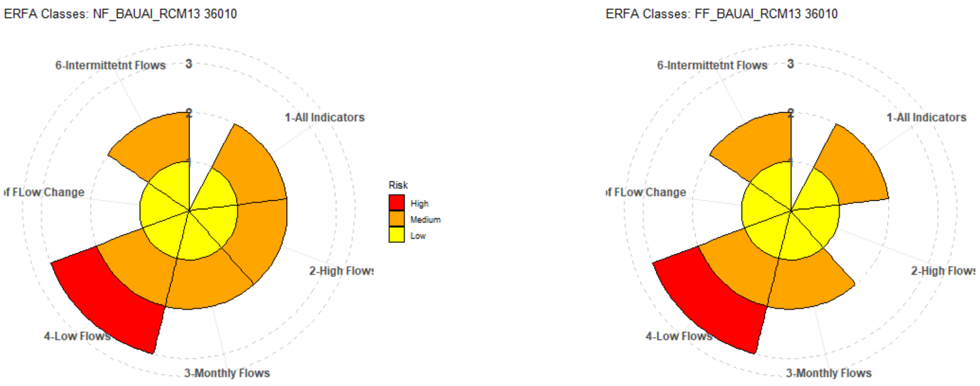


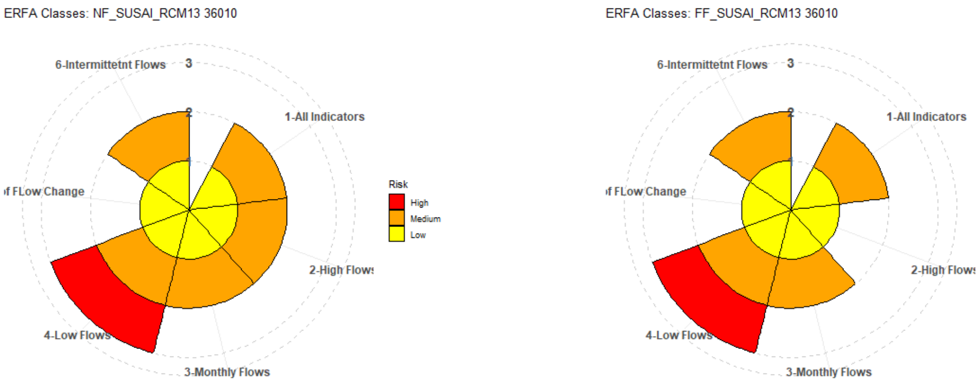
Figure 6.4: SOS framework using ERFA risk class analysis for selected indicators in the station Bumpstead Brook at Broad Green (36010) in East Anglia for the mild climate scenario (RCM07). Three socio-economic water abstraction scenarios: Business as Usual (BAU, top), Sustainability (SUS, middle), and Economic Growth (EG, bottom), for the near future (NF: 2040-2059; left) and far future (FF: 2060-2079; right). ERFA selected indicators are high flow, monthly flows, low flows, rate of flow change, and intermittent flow. Results considering all indicators are also shown.

RCM13 NF RCM13 FF

BAU scenario:



SUS scenario:



EG scenario:

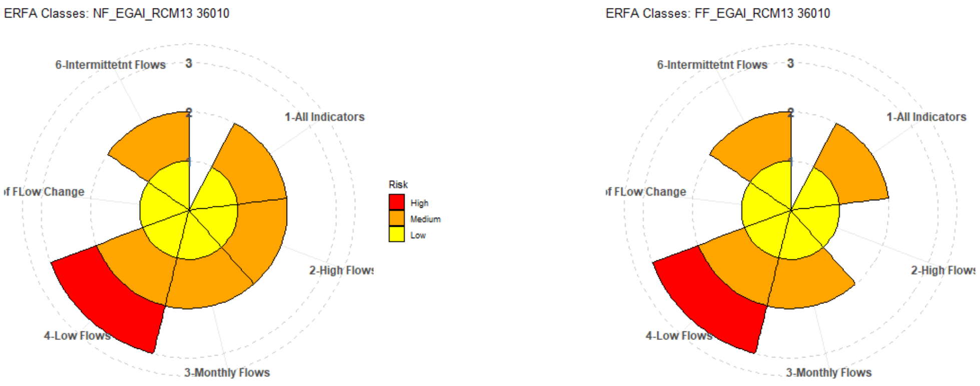


Figure 6.5: SOS framework using ERFA risk class analysis for selected indicators in the station Bumpstead Brook at Broad Green (36010) in East Anglia for the extreme low flow scenario (RCM13). Three socio-economic water abstraction scenarios: Business as Usual (BAU, top), Sustainability (SUS, middle), and Economic Growth (EG, bottom), for the near future (NF: 2040-2059; left) and far future (FF: 2060-2079; right). ERFA selected indicators are high flow, monthly flows, low flows, rate of flow change, and intermittent flow. Results considering all indicators are also shown.

Table 6.1: ERFA 'All-Indicators' risk class counts for 13 gauging stations in East Anglia, for the mild (RCM07) and extreme (RCM13) low flow scenarios, the three socio-economic scenarios (Business as Usual, BAU; Sustainability, SUS; Economic Growth, EG), and the near (NF: 2040-2059) and the far futures (FF: 2060-2079).

	BAU		EG		SUS	
	NF	FF	NF	FF	NF	FF
RCM07	8 Low 5 Medium	All Medium	9 Low 4 Medium	1 Low 12 Medium	7 Low 6 Medium	All Medium
RCM13	All Medium	All Medium	2 Low 11 Medium	All Medium	All Medium	All Medium

Table 6.2: ERFA risk class analysis for drought assessment in East Anglia, considering 14 gauging stations: number of stations in each risk class (no change; low risk; medium risk; high risk) and indicator group (all indicators; high flows; monthly flows; low flows; flow change; intermittent flows). Extreme climate scenarios are for low flows (less extreme RCM08 and most extreme RCM13), near (NF: 2040-2059) and far futures (FF: 2060-2079).

		All Indicators	High Flows	Monthly Flows	Low Flows	Flow Change	Intermittent Flows
RCM08 NF	No change	0	0	0	0	0	14
	Low risk	1	6	0	0	5	0
	Medium risk	11	4	12	8	6	0
	High risk	2	4	2	6	3	0
RCM08 FF	No change	0	0	0	0	0	14
	Low risk	1	9	0	0	11	0
	Medium risk	12	4	11	7	2	0
	High risk	1	1	3	7	1	0
RCM13 NF	No change	0	0	0	0	0	14
	Low risk	1	11	1	0	9	0
	Medium risk	12	2	10	7	4	0
	High risk	1	1	3	7	1	0
RCM13 FF	No change	0	0	0	0	0	14
	Low risk	0	2	0	0	7	0
	Medium risk	12	6	9	7	6	0
	High risk	2	6	5	7	1	0

6.4. Lessons learnt and perspectives

The abstraction assessment in East Anglia showed that the climate scenarios and the period of interest (near or far future) are the primary drivers of the potential risk to river ecosystems. The water management abstraction scenarios are secondary drivers, yet important at site level, since they affect different stations in different ways. The future drought assessment showed that there is a notable consistency in ecological risk regardless of the climate scenario and future period considered. Moreover, site-specific patterns can be important. The two assessments carried out used different data sources, and, yet, indicated a similar overall pattern where most East Anglian sites are at medium risk in terms of ecological flows. The ERFA method aims to identify a risk of impact on river ecology due to changes in hydrology and river flows. How this risk is translated in terms of actual impact may be complex. For example, for the same risk class, the impact of abstraction, which can change very fast and is directly controlled by human agents, may have very different consequences for river organisms than a slower change process, such as increased drought duration or occurrence, to which the ecosystems may start to adapt through time.

7. Messara River basin: projections of water stress conditions

Authors: Maggie Kossida, Fotis Fotopoulos, Ioannis Tsoukalas (SEVEN)

The Messara basin is located in the southern part of Crete, within the Regional Unit of Heraklion. It is the largest and most productive inland plain of the island, encompassing an area of approximately 600 km². The basin is characterized by a semi-arid Mediterranean climate, with long dry summers and mild, wet winters. Average annual precipitation ranges from 400 to 700 mm, decreasing from north to south, while evapotranspiration rates are high, particularly during the summer irrigation season. Rainfall is the primary source of groundwater recharge, either through direct infiltration in the central plain or indirectly via lateral inflows from the surrounding foothills and mountainous areas. Hydrologically, the region comprises both surface and groundwater systems. Surface water flow is ephemeral and generally confined to the winter months. Key surface water sub-catchments include the Geropotamos, Anapodaris, Litheos, and Plakiotissa. Three reservoirs, the Faneromeni dam, located in the northwest outside of the basin area, the small Gergeri reservoir, located in the foothills of Litheos basin, and the Damania reservoir, located in Plakiotissa sub-basin, support localized irrigation schemes but cover only a fraction of total demand.

The dominant land use in the basin is agriculture, representing 77% of the basin area. The main cultivated crops are olive groves (71% of the agricultural land), vineyards, and arable crops. Historically, the basin's water needs have been met predominantly through groundwater abstractions, with limited regulation or strategic allocation across competing uses. Over-abstraction from the region's main alluvial aquifer system, particularly in the central sub-basins corresponding to the Geropotamos and Anapodaris catchments, has led to a marked decline in groundwater levels, increasing pumping costs, and deterioration in water quality, including the presence of nitrates and other agrochemical contaminants. Surface water availability is constrained both seasonally and spatially, with small ephemeral streams and limited storage infrastructure, such as the Faneromeni and Gergeri reservoirs, playing a supplementary role.

In recent years, the need for sustainable water resource management in Messara has become increasingly urgent. Climate variability, recurrent droughts, and pressures from intensifying agricultural practices are exacerbating imbalances between supply and demand. In response, we developed a comprehensive water allocation model for the region using RIBASIM v.8 (River Basin Simulation Model), with a focus on representing the physical processes, demands, and management options at a disaggregated sub-basin level (9 general districts), and simulating what-if future scenarios (developed jointly with the stakeholders) to assess the future state of the basin and related risks.

7.1. Future scenarios of climate change

Climate change impacts in the Messara basin water budget were investigated as part of a wider study in Crete Island, which examined the impact of different climate scenario on the hydrological balance. The reference period used (baseline) was 1983-2009, and the scenarios looked at the future period 2060-2098. The following scenario assumptions were used:

- Temperature increase (from 16.1 degrees C in the baseline) by 0.7-3.1 degrees C, i.e. by 4% to 29%
- Reductions in rainfall by 4% to 29%
- Reductions in spring discharges (in the mainland) by 1.5% to 32%
- Reduction in the surface runoff by 2% to 38%
- Increase in irrigation water demand by 2.5% to 15%

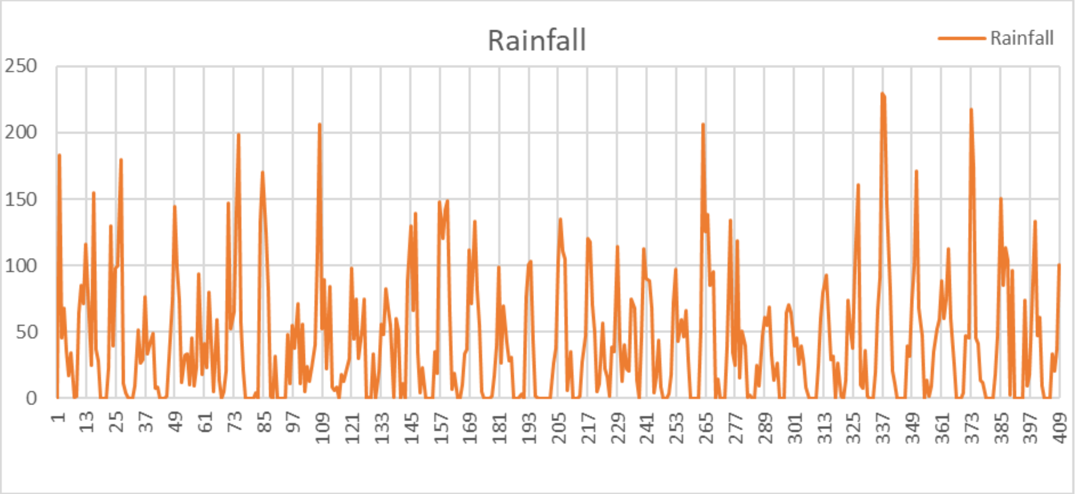
The most recent Regional Plan for Adaptation to Climate change in Crete (PESPKA), published in December 2021, simulated climate change conditions in Crete using EURO-CORDEX RCMs (CCLM4-8-17, HIRHAM5, RAMCO22, RCA4) downscaled for Crete, for the RCP 4.5 and RCP 8.5 scenarios. The reference (baseline) period was 1980-2000 and estimates of changes in meteorological parameters were simulated for the future periods 2021-2040, 2041-2060 and 2081-2100. The results obtained for some indicative parameters (average values) and for the two RCP scenarios are illustrated in Table 7.1.

Overall, the climate change report indicates that, for both groundwater and surface water, natural water resources availability is decreasing also due to climate change. Changing precipitation and evapotranspiration patterns drive changes in the spring outflows, with, consequently, impacts on the crop water needs, leading to increased water demands in the agricultural sector. The current water supply and infrastructure cannot meet the current water demands from the agriculture sector. It is clear that climate change is exacerbating this situation. It has already an impact on the Geropotamos and Anapodaris river flows, with a cascading negative effect on the recharge of groundwater aquifers.

Preliminary simulations with the RIBASIM model, with a 10% reduction in the annual rainfall (as depicted from the RCP4.5 and RCP8.5 for the next 15-35 years, resulted in a 20% increase of the water budget deficit in the Messara basin. Additionally, two what-if climate scenarios were developed and simulated in the RIBASIM model (for each of the 9 sub-basins of the Messara basin), as requested by the stakeholders: (i) a 34-year-long climate scenario with periods of 5 years of consecutive drought, and (ii) a 34-year-long climate scenario with periods of 7 years of consecutive drought. These scenarios are stochastic and based on the statistical properties of the historical time series of monthly rainfall and potential evapotranspiration. They are illustrated in Figure 7.1, for the rainfall time series.

Table 7.1: Climate change results for key parameters of the RCP4.5 and RCP8.5 scenarios for Messara (source: Region of Crete, Regional Plan for Adaptation to Climate change in Crete (PESPKA), December 2021).

Scenario	Parameter	2021 - 2040	2041 - 2060	2081 - 2100
RCP4.5	Increase in mean temperature	+1.33 °C ± 0.32	+1.71 °C ± 0.35	+2.41 °C ± 0.62
RCP4.5	Reduction in mean annual rainfall (mm/yr)	-71mm (or -9.2%)	-92mm (or -11.9%)	-114mm (or -16.0%)
RCP4.5	Increase in drought duration (consecutive days with rainfall < 1mm)	+10.1 days/yr	+10.1 days/yr	+14.1 days/yr
RCP8.5	Increase in mean temperature	+1.38 °C ± 0.49	+2.22 °C ± 0.38	+4.36 °C ± 0.63
RCP8.5	Reduction in mean annual rainfall (mm/yr)	-36mm (or -4.9%)	-88mm (or -12.8%)	-187mm (or -27.1%)
RCP8.5	Increase in drought duration (consecutive days with rainfall < 1mm)	+5.1 days/yr	+12.7 days/yr	+25.7 days/yr



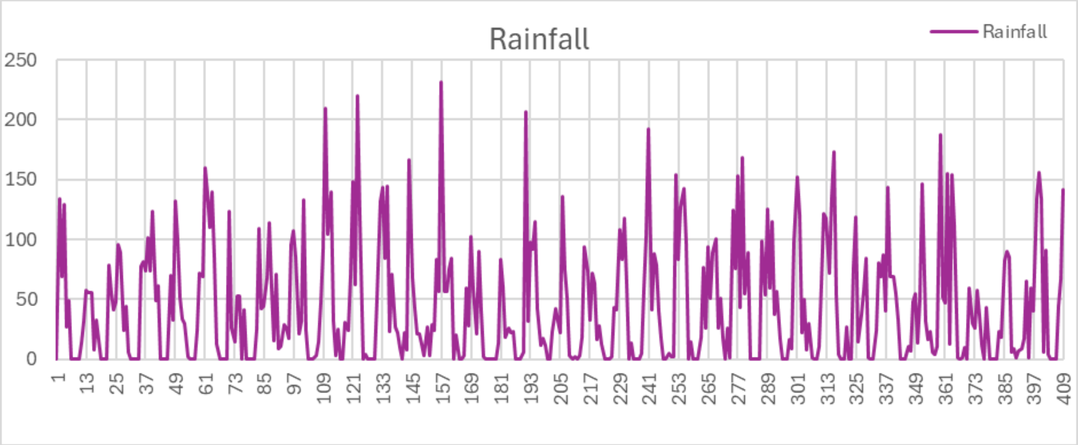


Figure 7.1: Stochastic monthly rainfall for 34 years, with periods of 5 years (top) and 7 years (bottom) of consecutive droughts, to be used in the what-if scenario analyses, as defined by stakeholders in the Messara.

7.2. Water management scenarios

The main source of water supply in the Messara basin is the groundwater stored in the underlying aquifer systems. Groundwater is exploited through a dense network of wells. Currently, there are 1,327 licensed agricultural wells that serve irrigation needs. The overexploitation of groundwater is a critical issue in the Messara basin. The recorded abstraction volumes systematically exceed the natural recharge rates, leading to a continuous decline in groundwater levels. In some locations, this has caused degradation in water quality due to salinization or increased concentrations of nitrates and other contaminants.

In terms of surface water supply and infrastructure, the Faneromeni Irrigation Dam (Figure 7.2), located in the adjacent Koutsoulidis basin to the east of Messara, is the most significant surface water infrastructure supporting the region. It has been operational since 2013 and plays a central role in alleviating water stress in the Moires sub-basin. The dam has a total storage capacity of 19 million cubic meters (Mm^3), with median annual runoff at the dam site estimated at 9.4 Mm^3. Historical records from 1987–1993 suggest an observed average inflow of 11.5 Mm^3, although current inflows are lower due to upstream abstractions, notably from the Zaros springs for municipal supply and bottling.

The dam currently supplies irrigation water based on a regional agreement that allocates a total of 8.5 Mm³ per year, conditional on available water resources. This supply supports both areas within and outside the Messara basin. Notably, Zones B and C (located within the study area) and Zone A (located in the adjacent region) receive partial coverage through the dam's network. Additionally, five surrounding irrigation schemes rely exclusively on Faneromeni reservoir water. For the TOEB-managed Zones B and C in Figure 7.1 (located within the Messara basin), the agreement provides about 0.7 Mm³ and 3 Mm³, respectively, covering roughly 43% of their irrigation demands (subject to prioritization due to over-dimensioned design and water constraints).

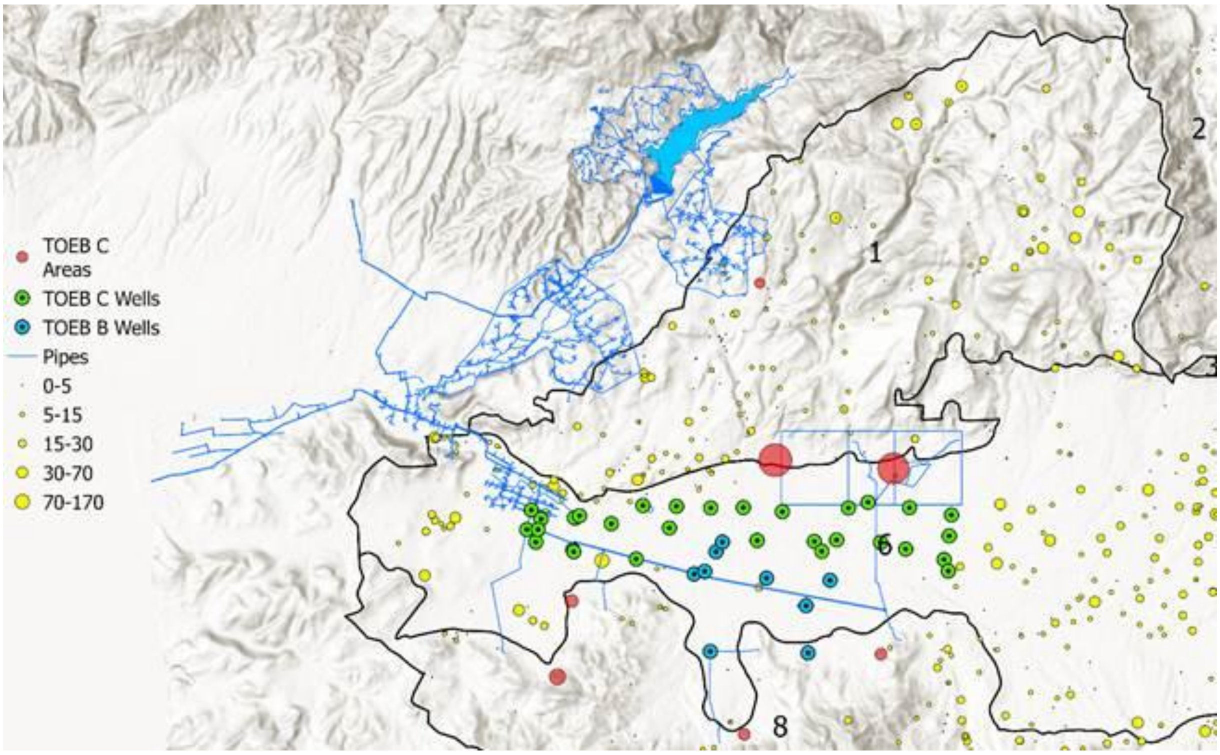


Figure 7.2: The Faneromeni Dam and associated irrigation infrastructure. The pipe network enables mixed groundwater and surface water supply, supporting water delivery and resource management across the area.

Three small-scale water storage projects have also been constructed within the study area. The Gergeri reservoir, located in the upper reaches of the Litheos basin, is supplied by the winter outflows of the homonymous springs. It has a storage capacity of 0.244 Mm³. The Damania and the Metaxochori reservoirs, situated in the upper reaches of the Anapodaris–Plakiotissa basin and upstream of the under-construction Plakiotissa dam, have storage capacities of 0.6 Mm³ and 0.5 Mm³, respectively.

There is an urgent need to reorient water management in Messara toward a more sustainable and adaptive model. Key priorities include improving irrigation efficiency, aligning crop selection with water availability, and investing in modernized conveyance systems to reduce distribution losses. Equally important are supply-side interventions, such as the development of small reservoirs, expansion of aquifer recharge schemes, and inter-basin transfers to enhance system resilience. Demand-side measures, including regulatory enforcement and awareness campaigns, must complement these efforts to achieve behavioural shifts in water use.

A particularly promising intervention is the transfer of surplus runoff from the Platis River into the Faneromeni Dam system (about 3 Mm^3 per year). This project, foreseen in the regional water resource plans, could significantly augment available surface water storage, reduce reliance on groundwater, and help stabilize the basin-wide water balance, particularly in the high-deficit zones of the plain. Preliminary RIBASIM analyses suggest that this measure, if effectively implemented and combined with local recharge and efficiency strategies, can form the backbone of a more integrated and sustainable water management framework for the region.

The future management scenarios for Messara were developed in alignment with the priorities of the Region of Crete Water Directorate and the STARS4Water co-design process carried out with the basin's stakeholders. They combine demand-side efficiency measures with supply-side augmentations to restore basin-scale balance and resilience. Three indicative strategy clusters were explored through the RIBASIM model:

1. **Reference or Business-as-Usual (BAU):** it is a continuation of current practices and existing infrastructure operations (Faneromeni, Gergeri, Damania dams), with no significant policy changes. This scenario shows continued groundwater depletion and increasing deficits in sub-basins 6 (Geropotamos) and 7 (Anapodaris).
2. **Enhanced Efficiency and Crop Adaptation (EECA)**: this scenario comprises the implementation of water-saving irrigation technologies (drip systems, regulated deficit irrigation), the modernization of conveyance networks, and a gradual shift from high-demand crops to drought-tolerant varieties. Crop adaptation in this scenario does not mean uprooting olive trees (physical constraints, economic and cultural lock-in). It means optimizing irrigation for olives and gradually diversifying peripheral agricultural areas toward low-input, drought-tolerant species (e.g., aromatics, carob). Also, it includes replacement of water-intensive crops in irrigated pockets (e.g., open-field vegetables, such as tomato and melon, to greenhouse or net-covered production, or vineyards shifted to earlier-maturing, less water-demanding varieties). This scenario achieves a 10–15% reduction in annual irrigation demand basin-wide.
3. **Increase Surface Water Supply (ISWS):** this scenario sees a full integration of new infrastructure projects, notably the Platis diversion–Faneromeni transfer (diversion of ~ 3 Mm^3 surplus runoff into the Faneromeni system), small-scale recharge ponds, and aquifer storage and recovery schemes. When combined with EECA measures, this scenario substantially improves summer storage, reduces pressure on the alluvial aquifer, and supports stable groundwater levels across the central plain.

Finally, we note that, across all strategies, governance and monitoring improvements, such as systematic licensing of private wells, real-time metering, and participatory water allocation, are essential to maintain system integrity and equitable resource use.

7.3. Water resources availability and risks

To support detailed evaluation of changes in water resources availability in the Messara basin, a disaggregated water resources model was developed in the RIBASIM v.8 modelling framework. The basin was divided into nine distinct sub-basins (Figure 7.3). This division reflects the underlying hydrogeological framework, surface drainage patterns, and dominant groundwater flow directions. Each sub-basin was delineated based on physiographic and geologic boundaries, aiming to group areas of homogeneous hydrogeological behaviour, recharge potential, and water management significance.

This sub-basin breakdown served as a foundation for attributing water demands, inflows, and management strategies within the modelling framework, enabling the detailed evaluation of the state of water resources availability and related risks. Sub-basins 6 and 7 (also in Figure 7.2) form the hydrogeological core of the Messara basin, encompassing the extensive alluvial aquifer that underpins the majority of irrigated agriculture in the region. These units exhibit high groundwater storage capacity and recharge potential due to the presence of permeable alluvial sediments. Sub-basin 6, which aligns with the Geropotamos River system, drains westward, while sub-basin 7 is aligned with the Anapodaris River, flowing eastward. Both sub-basins are characterized by intense agricultural activity and are central to water allocation and management concerns.

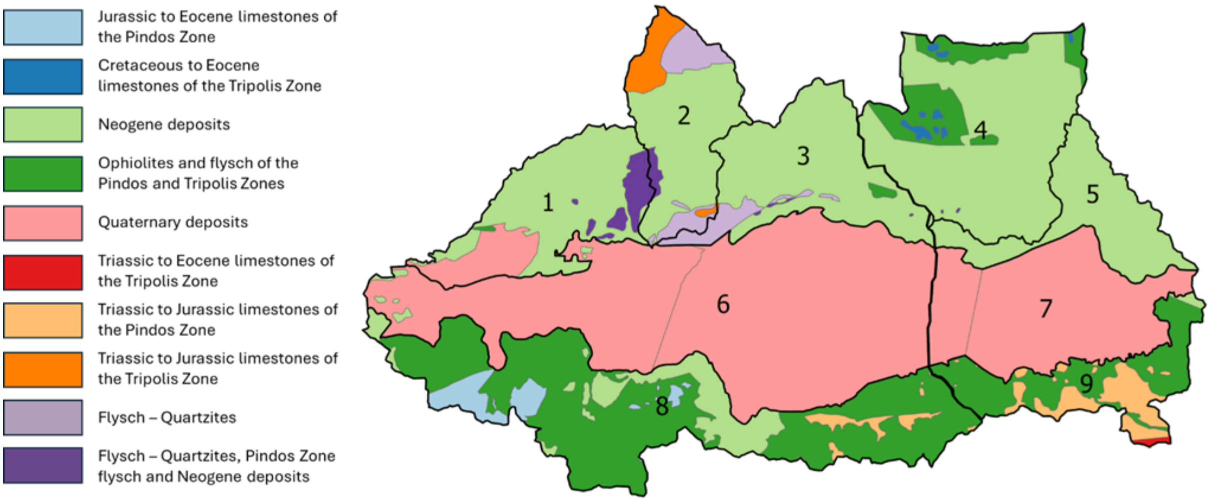


Figure 7.3: Delineation of the nine sub-basins within the Messara basin, based on hydrogeological and surface drainage characteristics. Sub-basins 6 (Geropotamos) and 7 (Anapodaris-Harakas) form the central alluvial aquifer system with high recharge and storage capacity. Sub-basins 1, 2, 3, and 8 contribute to the recharge of Sub-basin 6, while Sub-basins 4, 5, and 9 drain toward Sub-basin 7. The delineation supports the conceptual schematization and spatial parameterization of the RIBASIM model and allows for the detailed assessment of the state of water resources availability and related risks.

The total annual irrigation demand in the Messara basin is estimated at 72 Mm^{3,} with the highest ones observed in sub-basin 6 (42 Mm^3/year) and sub-basin 7 (15 Mm^3/year) (Figure 7.4). Table 7.2 presents the annual water balance in the Messara per sub-basin for the total simulation (reference) period 1989-2022, including supply and demand components, obtained by using the RIBASIM model.

The simulation results reveal distinct spatial patterns in the annual water budget across the sub-basins, highlighting areas of sustained surplus and others with escalating deficits. Sub-basins 1, 2, 3, 4, and 9 exhibit a positive water budget over the full simulation period, indicating that, despite water stress conditions, the available supply (including groundwater, external sources, and return flows) exceeds the total water demand for irrigation, domestic, and industrial uses (Figure 7.5). In contrast, sub-basins 5, 6, 7, and 8 show a persistent water deficit, with sub-basins 6 and 7 emerging as critical hotspots where annual supply falls significantly short of demand, by 11.14 and 5.27 Mm^3, respectively (Figure 7.6).

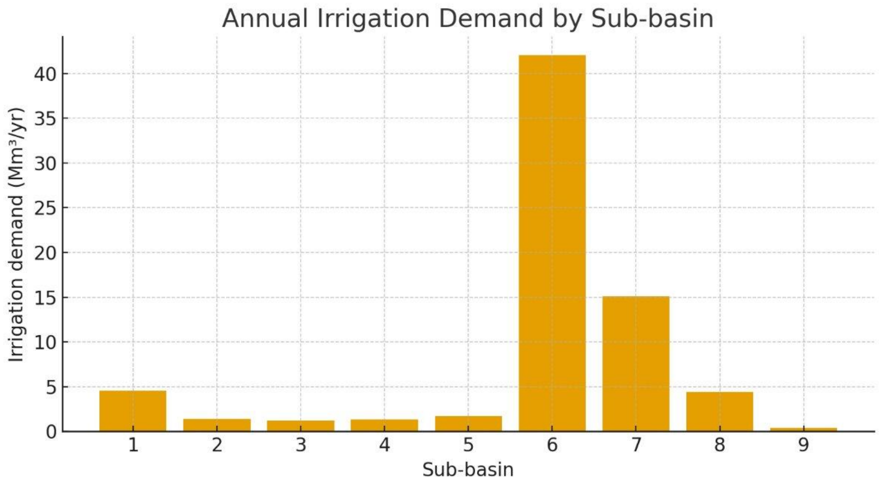


Figure 7.4: Annual irrigation demand by sub-basin in the Messara.

Table 7.2: Annual water budget components in the Messara per sub-basin, by using the RIBASIM model for the total simulation period 1989-2022. Budget is calculated as total supply minus total demand.

	Total Simulation Period: 1989-2022								
Sub-basin	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Supply to GD (Irrigation) (Mm^3)	3.98	0.90	1.00	1.15	0.80	27.46	10.41	3.07	0.41
Supply to PWS (Mm^3)	0.33	0.15	0.08	0.09	0.17	1.17	0.14	0.40	0.00
Excess water to GWR (Mm^3)	1.31	5.48	4.47	3.07	0.14	5.10	0.17	0.14	0.62
Supply total (Mm^3)	**5.62**	**6.53**	**5.55**	**4.31**	**1.11**	**33.73**	**10.72**	**3.61**	**1.03**
Irrigation Demand (Mm^3)	4.51	1.17	1.16	1.30	1.85	43.54	15.84	4.94	0.41
Domestic and Industrial Demand (Mm^3)	0.33	0.15	0.08	0.09	0.21	1.33	0.15	0.48	0.01
Demand Total (Mm^3)	**4.84**	**1.32**	**1.24**	**1.39**	**2.06**	**44.87**	**15.99**	**5.42**	**0.42**
Budget (Mm^3)	**0.78**	**5.21**	**4.31**	**2.92**	**-0.95**	**-11.14**	**-5.27**	**-1.81**	**0.61**

Notably, sub-basin 6, which already exhibited overexploitation tendencies in earlier periods, now shows an amplified deficit, underscoring the unsustainable abstraction pressure on local resources. This sub-basin serves the most extensive irrigated areas of 14,939 ha, of which the 1,727 ha are supplied by the Faneromeni dam, while the sub-basin 7 also serves wide irrigated areas of 5,196 ha; yet these are not satisfied by the existing water resources, since the annual water budget is considerably negative for the period 1989-2022, equal to -11.14 Mm^3 and -5.27 Mm^3, respectively. In addition, the sub-basin 5 supplies irrigated areas of 605 ha, and the sub-basin 8 serves irrigated areas of 1,830 ha, of which the 196 ha are supplied by the Faneromeni dam. The sub-basins 5 and 8 also exhibit a noteworthy negative annual water budget for the simulation period (1989-2022), equal to, respectively, -0.95 Mm^3 and -1.81 Mm^3.

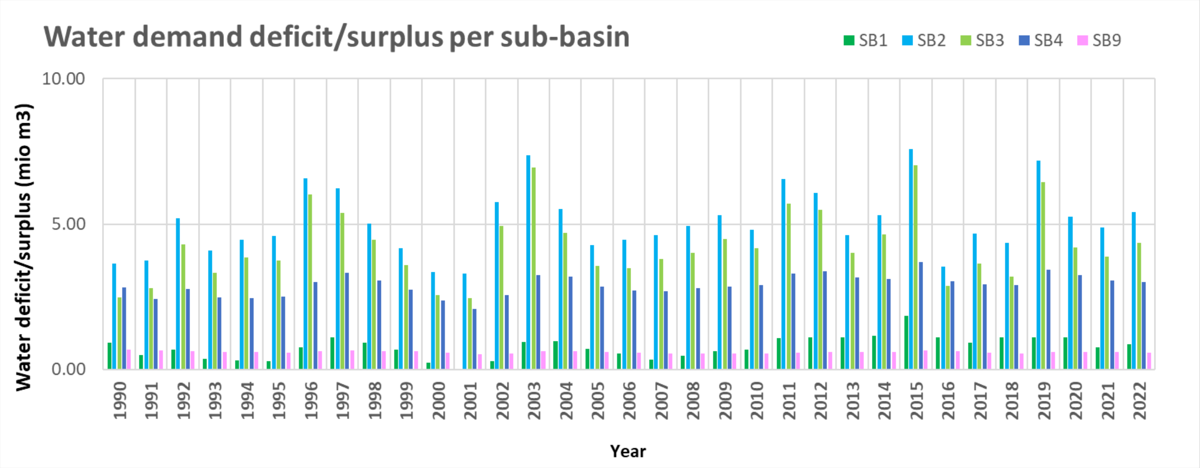


Figure 7.5: Annual water demand surplus (positive values) in the sub-basins (SB) 1, 2, 3, 4 and 9 of the Messara River basin for the period 1989–2022.

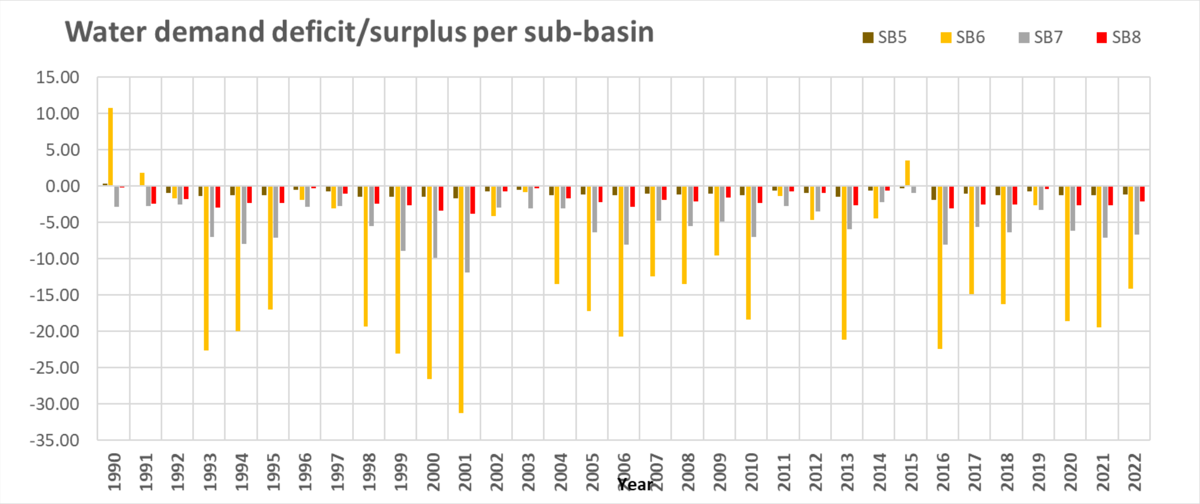


Figure 7.6: Annual water demand deficits (negative values) in the sub-basins 5, 6, 7 and 8 of the Messara River basin for the period 1989–2022.

The sub-basins 1, 2, 3, 4 and 9 serve also considerable irrigated areas, of extent equal to 1,668 ha, 506 ha, 442 ha, 543 ha and 188 ha, respectively, of which the sub-basins 1, 2 and 4 are also supplied by the Faneromeni dam, the Gergeri reservoir and the Damania reservoir, respectively, specifically its corresponding areas of 503 ha, 363 ha and 240 ha. The irrigation requirements of the sub-basins 1, 2, 3, 4 and 9 are satisfied enough since the annual water budget for the simulation period is positive, equal to 0.78 Mm^3, 5.21 Mm^3, 4.31 Mm^3, 2.92 Mm^3 and 0.61 Mm^3, respectively.

From the water management perspective, several sub-basins of the Messara River basin are therefore under severe stress as water consumption is at high levels when compared to water resources availability, as seen by the annual water deficits computed for the period 1989–2022. In several sub-basins, this puts high stress on the groundwater resources. For the evaluation of the safe operating space framework in the Messara River basin, we will thus consider an indicator of the reliability of the system in supplying the requested water demand among the water uses. Reliability is defined as the percent of time in which the demand of a site was fully satisfied. For example, if a demand site has unmet demands (deficit) in 6 years out of a 10-year scenario, the reliability would be (10-6) / 10 = 40%.

Water supply reliability for irrigation was first evaluated for the reference historic period 1989–2022. Table 7.3 summarizes the water supply reliability for irrigation in the nine sub-basins of the Messara. It provides also their classification under different reliability classes, defined as very high (>95%), high (80-95%), medium (60-80%), low (40-60%), and very low (<40%). It can be seen that, out of the 45,872 ha of total agricultural land in the Messara basin, a total of 26,797 ha (i.e., 58% of the agricultural area) faces water deficit almost every year, and display irrigation water supply reliability that is very low (0% to 9%). In the sub-basin 6, the deficit is more than 10 Mm^3/year in 52% of the years of the period 1990-2022. In the sub-basin 7, it is more than 5 Mm^3/year in 52% of the years of the historic reference period.

Table 7.3: Water supply reliability for irrigation and classification (right column) for each sub-basin (1 to 9) in the Messara for the period 1989-2022. Reliability is defined as the percent of time in which the demand of a site was fully satisfied. The agricultural area of each sub-basin is also indicated (in ha). In red, sub-basins falling within the 'very low' reliability class.

Sub-basin	Agricultural Area (ha)	Water supply reliability (%)	Reliability class
1	4,405	97%	Very High (>95%)
2	2,910	100%	Very High (>95%)
3	4,480	100%	Very High (>95%)
4	6,778	100%	Very High (>95%)
5	2,937	3%	Very Low (<40%)
6	14,939	9%	Very Low (<40%)
7	5,615	0%	Very Low (<40%)
8	3,306	3%	Very Low (<40%)
9	502	100%	Very High (>95%)

In the Messara River basin, it is expected that water supply reliability for irrigation will be affected in the future by climate change. Climate projections for Crete indicate a substantial rise in mean annual temperature of +1.5 to +3.0°C by mid-century under RCP4.5, with further increases toward the end of the century. Annual precipitation is projected to decline by 10–16%, with rainfall becoming more erratic and concentrated in fewer, high-intensity events. Evapotranspiration rates are expected to rise, lengthening the dry season and reducing effective groundwater recharge. For the Messara basin, this implies lower aquifer replenishment, increased irrigation demand, and heightened risk of seasonal water deficits. The frequency of multi-year droughts, similar to 1990–1993 or 2016–2018, is projected to increase. These changes threaten the sustainability of the alluvial aquifer system that underpins most agricultural activity in the plain. It is expected that this will exacerbate the existing structural imbalance between groundwater abstraction and recharge, identified in the baseline RIBASIM simulations (1989–2022).

To evaluate future impacts on reliability, we considered that expected changes in climate variables, by evaluating future scenarios of consecutive drought years. Table 7.4 shows the water supply budget per sub-basin in the Messara basin, under future climate scenarios of more prolonged drought periods (i.e., 5 and 7 consecutive dry years; Figure 7.1). It can be observed that the water supply reliability of the system deteriorates. Namely, sub-basin 1 falls under the "medium reliability" class as opposed to the previous "very high" reliability class it was in when analysing the baseline (Table 7.3). In the sub-basin 6, the deficit is more than 10 Mm^3/year in 67% of the years of the 33-year period. In the sub-basin 7, the deficit of more than 5 Mm^3/year is observed in 76% of the years.

Table 7.4: Water supply budget per sub-basin in the Messara for the baseline scenario (1989-2022) and under future climate scenarios of more prolonged drought periods of 5 and 7 consecutive dry years.

Scenario	**Messara sub-basins**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Reference 1989-2022	0.78	5.21	4.31	2.92	-0.95	-11.14	-5.27	-1.81	0.61
Climate scenario (5-yrs consecutive drought)	0.53	4.90	4.00	2.78	-0.98	-12.76	-5.72	-1.99	0.57
Climate scenario (7-yrs consecutive drought)	0.36	4.74	3.86	2.65	-1.04	-13.63	-6.14	-2.10	0.53

7.4. Lessons learnt and perspectives

The persistent deficits in several sub-basins in the Messara, particularly in sub-basins 6 and 7, underscore the need for urgent and coordinated water management interventions. Seasonal mismatches between supply and demand further exacerbate pressures on groundwater systems, particularly during the summer irrigation peak. Key recommendations are:

- enhancing irrigation efficiency and demand-side measures by promoting the adoption of water-saving technologies (e.g. drip irrigation, soil moisture monitoring) and by incentivizing scheduling practices aligned with actual crop needs;
- expanding and optimizing surface water infrastructure by prioritizing the development of new reservoirs (e.g., Plakiotissa) and inter-basin transfer systems to increase supply reliability and reduce dependence on groundwater. Moreover, the planned diversion of surplus flows from the Platis River to the Faneromeni Reservoir, as part of the regional water masterplan, offers significant added value. It would substantially enhance the capacity of Faneromeni Dam to meet irrigation demands in the main deficit zones (TOEB B and C), particularly during dry years or under future climate change scenarios;
- implementing managed aquifer recharge in targeted recharge zones using seasonal floodwaters or treated wastewater can help stabilize groundwater levels, especially in sub-basins 6 and 7;
- strengthening water governance and monitoring, by establishing transparent and flexible allocation rules (especially for Faneromeni reservoir), enforcing abstraction limits, and enhancing monitoring of both licensed and informal groundwater use; and
- promoting awareness and behavioural change by engaging local stakeholders, including farmers and municipalities, through training and outreach campaigns that emphasize the risks of over-abstraction and the benefits of sustainable water use.

These actions, integrated into a basin-wide management framework, are essential to ensure long-term water security in the Messara region under increasing climatic and socio-economic pressures. The Messara experience also illustrates the critical role of integrated modelling and stakeholder dialogue in diagnosing and addressing groundwater overexploitation in semi-arid Mediterranean systems:

- Localized over-abstraction hotspots must be managed through targeted restrictions and recharge interventions rather than uniform basin-wide quotas.

- Infrastructure–policy coupling (e.g., Platis–Faneromeni transfer, combined with irrigation modernization) yields the most effective outcomes for restoring a safe operating space.
- Climate adaptation requires data transparency and monitoring, as continuous observation of groundwater levels and abstraction volumes is indispensable for adaptive management.
- Stakeholder engagement, including farmers' acceptance of efficiency measures, depends on clear communication of benefits and reliable alternative supplies.

8. Rhine River basin: river flow projections and risks

Authors: Ümit Taner, Devi Purnamasari, Judith ter Maat (Deltares).

The Rhine River basin is one of Europe's largest and most economically significant river systems, extending across nine countries and draining an area of about 185,000 km². It is characterized by a temperate climate, with precipitation patterns varying substantially by altitude and latitude, ranging from over 2,000 mm/year in headwaters, around 700 – 900 mm/year in maritime downstream lowland areas in the Netherlands, and only 500 mm/year in the rain shadow of the low mountain ranges. The river regime is shaped by snowmelt, glacier contributions, and year-round rainfall, resulting in in the southern catchment area with high runoff in early summer and low runoff in winter, whereas in the northern catchment area, maximum runoff is generally to be expected in late winter and minimum runoff in autumn. Major tributaries of the Rhine River include Aare, Neckar, Main, Moselle (Mosel), and Ruhr.

Figure 8.1 shows an overview of the Rhine River basin, highlighting its main sub-basins for water availability analysis, co-defined with stakeholders, and the location of discharge stations used for inland navigation and ecological flow risk analyses. The Rhine River basin is heavily industrialized and densely populated because of its long history of settlement and development. Main water uses include agriculture, water supply, hydropower, inland navigation and environmental functions. Agriculture is significant in lowland areas (Germany, France, Netherlands) and relies on both surface water and groundwater, with irrigation demands increasing during warm and dry summers.

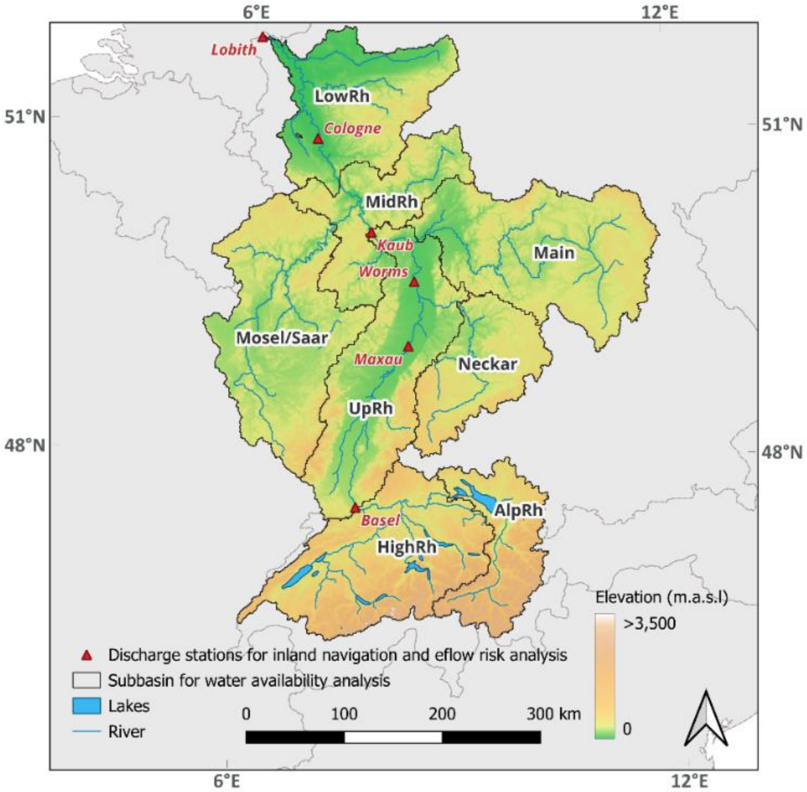


Figure 8.1: Overview of the Rhine River basin, showing its main sub-basins for water availability analysis and the location of discharge stations for inland navigation and ecological flow risk analyses.

In recent years, low-flow conditions have occurred more frequently, which led to increasing pressure on water demand and inland navigation. Irrigation water demand has also risen in areas stretching from the south to the north along the French German border. Further downstream in the Middle Rhine, stakeholders identified the inland-navigation bottleneck at Kaub as particularly critical. The Kaub gauge is representative of the Rhine reach between Mainz and St. Goar, which forms the shallowest navigable section, with a guaranteed channel depth of 1.90 m for 345 days per year. Consequently, vessel loading capacity in this reach is highly sensitive to low-flow conditions.

Within the STARS4Water project, we explored the future hydrological changes in the Rhine River basin and the impacts on sectors through the assessing the Safe Operating Space (SOS) of the Rhine River to inform management decisions and includes impacts on navigation, environmental flows and water use by agriculture, industries and domestic sector. The climate risk analysis begins with a climate stress test experiment on daily discharges, and on reduced summer low flows. Hydrological changes are then translated into key metrics specified for each sector based on stakeholder's guidance. Finally, we summarize the risks in association with IPCC's Shared Socioeconomic Pathways (SSP) scenarios and present findings at the river basin level and key locations and sub-basins (IPCC, 2021). While this work focuses on current water policies and existing infrastructure, the identified risks highlight the needs and opportunities for new management interventions.

8.1. Future scenarios of climate change

Figure 8.2 shows the Coupled Model Intercomparison Project Phase 6 (CMIP6) projections for the Rhine River basin relative to the baseline (1990-2020). It shows annual precipitation anomalies (in mm), annual temperature anomalies (in °C), and annual changes for the years 2050 and 2080. The projections show a wide range of uncertainty, especially towards the late century (2080). Mean temperatures are projected to increase up to 4°C by 2050 and 6°C by 2080, depending on the scenario considered, and relative to 1990-2020 baseline averages. Precipitation changes are far more uncertain, with model results ranging from ±20%, hence with no clear agreement on whether conditions will be wetter or drier. As temperatures rise and rainfall becomes more variable, river discharge patterns are projected to shift, affecting water availability and low flows.

8.2. Future water resources scenarios

Based on plausible climate uncertainty derived from the CMIP6 ensemble, we conducted a climate stress-testing experiment on daily river flows representing future conditions centred on 2050 (2035–2065) and 2080 (2065–2095). The stress test consists of three steps. First, we generated 125 synthetic climate scenarios for the Rhine River basin, informed by IPCC CMIP6 projections. These scenarios were produced using a stochastic weather generator that reproduces historical climate patterns and statistics in both time and space, while capturing long-term natural variability and projected shifts in climate statistics. Second, each synthetic climate scenario was propagated through a distributed hydrological model to simulate daily river discharge. Finally, navigation, environmental flow, and water-demand indicators were derived from the simulated discharge series to assess sector-specific risks based on stakeholder's input.

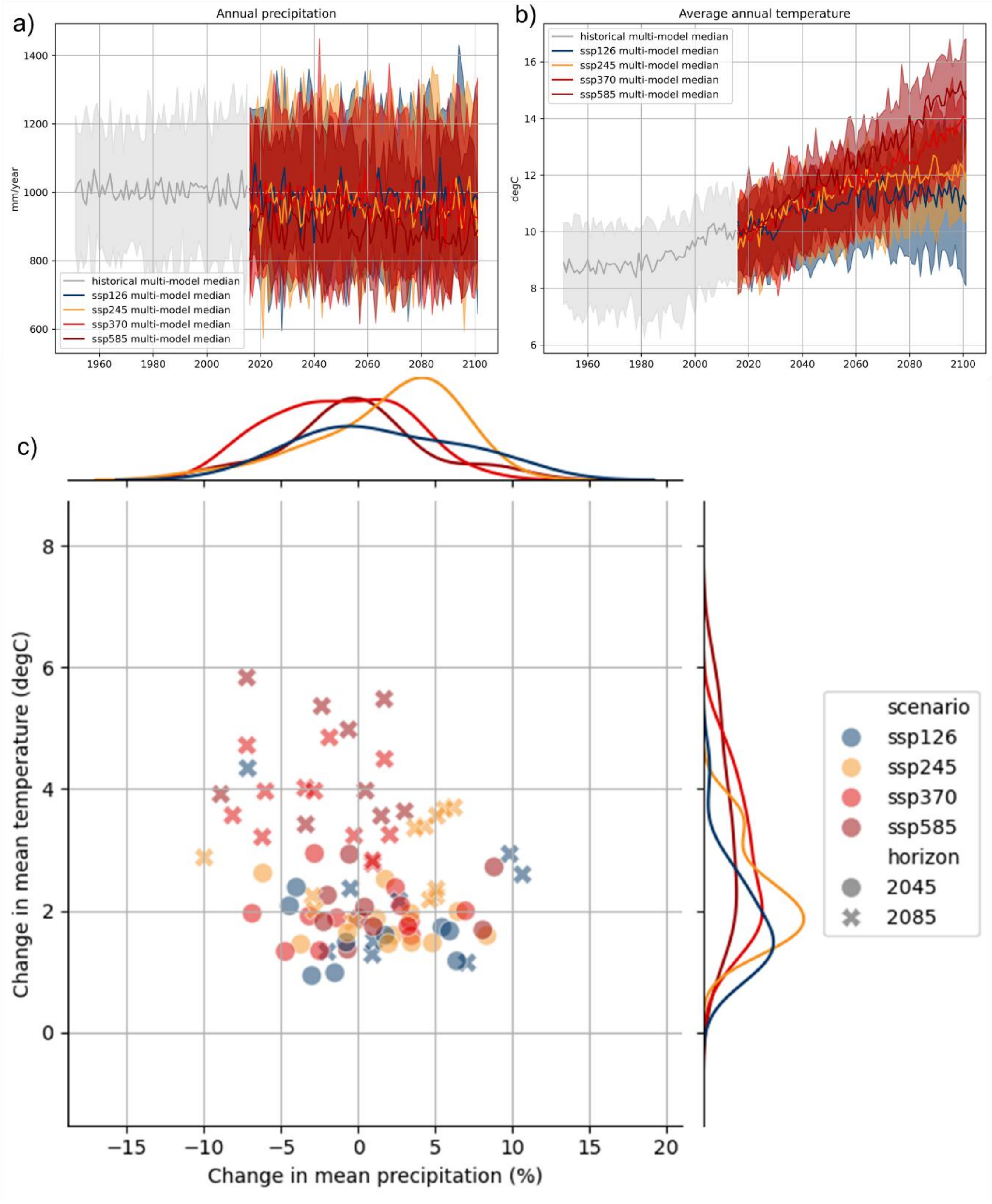


Figure 8.2: CMIP6 climate projections for the Rhine River basin relative to the baseline period (1990–2020). Panels (a) and (b) show time series of annual precipitation and annual mean temperature from the multi-model ensemble (median and spread) for historical conditions and future SSP scenarios. Panel (c) shows joint changes in mean annual precipitation (%) and mean annual temperature (°C) averaged over 30-year future periods centred on 2050 (mid-century) and 2080 (late-century). The marginal curves along the top and right axes represent kernel density estimates of the corresponding precipitation and temperature changes across the CMIP6 ensemble, shown separately for each model and scenario pair for 2050.

Hydrological modelling and analysis: the synthetic climate scenarios were translated into daily river discharge using a wflow_sbm application, which consists of a spatially distributed hydrological model, previously developed for the Rhine River basin, with a spatial resolution of approximately 0.0083°. The model includes key human influences on the system, such as water withdrawals, gross water demand, and consumptive use, as these factors affect the hydrological processes that shape river flows. The simulated discharge series are used to calculate sector-specific performance indicators. For navigation and eflows, we focused on six main locations along the Rhine, from upstream to downstream: Basel (CH), Maxau (DE), Worms (DE), Kaub (DE), Cologne (DE), and Lobith (NL). For water-availability assessments, we summarised results at the sub-catchment scale.

Navigation: navigability in the Rhine River basin is assessed using the GIW (Equivalent Water Level) indicator[9]. GIW can be translated into an equivalent discharge metric, GIQ, which is statistically defined as the average discharge (m³/s) that is reached or exceeded on no more than 20 ice-free days per year. GIW represents the water-level counterpart of this discharge-based threshold and is expressed in centimetres. For the implementation of the SOS framework, a GIQ-based indicator was adopted and defined as the average number of days per year with discharge below the GIQ threshold. This approach was chosen because GIW requires explicit simulation of channel water levels and depths, whereas GIQ can be computed directly from daily discharge time series. Navigation risk levels were classified as follows: no risk (< 20 days below GIQ), low risk (20–30 days), medium risk (30–40 days), and high risk (> 40 days).[10,11]

Environmental flows: assessing aquatic ecosystem health typically requires biological, chemical, and hydro-morphological data. In this study, however, we applied a rapid, basin-scale screening of flow-related risks along the main stem of the Rhine River using the ERFA approach. ERFA evaluates 70 Indicators of Hydrological Alteration (IHA) covering flow magnitude, frequency, duration, and timing (see Rickards et al., 2024, for details). Although critical for aquatic ecosystems, groundwater influences, water quality, and water temperature were not considered and remain outside the scope of this analysis. Results were summarised both as an overall ERFA score and by flow-type groups: High Flows (HF; peak and flood-related discharges), Monthly Flows (MF; mean monthly conditions), Low Flows (LF; drought and minimum-flow conditions), Rate of Flow Change (RFC; frequency and speed of rising and falling flows), and Intermittent Flows (IF; occurrence and duration of zero or near-zero flows). This grouping allows us to identify which flow regimes are most affected by climate change and where reductions in critical flow conditions may adversely affect aquatic and riparian flora and fauna. For risk classification, a 20% deviation threshold was applied to identify significant changes between the historical baseline and each future scenario, following consultation with the International Commission for the Protection of the Rhine (ICPR). Based on the ERFA framework, four risk levels—no, low, medium, and high—were defined according to the number of indicators exceeding the threshold.

Water availability: water availability risk was assessed based on the total unmet water demand due to low water availability across all sectors: livestock, irrigation, domestic, and industrial water for eight sub-basins of the Rhine (Figure 8.1). Water demand is supplied by both groundwater and surface water with several assumptions of allocation rules depending of available water for abstraction (van

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[9] https://www.weseranpassung.wsv.de/Webs/Projektseite/Mittelrheinoptimierung/DE/02_Unterseiten/6_FrueheOEA/2_FOEB/5_FAQ_TA2/FAQ_node.html

[10] This analysis considers only the number of days with discharge below the GIQ threshold and does not account for the severity of low flow conditions. As the latter imposes stronger constraints on inland navigation, future studies are advised to incorporate the severity aspect.

[11] These thresholds were defined through internal expert judgment and stakeholder consultations and do not represent formal policy or regulatory standards.

Verseveld et al., 2025). In case of insufficient water, available water is distributed among sectors based on their proportion of the total water demand. The future risk is represented as a water deficit, defined as the percentage of unmet demand relative to the total water demand. This calculation was performed for each season of the year: winter (DJF), spring (MAM), summer (JJA), and fall (SON). Based on the analysis, we classified the results into four varying risk level: low (<5%), moderate (5-10%), high (10-15%, and very high (>15%).

8.3. Emerging risks related to changes in river flow conditions

This section presents the results of the implementation of the safe operating space framework for risk assessment for navigation, environmental flows and water availability in the Rhine River basin.

Risks for navigation

Navigation risks were assessed using our GIQ-based metric defined earlier. Figure 8.3 shows a climate response surface for Kaub, illustrating how navigation risk (contour lines) changes under different levels of precipitation changes (x-axis) and temperature changes (y-axis). The pattern in the figure shows that changes in precipitation have the strongest influence on navigation risk, i.e., lower precipitation leads to higher risk. Temperature changes (y-axis) also matter, but the effect is smaller. Most CMIP6 scenarios (shown with different shapes overlayed on the response surface) fall under no risk (green colour) to low-risk (yellow colour) level for the year 2050.

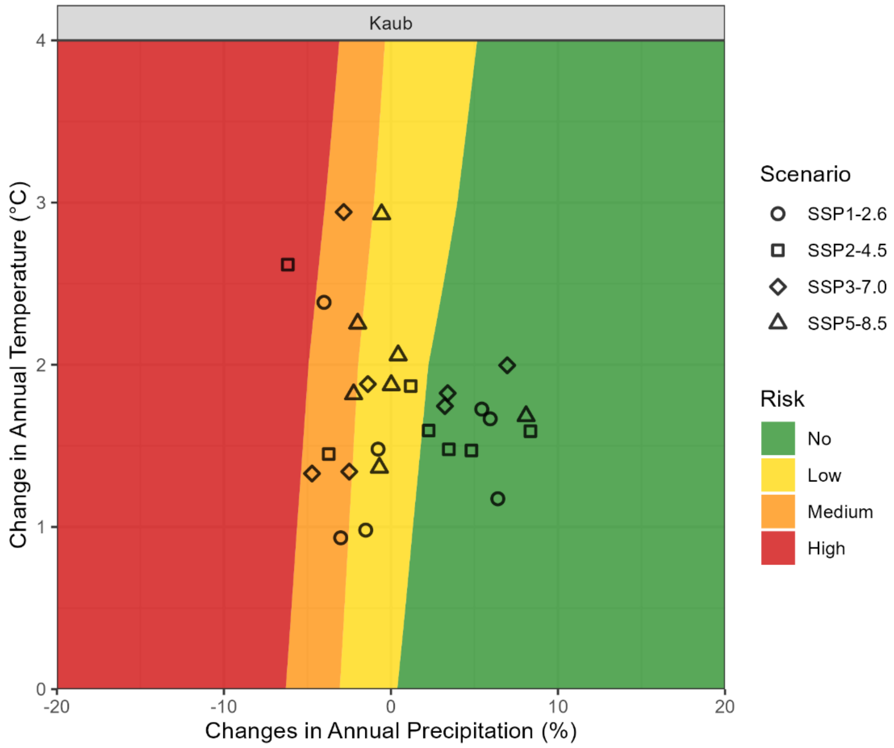


Figure 8.3: Climate response surface showing navigation risk at Kaub under different changes in annual precipitation (%) and temperature (°C). The coloured zones represent the four risk levels. The shapes show individual CMIP6 projections for the year 2050 plotted on the surface.

Figure 8.4 depicts the results across all six Rhine locations for both the target years of 2050 and 2080. Across the basin, most locations show no or low risk in 2050, but the risk increases to medium levels by 2080, especially under more higher emission scenarios. The upstream site Basel consistently shows the lowest risk, while the downstream location Lobith shows the highest risk in all scenarios.

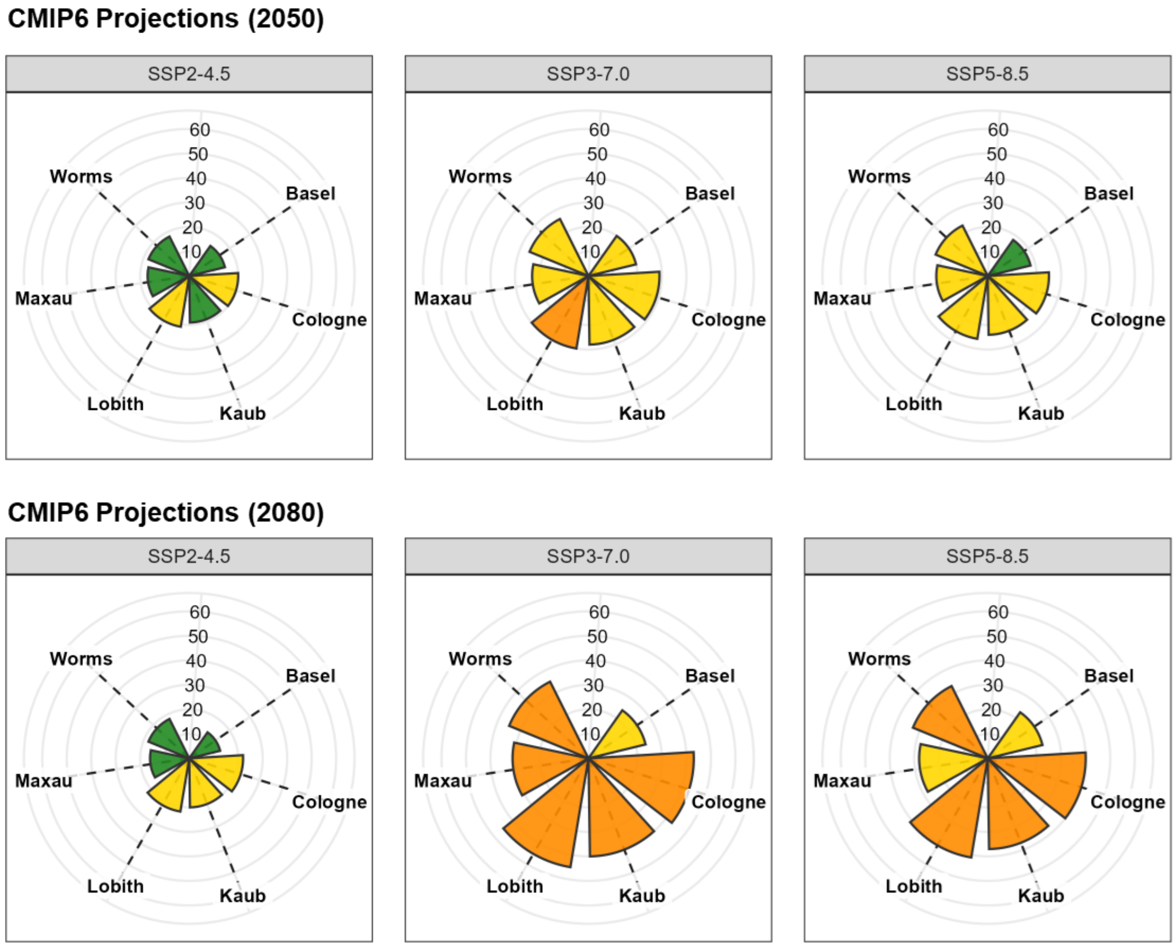


Figure 8.4: Radial charts showing navigation risk based on the CMIP6 ensemble mean for the selected SSP scenarios for 2050 and 2080. Each bar represents the average number of days per year during which discharge falls below the GIQ threshold at six Rhine locations: Basel, Cologne, Kaub, Lobith, Maxau, and Worms. Colours indicate navigation risk levels: green = no risk (< 20 days), yellow = low risk (20–25 days), orange = medium risk (25–30 days), and red = high risk (> 30 days).

Risks for environmental flows (eflows)

Figure 8.5 shows the estimated eflow risk levels at Kaub, which stakeholders identified as a hotspot for low-flow conditions. Using the ERFA indicators, we can see very low or no risk across all flow type groups in the 2050 future, and only slight increases in risk by 2080 (shown in yellow). The highest emissions scenario (SSP5-8.5) shows more risks in 2080 compared with the other scenarios. We also notice that Low Flows (LF) tend to have higher risk than the other flow groups, which highlights the higher sensitivity of low flows to future climate change and, consequently, also the ecological problems that would occur during low flow events.

Figure 8.6 compares the overall eflow risk levels at the six analysis locations along the Rhine River for the SSP3-7.0 scenario. Based on our analysis, all six locations show low risk level for the year (2050), and all except Basel for the year 2080.

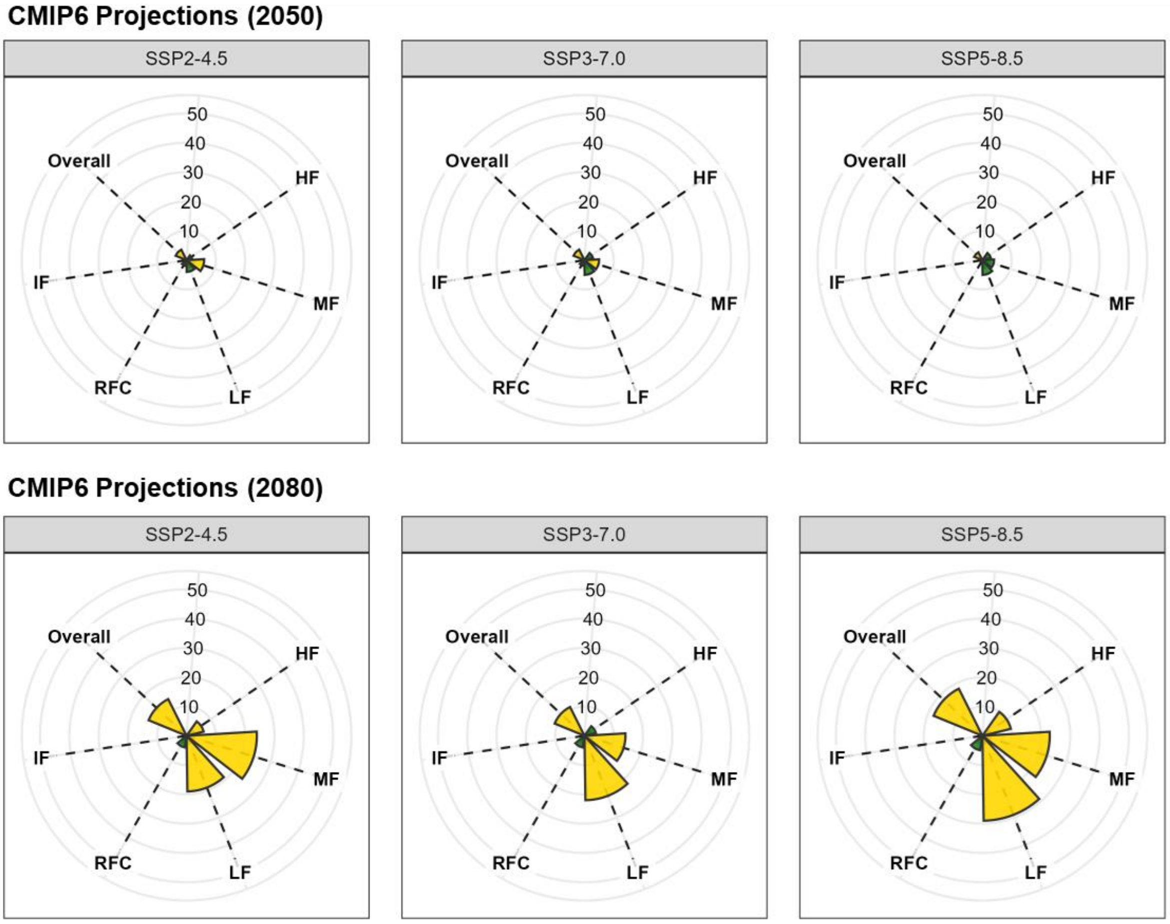
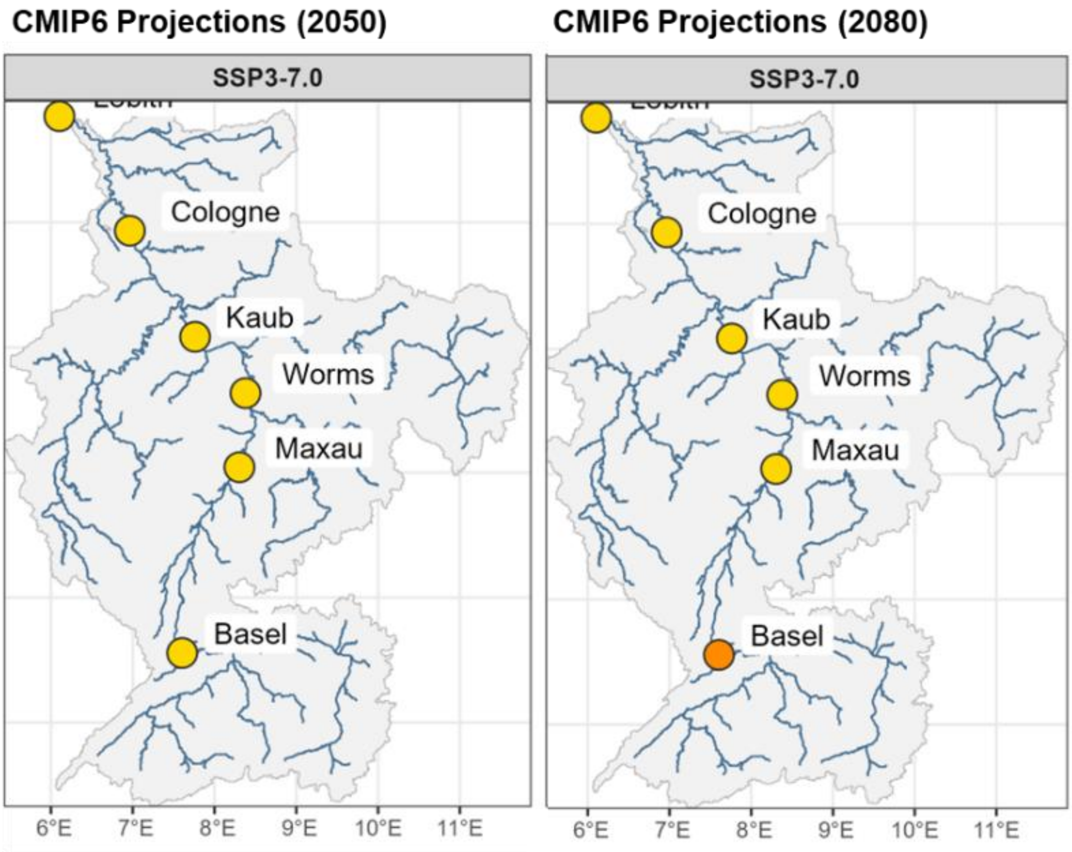


Figure 8.5: Radial charts showing risks for environmental flows (eflows) at Kaub for the selected SSP scenarios (2050 and 2080). Bars show average risk for flow-type groups: High Flows (HF), Monthly Flows (MF), Low Flows (LF), Rate of Flow Change (RFC), and Intermittent Flows (IF). Colours indicate the risk level: green = no risk, yellow = low risk, orange = medium risk, and red = high risk.


CMIP6 Projections (2050)

CMIP6 Projections (2080)

Figure 8.6: Overall eflow risk at six analysis locations along the Rhine River under SSP3-7.0 scenario for (2050 and 2080). Colours indicate the risk level: green = no risk, yellow = low risk, orange = medium risk, and red = high risk.

Risks related to water availability

Figure 8.6 depicts the results for the water availability by sector using the same approach applied for navigation and environmental flows. In this case, the results are presented at the sub-basin scale: Alpine Rhine (AlpRh), High Rhine (HighRh), Upper Rhine (UpRh), Mosel/Saar, Neckar, Main, Middle Rhine (MidRh), and Lower Rhine (LowRh). At the current level of water demand, all subbasins will experience a water deficit of more than 10% relative to the current demand in all seasons during the period 2030–2050. Elevated water deficit is much higher in fall (SON) for all subbasins except in the Alpine Rhine and High Rhine. This is likely due to lower precipitation, higher evapotranspiration, higher water demand in non-Alpine regions. The increased risk of water deficit propagates downstream that leads to the Middle Rhine and Lower Rhine experiencing water deficits exceeding 15% (very high) from the current level of water demand.

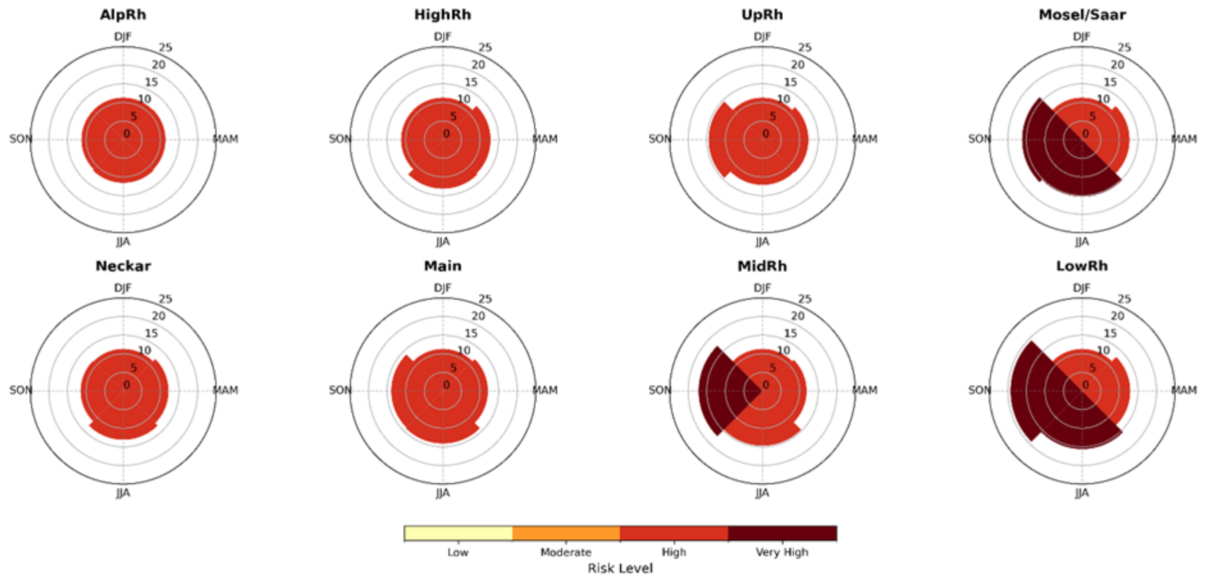


Figure 8.7: Average ensemble risk level of water availability due to changes in temperature and precipitation for the eight subbasins of the Rhine. The radial interval represents 5%.

8.4. Lessons learnt and perspectives

The Rhine River basin risk assessment helps decision makers understand how its safe operating space might shift under climate change for navigation, environmental flows, and water availability. These insights can support planning and guide future strategies for both water management and infrastructure. The results indicate low risk for navigation and environmental flows around 2050, increasing to low to moderate risk by 2080 across the CMIP6 ensemble. However, two factors strongly influence these outcomes. First, climate-related risks are spatially heterogeneous within the basin. Downstream locations such as Kaub and Maxau exhibit substantially larger alterations relative to baseline conditions than upstream stations such as Basel. Second, reliance on long-term mean indicators alone can be misleading in a basin characterised by strong interannual variability. While long-term averages suggest moderate impacts, our simulation study showed individual years with more than 80 days below the navigation (GIQ) threshold, indicating that extreme low flow years are masked by multi-year averaging. Taken together, the findings suggest that the Rhine River basin may face increasing challenges later in the century, with a growing likelihood of operating outside its current safe operating space. These results should be interpreted as preliminary, as the analysis represents a rapid scoping assessment. Future work should extend the framework to include additional drivers and processes, such as demographic and socio-economic change, groundwater interactions, and water quality, which may further amplify pressures on the Rhine River system.

9. Seine River basin: hydrological projections for reservoir operations

Authors: Julie Collignan, Alban de Lavenne, Maria-Helena Ramos (INRAE)

The Seine River basin is the most densely populated catchment in France. Its main water management infrastructure consists of four large reservoirs located upstream of Paris (Figure 9.1). These reservoirs are designed to mitigate flood risks and sustain low flows during the summer, dryer season. They operate in the same way: overall, in winter and spring (November to June), the reservoirs are progressively filled to secure enough water in the summer; from July to October, when rivers are at their lowest during the summer, the water in the reservoirs is progressively released. In the event of an exceptional drought, reservoir releases can exceptionally extend into November and December.

As part of the STARS4Water project, discussions with stakeholders have highlighted growing concerns about the increasing frequency and duration of low-flow events, with consequences in the operation of the water filling and releasing period. Concerns were particularly related to the risk that reservoirs may fail to completely fill by June and maintain sufficient discharge during the summer period across the basin and until the end of the typical releasing period (1rst November). In the safe operating space framework implementation, the assessment was focused on two key issues: how climate projections may affect the reservoirs' filling potential, and how effectively these reservoirs will be able to support river flows during the drier periods in the future.

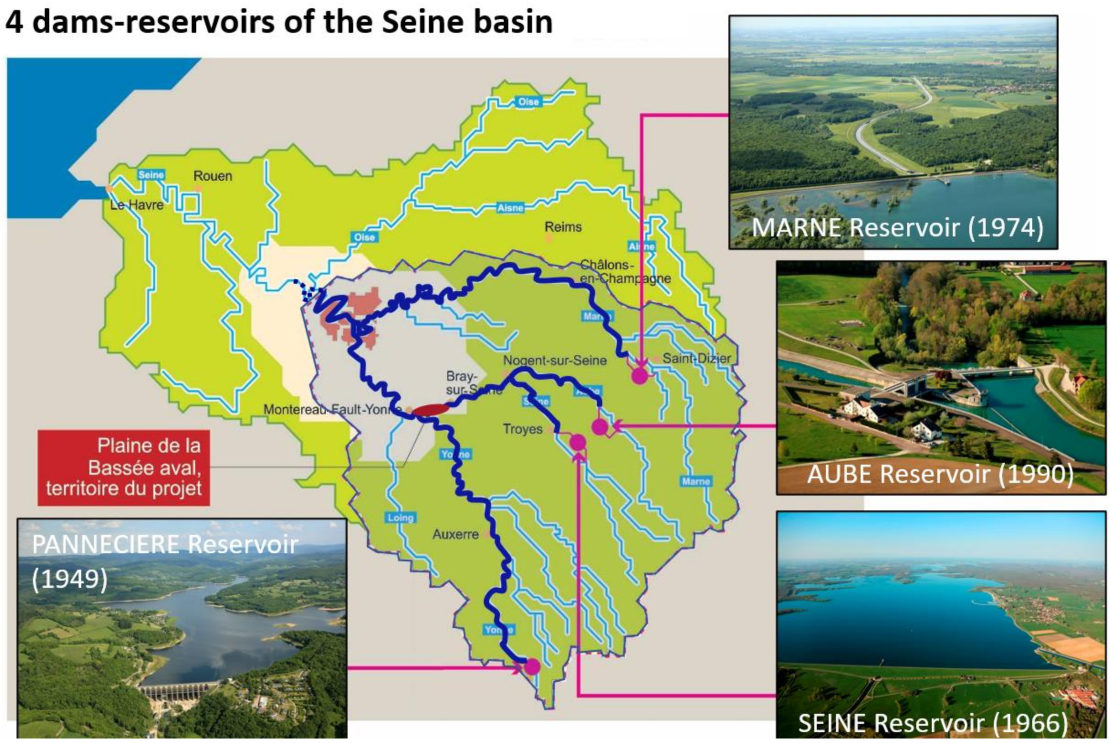


Figure 9.1: Location of the four upstream reservoirs in the Seine River basin operated by EPTB Seine Grands Lacs to regulate flows, with indication of the year they started operating (source: EPTB Seine Grands Lacs; https://www.seinegrandslacs.fr/).

9.1. Future scenarios of climate change

In France, a recent national-wide study, Explore2 (2021-2024), brought together several partners to update knowledge on the impact of climate change on hydrology and support stakeholders in understanding and using these results to adapt their water resources management strategies. Explore2 took into account CMIP5 projections for RCP scenarios (RCP8.5, 4.5 and 2.6), the reference period 1976-2005 and two future horizons (2041-2070 and 2071-2100). Explore2 considered a set of 17 downscaled regional climate projections (based on 9 regional models forced by 6 global models) and a set of hydrological projections (based on 1 to 9 hydrological models, depending on the river basin), using a target grid resolution of 8 × 8 km[12] (Évin et al., 2024; Sauquet et al., 2026).

The project also built four narratives to embrace the range of possible futures at the national scale, namely the 'green narrative' (marked climate warming and increase in precipitation), the 'yellow narrative' (future changes relatively minor); the 'violet narrative' (strong warming and strong seasonal contrasts in precipitation), and the 'orange narrative' (strong warming and strong drying in summer as well as annually). Figure 9.2 illustrates the results for the Seine River basin, based on the GR6J hydrological model, for the end of the century and RCP8.5, and with regard to three flow-based indicators: average annual flows (Qan), high flows (QJXA10), and low flows (QMNA5). It illustrates the expected strong impacts on the extremes of river flows across the entire river basin.

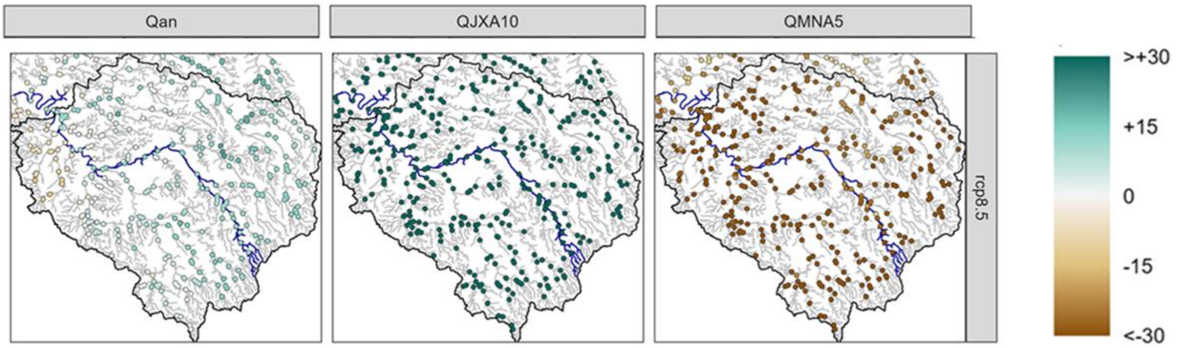


Figure 9.2: Relative change of hydrological projections in the Seine River basin up to Paris for the future period 2070-2099 with reference to 1976-2005, and RCP8.5. Results are based on simulations of the GR6J model, for average annual flows (Qan), high flow (QJXA10) and low flow (QMNA5) indicators (data source: project Explore2).

In the STARS4Water project, our analysis relied on the outputs from the Explore2 project (Evin et al., 2024). We used the four contrasted narratives for the GCM/RCM pairs under the RCP 8.5 scenario. These scenarios were chosen as they exhibit contrasting conditions in the Seine and during the reservoir filling and release periods. These scenarios are: (i) particularly dry scenario (ICHEC–MOHC); (ii) a wet scenario (MOHC–ALADIN63); (iii) a seasonally contrasted scenario that is drier during the filling period and wetter during the release period (CNRM–ALADIN63, which also shows the weakest trends in climate variables); and (iv) a scenario with the strongest contrasts and the driest release period (MOHC–CCLM4). We note that, even in the wetter scenarios, the Seine River basin is projected to experience an overall decrease in precipitation during the release period of the reservoir operations, while most scenarios (except the driest one) indicate an increase in precipitation during the filling period. Figure 9.3 illustrates the four scenarios used in our study.

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[12] https://www.inrae.fr/sites/default/files/projetexplore2-synthese.pdf

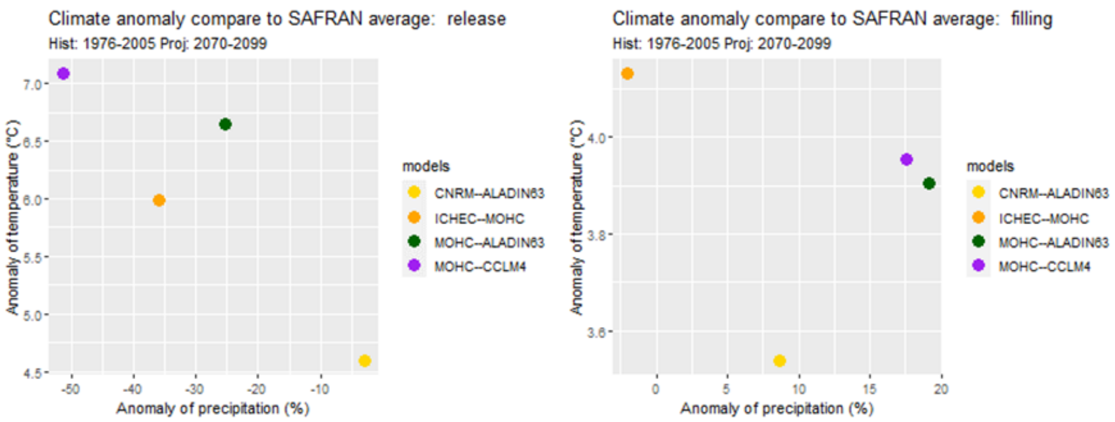

Figure 9.3: Anomalies of P (%) and T (in ◦C) compared to the historical reference period for the four scenarios over the Seine River basin, for the filling period (November to June, right) and the release period (July to October, left) of the operation of the upstream water reservoirs.

9.2. Future management strategies of reservoir operation

To account for the effects of reservoir management under future climate conditions, we developed a set of management scenarios for the four reservoirs. These scenarios represent different withdrawal (for reservoir filling) and release strategies. They were implemented within the semi-distributed hydrological model GRSD (de Lavenne et al., 2019), previously calibrated and validated for the river basin (Collignan et al., 2026). These potential management scenarios were derived from observational data, current operational guidelines (target rule curves), and the existing design constraints of the reservoirs. They were built and validated after consultation with stakeholders (EPTB Seine Grands Lacs), and explore three key modifications to the rule curve, and all their combinations: an earlier start of the release period (by one month); an extended release period (by one additional month); a lower filling target, representing situations where the reservoirs fail to reach full capacity during the filling phase (Collignan et al., 2025).

Figure 9.4 illustrates the scenarios of reservoir management for the case of the Marne reservoir. The construction of management scenarios followed the same logic for all four reservoirs in the river basin. Scenario JASO represents the release period running through the months of July (J), August (A) and September (S) and October (O). Scenario JJASO means the release starts already in June (J), while scenarios JASON and JJASON extends the release to the month of November (N). The reservoir is either considered at its maximum in the beginning of July (Vmax) or half-full (0.5Vmax).

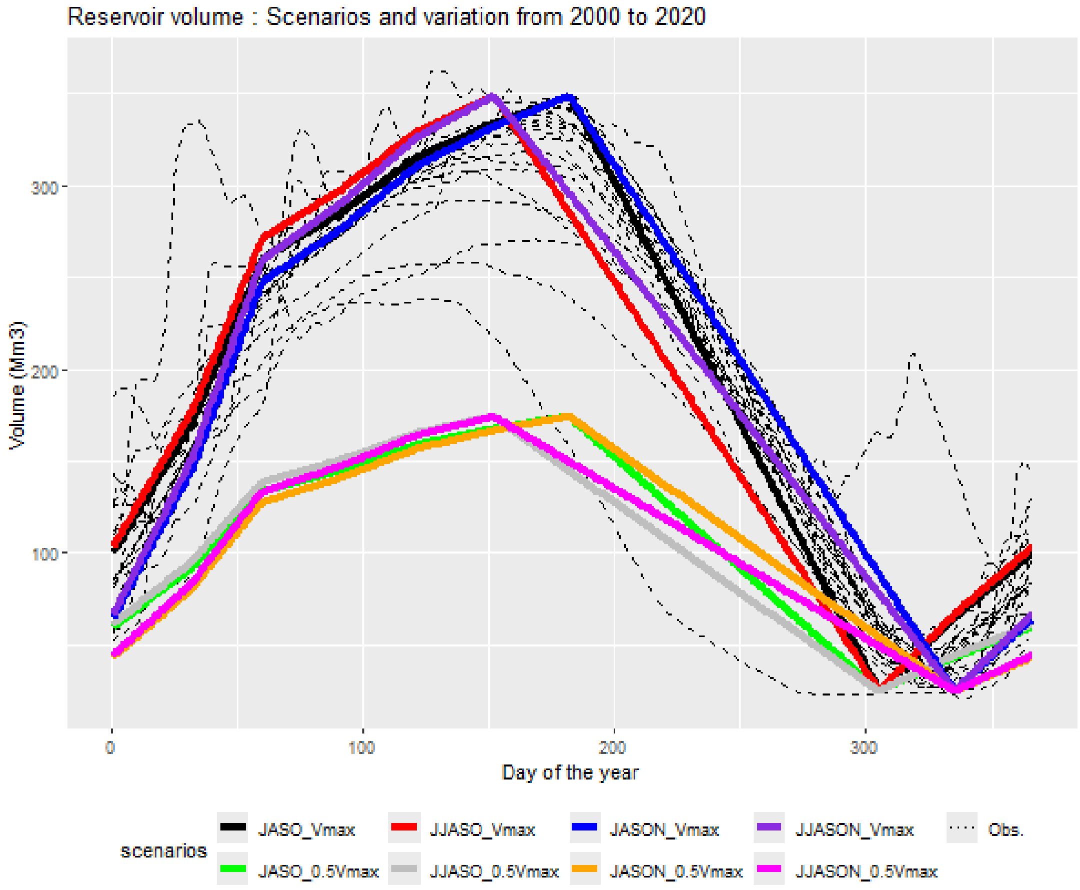

Figure 9.4: Management scenarios for the Marne reservoir presented through the volume curve, compared to actual volume evolution from the year 2000 to the year 2020.

9.3. Risks related to future water resources availability

Risks related to filling deficit of reservoirs

For the projected period (2070–2098), across the four tested climate scenarios, we observe an overall increase in the frequency of filling deficits compared with the historical period throughout the filling phase (Figure 9.5). The only exception is the CNRM–ALADIN63 scenario, where the deficit pattern remains similar to the historical reference and can therefore be considered manageable through some operational flexibility.

In the three other scenarios, filling deficits become more pronounced over the year, indicating a reduced capacity to compensate for deficits during subsequent stages of the filling period. This trend is particularly evident in months already sensitive to shortfalls in the reference period, namely November to December, around March, and at the end of the filling period in June.

These findings can inform potential adjustments to the operational rule curves by highlighting weaknesses in current filling targets, which tend to overestimate reservoir filling potential, particularly in November, March and June. Although early-season deficits can be recovered in approximately 85% of the years, the three driest scenarios each include at least one exceptional year in which a purely climate-driven filling deficit reaches 30–50% of the target volume by the end of the filling period. Such years correspond to the extreme management scenarios with a reduced filling target.

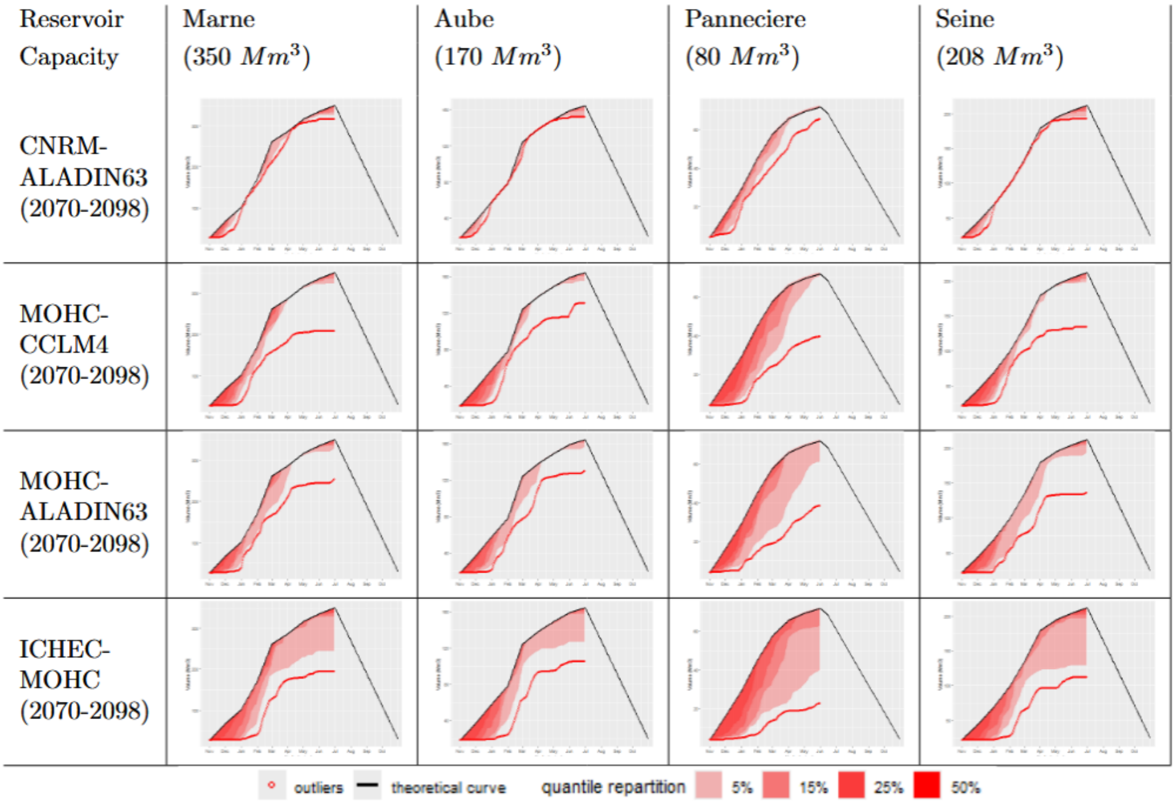

Figure 9.5: Reservoir volume curves for the four reservoirs in the Seine River basin (Marne, Aube, Panneciere, Seine) showing the distribution of the filling deficit over the filling period (Nov-Jul). Y-axis: Volume in Mm^3; X-axis: Months of the year starting on 1st November. The colour scale shows the frequency of the filling deficit over the filling period compared to the theoretical targeted rule curve for the reference management scenario in black, over the period 2070-2098 for the climate scenarios. The colour intensity corresponds to the frequency for which the deficit is reached (5%, 15%, 25%, 50% of the years), with outliers shown in red (deficit reached 1% of years only).

Increase of low-flow events downstream of reservoirs despite low-flow support

Here, we focus on low-flow conditions at the Paris station. Considering first the effect of the release period duration, the scenarios featuring an extension of the release period into November (JASON or JJASON) are those in which the crisis threshold is exceeded least frequently—in fewer than 5% of years, even under the driest climate scenario, and regardless of the initial release volume (either Vmax or 0.5Vmax) (Figure 9.6).

When examining the effect of the initial reservoir volume at the beginning of the release period on low-flow support, we observe that scenarios starting with only 50% of the reference filling volume show a marked increase in the frequency of threshold exceedances (warning and alert levels) at the Paris station. In these scenarios, the linear low-flow support throughout the release period is significantly reduced, resulting in lower sustained discharge and a higher frequency of low-flow events.

Nevertheless, across all management scenarios, the presence of reservoirs consistently has a positive effect compared to simulations without reservoirs, notably in reducing the frequency of threshold exceedances, particularly the crisis threshold, which is crossed every month in all climate scenarios with no reservoirs.

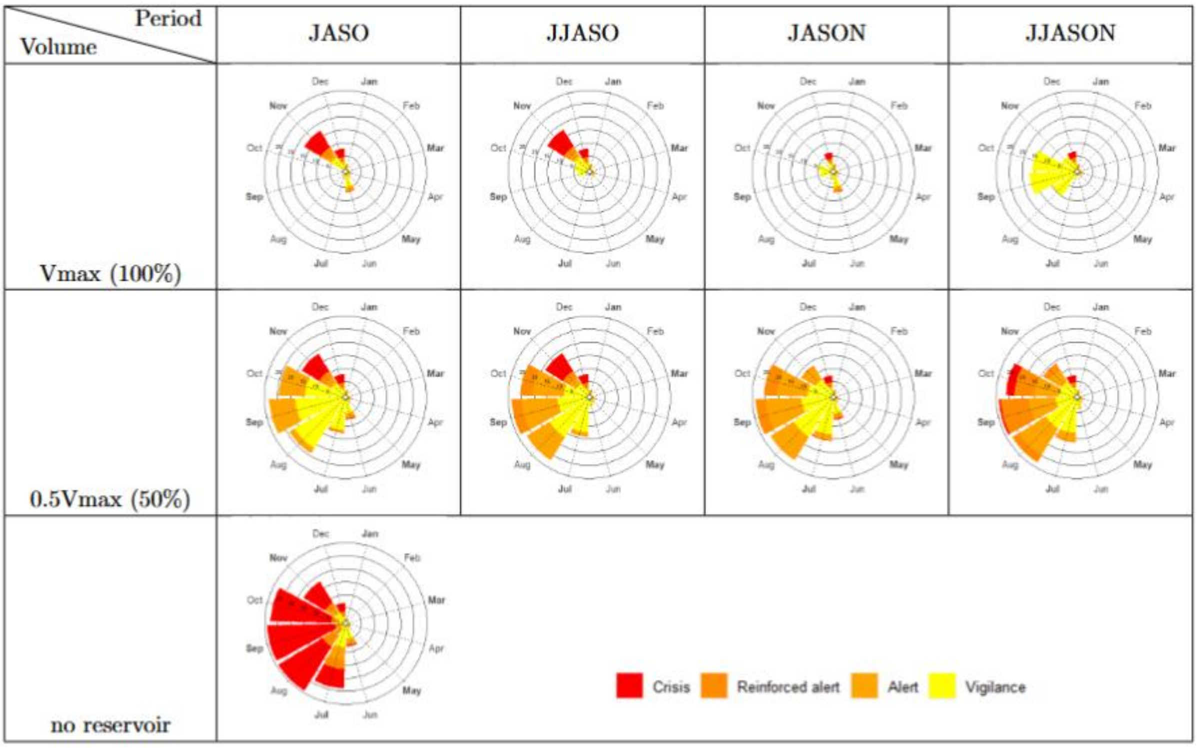

Figure 9.6: Average number of days per month (between 0 and 30 days) below each threshold for the station of Paris in the Sein Reiver basin, considering the projected driest climate scenario ICHEC-MOHC (2070-2098) and the management scenarios JASO, JJASO, JSAON, JJASON. The first row shows the scenarios for which we start the release period with the reservoirs fully filled. The second row shows the scenarios for which we start the release period with only 50% of the reservoir capacity filled. Each column shows the management scenarios with different lengths of the release period from June (J) to November (N).

9.4. Lessons learnt and perspectives

The implementation of the safe operating space allowed us to explore the limitations and risks of the current reservoir management system in the Seine River basin under future climate conditions and possible future management (operation reservoir rule curve) scenarios. The main lesson learnt across all scenarios is that the current reservoir operating curve might need to shift, with a releasing curve increasingly extended towards November, as the end of the year might be more susceptible to experience low flow events. This is the case when the reservoirs cannot start filling early November and, consequently, do not reach their filling targets in June for the next operation year.

This assessment allows to identify the general directions the management needs to take to improve its performances under future drier conditions. These results can be helpful to accompany the stakeholders during their discussions with the downstream water uses and to guide decisions to adapt the target rule curves for the filling and release of the reservoirs, in preparation for an increased risk of low flow events in the river basin.

In practice, the operation of the system is flexible towards avoiding risks of failure. The operational managers can adjust the release slope, for instance, by lowering the slope during the months of July, to keep more water to support low flow during the driest months (August to September) and better balance the low flow support across the release period. The risk assessment framework developed here could be further applied and evaluated to consider this flexibility of management, among other factors such as flood risks.

10. Conclusions

In the STARS4Water project, the SOS framework 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 operations. The SOS approach was evaluated in its ability to support river basin stakeholders to better understand complex information on climate change risks, and facilitate linking this information to current and future strategies of water management. By adapting the framework to local concerns and implementing relevant tools and services, the project has contributed to raise awareness of river basin stakeholders to climate change risks, and to start new initiatives to strengthen their preparedness for a future changing climate and extreme events affecting the hydrological cycle.

Despite this diversity of applications, all hubs were connected through a shared knowledge co-creation process that shaped the overarching SOS framework. This process enabled the integration of management scenarios alongside climate and IPCC socioeconomic scenarios when assessing indicators and thresholds for safe or at-risk operations. Rather than providing a precise and definitive response on the future of water resources in each river basin, the analysis sheds light on how water managers can become integral actors in climate risk assessment and adaptation, by continuously bringing their operational expertise into the process. Ultimately, 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.

With the implementation of the STARS4Water SOS Framework in seven river basins in Europe, we showed that **climate change can be a threat to water resources management**, with 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 could be further exacerbated in the future. economic and environmental risks

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

Identifying relevant indicators to distinguish safe from at-risk operational conditions is essential for this integrative approach and for drawing robust conclusions about complex system interdependencies. Tailormade visualisations and dashboards can facilitate information sharing and guide coordinated action on future water management strategies, improving preparedness for joint responses across different water users. Incorporating operational and management practices adds flexibility to the continuous assessment of climate risks and helps identify effective actions today for tomorrow’s challenges. The SOS framework offers a valuable tool for evaluating the robustness and resilience of water systems and their management.

Our results showed that applying the SOS concept in river basin management is far from straightforward. Early in the process, a key challenge was to establish a shared understanding of the concept itself, including clarifying how it relates to existing approaches in integrated river basin management or complements them, such as risk assessment analyses and scenario-based evaluations used in climate change impact assessments and adaptation planning.

Incorporating the perspectives of water managers and stakeholders proved essential for shaping the contours of the project's SOS framework. Their input enabled us to integrate a management and operational dimension into the physical, social, and ecological components of risk analysis, thereby strengthening and adding value to the inhouse expertise within water management organisations and public services.

Climate and water risk analyses are therefore enriched, as risk becomes not only the intersection of hazard, vulnerability, and exposure, but also more explicitly incorporates existing knowledge about how water systems operate within the river basin. This operational knowledge, reflected in current practices such as water quantity and quality monitoring, reservoir management and control, and the prioritisation of water uses, can be integrated alongside ongoing or planned adaptation actions. Within such a framework, the operations of water systems can be better understood in relation to climate risks. They may emerge as a strong and flexible tool for mitigating climate related impacts, or they can be adapted themselves to ensure they do not become amplifiers of future risks.

This deliverable marks a beginning rather than a conclusion. Stakeholders and water managers gained awareness on climate change impacts on water resources, as well as on the impacts of their current and future (strategic) operations on indicators of water availability and risks. In STARS4Water, they were empowered with improved modelling frameworks and data services. The project has demonstrated their added value to water resources and risk analyses and the applicability of the Safe Operating Space framework at the scale of river basins.

Across all river basins, additional analyses are underway to consolidate the knowledge gained, refine indicators and thresholds, strengthen the translation of modelling outputs into actionable local and regional management strategies, and communicate these insights more effectively to decisionmakers 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. This is the focus of ongoing work in Work-package 5 of the STARS4Water project.

The results of the assessments in the 7 river basin hubs have been presented in scientific conferences (e.g. European Geosciences Union General Assemblies in 2025 and 2026) peer-reviewed publications. Additional peer-reviewed publications are under preparation (e.g. special issue of International Journal of River Basin Management) with the respective generated datasets at river basin scale published/in preparation to be published in Zenodo or national permanent open data repositories.

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