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D5.2 Final Evaluation of Safe Operating Space

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			for the Mekong Delta case study		
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Publishable Executive Summary

The SOS-Water project aims to establish a comprehensive and participatory framework for assessing the Safe Operating Space (SOS) of regional and local water systems, considering multiple water-related dimensions across sectors and spatial scales under the influence of climatic and socio-economic change.

This Deliverable 5.2 presents the final SOS-Water evaluation framework and the results of its application in all four case studies of the project: the Jucar River Basin, the Danube River Basin, the Rhine River Basin, and the Mekong River Basin (both upstream and delta regions). Building on Deliverable 5.1, which introduced the framework and provided preliminary results for the Jucar case study, this report offers a more complete evaluation for all the case studies, showing its applicability across diverse hydrological, environmental, and socio-economic contexts.

The SOS-Water framework consists of three stages:

1. Assessment under current conditions, where indicators and thresholds are used to evaluate whether different processes remain within the SOS.
2. Assessment under future scenarios and global policies, which investigates how the SOS evolves under different climatic and socio-economic conditions.
3. Assessment under management pathways, which evaluates how local actions can help maintain or restore the SOS.

This deliverable focuses on the first two stages, while the analysis of management pathways will be reported in Deliverable 5.5.

For each case study, the framework is applied consistently but also adapted to basin-specific characteristics. This demonstrates its flexibility while maintaining a common methodological foundation. The results show that several indicators already transgress their thresholds under current conditions, and that future scenarios could further amplify these pressures. While the thresholds presented in this deliverable represent the best available estimates, future work will explore complementary methods to obtain additional threshold estimates, thereby complementing the current ones and providing uncertainty ranges around threshold values.

In summary, Deliverable 5.2 represents a major milestone in the SOS-Water project, providing the first complete application of the SOS evaluation framework across four diverse case studies. While refinements are still expected, this work lays the foundation for a comprehensive, flexible, and policy-relevant approach to assessing and managing water systems within their safe operating space.



Table of Content

1	<i>Introduction</i>	8
2	<i>Methods and Frameworks</i>	10
2.1	SOS-Water implementation framework	10
2.1.1	Indicators and thresholds.....	11
2.1.2	Future scenarios and global policies.....	15
2.1.3	Local management pathways.....	21
2.1.4	Integrated water modeling system	22
3	<i>Applications and Assessment of SOS Water</i>	24
3.1	Jucar Case Study	24
3.1.1	Indicators and Thresholds.....	25
3.1.2	Future Scenarios.....	28
3.1.3	Integrated Water Modeling System.....	30
3.1.4	Multi-Dimensional SOS Assessment Results	31
3.2	Danube Case Study	37
3.2.1	Indicators and Threshold	39
3.2.2	Future Scenarios.....	42
3.2.3	Integrated Water Modeling System.....	44
3.2.4	Multi-Dimensional SOS Assessment Results	45
3.3	Rhine Case Study	52
3.3.1	Indicators and Thresholds	53
3.3.1	Future Scenarios.....	54
3.3.2	Integrated Water Modeling System.....	57
3.3.3	Multi-Dimensional SOS Assessment Results	57
3.4	Upstream Mekong Case Study	59
3.4.1	Indicators and Thresholds	60
3.4.2	Future Scenarios.....	63
3.4.3	Integrated Water Modeling System.....	66
3.4.4	Multi-Dimensional SOS Assessment Results	68
3.5	Mekong Delta Case Study	73
3.5.1	Indicators and Thresholds	75
3.5.2	Future Scenarios.....	76
3.5.3	Integrated Water Modeling System.....	77
3.5.4	Multi-Dimensional SOS Assessment Results	78
4	<i>Conclusions</i>	81
5	<i>Appendix A: Danube case study indicators definitions</i>	90
5.1	Magnitude of Monthly Flow Alteration (MMFA)	90



5.2	Connectivity Status Index (CSI)	90
5.3	Aquifer recharge rate (ARR)	90
5.4	Water supply reliability	91
5.5	Species Habitat Suitability	91
5.6	Number of Navigation Days (NND)	91
5.7	P and N concentrations	92
6	<i>Appendix B: Complete list of Upper Mekong basin indicators and thresholds</i>	1

List of Tables and Figures

Table 1.	List of examples of actions in local water system management pathways.	21
Table 2.	Indicators chosen for the Jucar River Basin case study.	25
Table 3.	Thresholds adopted for the Jucar River Basin case study.....	26
Table 4.	List of Danube basin indicators and their division into water functions as defined by Falkenmark & Wand-Erlandsson, 2021.....	39
Table 5.	Indicators and thresholds chosen for the Danube River Basin case study.	40
Table 6.	Reformulation of the indicators according to the aggregation and frequency-based (or other, if needed) transformation performed.	47
Table 7.	Summary of the worst indicators' performance for each water function in the Northern, Central and Southern Danube sub-basins. Colors differentiate among safe (green) and unsafe (red) spaces, following Figure 22.....	51
Table 8.	Given discharge thresholds from the Dutch national water authority that are used to assess the local SOS at Lobith, NL.	54
Table 9.	Basin-wide indicators and their thresholds, both in absolute values and normalized between 0 and 1.	62
Table 10.	Mekong Delta indicators and their thresholds.	76
Table 11.	Results on the annual maximum daily flow frequency from historical simulations and baseline SSP126 scenarios.	77
Table 12.	Results on the annual minimum daily flow frequency from historical simulations and baseline SSP126 scenarios.	77
Table 13.	Application of flood thresholds for SOS-Water evaluation: Mekong delta-flood level at Tan Chau.....	79
Table 14.	Original indicator matrix (historical observation and simulation of GCMs): Mekong delta-flood level at Tan Chau.	79
Table 15.	Original indicator matrix (baseline management pathway-SSP1-2.6 and GCMs): Mekong delta-flood level at Tan Chau.	79
Table 16.	Original indicator matrix (baseline management pathway: SSPs-RCPs and GCM1): Mekong delta-flood level at Tan Chau.	80
Table 17.	Application of salinity thresholds for SOS-Water evaluation: Mekong delta-saline intrusion length in Cua Dai river mouth.	80



Table 18. Original indicator matrix (baseline management pathway: SSPs-RCPs and GCM1): Mekong delta-saline intrusion length in Cua Dai river mouth. 80

Figure 1. Cross-dependencies between Task T5.1 and other tasks in the SOS-Water project..... 10

Figure 2. Overview of the SOS-Water evaluation framework. 11

Figure 3. Examples of indicators of a multi-dimensional water system..... 13

Figure 4. Different approaches for threshold identification of indicator variable. 14

Figure 5. Multiple future change scenarios generation approaches (including Top-Down, Bottom-Up, and Integrated). 16

Figure 6. SSPs-RCPs scenario matrix from O’Neill et al. (2016)..... 18

Figure 7. Integrated water modelling system composed of water system models and local impact models and its linkage with other components in the SOS-Water project e.g., scenario design, local management pathways and indicators..... 23

Figure 8. Jucar River Basin hydrological scenarios. 29

Figure 9. Jucar River Basin modelling framework. 31

Figure 10. Performance of GLI, WSR and CWSI indicators in the Jucar River Basin case study..... 33

Figure 11. Performance of WUA indicators (Alarcon, Madrigueras and Molinar) in the Jucar River Basin case study. 34

Figure 12. Performance of WUA indicators (Contreras, Dos Aguas and Antella) in the Jucar River Basin case study. 34

Figure 13. SOS evaluation for GLI, WRS and CWSI in the Jucar River Basin case study..... 35

Figure 14. SOS evaluation for WUA in the Jucar River Basin case study. 36

Figure 15. Danube Basin states and basin divisions. The upper, middle, and lower Danube Basin are presented..... 38

Figure 16. Division of the Danube basin in the 11 major subbasin utilized for the indicators evaluation. 42

Figure 17. Temperature (degrees) and precipitation (%) change over the entire Danube basin between a historical reference period (1981-2010) and future projections (2030-2070) under the SSP-RCP 1.26 scenario. 43

Figure 18. Temperature (degrees) and precipitation (%) change over the entire Danube basin between a historical reference period (1981-2010) and future projections (2030-2070) under the SSP-RCP 5.85 scenario. 43

Figure 19. Monthly precipitation (pr, mm) and reference evapotranspiration (ETo, mm) under three future scenarios for three sections of the Danube River basin: Lower Danube, Middle Danube, and Upper Danube (ICPDR). Blue: reference period; Green: SSP1-2.6; Orange: SSP3-7.0; Pink: SSP5-8.5. 44

Figure 20. Danube River Basin integrated modelling framework. 45

Figure 21. Workflow utilized for the indicator’s evaluation and the multi-dimensional SOS assessment. 47

Figure 22. SOS Evaluation by functions of the Northern, Central and Southern Danube sub-basin..... 51

Figure 23. Graph of the changes in water temperature at Lobith, NL across the different scenarios considered. 55

Figure 24. Individual plots of the Lobith specific indicators. Each color corresponds to a different SSP. The drought and flood indices correspond to the 95th percentile of the modelled discharge values. The navigation index corresponds to the number of navigable days across the 30 year period..... 56

Figure 25. Modelling chain for biodiversity impact modelling in the Rhine River basin. 57



Figure 26. Preliminary evaluation of the SOS for the Rhine basin using Lobith, NL as the evaluation point. The different colors correspond to the threshold levels set by the Dutch national water authority for acceptable ranges in at Lobith, NL. We plot six indicators and their relative threshold to show where the SOS might be exceeded and where the SOS is still within the limit. 58

Figure 27. Average daily precipitation anomaly compared to a 1981-2010 baseline (dry season)..... 64

Figure 28. Average daily precipitation anomaly compared to a 1981-2010 baseline (monsoon season). 65

Figure 29. Average maximum daily temperature anomaly compared to a 1981-2010 baseline. 65

Figure 30. Average minimum daily temperature anomaly compared to a 1981-2010 baseline..... 66

Figure 31. Integrated Water Modeling System (IWMS) for the Upstream Mekong, detailing the inputs needed by the different modules and the outputs they main outputs they produce. 68

Figure 32. Upstream Mekong indicator matrix showing the mean values of the basin-wide indicators, calculated over specific time windows for both historical and future periods and under different climate change scenarios..... 70

Figure 33. Matrix representing the final SOS evaluation for the Upstream Mekong. Red cells represent unsafe indicators, while green cells safe ones. 71

Figure 34. Violin plots representing Upstream Mekong normalized indicators' performance across scenarios..... 72

Figure 35. Violin plots representing the performance of the normalized hydropower indicator across scenarios for each country in the Upstream Mekong basin. 73



Description of deliverable

1 Introduction

The present Deliverable D5.2 (Final Evaluation of Safe Operating Space) describes the outcomes and activities conducted in Task T5.1 (SOS Evaluation) of WP5 (Design and assessment of SOS) within the SOS-WATER project (SOS-WATER, 2023). The broader goal of WP5 is to develop the concept of Safe Operating Space (SOS) both methodologically and practically at the regional or local level, as a multi-dimensional space of policies evaluated across various scenarios and management pathways (developed in WP1), with respect to a set of indicators (identified in WP4), and simulating the integrated water modelling system, IWMS (established in WP2). Figure 1 shows the cross-dependencies of T5.1 with tasks in other WPs. The SOS concept and framework for local water systems is developed through four case studies: the Jucar River basin, the Danube River basin, the Rhine River basin, and the Mekong River Basin, split into Upstream region and Delta region, each facing different water-related challenges under distinct environmental and socio-economic conditions.

The purpose of this deliverable is to present the final SOS-Water evaluation framework and to show the results of its application in all four case studies of the project. Accordingly, the first part of the deliverable describes the framework from a methodological perspective, building on what was presented in D5.1 and providing more detailed information on each of its components. It is important to note that this deliverable only includes the SOS evaluation under different future scenarios in a business-as-usual setup. The SOS evaluation under local management pathways will be discussed in deliverable D5.5 (Synthesis of Safe Operating Space) building on the simulations reported in deliverable D2.4 (Setup and outcome of simulations under scenarios and management pathways).

In a nutshell, the proposed framework is based on three main steps. The first step focuses on the SOS-Water evaluation under current conditions (i.e., status quo). In this step, we calculate the indicator values for all identified natural and socio-economic processes within the water system and quantify how many of these processes have transgressed their respective indicator thresholds (i.e., are in an unsafe state). The second step evaluates the SOS under co-developed future scenarios and global policies, to assess how it may evolve under different conditions. The third step investigates changes in the SOS resulting from the implementation of locally developed management pathways.

Therefore, the SOS-Water evaluation framework requires several key components:

- Indicators and thresholds
- Co-developed future scenarios and global policies
- Local management pathways
- An integrated water modelling system (IWMS) for the basin under consideration.

All these components will be discussed in detail in the following chapter.

After the detailed presentation of the final SOS-Water evaluation framework, this deliverable will present the results of its application to all four case studies of the project. For each case study, all



previously listed components are applied and tailored to the specific context. Specifically, the indicators and thresholds considered for each basin will be highlighted, along with the developed future scenarios, the integrated water system modelling built and used to evaluate the SOS, and the final multidimensional matrix showing the SOS results. The four case studies presented here are used to exemplify how the general SOS-Water evaluation framework can be adapted to specific river basins by incorporating the necessary adjustments to fit each local context.

Since the project will conclude in one year, some phases may still be refined at a later stage. In particular, regarding indicators and thresholds, we have tried to use the most definitive definitions and values possible. However, especially for the definition of thresholds, several case studies' leaders expected more substantial input from their stakeholders, input which was not always provided or was not sufficiently reliable to accurately characterize them. As a result, some thresholds are currently considered tentative, with the aim of improving their definition and subsequently updating the SOS evaluation in future participatory phases of the project.

With this deliverable, task T5.1 is essentially concluded. However, the SOS-Water analysis produced in T5.1 will be further refined in T5.2 (Analysis and synthesis of SOS) to address the challenges associated with implementing local management pathways, as well as the resulting multi-dimensionality of the SOS. The uncertainty propagation in multi-dimensional SOS evaluation will be investigated in T5.3 (Uncertainty and robustness analysis). Furthermore, the outputs from T5.1 will also be used in T5.4 (Reconciling SOS across scales) to address scale discrepancies in the evaluation of the SOS, considering models and indicators operating at different spatial resolutions.

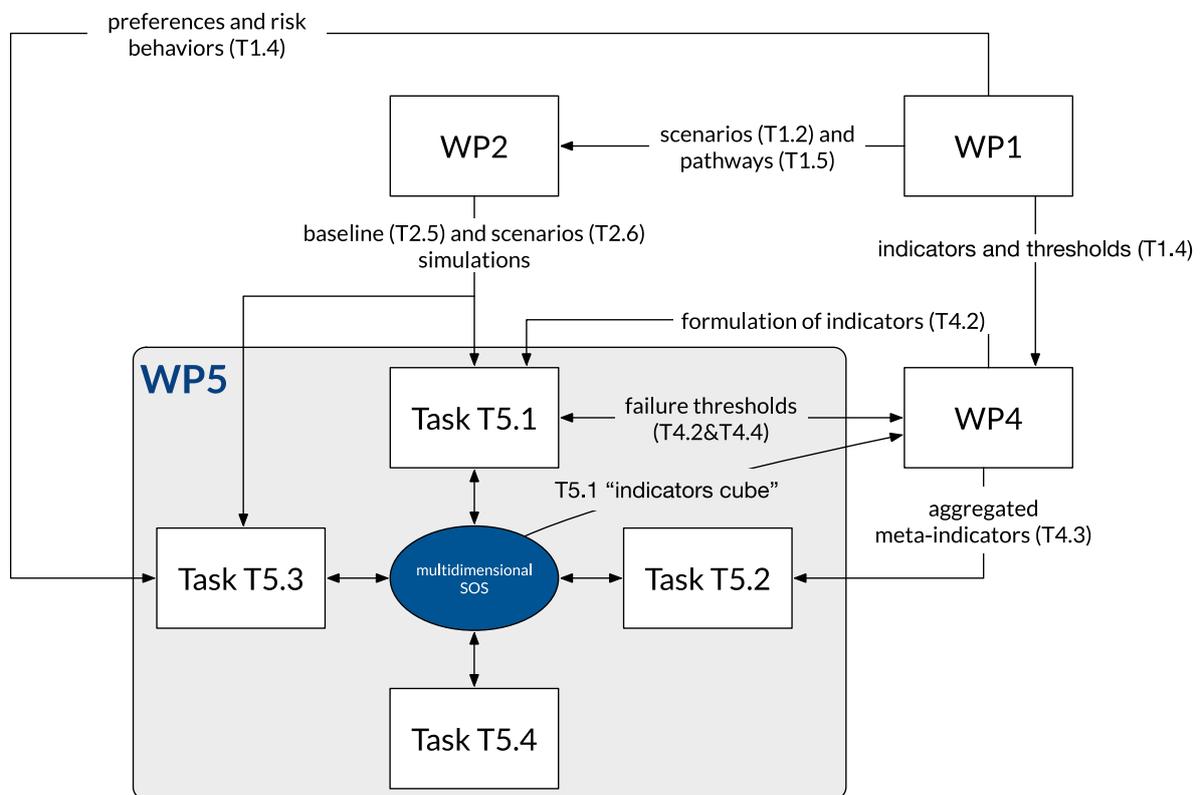




Figure 1. Cross-dependencies between Task T5.1 and other tasks in the SOS-Water project.

The report is structured as follows: [Section 2](#) describes the SOS-Water evaluation framework, detailing each of its components introduced above. [Section 3](#) reports the results of SOS-evaluation under different case studies. In particular, the Mekong case study has been divided into two parts: the Upstream Mekong and the Mekong Delta. Although the main focus of the project is on defining and assessing the SOS for the Mekong Delta, it is essential to also consider the upstream portion of the river. This inclusion is necessary to evaluate the future conditions of the Mekong Delta under different global climatic and socio-economic scenarios, as well as under alternative local management pathways that could be implemented upstream. The inclusion of the upstream part of the Mekong was carried out using a different approach from that of the Mekong Delta. The Mekong Delta assessment followed a more participatory process, involving a larger number of stakeholders. Conversely, in the upstream part, the framework was primarily applied to provide the necessary boundary conditions for assessing the SOS in the Delta. As a result, the upstream assessment was less stakeholder-driven and more centered on building the modeling system and defining the relevant indicators. Therefore, for the sake of clarity, the two Mekong sub-cases are hereby presented separately. In each case study the framework is applied with its own specific set of indicators, models, and final SOS evaluation.

2 Methods and Frameworks

2.1 SOS-Water implementation framework

Our project aims at developing a framework that comprises three stages of SOS-Water evaluation (as described in Section 2 of D5.1). The first stage is mainly focused on the SOS-Water evaluation for the current condition (i.e., status quo). At this stage, we calculate the indicator values for all identified natural and socio-economic processes of the water system and quantify how many processes have transgressed the thresholds of the indicators (i.e., being in an unsafe state). In the second stage, we evaluate the SOS under co-developed future scenarios and global policies, to understand how the SOS evolves under different scenarios. In the last stage, we investigate how the SOS changes when implementing different locally developed management pathways. The SOS-Water evaluation framework requires multiple components: 1) indicators and thresholds, 2) co-developed future scenarios and global policies, 3) local management pathways, and 4) integrated water modelling system (IWMS). The indicators and thresholds associated with all the natural and socio-economic processes of the water system are developed in WP4 to fully assess the environmental, social, and economic status and performance of the water system. The co-designed scenarios and local management pathways, as generated in WP1 in collaboration with local stakeholders, serve as the driving force for the IWMS established in WP2. The resulting model output is then utilized to compute the values of indicators under future scenarios with or without the implementation of local management pathways. Ultimately, the SOS-Water framework yields a multi-dimensional SOS that encapsulates the performance of the entire water system under the status quo, co-developed future scenarios, and various local management pathways. Figure 2 provides an overview of the final SOS-Water framework. The subsequent subsections provide detailed insights into each of these components.

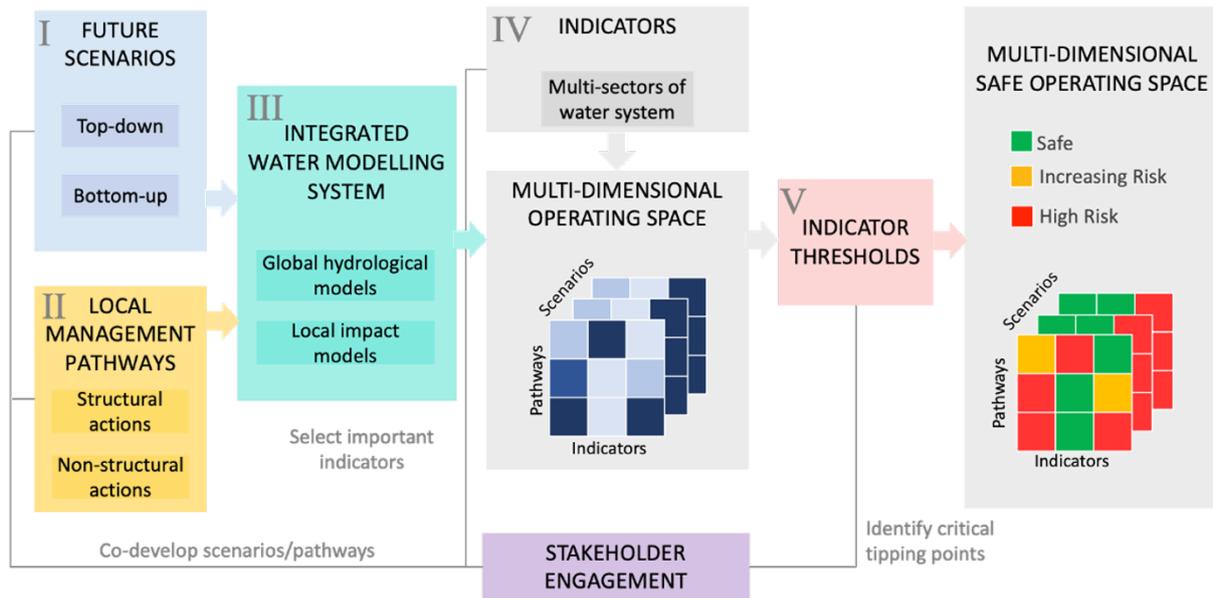


Figure 2. Overview of the SOS-Water evaluation framework.

2.1.1 Indicators and thresholds

An *indicator*, in the context of water system management, refers to a measurable and quantifiable parameter or variable used to assess the status, performance, or condition of the water system. Indicators offer valuable information on the water system’s state in terms of different natural and socio-economic processes and help decision-makers in assessing whether the water system operates within a safe range. Deliverable D4.1 of the SOS-Water project conducted a thorough review of indicators and identified gaps within the context of water resources systems. Deliverable D4.2 of the SOS-Water project critically assessed existing water indicators, identified key gaps, and proposed guidelines for the development of innovative indicators. The deliverable also developed a systematic aggregation mechanism to improve decision-making in water resource management.

We identify seven key sectors (as illustrated in Figure 3) that are influenced by both geophysical drivers—such as climate change, including temperature rise and altered rainfall patterns—and anthropogenic drivers, including population growth, economic expansion, urbanization, and industrialization. These drivers can exert such significant pressures on the multi-dimensional water system, that the underlying processes within each water-related sector may approach thresholds where stability deteriorates (commonly referred to as ‘tipping points’). Once these tipping points are exceeded, negative consequences can unfold, including economic decline, increased household vulnerability, biodiversity loss, rising unemployment, and even social conflicts.

Effective indicators should capture the impacts of both geophysical and anthropogenic drivers, monitor the state of the water system, and help identify tipping points that could lead to adverse consequences. Given the complexity and interdependence of these processes, it is crucial to recognize that each sector is often influenced by multiple interacting drivers.



Beyond the identification of water-related sectors, we propose an additional, higher-level aggregation into five water functions (Figure 3). These functions build on the five blue water functions described by Falkenmark & Wand-Erlandsson (2021) and aim to bridge the scale gap between local, sector-specific indicators and global social-ecological aquatic systems. In doing so, they highlight the fundamental role of water in maintaining Earth's resilience and stability, while linking our framework to the broader concepts of SOS and planetary boundaries (Rockström et al., 2009).

The five water functions are defined as follows:

- Supply: the function of withdrawn water used to provide water supply for society.
- Carrier: the function of river and base flows in transporting nutrients and pollutants.
- State: the function of lakes, wetlands, groundwater, reservoirs, and river volumes in maintaining aquatic conditions.
- Productive: the function of withdrawn water used for irrigation in agriculture to produce food, as well as lakes, wetlands, and river volumes supporting aquatic biomass growth.
- Regulatory: the function of river and base flows in regulating Earth's energy balance and climate (i.e., through albedo and carbon storage), as well as groundwater and glaciers in regulating sea levels and geological processes such as subsidence.

While these definitions are drawn from Falkenmark & Wand-Erlandsson (2021), they can still be broadened or adjusted during the next steps of the project to fully capture the diversity of indicators and sectors that characterize local water systems. The aggregation into sectors may vary depending on the specific case study and can, in some instances, be omitted, whereas the final aggregation into water functions remains common and comparable across all cases. In this deliverable, results are presented either at the level of indicators, of water-related sectors, or at the level of water functions, allowing each case study the flexibility to highlight the dimensions most relevant to its context.

To identify critical and context-specific indicators, a systematic assessment tailored to local conditions is necessary. This can be effectively achieved through stakeholder engagement, ensuring that the selected indicators accurately reflect sector-specific concerns and potential tipping points. By engaging stakeholders associated with each water-related sector and function, key tipping point events can be identified, and corresponding indicators can be selected to effectively monitor shifts in the system state. Figure 3 provides examples of indicators across different sectors and functions; however, this is not an exhaustive list. Rather than aiming to provide a universal indicator framework, our approach emphasizes case-specific adaptability, recognizing that relevant indicators will vary depending on local contexts and study objectives.

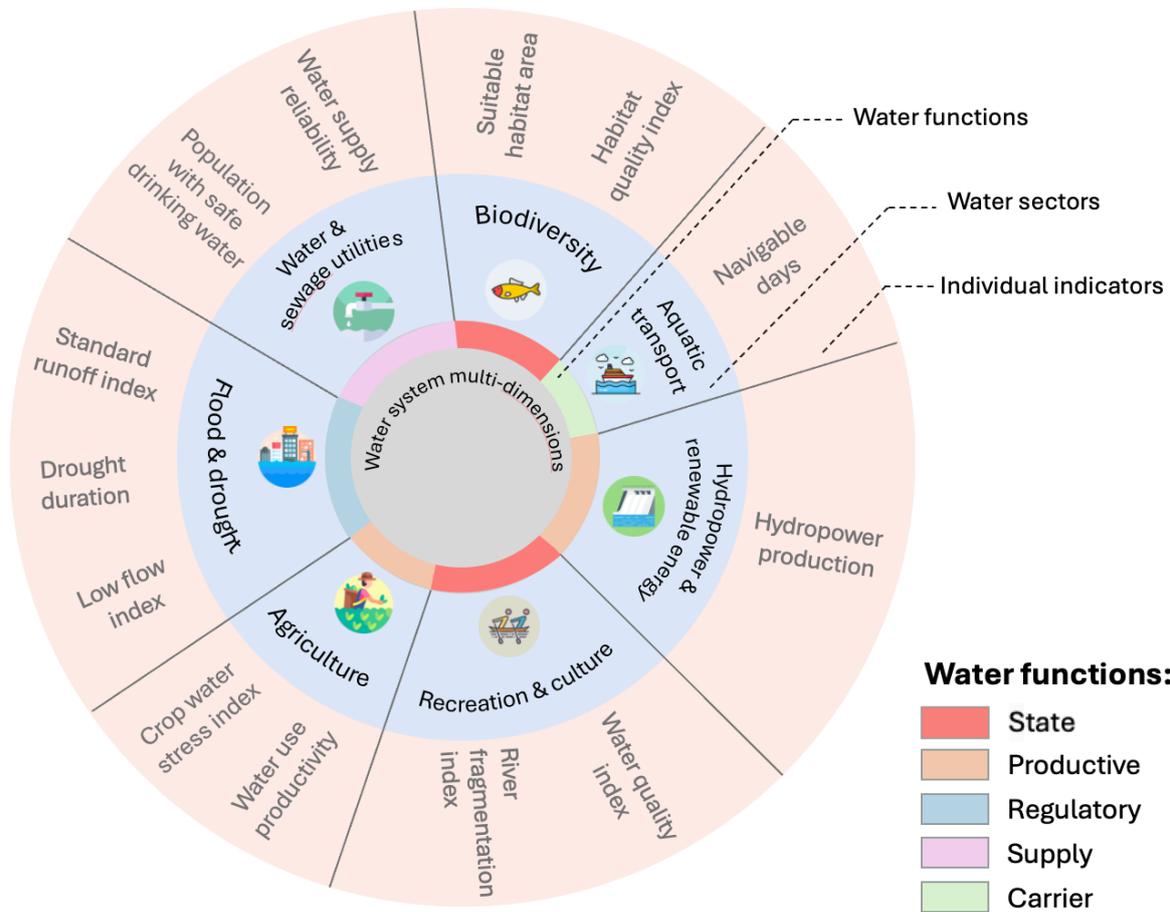


Figure 3. Examples of indicators of a multi-dimensional water system.

Thresholds denote a crucial limit or level pertaining to the positioning of indicators. They represent critical points beyond which the functioning of the water system may undergo significant alterations, potentially leading to risks or undesirable outcomes for humanity. These thresholds play a pivotal role in delineating operational boundaries within the water system, ensuring its safe functioning. Depending on the risk profiles of local stakeholders, these boundaries may be set more conservatively, reflecting a lower tolerance for risk in the assessed indicators. Identifying these thresholds and establishing boundaries is a crucial step in shaping the SOS framework for the water system.

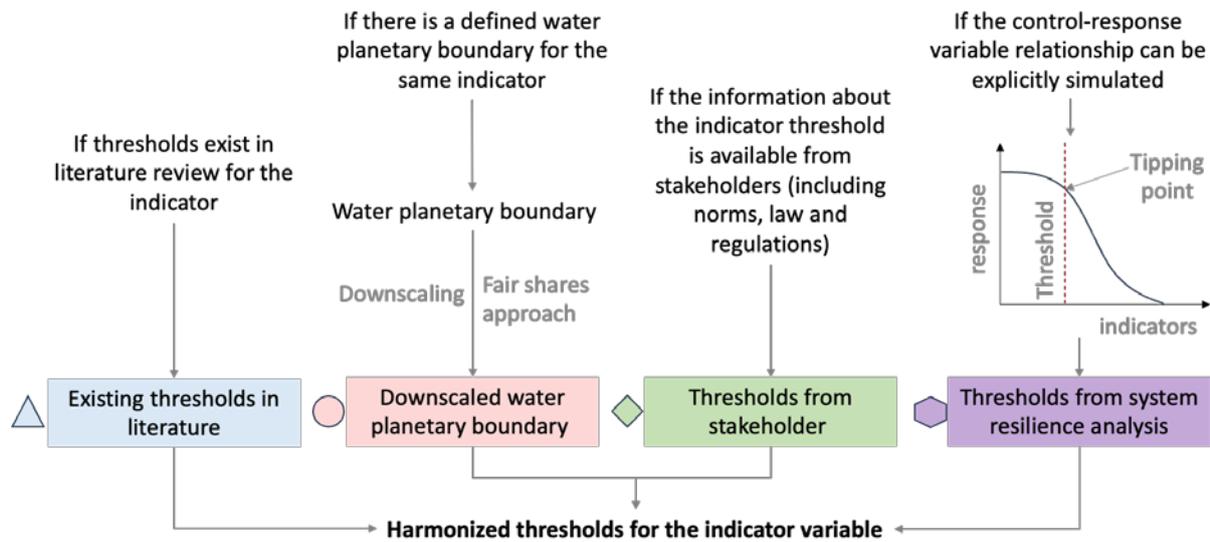


Figure 4. Different approaches for threshold identification of indicator variable.

Identifying thresholds in the context of SOS-Water involves a combination of scientific analyses, monitoring, modeling, and stakeholder engagement. There are four approaches (as shown in Figure 4) that could be employed for the threshold identification:

- 1) **Scientific literature review:** by conducting a comprehensive review of the existing scientific literature, we can identify established thresholds for key indicators that have already been examined in the context of local case studies. These studies may have explored potential responses of the water system to changes in indicator values resulting from various future scenarios. Consequently, we can directly apply these thresholds to the SOS-Water evaluation framework within the same local case study.
- 2) **Stakeholder engagement:** incorporating local perceptions and experiences into the threshold identification process, leveraging the knowledge and insights of local stakeholders regarding water conditions and potential thresholds, could be highly beneficial for identifying indicator thresholds.
- 3) **Local impact modelling analysis:** using modeling tools to assess the water system's response to changes in indicator values resulting from different future scenarios is a crucial approach for threshold identification. The simulation results can aid in constructing a response curve for the water system, enabling us to pinpoint tipping points in indicator values that may lead to the collapse or dysfunction of the water system. These tipping points can be identified as thresholds for the indicator.
- 4) **Downscaling from planetary boundaries:** previous studies on water planetary boundaries (Rockström et al., 2009, 2023; Gerten et al., 2013; Richardson et al., 2023) have identified certain limits for indicators, such as freshwater use, at the planetary level. Translating these planetary boundaries for water resources to the local scale can complement the definition of SOS boundaries at the basin or regional level. It is crucial to note, however, that past research has only defined water planetary boundaries in a limited number of dimensions, which may not fully capture the multi-



dimensional nature of the entire water systems. Therefore, downscaling the water planetary boundary alone is insufficient for establishing SOS boundaries at the local scale.

The identification of thresholds is an iterative process that may need to be re-evaluated multiple times as our understanding of water systems deepens. Once all indicator values have been computed from the IWMS outputs, the identified thresholds are used as benchmarks to assess whether the local water system operates within the safe operating space under different scenarios and pathways. This final step leads to the definition of the multi-dimensional SOS of the local water systems.

2.1.2 Future scenarios and global policies

Scenarios describe possible trajectories of future climate and socio-economic conditions (Moss et al., 2010) and play an important role in understanding the impact of global change on regional and local water systems. Designing scenarios allows us to assess the SOS-Water under different climatic and socio-economic futures, while also contributing to the development of management pathways to address evolving climate conditions and socio-economic changes. Scenario design for evaluating the SOS-Water faces the intricate challenge of addressing the multi-faceted and dynamic nature of climate change impacts. The complexity arises from the uncertainty associated with future climatic conditions, socio-economic developments, and the interconnectedness of various variables. Capturing this complexity requires an approach that goes beyond a singular perspective. In the SOS-Water project, we aim to develop a rigorous and innovative scenario design approach to evaluate the SOS framework under changing climate and socio-economic conditions. The final approaches for future scenario design are investigated in WP1 (Co-developed water values and scenarios) and are available in deliverable D1.2 (From global to local scenario narratives) and milestone M1.1 (Scenarios and Management pathways available).

In this section, we explore various scenario design approaches applicable to the final future scenario design (as shown in Figure 5). These approaches can be classified based on how information is cascaded across different scales. There are three primary approaches: 1) the top-down approach, involving the downscaling of global climate and socio-economic projections; 2) the bottom-up approach, entailing the perturbation of local historical climate and socio-economic conditions; and 3) the hybrid approach, which integrates elements of both top-down and bottom-up methodologies. Additionally, the scenario design process can be categorized into expert-driven scenario design and participatory scenario co-design (i.e., stakeholders actively participate in the scenario development). Depending on the specific needs of each case study, the most fitting approach is selected.

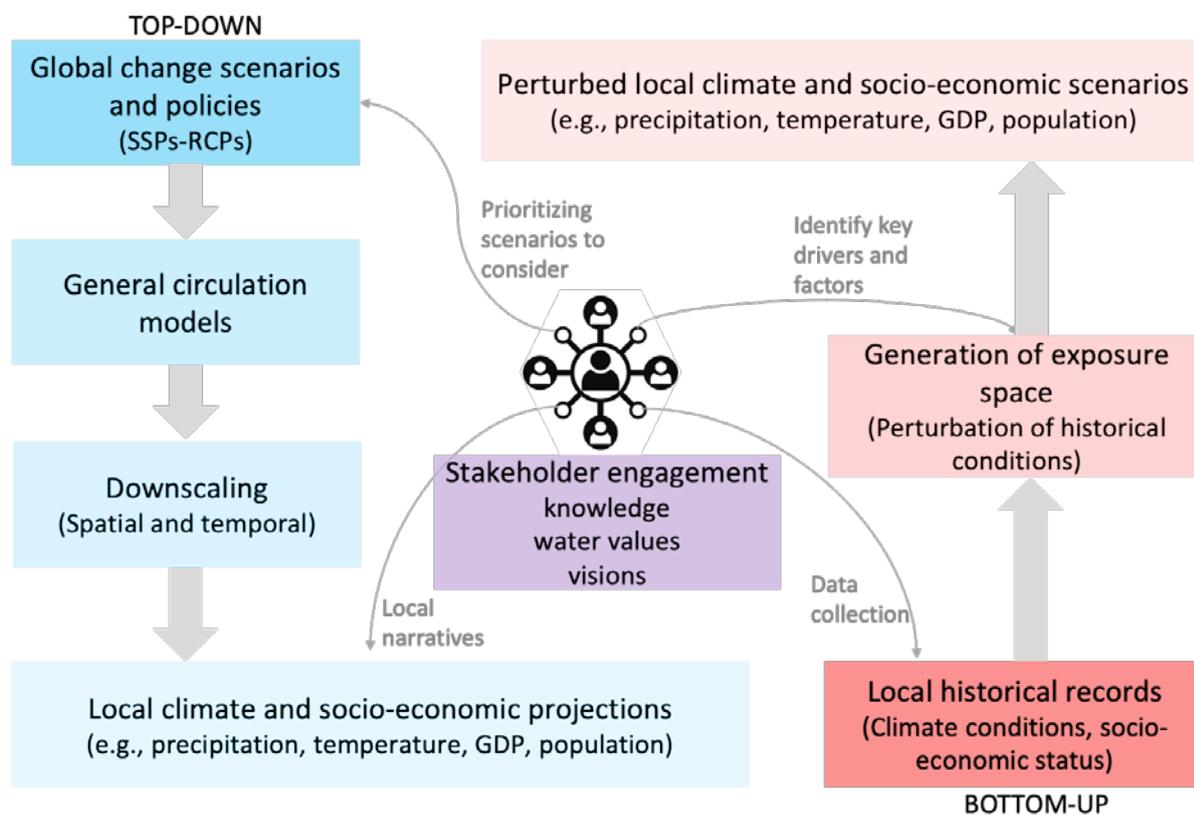


Figure 5. Multiple future change scenarios generation approaches (including Top-Down, Bottom-Up, and Integrated).

Global Change Scenarios and Policies

Global change scenarios, such as Representative Concentration Pathways (RCPs; Van Vuuren et al., 2011), and Shared Socio-economic Pathways (SSPs; Riahi et al., 2017), form the basis for investigating the potential impacts of diverse projected greenhouse gas emission trajectories and socio-economic development pathways at the global level.

The RCPs project potential climate futures by anticipating alterations in radiative forcing values relative to pre-industrial levels (Van Vuuren et al., 2011). These scenarios encompass a wide range of plausible future greenhouse gas emissions and are labeled based on their radiative forcing levels (in W/m^2) anticipated by the end of the 21st century. A set of four pathways of land use and emission of air pollutants and greenhouse gases that spanned a wide range of future outcomes until 2100 was originally identified: RCP2.6 (characterized by peaking and subsequent decline), RCP4.5 and RCP6.0 (representing stabilization pathways), and RCP8.5 (a business-as-usual trajectory). RCP2.6 represents a set of low-range emission scenarios and requires stringent climate policies to limit emissions (for example, the use of bioenergy and carbon capture and storage techniques). In contrast, RCP8.5 is representative of a high



range of non-climate policies scenarios. Climate models in CMIP5 (Taylor et al., 2012) and their evaluation in the IPCC AR5 (IPCC, 2013) were founded on these four RCPs. Notably, although RCPs are derived from internally consistent socio-economic assumptions, they intentionally did not cover a full range of possible socio-economic trajectories (Van Vuuren et al., 2011), hindering the correlation of socio-economic changes, such as population, education, and urbanization projections, with climate targets.

SSPs, developed alongside the RCPs, provide a comprehensive framework for assessing how different socio-economic drivers (e.g., population, economic growth, and urbanization) might change under various narratives and how these projections may influence greenhouse gas emissions and other factors relevant to climate change (Riahi et al., 2017). SSPs consist of five distinct narratives (labeled SSP1 through SSP5) that provide a textual description of how the future broad societal trends might change (O'Neill et al., 2017). SSP1 corresponds to a sustainable world with low challenges to mitigation and adaptation, while SSP3 portrays a world with high challenges in both mitigation and adaptation. SSP4 and SSP5 are “asymmetric cases,” with SSP4 assuming low challenges in mitigation and high challenges in adaptation, and SSP5 assuming the opposite. SSP2 is crafted envisioning intermediate challenges for both adaptation and mitigation.

The SSPs baseline scenarios represent alternative storylines about how the world might develop over the coming century in the absence of climate policy, while the RCPs represent radiative forcing levels that could be seen as targets for new mitigation policies. To build the climate and societal change scenarios, the Scenario Model Comparison Project (ScenarioMIP) (O'Neill et al., 2016) combined the SSP narratives with levels of radiative forcing projected for the year 2100 as a result of human GHG emissions. Eight forcing pathways were selected in the CMIP6 scenarios design, including four forcing pathways adopted from four updated RCPs used in CMIP5 and four new forcing pathways not covered by the RCPs, comprising unmitigated SSP baseline scenarios and new mitigation pathways (such as those reaching 2.6, 7.0, and 3.4 W/m² in 2100). This combination allows for a nuanced exploration of complex interactions between human activities and the climate system (as shown in Figure 6). These scenarios were arranged into two tiers differentiated by priority (O'Neill et al., 2016). Tier 1 (e.g., SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) spans a wide range of uncertainty in future forcing pathways, which is important for research in climate science, integrated assessment modelling, impacts adaptation, and vulnerability communities. Tier 2 includes additional scenarios of interest (e.g., SSP1-1.9, SSP4-3.4, SSP4-6.0, SSP5-3.4).

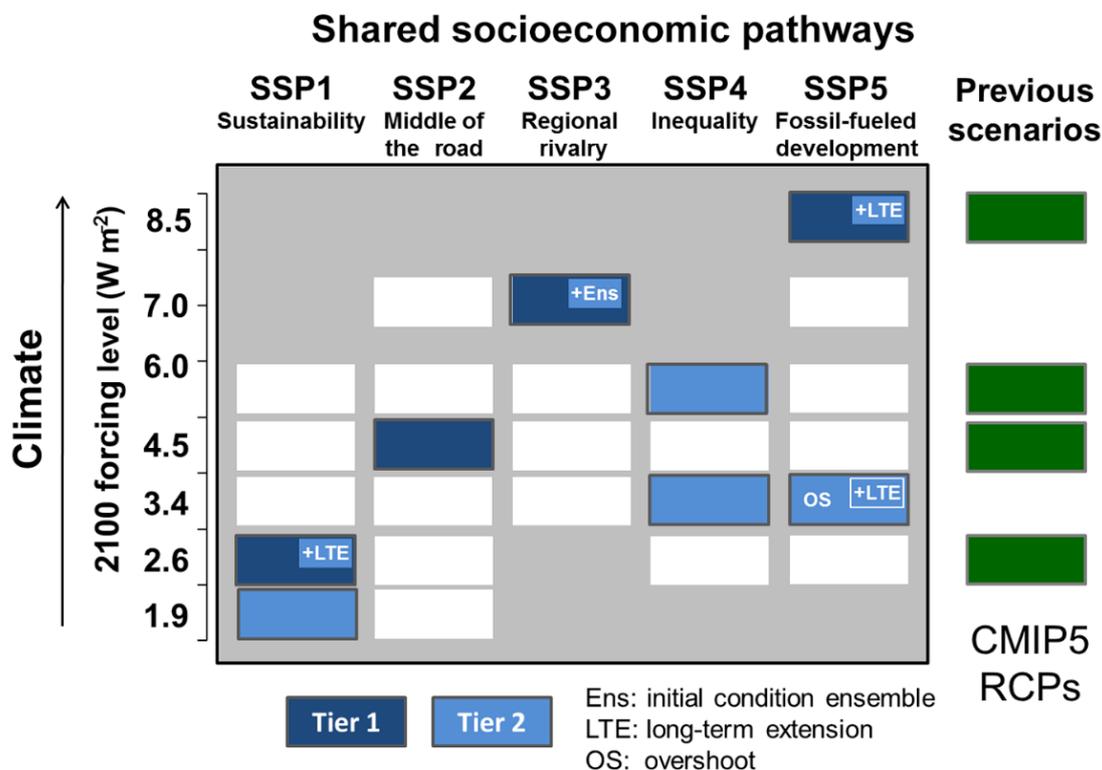


Figure 6. SSPs-RCPs scenario matrix from O'Neill et al. (2016).

There are five illustrative scenarios used in IPCC AR6 (IPCC, 2021), namely, SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. Each scenario represents a distinct narrative of potential future developments in society, economy, and technology, paired with specific greenhouse gas concentration trajectories. SSP1-1.9 envisions a sustainable world with stringent mitigation efforts, aiming to limit global warming to 1.9 °C. SSP1-2.6 represents a similar sustainable trajectory with a focus on peaking and subsequent decline in emissions. SSP2-4.5 portrays an intermediate scenario with stabilization pathways, while SSP3-7.0 depicts a world facing high challenges in mitigation and adaptation efforts. Lastly, SSP5-8.5 outlines a scenario characterized by high emissions, representing a future trajectory with limited climate policies, leading to substantial global warming. These illustrative scenarios offer a comprehensive exploration of different socio-economic and climate pathways for a more thorough understanding of potential future developments.

It is important to note that in this report, SSPs and RCPs are considered as “scenarios” because of their global definition, distinguishing them from the local management pathways (which are essentially local actions to be implemented in the individual case studies) discussed in [Section 2.1.3](#). It is noteworthy that, while some of the SSPs and RCPs (particularly, RCP2.6) assume the implementation of global mitigation and adaptation policies, such as stringent air pollution control, reforestation policies, and climate policies, these global-level policies and pathways are beyond the control of local management during regional or local-scale impact assessments. Global-level policies differ from the local policies and pathways which can be fully controlled at the regional or local level.



Top-Down, Bottom-Up and Integrated Scenario Design

Broadly, there are three main approaches applied to design climate change impact assessments at the regional or local scale: the “top-down”, the “bottom-up”, and the “integrated approaches” (as shown in Figure 5). The “top-down” (also known as “scenario-led”) approach involves downscaling climate change projections from Global Circulation Models (GCMs) under a range of emission scenarios (Wilby & Dessai, 2010). The resulting local scenarios, such as projections of climate variables (e.g., precipitation and temperature at the local scale), are used to drive local impact assessment models to evaluate the water system’s response to different conditions (e.g., estimating future stream flow or biodiversity). The term “top-down” is used because information flows from global-scale models down to local-scale applications, considering permutations of emission scenarios, climate models, and downscaling methods. Although widely used for climate change impact assessment, this approach poses a challenge due to the cascading propagation of uncertainty, which requires considerable time and effort to characterize and reduce. Despite its utility for decision-makers focusing on climate-related risks on a global scale, a lack of attention to the complexity of local contexts creates a communication gap between climate experts and policymakers (Pilli-Sihvola et al., 2015). It is therefore essential to move beyond simple downscaling toward a practice-oriented and context-dependent scenario design, obtained by incorporating the perspectives of local and scientific experts in the top-down scenario building approach (Swart et al., 2014). As an example, the selection of appropriate scenarios and models can be made through engagement with local stakeholders.

On the other hand, “bottom-up” approaches (also known as “scenario-neutral”) focus on the assessment of impacts caused by past and present climate variability (Wilby & Dessai, 2010) and may not necessarily be linked to global future scenarios (Nilsson et al., 2017). The “bottom-up” approach has as a starting point a specific domain, such as a local region or a specific sector (Nilsson et al., 2017). In the context of climate and socio-economic scenario design, this often means considering factors and conditions that are sensitive to climate-related threats at the local level (e.g., climate conditions or socio-techno-economic factors). A comprehensive exposure space, composed of a wide range of plausible scenarios, is generated based on the perturbation of historical and present climate (e.g., precipitation and temperature), and used to evaluate the response of the local water system to a changed climate. This approach allows for a nuanced understanding of the unique challenges faced by local water resources and facilitates the development of tailored adaptation strategies.

The “top-down” and “bottom-up” approaches offer two distinct perspectives on addressing uncertainty of future conditions in scenario design. The “top-down” approach allows for impact assessment associated to official projections at the global scale but has the drawback of an uncontrolled expansion of uncertainty. The “bottom-up” approach does not explicitly consider official climate change projections (e.g., SSPs and RCPs) when designing scenarios and comes with the risk of underestimating the potential impacts of global climate change. Therefore, combining these two approaches (i.e., “integrated” approach) for future scenario design can ensure a holistic view, encompassing both global trends and localized intricacies. There are multiple studies that have combined both the top-down and



bottom-up approaches in the adaptation process (Bhave et al., 2013; Girard et al., 2015; Mastrandrea et al., 2010).

Stakeholder Engagement in Scenario Design

In addition, it is crucial to ensure that future scenarios are designed to be relevant to real-world situations and local contexts. Therefore, in the scenario design process, SOS-Water implements an inclusive and iterative stakeholder engagement approach to identify and incorporate stakeholders' knowledge, water values, visions, and management options. This is in contrast with expert-driven scenario design, where scenarios are primarily developed by experts without involving local stakeholders. The active engagement of local stakeholders is essential for several reasons. Firstly, stakeholders possess invaluable local knowledge often overlooked in the top-down approach. Their insights contribute to a more accurate representation of vulnerabilities and potential impacts. Secondly, involving stakeholders fosters a sense of ownership, trust, and commitment to the developed scenarios, which is vital for the successful implementation of adaptation measures. Thirdly, stakeholders bring diverse perspectives, ensuring that the scenarios consider social, economic, and cultural dimensions, making them more resilient and adaptable to the specific needs of the community. Lastly, the involvement of stakeholders enables the careful consideration and inclusion of local communities, preventing the inadvertent exclusion of misrecognized and marginalized groups in influencing the definition of local SOS-Water boundaries. These groups' contribution is essential to ensure social justice in the definition of the SOS for water resources at a local level (Gupta et al., 2023). In essence, stakeholder involvement bridges the gap between theoretical scenario design and practical, on-the-ground implementation.

Stakeholders can be involved in multiple steps of the scenario design process described in the previous section (as shown in Figure 5). In the top-down scenario design process, regional and local stakeholders can participate in highly interactive workshops and forums that include planners, public governors, sector representatives, local experts, and researchers. In such instances, the modeler has the opportunity to present the top-down global change scenarios, enabling stakeholders to understand the broader context and potential global impacts. Stakeholders can then provide their narratives and feedback, expressing concerns, priorities, and local observations in response to the global change scenarios. Through a collaborative and iterative decision-making process, the modeler can, in the end, select the most prioritized global change scenarios for SOS-Water evaluation and incorporate local narratives for scenario generation, capturing local contexts.

There is also ample opportunity for local stakeholder involvement in the bottom-up scenario design process. Firstly, local stakeholders can be very helpful in historical data collection, ensuring the accuracy and richness of data used for perturbation. Secondly, they can assist in identifying key variables and factors that impact the water system at the local level. Their insights and local narratives contribute to a more nuanced bottom-up scenario design. Lastly, local stakeholders can help to co-construct future scenarios based on perturbed historical records. This helps to capture local knowledge and ensures that scenarios align with the community's unique context.



In top-down, bottom-up, and integrated or hybrid top-down and bottom-up approaches, ongoing communication and collaboration with stakeholders are crucial. Establishing partnerships that value local knowledge and perspectives ensures that scenarios are not only scientifically robust but also reflective of the diverse and context-specific challenges faced by communities.

2.1.3 Local management pathways

Pathways are defined as a time-sequence of structural and non-structural actions (as illustrated in Table 1) that enable policymakers to explore alternative adaptation options to climatic and socio-economic changes (Haasnoot et al., 2012). In the context of water system management, actions are elementary options of intervention on the system (e.g., the construction of a new dam or irrigation canal, the imposition of an environmental flow in a specific river stretch) that are expected to allow the achievement of a pre-defined goal (e.g., water, energy, food security). Structural actions concern the physical modifications of the system, such as designing and determining the location and size of infrastructures for collecting, transporting, distributing, and utilizing water resources. Examples of structural actions are the construction of a dam or a canal, the installation of an irrigation system, or the construction of a wastewater treatment plant. Non-structural actions either modify the system only functionally or they alter the effects that the system produces. Examples of non-structural actions are regulations that set water quality standards or environmental flows, tariffs for water services, incentives for farmers to encourage ‘virtuous’ behavior (e.g. adopting less water-intensive crops or planting woody buffer strips), or the operating policy of a reservoir.

Actions can also be categorized into planning actions and management actions according to the time step with which the actions are decided. A planning action is decided over a very long time-horizon (e.g. years), sometimes once and for all. A typical example of planning action is the construction of a new dam. Conversely, a management action is taken and revised periodically. A typical example of management action is the operation of a dam, which determines the volume of water to be released from the dam on an hourly/daily/weekly/monthly basis, with the action frequency depending on the characteristics of the case study.

Table 1. List of examples of actions in local water system management pathways.

Local management pathways	Planning actions	Management actions
Structural actions	<ul style="list-style-type: none"> • Construction of new dam or reservoir • Implementation of irrigation system 	<ul style="list-style-type: none"> • Maintenance of storage structures • Rehabilitation or retrofitting of aging water infrastructure • Afforestation: number of trees, type of plants



	<ul style="list-style-type: none"> • Development of water supply infrastructure for a growing urban area 	
Non-structural actions	<ul style="list-style-type: none"> • Management criteria for reservoirs and diversions • Land use regulations: zoning, limits to expansion, urban regulation • Regulation and/or water distribution policies 	<ul style="list-style-type: none"> • Release of water from reservoirs • Adoption of incentive programs for sustainable farming • Broadcast of alarms and pre-flood alarms

Local management pathways can be identified through a combination of three approaches: 1) extensive literature view, which includes peer-reviewed journals, technical reports, and planning documents; 2) communication with local experts, such as water managers and researchers; and 3) stakeholder consultation seminars or workshops. In the SOS-Water project, we employ these three approaches for the identification of ongoing (i.e., already implemented), as well as planned and potential alternative management pathways.

The determination of the actions to be evaluated in local impact assessment depends on several factors: 1) the technical, institutional, financial, and legal feasibility of the measures at the local level; 2) the preference of the local decision maker to adopt the pathways; 3) the capacity of available models to incorporate the pathways in the simulation processes. From the impact assessment perspective, it is also important to consider the lifetime of the pathways, as this can influence the experimental design of future scenarios. If the lifetime of the pathways (actions) is short (e.g., a few years or less), investigating impact assessments using recent climatology may suffice. However, if the pathways have a long lifetime, spanning multiple decades (e.g., in the case of dam construction), it is necessary to carry out local impact assessment across a range of long-term future scenarios. Information on these local management pathways is essential for assessing the local water system’s safe operating space and requires deep collaboration with local stakeholders.

2.1.4 Integrated water modeling system

SOS-Water uses an integrated water modelling system (IWMS) to represent all natural and socio-economic processes of the water system, including ecological, environmental, agricultural, and energy dimensions. The IWMS aims to simulate all relevant information in both the current state and future scenarios developed in [Section 2.1.2](#) and with or without the implementation of local management pathways developed in [Section 2.1.3](#). In this way, the IWMS can be used to evaluate the response of the water system under various conditions and help stakeholders to develop adaptation pathways to

achieve sustainable water resources management. To achieve this goal, the IWMS developed in the SOS-Water project consists of two components: 1) global hydrology models (i.e., models that assess the impacts of climate variability and change and human activities on water resources availability) and 2) local impact models (i.e., models that assess the impacts of water availability constraints on the economy, society, and environment). The IWMS framework and its links with other components in the SOS-Water project are demonstrated in Figure 7, and its development is carried out in WP2 (Integrated water modelling system). The linkages between global hydrology models and local impact models, and model calibrations and simulation results will be described in D2.2, D2.3 and D2.4.

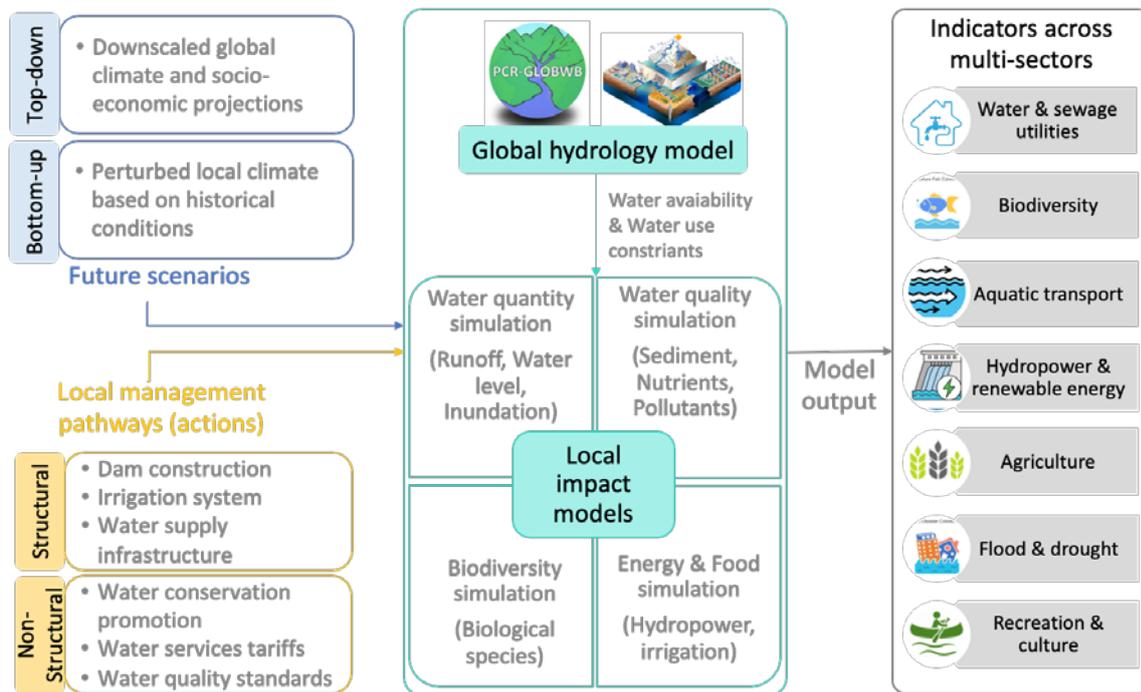


Figure 7. Integrated water modelling system composed of water system models and local impact models and its linkage with other components in the SOS-Water project e.g., scenario design, local management pathways and indicators.

Global Hydrology Models

Global hydrology models (e.g., PCR-GLOBWB (Sutanudjaja et al., 2018), and CWatM (Burek et al., 2020) are useful tools in understanding water resources by simulating the complex interactions within hydrological systems. These models take climate variables (e.g., precipitation, temperature, humidity), characteristics of landscape (e.g., land use, soil types, topography) as inputs and simulate fundamental hydrological processes such as precipitation, evaporation, infiltration, surface runoff and groundwater flow. They can calculate state variables that represent certain dimensions of the water systems (e.g., water availability and water use for different sectors). These global hydrology models are useful to assess water demand, water supply and environmental needs over time under global future scenarios. They have been previously applied to several case studies around the world and at European and global scales (Burek et al., 2020; Sutanudjaja et al., 2018; Long et al., 2020).



Local Impact Models

Global hydrology models alone cannot simulate all the water system state variables required to assess the multi-dimensional SOS. This includes various aspects such as water availability (e.g., water supply) and demand (e.g., sectoral water withdrawals), environmental factors (e.g., water quality), ecological considerations (e.g., biodiversity), and impacts on energy and economy (e.g., hydropower generation). Moreover, these global hydrological models are constrained by limited spatial resolutions and simplified modeling processes. It is therefore important to couple global hydrology models with regional or local impact models that can better capture local water system dynamics.

A diverse set of local impact models are built or under development within each case study to simulate variables according to stakeholders' preference. Examples of these local impact models include CASCADE (Schmitt et al., 2018, 2019; Tangi et al., 2019) for sediment transport, VRSAP (Phong et al., n.d.) for water salinity, SNN (Hoef et al., 2014) for biodiversity, hydro-economic models (Macian-Sorribes et al., 2017) for water supply, energy, and economic benefits simulation. A detailed description of the local impact models used will be presented in each of the case studies.

3 Applications and Assessment of SOS Water

This section will describe the comprehensive SOS evaluation for all case studies. For each case study, a brief description of the basin's characteristics will be provided to contextualize the work, along with the stakeholder engagement activities carried out to support the definition of the system's SOS. This will be followed by the presentation of the final indicators and thresholds identified and applied, together with the future scenarios used to evaluate the system under future conditions, and the Integrated Water Modeling System (IWMS) developed for the SOS assessment. Finally, the section will present the system's final SOS evaluation under different future scenarios in a business-as-usual setup.

3.1 Jucar Case Study

The Jucar River Basin (JRB) is one of the main basins in Eastern Spain, with an area equal to 22,261 Km². Its climatic patterns are mostly Mediterranean, with mild winters, dry and hot summers, and peak precipitation (and flood risk events) in autumn. With an intensive use of water, in particular for agriculture, it is characterized by a weak equilibrium between surface water resources and water demands, whose annual values are very similar, and by severe and multiannual droughts. This combination of issues has driven an intensive infrastructure development, well-established water planning and management protocols, and governance. The main regulation facilities are the reservoirs of Alarcon, Contreras and Tous. Moreover, groundwater use and conjunctive use are established practices in the Jucar River Basin, which has caused issues related to overpumping. This issue is particularly prominent in two aquifers: the Mancha Oriental and the Requena-Utiel, in which actions have been triggered to prevent overexploitation and enable a sustainable management of groundwater bodies.

Currently, a significant percentage of surface and groundwater bodies are classified as being in poor status under the EU Water Framework Directive. Despite the efforts made by the JRB Agency (CHJ),



future prospects remain unpromising. The majority of climate change projections anticipate a decrease in water resources, which could further challenge water allocation and ecosystem services provision. Moreover, extreme droughts are also predicted to increase, both in frequency and severity, adding more pressure to the current situation.

The main challenges and pressures of the JRB are related to water scarcity (both in average and extreme drought events), energy transition (reducing energy demand and limiting the impact of energy price volatility in the farming sector), sustainability of crop production, and sustainability of ecosystems (with two main targets: the preservation of the Albufera wetland and of native fish habitat through the inland water bodies of the Jucar).

Stakeholder engagement

UPV has a long record of participatory approaches and stakeholder engagement in the JRB. Activities from past projects have contributed to refining and validating the future scenarios used and the definition of the hydro-economic model employed, as well as the implementation and expected impacts of climate change adaptation measures. The participatory approaches related to SOS-WATER revolve around the choice of indicators and thresholds to define the Safe Operating Space (SOS). In this regard, a workshop was held on April 4, 2025, to decide which indicators would be used in the SOS definition. The main outcome of this activity was the final list of indicators to be computed and used in further steps of SOS-WATER developments in the Jucar River Basin.

3.1.1 Indicators and Thresholds

Table 2 shows the indicators chosen for the JRB case study and their main features. These indicators come from those included and described in D4.1.

Table 2. Indicators chosen for the Jucar River Basin case study.

Indicator	Unit	Spatial domain	Observations
Groundwater Level Index (GLI)	Mm ³ /year	Mancha Oriental aquifer	The main groundwater body in the basin is subject to overexploitation. Measured as the annual change in storage foreseen by the model.
Water Supply Reliability (WSR)	Mm ³	Urban demands of Valencia, Albacete and Sagunto, and Mancha Oriental municipalities	Measured as the sum of annual deficits over the last 10 years.
		Cofrentes nuclear power plant	Measured as the annual deficit



Indicator	Unit	Spatial domain	Observations
		Inflows to the Albufera wetland	Measured as the annual deficit
	GWh/year	Hydropower production	Measured as the annual production
Crop Water Stress Index (CWSI)	Dimensionless	All agricultural demands, grouped into Mancha Oriental aquifer demands, Traditional crops and Jucar-Turia canal demands	Measured as the percentage of the crop production that would be achieved in the absence of water deficits.
Mean Monthly Flow Alteration (MMFA) measured through differences in the Weighted Usable Habitat (WUA)	Dimensionless	Trout fish in Alarcon (fry, juvenile and adult)	Representative native fish per stream. Measured as the cumulative Distribution Functions (CDFs) of the percentage of maximum possible habitat for the whole period.
		Chub, barbel and loina fish in the Mancha Oriental (fry, juvenile and adult)	
		Loina fish downstream of the Molinar reservoir (fry, juvenile and adult)	
		Loina fish downstream of the Contreras reservoir (fry, juvenile and adult)	
		Loina fish downstream of the Naranjero reservoir (fry, juvenile and adult)	
		Chub and barbel fish downstream of the Antella weir (fry, juvenile and adult)	

Concerning thresholds, Table 3 illustrates, for each indicator, the threshold chosen and the information source. In most cases, they refer to the Jucar River Basin Management Plan (JRBMP) or to the concept of maintaining or improving the current level of performance. In most cases, the threshold value could be subject to refinement in further participatory approaches.

Table 3. Thresholds adopted for the Jucar River Basin case study.



Indicator	Threshold	Status	Source
Groundwater Level Index (GLI)	The average value of the analysis period should be positive	Tentative	Modelers
Water Supply Reliability (WSR)	Urban demands: the 10-year cumulative deficit should never be higher than 8% of the annual demand	Final	JRBMP
	Cofrentes nuclear power plant: no deficits are allowed	Final	JRBMP, stakeholders
	Hydropower production: the average annual production should not fall below the current level	Tentative	Stakeholders
	Albufera wetland: deficits must be zero at least 90% of the years of the analysis period	Final	JRBMP
Crop Water Stress Index (CWSI)	The average percentage of the analysis period for the given demand should not be lower than that of the current climate	Tentative	Stakeholders
Mean Monthly Flow Alteration (MMFA) measured through differences in the Weighted Usable Habitat (WUA)	<p>Fish species coined as “representative” by the Jucar RBA (one per stream, adult stage): WUA should never fall below 30%.</p> <p>All fish species and growing stages: either the minimum habitat should be equal to or higher than the natural regime; or the first tercile, the second tercile and the maximum habitat should be equal to or higher than the natural regime.</p>	Tentative	Modelers

Setting thresholds for fish habitat was particularly complex due to the coexistence of different fish species and growing stages. Given that referring to the natural regime in setting thresholds is challenging for the Jucar, it was decided that, within each pair of fish species and stages, a safe status would be reached if either the minimum habitat is equal or higher than the one of the natural regime (implying a maintenance or improvement of the fish habitat in extreme drought events) or, in case of failing, the first and second terciles and maximum levels remain the same or higher than those of the natural regime (in which case fish would be on average in the same or even in a better status, regardless of being more vulnerable during extreme droughts).



3.1.2 Future Scenarios

As presented in D1.2, the SSP-RCP combinations selected for the Jucar case study are SSP1-2.6 (sustainable pathways scenario), SSP3-7.0 (regional rivalry scenario) and SSP5-8.5 (fossil fuel-rich development scenario). For these scenarios, bias-adjusted daily-scale meteorological variables were obtained for the ISMIP3b ensemble of 5 models: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL. In particular, we used bias-adjusted projections developed by the GoNEXUS project at 10 Km resolution, developed by applying the BASD algorithm using ERA5-Land as reference. Further information can be found in the GoNEXUS D2.2, publicly available at CORDIS (<https://cordis.europa.eu/project/id/101003722/results/es>). The meteorological variables considered are precipitation (pr), near-surface air temperature (tas), maximum and minimum air temperature (tasmax, tasmin), and surface downwelling radiation (rsds). The following time horizons were considered: historical (1979-2014), short-term (2015-2040) and mid-term (2041-2070).

Using as inputs the meteorological projections described above, hydrological discharges for the Jucar River Basin were obtained from the TETIS eco-hydrological model, a fully distributed model at 250 m resolution that includes the main hydrological processes. The resulting hydrological projections at the annual scale can be found in Figure 8. The boxplots are grouped by model, each associated to a different color. Within each group, the boxplots show the total yearly hydrological discharge of the Jucar for the historical, short-term and mid-term periods, respectively. As expected, the severity of climate change impacts is aligned with the severity of the SSP-RCP combination. SSP1-2.6 depicts a maintenance or even a slight increase of discharges in the short-term, followed by a decrease afterwards. Two of the five models depict a minor increase of streamflows in the mid-term compared to the historical period, while the rest show a slight reduction.

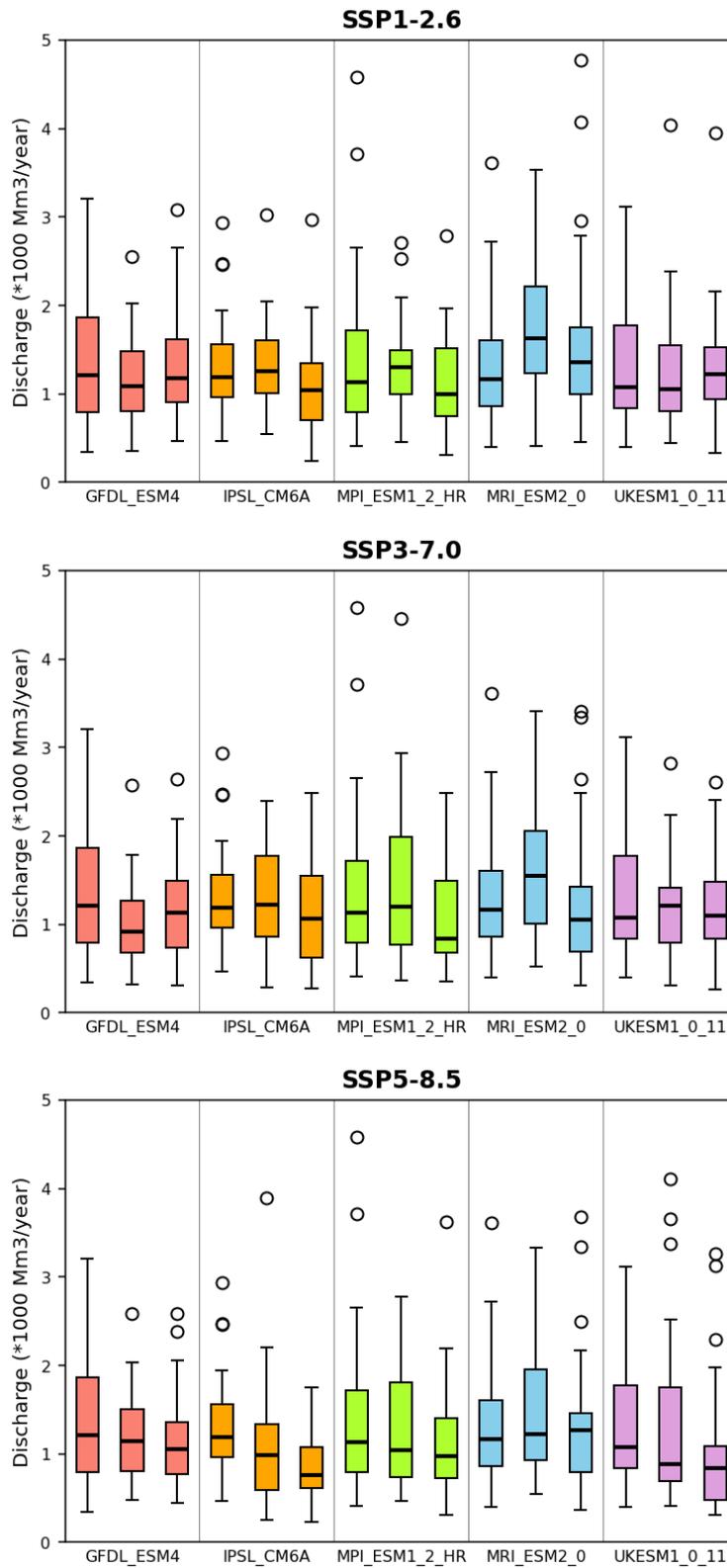


Figure 8. Jucar River Basin hydrological scenarios.



SSP3-7.0 shows the same temporal pattern, but with smaller increases in the short-term (and even decreases in the most pessimistic model) and steeper falls in the mid-term. In contrast to SSP1-2.6, no climate model shows a situation in which mid-term discharges are higher than historical ones. SSP5-8.5 does not show any increase of discharge in the short-term, but instead a maintenance (in two models) or a slight decrease (in three of them). These are followed by a decrease whose steepness depends on the climate model considered, with only one model providing similar average discharge values.

3.1.3 Integrated Water Modeling System

The modelling chain adopted for the Jucar River Basin is shown in Figure 9. The individual model components are described in D2.2 and D5.1, with a focus on the hydro-economic STIG-CROPROP Integrated Water Resources Management model. CMIP6 meteorological scenarios are employed to force the TETIS ecohydrological model and produce hydrological time series in response to climate scenarios. These discharge projections are then used as inputs for the STIG-CROPROD hydro-economic model. This model computes stocks and flows in the Jucar River system (storages in reservoirs and aquifers, streamflows, deliveries and deficits in consumptive demands, hydropower production, crop production, and economic benefits in demands), which are then used to compute the GLI, WSR and CWSI indicators. On the other hand, streamflows in river reaches with fish habitat models are used to compute the WUA metrics employed to estimate the MMFA. These reaches are:

- Immediately downstream of the Alarcon reservoir (Alarcon)
- In the middle of the Mancha Oriental area, influenced by the stream-aquifer interaction shared between the Jucar River and the Mancha Oriental aquifer (Madrigueras)
- Immediately downstream of the Molinar hydropower reservoir (Molinar)
- Immediately downstream of the Contreras reservoir (Contreras)
- Immediately downstream of the Naranjero hydropower reservoir, a sport fishing area (Dos Aguas)
- Immediately downstream of the Antella weir, which diverts water to the main surface demand of the Jucar, the Acequia Real (Antella)

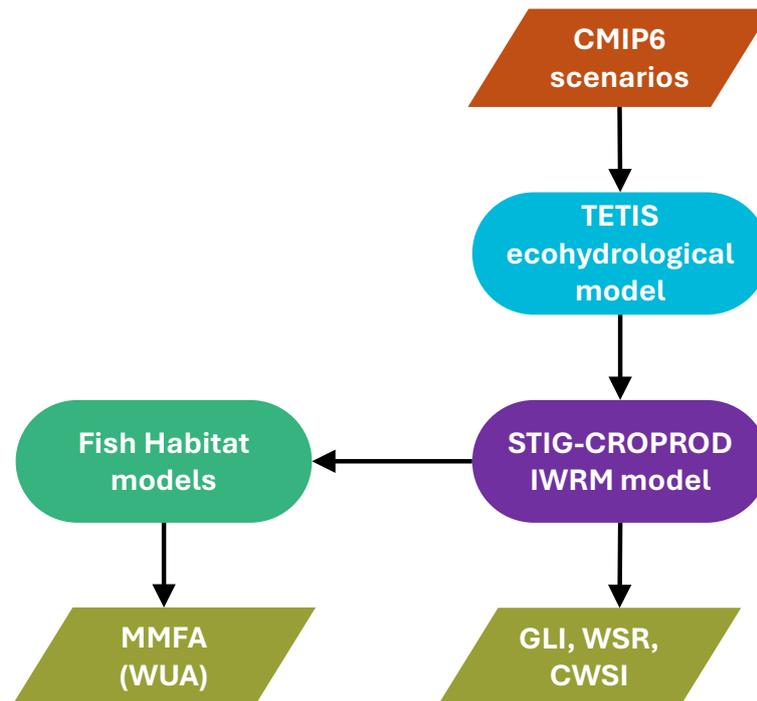


Figure 9. Jucar River Basin modelling framework.

3.1.4 Multi-Dimensional SOS Assessment Results

The first stage in the SOS assessment is the transformation of model outputs into indicators. For each time series, the following stages are applied to this end:

- **GLI:** the difference in groundwater storage in the Mancha Oriental aquifer between the end and the beginning of each year is computed. Then, the average over each time period is calculated in order to apply the threshold. The Jucar River basin is safe in terms of GLI if this average value is positive.
- **WSR:** the process depends on the demand:
 - Urban demands: for each urban demand, from the 10th year of the time series, the monthly deficits of the last 10-year moving horizon are added. The Jucar River basin is safe for this demand if the highest 10-year deficit is equal to or lower than 8% of the annual demand for each given urban area.
 - Cofrentes nuclear power plant: the monthly time series of deficits to this demand is used. In order to be in a safe operating space, all monthly deficits need to be zero.
 - Hydropower production: the monthly amount of energy produced in all hydropower plants is added and upscaled to the annual scale. To be safe, the annual average hydropower production must be equal to or higher than the average value of the historical scenarios.
 - Albufera wetland: the monthly deficits in the inflows to the wetland are aggregated to the annual scale. The Jucar River basin is safe in terms of the Albufera if these annual values are equal to zero for at least 90% of the years.



- **CWSI**: for each agricultural demand, the annual production (in percentage of the total maximum production achieved in the absence of water deficits) of all crops is aggregated. To be safe, the average over each period should be equal to or higher than the average value computed for the historical scenarios.
 - **MMFA**: for each river reach, fish species and growing stages, the monthly time series of WUA are computed and their cumulative probability functions (CDFs) are calculated. From each CDF, the minimum, first tercile, second tercile and maximum values are extracted. In order to be safe for the given reach, fish species and growing stage, the following requirements should be fulfilled:
 - If the fish species is named as “representative” by the Jucar RBA, WUA must be equal to or higher than 30% for the whole period (threshold set by law).
 - Regardless of being considered representative or not, either:
 - The minimum WUA must be equal to or higher than the value achieved, for the same reach, fish species and growing stage, in a scenario corresponding to the current climate and natural regime.
- Or:
- The first and second terciles, as well as the maximum WUA, should be equal to or higher than the value obtained by the natural regime scenario with the current climate.

Figure 10, Figure 11 and Figure 12 present the indicator values achieved under the climate change scenarios and periods previously described. The results have been split into two tables to present the WUA indicators separately, given their large number compared to the others. Both tables share the same red-blue colormap, in which red represents the poorest performance and blue the best one. Apart from GLI and WSR for hydropower, all indicators are expressed in a normalized 0-1 interval. WSR for urban (Albacete, MO urban, Valencia, Sagunto) and for the nuclear demand (Cofrentes) show null values regardless of the scenario and period considered, which implies that no deficits would be suffered in the future. The rest of WSR indicators, GLI and CWSI tend to show a decreasing future performance with a direct relationship between degradation and scenario severity, as well as with the time period. The only exception is the GLI index, whose performance improves in the short-term for both SSP1-2.6 and SSP3-7.0.



SCENARIO	GLI	WSR							CWSI			
		MO aquifer	Albacete	MO Urban	Valencia	Sagunto	Cofrentes	Hydropower	Albufera	Mancha	Jucar-Turia	Traditional
Historical - GFDL_ESM4 (1979-2014)	6.59	0.00	0.00	0.00	0.00	0.00	0.00	497.80	0.03	0.54	0.81	0.77
Historical - IPSL_CM6A (1979-2014)	8.51	0.00	0.00	0.00	0.00	0.00	0.00	465.95	0.00	0.58	0.83	0.85
Historical - MPI_ESM1_2_HR (1979-2014)	12.17	0.00	0.00	0.00	0.00	0.00	0.00	475.51	0.06	0.69	0.79	0.77
Historical - MRI_ESM2_0 (1979-2014)	7.85	0.00	0.00	0.00	0.00	0.00	0.00	496.39	0.03	0.67	0.80	0.78
Historical - UKESM1_0_11 (1979-2014)	3.78	0.00	0.00	0.00	0.00	0.00	0.00	437.01	0.11	0.45	0.72	0.64
SSP1-2.6 - GFDL_ESM4 (2015-2040)	12.25	0.00	0.00	0.00	0.00	0.00	0.00	377.04	0.04	0.47	0.70	0.74
SSP1-2.6 - IPSL_CM6A (2015-2040)	14.48	0.00	0.00	0.00	0.00	0.00	0.00	424.34	0.00	0.46	0.79	0.84
SSP1-2.6 - MPI_ESM1_2_HR (2015-2040)	17.66	0.00	0.00	0.00	0.00	0.00	0.00	397.94	0.08	0.48	0.78	0.84
SSP1-2.6 - MRI_ESM2_0 (2015-2040)	24.88	0.00	0.00	0.00	0.00	0.00	0.00	633.28	0.00	0.83	0.96	0.99
SSP1-2.6 - UKESM1_0_11 (2015-2040)	19.87	0.00	0.00	0.00	0.00	0.00	0.00	404.99	0.12	0.31	0.71	0.58
SSP1-2.6 - GFDL_ESM4 (2041-2070)	7.08	0.00	0.00	0.00	0.00	0.00	0.00	448.12	0.03	0.39	0.82	0.87
SSP1-2.6 - IPSL_CM6A (2041-2070)	-1.44	0.00	0.00	0.00	0.00	0.00	0.00	308.14	0.14	0.23	0.65	0.49
SSP1-2.6 - MPI_ESM1_2_HR (2041-2070)	1.07	0.00	0.00	0.00	0.00	0.00	0.00	359.67	0.10	0.37	0.73	0.70
SSP1-2.6 - MRI_ESM2_0 (2041-2070)	-5.60	0.00	0.00	0.00	0.00	0.00	0.00	575.22	0.00	0.53	0.88	0.93
SSP1-2.6 - UKESM1_0_11 (2041-2070)	3.56	0.00	0.00	0.00	0.00	0.00	0.00	436.79	0.10	0.31	0.85	0.82
SSP3-7.0 - GFDL_ESM4 (2015-2040)	10.53	0.00	0.00	0.00	0.00	0.00	0.00	358.11	0.15	0.30	0.64	0.48
SSP3-7.0 - IPSL_CM6A (2015-2040)	14.51	0.00	0.00	0.00	0.00	0.00	0.00	395.79	0.04	0.52	0.77	0.70
SSP3-7.0 - MPI_ESM1_2_HR (2015-2040)	16.68	0.00	0.00	0.00	0.00	0.00	0.00	484.96	0.08	0.49	0.78	0.84
SSP3-7.0 - MRI_ESM2_0 (2015-2040)	19.11	0.00	0.00	0.00	0.00	0.00	0.00	565.63	0.00	0.53	0.87	1.00
SSP3-7.0 - UKESM1_0_11 (2015-2040)	15.82	0.00	0.00	0.00	0.00	0.00	0.00	346.86	0.08	0.22	0.64	0.62
SSP3-7.0 - GFDL_ESM4 (2041-2070)	-10.20	0.00	0.00	0.00	0.00	0.00	0.00	351.98	0.10	0.21	0.72	0.64
SSP3-7.0 - IPSL_CM6A (2041-2070)	-18.81	0.00	0.00	0.00	0.00	0.00	0.00	315.97	0.14	0.24	0.70	0.58
SSP3-7.0 - MPI_ESM1_2_HR (2041-2070)	-5.09	0.00	0.00	0.00	0.00	0.00	0.00	284.91	0.14	0.18	0.66	0.44
SSP3-7.0 - MRI_ESM2_0 (2041-2070)	-4.51	0.00	0.00	0.00	0.00	0.00	0.00	446.30	0.10	0.39	0.77	0.73
SSP3-7.0 - UKESM1_0_11 (2041-2070)	6.13	0.00	0.00	0.00	0.00	0.00	0.00	400.31	0.03	0.16	0.76	0.76
SSP5-8.5 - GFDL_ESM4 (2015-2040)	16.85	0.00	0.00	0.00	0.00	0.00	0.00	379.78	0.08	0.39	0.75	0.74
SSP5-8.5 - IPSL_CM6A (2015-2040)	-4.01	0.00	0.00	0.00	0.00	0.00	0.00	313.98	0.12	0.28	0.60	0.43
SSP5-8.5 - MPI_ESM1_2_HR (2015-2040)	12.28	0.00	0.00	0.00	0.00	0.00	0.00	428.69	0.04	0.38	0.74	0.60
SSP5-8.5 - MRI_ESM2_0 (2015-2040)	17.94	0.00	0.00	0.00	0.00	0.00	0.00	523.32	0.00	0.62	0.87	0.96
SSP5-8.5 - UKESM1_0_11 (2015-2040)	9.01	0.00	0.00	0.00	0.00	0.00	0.00	432.62	0.15	0.37	0.69	0.60
SSP5-8.5 - GFDL_ESM4 (2041-2070)	1.96	0.00	0.00	0.00	0.00	0.00	0.00	329.81	0.10	0.19	0.69	0.51
SSP5-8.5 - IPSL_CM6A (2041-2070)	-106.24	0.00	0.00	0.00	0.00	0.00	0.00	181.99	0.34	0.21	0.56	0.10
SSP5-8.5 - MPI_ESM1_2_HR (2041-2070)	-0.76	0.00	0.00	0.00	0.00	0.00	0.00	357.60	0.17	0.28	0.71	0.56
SSP5-8.5 - MRI_ESM2_0 (2041-2070)	-5.65	0.00	0.00	0.00	0.00	0.00	0.00	438.47	0.03	0.34	0.81	0.77
SSP5-8.5 - UKESM1_0_11 (2041-2070)	-8.91	0.00	0.00	0.00	0.00	0.00	0.00	268.39	0.34	0.07	0.63	0.27

Figure 10. Performance of GLI, WSR and CWSI indicators in the Jucar River Basin case study.

For MMFA, performance levels in the future remain similar to current levels. However, there are some tensions showing habitat degradation in minimum values. This implies that fish habitat would on average hold its current performance, either good or bad, but it would be more vulnerable to extreme drought events. These results were expected, since minimum streamflow values are considered constraints for the management of the Jucar river, and thus they would provide a stable fish habitat unless very extreme hydrological conditions are found.

SCENARIO	Alarcón										WUVA										Molíjar					
	Trout char					Trout tenc1					Chub char					Madrigueras					Loira char		Loira tenc2		Loira max	
	Trout char	Trout min	Trout tenc1	Trout tenc2	Trout max	Chub char	Chub min	Chub tenc1	Chub tenc2	Chub max	Barbel min	Barbel tenc1	Barbel tenc2	Barbel max	Loira min	Loira tenc1	Loira tenc2	Loira max	Loira char	Loira min	Loira tenc1	Loira tenc2	Loira max			
Historical - GFDL_ESM4 (1979-2014)	0.00	0.70	0.77	0.77	0.77	0.03	0.08	0.94	0.94	0.98	0.00	0.10	0.24	0.41	0.02	0.24	0.35	0.49	0.17	0.06	0.32	0.32	0.32			
Historical - IPSL_CM6A (1979-2014)	0.00	0.76	0.77	0.77	0.77	0.00	0.78	0.93	0.94	0.96	0.00	0.09	0.18	0.39	0.14	0.23	0.31	0.48	0.11	0.29	0.32	0.32	0.32			
Historical - MPI_ESM1_2_HR (1979-2014)	0.00	0.73	0.77	0.77	0.78	0.00	0.84	0.94	0.96	0.98	0.00	0.04	0.18	0.66	0.08	0.19	0.29	0.67	0.23	0.06	0.32	0.32	0.32			
Historical - MRI_ESM2_0 (1979-2014)	0.00	0.72	0.77	0.77	0.78	0.00	0.37	0.94	0.95	0.96	0.00	0.10	0.18	0.54	0.08	0.25	0.32	0.58	0.20	0.17	0.32	0.32	0.32			
Historical - UKESM1_0_11 (1979-2014)	0.00	0.71	0.77	0.77	0.78	0.00	0.08	0.78	0.84	0.96	0.00	0.03	0.16	0.54	0.01	0.16	0.29	0.58	0.34	0.04	0.30	0.32	0.32			
SSP1-2.6 - GFDL_ESM4 (2015-2040)	0.00	0.68	0.77	0.77	0.77	0.00	0.32	0.79	0.93	0.94	0.00	0.03	0.11	0.28	0.07	0.18	0.24	0.37	0.27	0.18	0.32	0.32	0.32			
SSP1-2.6 - IPSL_CM6A (2015-2040)	0.00	0.71	0.77	0.77	0.78	0.00	0.31	0.78	0.84	0.85	0.00	0.03	0.12	0.43	0.07	0.19	0.25	0.51	0.38	0.19	0.29	0.32	0.32			
SSP1-2.6 - MPI_ESM1_2_HR (2015-2040)	0.00	0.76	0.77	0.77	0.77	0.23	0.08	0.47	0.93	0.95	0.00	0.00	0.08	0.31	0.01	0.08	0.23	0.41	0.46	0.69	0.22	0.32	0.32			
SSP1-2.6 - MRI_ESM2_0 (2015-2040)	0.00	0.77	0.77	0.77	0.77	0.00	0.87	0.94	0.95	0.96	0.00	0.14	0.29	0.48	0.15	0.27	0.39	0.56	0.60	0.31	0.32	0.32	0.32			
SSP1-2.6 - UKESM1_0_11 (2015-2040)	0.00	0.73	0.77	0.77	0.77	0.00	0.31	0.69	0.93	0.95	0.00	0.01	0.14	0.59	0.06	0.15	0.28	0.63	0.38	0.18	0.28	0.32	0.32			
SSP1-2.6 - GFDL_ESM4 (2041-2070)	0.00	0.74	0.77	0.77	0.79	0.03	0.08	0.86	0.94	0.95	0.00	0.07	0.16	0.36	0.02	0.20	0.28	0.44	0.24	0.07	0.32	0.32	0.32			
SSP1-2.6 - IPSL_CM6A (2041-2070)	0.00	0.63	0.76	0.77	0.77	0.34	0.00	0.29	0.66	0.84	0.00	0.00	0.06	0.46	0.00	0.06	0.15	0.53	0.66	0.65	0.17	0.29	0.32			
SSP1-2.6 - MPI_ESM1_2_HR (2041-2070)	0.00	0.69	0.77	0.77	0.77	0.07	0.24	0.74	0.94	0.95	0.00	0.04	0.10	0.24	0.06	0.19	0.24	0.36	0.31	0.13	0.30	0.32	0.32			
SSP1-2.6 - MRI_ESM2_0 (2041-2070)	0.00	0.75	0.77	0.77	0.77	0.00	0.39	0.94	0.94	0.96	0.00	0.11	0.20	0.61	0.07	0.25	0.33	0.68	0.10	0.18	0.32	0.32	0.32			
SSP1-2.6 - UKESM1_0_11 (2041-2070)	0.00	0.68	0.77	0.77	0.78	0.07	0.08	0.84	0.84	0.90	0.00	0.08	0.19	0.42	0.02	0.21	0.32	0.50	0.14	0.08	0.32	0.32	0.32			
SSP3-7.0 - GFDL_ESM4 (2015-2040)	0.00	0.62	0.77	0.77	0.78	0.27	0.00	0.39	0.70	0.84	0.00	0.00	0.07	0.31	0.00	0.08	0.17	0.55	0.85	0.63	0.24	0.28	0.40			
SSP3-7.0 - IPSL_CM6A (2015-2040)	0.00	0.66	0.77	0.77	0.77	0.00	0.32	0.79	0.94	0.95	0.00	0.01	0.11	0.33	0.07	0.14	0.24	0.43	0.38	0.16	0.30	0.32	0.32			
SSP3-7.0 - MPI_ESM1_2_HR (2015-2040)	0.00	0.66	0.77	0.77	0.78	0.08	0.18	0.67	0.94	0.96	0.00	0.10	0.15	0.68	0.04	0.24	0.28	0.70	0.19	0.11	0.32	0.32	0.32			
SSP3-7.0 - MRI_ESM2_0 (2015-2040)	0.00	0.77	0.77	0.77	0.77	0.00	0.69	0.94	0.95	0.96	0.00	0.10	0.20	0.46	0.19	0.34	0.34	0.54	0.60	0.22	0.32	0.32	0.32			
SSP3-7.0 - UKESM1_0_11 (2015-2040)	0.00	0.61	0.77	0.77	0.77	0.04	0.00	0.60	0.83	0.95	0.00	0.02	0.08	0.26	0.00	0.16	0.21	0.37	0.27	0.02	0.31	0.32	0.32			
SSP3-7.0 - GFDL_ESM4 (2041-2070)	0.00	0.71	0.77	0.77	0.77	0.07	0.00	0.88	0.94	0.94	0.00	0.02	0.08	0.33	0.00	0.16	0.24	0.43	0.31	0.01	0.30	0.32	0.32			
SSP3-7.0 - IPSL_CM6A (2041-2070)	0.00	0.68	0.77	0.77	0.77	0.21	0.00	0.52	0.87	0.94	0.00	0.01	0.07	0.29	0.00	0.11	0.20	0.38	0.48	0.61	0.25	0.32	0.32			
SSP3-7.0 - MPI_ESM1_2_HR (2041-2070)	0.00	0.65	0.75	0.77	0.77	0.41	0.00	0.23	0.69	0.94	0.00	0.00	0.03	0.22	0.00	0.04	0.12	0.30	0.78	0.04	0.17	0.29	0.32			
SSP3-7.0 - MRI_ESM2_0 (2041-2070)	0.00	0.59	0.77	0.77	0.77	0.07	0.16	0.83	0.94	0.96	0.00	0.06	0.16	0.49	0.04	0.22	0.29	0.56	0.21	0.09	0.32	0.32	0.32			
SSP3-7.0 - UKESM1_0_11 (2041-2070)	0.00	0.62	0.77	0.77	0.77	0.03	0.08	0.83	0.94	0.95	0.00	0.07	0.14	0.26	0.01	0.22	0.28	0.57	0.17	0.02	0.32	0.32	0.32			
SSP5-8.5 - GFDL_ESM4 (2015-2040)	0.00	0.76	0.77	0.77	0.77	0.00	0.33	0.85	0.86	0.85	0.00	0.00	0.11	0.24	0.07	0.15	0.23	0.37	0.31	0.19	0.39	0.32	0.32			
SSP5-8.5 - IPSL_CM6A (2015-2040)	0.00	0.65	0.76	0.77	0.78	0.31	0.00	0.31	0.70	0.84	0.00</															



Figure 11. Performance of WUA indicators (Alarcon, Madrigueras and Molinar) in the Jucar River Basin case study.

SCENARIO	WUA																		
	Contreras					Dos Aguas					Antella								
	Loiachar	Loia min	Loia terc1	Loia terc2	Loia max	Loiachar	Loia min	Loia terc1	Loia terc2	Loia max	Chub min	Chub terc1	Chub terc2	Chub max	Barbet char	Barbet min	Barbet terc1	Barbet terc2	Barbet max
Historical - GFDL_ESM4 (1979-2014)	0.00	0.84	1.00	1.00	1.00	0.86	0.29	0.29	0.29	0.46	0.48	0.53	0.57	0.65	0.00	0.32	0.44	0.51	0.63
Historical - IPLS_CM6A (1979-2014)	0.00	0.98	1.00	1.00	1.00	0.94	0.29	0.29	0.29	0.41	0.48	0.53	0.58	0.62	0.00	0.34	0.42	0.51	0.69
Historical - MPI_ESM1_2_HR (1979-2014)	0.00	0.95	1.00	1.00	1.00	0.86	0.29	0.29	0.29	0.73	0.43	0.52	0.58	0.65	0.00	0.32	0.40	0.52	0.83
Historical - MRI_ESM2_0 (1979-2014)	0.00	0.97	1.00	1.00	1.00	0.89	0.29	0.29	0.29	0.56	0.47	0.52	0.56	0.64	0.00	0.32	0.43	0.52	0.72
Historical - UKESM1_0_11 (1979-2014)	0.00	0.90	1.00	1.00	1.00	0.89	0.29	0.29	0.29	0.53	0.42	0.54	0.60	0.64	0.00	0.32	0.38	0.50	0.82
SSP1-2.6 - GFDL_ESM4 (2015-2040)	0.00	0.91	0.99	1.00	1.00	1.00	0.29	0.29	0.29	0.30	0.51	0.54	0.57	0.64	0.00	0.32	0.43	0.46	0.56
SSP1-2.6 - IPLS_CM6A (2015-2040)	0.00	0.88	1.00	1.00	1.00	0.92	0.29	0.29	0.29	0.52	0.48	0.55	0.60	0.64	0.00	0.33	0.39	0.48	0.63
SSP1-2.6 - MPI_ESM1_2_HR (2015-2040)	0.00	0.91	1.00	1.00	1.00	0.96	0.29	0.29	0.29	0.39	0.49	0.55	0.60	0.65	0.00	0.32	0.37	0.45	0.55
SSP1-2.6 - MRI_ESM2_0 (2015-2040)	0.00	1.00	1.00	1.00	1.00	0.77	0.29	0.29	0.29	0.58	0.48	0.51	0.55	0.60	0.00	0.34	0.47	0.55	0.71
SSP1-2.6 - UKESM1_0_11 (2015-2040)	0.00	0.93	0.99	1.00	1.00	0.92	0.29	0.29	0.29	0.63	0.48	0.54	0.60	0.64	0.00	0.32	0.38	0.48	0.66
SSP1-2.6 - GFDL_ESM4 (2041-2070)	0.00	0.92	1.00	1.00	1.00	0.90	0.29	0.29	0.29	0.47	0.51	0.54	0.57	0.64	0.00	0.32	0.43	0.48	0.60
SSP1-2.6 - IPLS_CM6A (2041-2070)	0.00	0.68	0.96	1.00	1.00	0.97	0.29	0.29	0.29	0.53	0.45	0.58	0.62	0.65	0.00	0.31	0.36	0.39	0.69
SSP1-2.6 - MPI_ESM1_2_HR (2041-2070)	0.00	0.74	0.99	1.00	1.00	1.00	0.29	0.29	0.29	0.29	0.51	0.55	0.61	0.65	0.00	0.32	0.37	0.48	0.55
SSP1-2.6 - MRI_ESM2_0 (2041-2070)	0.00	0.95	1.00	1.00	1.00	0.83	0.29	0.29	0.29	0.69	0.43	0.53	0.55	0.63	0.00	0.32	0.46	0.52	0.81
SSP1-2.6 - UKESM1_0_11 (2041-2070)	0.00	0.81	1.00	1.00	1.00	0.97	0.29	0.29	0.29	0.52	0.48	0.54	0.60	0.64	0.00	0.32	0.38	0.46	0.66
SSP3-7.0 - GFDL_ESM4 (2015-2040)	0.00	0.64	0.99	1.00	1.00	0.92	0.29	0.29	0.29	0.64	0.50	0.58	0.60	0.65	0.04	0.29	0.37	0.40	0.62
SSP3-7.0 - IPLS_CM6A (2015-2040)	0.00	0.84	0.96	1.00	1.00	0.86	0.29	0.29	0.29	0.39	0.51	0.57	0.60	0.64	0.00	0.32	0.37	0.45	0.50
SSP3-7.0 - MPI_ESM1_2_HR (2015-2040)	0.00	0.92	1.00	1.00	1.00	0.88	0.29	0.29	0.29	0.62	0.47	0.55	0.58	0.65	0.00	0.32	0.41	0.51	0.61
SSP3-7.0 - MRI_ESM2_0 (2015-2040)	0.00	1.00	1.00	1.00	1.00	0.88	0.29	0.29	0.29	0.52	0.43	0.54	0.55	0.60	0.00	0.35	0.45	0.50	0.79
SSP3-7.0 - UKESM1_0_11 (2015-2040)	0.00	0.82	0.99	1.00	1.00	1.00	0.29	0.29	0.29	0.29	0.52	0.57	0.62	0.64	0.00	0.32	0.37	0.44	0.56
SSP3-7.0 - GFDL_ESM4 (2041-2070)	0.00	0.85	0.98	1.00	1.00	0.93	0.29	0.29	0.29	0.41	0.51	0.57	0.60	0.64	0.03	0.30	0.37	0.44	0.58
SSP3-7.0 - IPLS_CM6A (2041-2070)	0.00	0.53	0.97	1.00	1.00	0.93	0.29	0.29	0.29	0.40	0.53	0.58	0.62	0.64	0.00	0.30	0.35	0.38	0.52
SSP3-7.0 - MPI_ESM1_2_HR (2041-2070)	0.00	0.82	0.97	1.00	1.00	1.00	0.29	0.29	0.29	0.29	0.52	0.60	0.62	0.64	0.00	0.32	0.35	0.38	0.55
SSP3-7.0 - MRI_ESM2_0 (2041-2070)	0.00	0.79	1.00	1.00	1.00	0.90	0.29	0.29	0.29	0.47	0.50	0.53	0.57	0.65	0.00	0.32	0.41	0.49	0.66
SSP3-7.0 - UKESM1_0_11 (2041-2070)	0.00	0.66	1.00	1.00	1.00	0.97	0.29	0.29	0.29	0.32	0.48	0.55	0.58	0.65	0.00	0.32	0.42	0.48	0.61
SSP5-8.5 - GFDL_ESM4 (2015-2040)	0.00	0.95	1.00	1.00	1.00	0.96	0.29	0.29	0.29	0.33	0.50	0.55	0.59	0.64	0.00	0.31	0.38	0.44	0.55
SSP5-8.5 - IPLS_CM6A (2015-2040)	0.00	0.65	0.98	1.00	1.00	0.96	0.29	0.29	0.29	0.57	0.53	0.58	0.62	0.64	0.00	0.32	0.36	0.41	0.56
SSP5-8.5 - MPI_ESM1_2_HR (2015-2040)	0.00	0.96	0.99	1.00	1.00	0.85	0.29	0.29	0.29	0.47	0.48	0.55	0.61	0.64	0.00	0.32	0.37	0.48	0.67
SSP5-8.5 - MRI_ESM2_0 (2015-2040)	0.00	0.95	1.00	1.00	1.00	0.85	0.29	0.29	0.29	0.52	0.38	0.53	0.56	0.64	0.00	0.32	0.46	0.53	0.86
SSP5-8.5 - UKESM1_0_11 (2015-2040)	0.00	0.47	0.99	1.00	1.00	0.88	0.29	0.29	0.29	0.58	0.50	0.55	0.59	0.64	0.00	0.32	0.39	0.47	0.60
SSP5-8.5 - GFDL_ESM4 (2041-2070)	0.00	0.80	0.97	1.00	1.00	0.83	0.29	0.29	0.29	0.41	0.48	0.58	0.62	0.64	0.00	0.32	0.37	0.39	0.69
SSP5-8.5 - IPLS_CM6A (2041-2070)	0.00	0.66	0.95	0.98	1.00	1.00	0.29	0.29	0.29	0.29	0.50	0.62	0.64	0.65	0.00	0.31	0.32	0.37	0.43
SSP5-8.5 - MPI_ESM1_2_HR (2041-2070)	0.00	0.81	0.96	1.00	1.00	0.97	0.29	0.29	0.29	0.47	0.51	0.56	0.61	0.64	0.00	0.32	0.37	0.47	0.57
SSP5-8.5 - MRI_ESM2_0 (2041-2070)	0.00	0.89	1.00	1.00	1.00	0.93	0.29	0.29	0.29	0.49	0.46	0.55	0.58	0.64	0.00	0.32	0.39	0.49	0.68
SSP5-8.5 - UKESM1_0_11 (2041-2070)	0.00	0.65	0.96	0.99	1.00	0.93	0.29	0.29	0.29	0.36	0.48	0.59	0.62	0.65	0.03	0.29	0.32	0.38	0.71

Figure 12. Performance of WUA indicators (Contreras, Dos Aguas and Antella) in the Jucar River Basin case study.

Figure 13 and Figure 14 show the SOS evaluation for individual indicators. In case of WUA, as its safety depends on the combination of all the indicators for the same reach and fish species, the SOS evaluation represents such combination.



SCENARIO	GLI	WSR							CWSI		
		MO aquifer	Albacete	MO Urban	Valencia	Sagunto	Cofrentes	Hydropower	Albufera	Mancha	Jucar-Turia
Historical - GFDL_ESM4 (1979-2014)	1	1	1	1	1	1	1	1	0	1	1
Historical - IPSL_CM6A (1979-2014)	1	1	1	1	1	1	0	1	0	1	1
Historical - MPI_ESM1_2_HR (1979-2014)	1	1	1	1	1	1	1	1	1	1	1
Historical - MRI_ESM2_0 (1979-2014)	1	1	1	1	1	1	1	1	1	1	1
Historical - UKESM1_0_11 (1979-2014)	1	1	1	1	1	1	0	0	0	0	0
SSP1-2.6 - GFDL_ESM4 (2015-2040)	1	1	1	1	1	1	0	1	0	0	0
SSP1-2.6 - IPSL_CM6A (2015-2040)	1	1	1	1	1	1	0	1	0	0	1
SSP1-2.6 - MPI_ESM1_2_HR (2015-2040)	1	1	1	1	1	1	0	1	0	0	1
SSP1-2.6 - MRI_ESM2_0 (2015-2040)	1	1	1	1	1	1	1	1	1	1	1
SSP1-2.6 - UKESM1_0_11 (2015-2040)	1	1	1	1	1	1	0	0	0	0	0
SSP1-2.6 - GFDL_ESM4 (2041-2070)	1	1	1	1	1	1	0	1	0	1	1
SSP1-2.6 - IPSL_CM6A (2041-2070)	0	1	1	1	1	1	0	0	0	0	0
SSP1-2.6 - MPI_ESM1_2_HR (2041-2070)	1	1	1	1	1	1	0	0	0	0	0
SSP1-2.6 - MRI_ESM2_0 (2041-2070)	0	1	1	1	1	1	1	1	0	1	1
SSP1-2.6 - UKESM1_0_11 (2041-2070)	1	1	1	1	1	1	0	0	0	1	1
SSP3-7.0 - GFDL_ESM4 (2015-2040)	1	1	1	1	1	1	0	0	0	0	0
SSP3-7.0 - IPSL_CM6A (2015-2040)	1	1	1	1	1	1	0	1	0	0	0
SSP3-7.0 - MPI_ESM1_2_HR (2015-2040)	1	1	1	1	1	1	1	1	0	0	1
SSP3-7.0 - MRI_ESM2_0 (2015-2040)	1	1	1	1	1	1	1	1	0	1	1
SSP3-7.0 - UKESM1_0_11 (2015-2040)	1	1	1	1	1	1	0	1	0	0	0
SSP3-7.0 - GFDL_ESM4 (2041-2070)	0	1	1	1	1	1	0	0	0	0	0
SSP3-7.0 - IPSL_CM6A (2041-2070)	0	1	1	1	1	1	0	0	0	0	0
SSP3-7.0 - MPI_ESM1_2_HR (2041-2070)	0	1	1	1	1	1	0	0	0	0	0
SSP3-7.0 - MRI_ESM2_0 (2041-2070)	0	1	1	1	1	1	0	0	0	0	0
SSP3-7.0 - UKESM1_0_11 (2041-2070)	1	1	1	1	1	1	0	1	0	0	0
SSP5-8.5 - GFDL_ESM4 (2015-2040)	1	1	1	1	1	1	0	1	0	0	0
SSP5-8.5 - IPSL_CM6A (2015-2040)	0	1	1	1	1	1	0	0	0	0	0
SSP5-8.5 - MPI_ESM1_2_HR (2015-2040)	1	1	1	1	1	1	0	1	0	0	0
SSP5-8.5 - MRI_ESM2_0 (2015-2040)	1	1	1	1	1	1	1	1	1	1	1
SSP5-8.5 - UKESM1_0_11 (2015-2040)	1	1	1	1	1	1	0	0	0	0	0
SSP5-8.5 - GFDL_ESM4 (2041-2070)	1	1	1	1	1	1	0	0	0	0	0
SSP5-8.5 - IPSL_CM6A (2041-2070)	0	1	1	1	1	1	0	0	0	0	0
SSP5-8.5 - MPI_ESM1_2_HR (2041-2070)	0	1	1	1	1	1	0	0	0	0	0
SSP5-8.5 - MRI_ESM2_0 (2041-2070)	0	1	1	1	1	1	0	1	0	1	1
SSP5-8.5 - UKESM1_0_11 (2041-2070)	0	1	1	1	1	1	0	0	0	0	0

Figure 13. SOS evaluation for GLI, WRS and CWSI in the Jucar River Basin case study.



SCENARIO	WUA								
	Alarcon	Madrigueras			Molinar	Contreras	Dos Aguas	Antella	
	Trout	Chub	Barbel	Loina	Loina	Loina	Loina	Chub	Barbel
Historical - GFDL_ESM4 (1979-2014)	1	0	0	0	0	1	0	1	0
Historical - IPSL_CM6A (1979-2014)	1	0	0	0	0	1	0	1	0
Historical - MPI_ESM1_2_HR (1979-2014)	1	0	0	0	0	1	0	1	0
Historical - MRI_ESM2_0 (1979-2014)	1	0	0	0	0	1	0	1	0
Historical - UKESM1_0_11 (1979-2014)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - GFDL_ESM4 (2015-2040)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - IPSL_CM6A (2015-2040)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - MPI_ESM1_2_HR (2015-2040)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - MRI_ESM2_0 (2015-2040)	1	0	0	1	0	1	0	1	0
SSP1-2.6 - UKESM1_0_11 (2015-2040)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - GFDL_ESM4 (2041-2070)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - IPSL_CM6A (2041-2070)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - MPI_ESM1_2_HR (2041-2070)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - MRI_ESM2_0 (2041-2070)	1	0	0	0	0	1	0	1	0
SSP1-2.6 - UKESM1_0_11 (2041-2070)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - GFDL_ESM4 (2015-2040)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - IPSL_CM6A (2015-2040)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - MPI_ESM1_2_HR (2015-2040)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - MRI_ESM2_0 (2015-2040)	1	0	1	1	0	1	0	1	0
SSP3-7.0 - UKESM1_0_11 (2015-2040)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - GFDL_ESM4 (2041-2070)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - IPSL_CM6A (2041-2070)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - MPI_ESM1_2_HR (2041-2070)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - MRI_ESM2_0 (2041-2070)	1	0	0	0	0	1	0	1	0
SSP3-7.0 - UKESM1_0_11 (2041-2070)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - GFDL_ESM4 (2015-2040)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - IPSL_CM6A (2015-2040)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - MPI_ESM1_2_HR (2015-2040)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - MRI_ESM2_0 (2015-2040)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - UKESM1_0_11 (2015-2040)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - GFDL_ESM4 (2041-2070)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - IPSL_CM6A (2041-2070)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - MPI_ESM1_2_HR (2041-2070)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - MRI_ESM2_0 (2041-2070)	1	0	0	0	0	1	0	1	0
SSP5-8.5 - UKESM1_0_11 (2041-2070)	1	0	0	0	0	1	0	1	0

Figure 14. SOS evaluation for WUA in the Jucar River Basin case study.

A significant number of the chosen indicators do not change their safe or unsafe status in the future scenarios analysed. In particular, this is found in all WUA indicators and the WSR indicators that correspond to urban and nuclear demands. WSR indicators remain safe for all scenarios due to urban and nuclear demands having priority over agriculture and not representing a share of the Jucar demands high enough to be compromised. In case of WUA, the fish species showing a safe status are, in general, the species considered representative by the Jucar RBA (trout in Alarcon and loina in Contreras), which are the ones targeted by the minimum streamflow regulations set in the Jucar River Basin Management Plan. In both cases, minimum streamflows could aim at guaranteeing WUA values higher than the 30% threshold set by law, which ensures a fair habitat for both fish. The third fish in a safe status is the chub in Antella, which benefits from the minimum flow set, although not being targeted by it. The remaining fish-location pairs are currently in an unsafe status, including some representative ones; and would remain unsafe in the future. This would imply the need of re-thinking minimum streamflow values in some parts of the Jucar River Basin.

On the contrary, GLI, WSR for hydropower and the Albufera lake, and CWSI indicators, show evolving safety status across climate change scenarios and periods. Of these, the CWSI in the Mancha Oriental



irrigated area is the only one that could be considered unsafe in the current climate, as most current scenarios show an unsafe situation, while the rest remain fully or mainly safe. However, all of them would be threatened by climate change, as there are scenarios in which most or even all climate models show unsafe performance levels. Among them, WSR for hydropower and CWSI in the Mancha Oriental are the most precarious ones, since they would transition to or remain in an unsafe situation for all scenarios and periods. On the contrary, the most optimistic outlook is offered by GLI in the Mancha Oriental aquifer, which would be unsafe only in the long-term for the SSP3-7.0 and SSP5-8.5 scenarios. WSR in the Albufera would turn into unsafe in the mid-term regardless of the scenario, CWSI for the Traditional irrigated areas would be unsafe for SSP3-7.0 and SSP5-8.5 scenarios, and CWSI in the Jucar-Turia irrigated area would fall below the safety threshold in the short-term and recover to a safe status only if the SSP1-2.6 scenario is realized.

3.2 Danube Case Study

The Danube Basin (DB) is the most international basin in the world, including 19 countries, home to 79 million people and covering an area of approximately 800,000 km², making it the second largest basin in Europe and the 21st in the world. The Danube stretches 2,850 km, starting from the Black Forest (Germany) and flowing South through Central Europe to the Romanian shores of the Black Sea.

Due to its extent, variety of habitats, flowing conditions and diversity of characteristics, the DB is conventionally divided into three sub-regions: the upper, middle, and lower Danube Basin (see Figure 15). The upper basin extends from the source, in the German Black Forest, to the capital city of Slovakia, Bratislava. This sub-region exhibits depths between 1 to 8 m and high mean flow velocities.

The middle basin stretches from the Gate of Devin Castle, near Bratislava, to the Iron Gate Gorge, at the border between Serbia and Romania. In this section, the Danube becomes a typical lowland river with slow flow, low banks, and expansive width, widening, in some stretches, to over 1.5 km. The major tributaries in this section are the Drava, Tisza, and Sava.

The lower basin begins downstream of the Iron Gates. From there, the Lower Danube meanders across a vast plain, spreading out and becoming shallower and marking a natural border between Romania and Bulgaria. The course of the Danube ends in the Danube Delta. The delta is the largest in Europe, covering an area of approximately 6,000 km². It is a biodiversity hotspot and is critical in filtering pollutants that otherwise would drain into the Black Sea.

The upper basin and, to a lesser extent, the middle basin have a glacial-naval hydrological regime governed by late spring glacial thaw. In contrast, the lower basin exhibits a bimodal regime, with peaks in late spring and the beginning of winter.

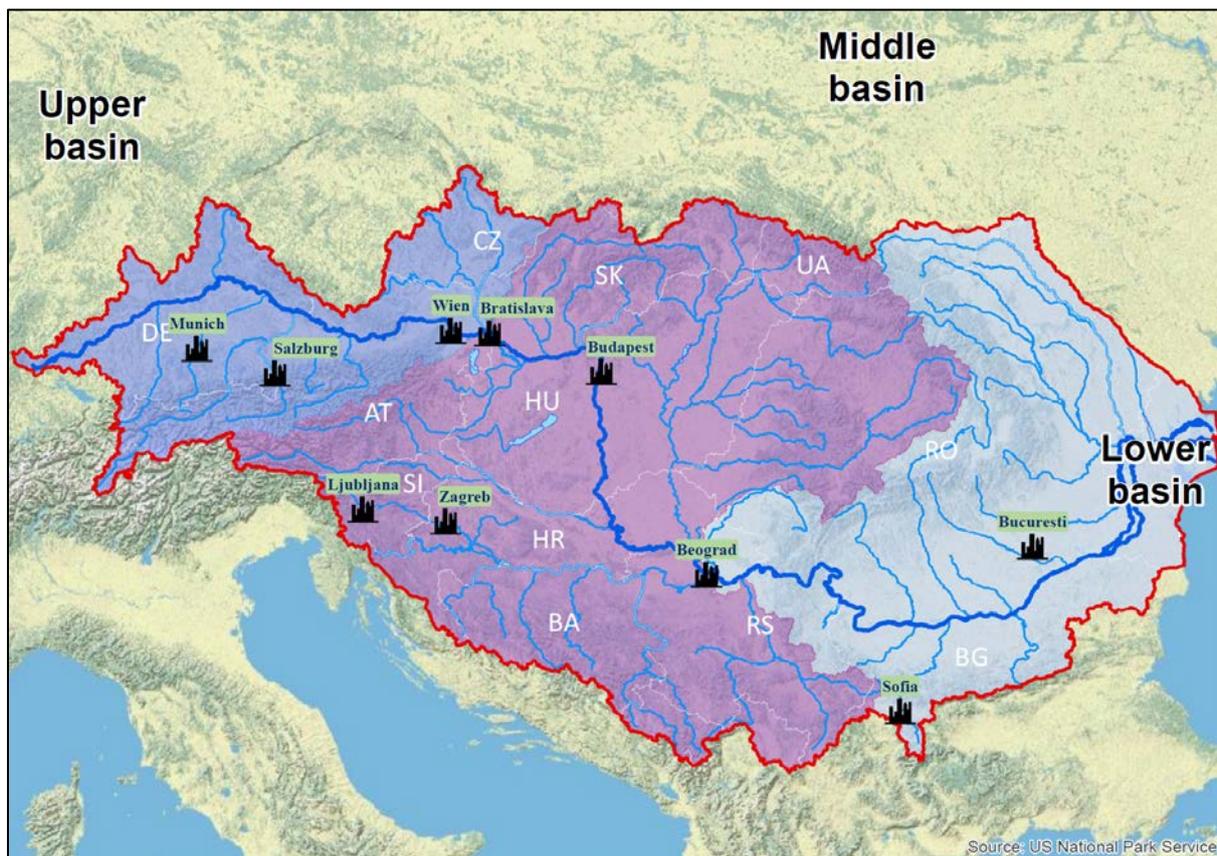


Figure 15. Danube Basin states and basin divisions. The upper, middle, and lower Danube Basin are presented.

Due to its extent and diversity, and the large number of people living within its limits, the DB is subject to several environmental management issues. The following are those recognised by the the International Commission for the Protection of the Danube River (ICPDR) as the main environmental pressures currently affecting the DB:

- Organic pollution originating from urban wastewater and industrial emissions.
- Nutrient pollution.
- Hazardous substances.
- Hydromorphological alterations.
- Alien species.
- Macro and microplastics.
- Pressures on groundwater.

Stakeholder engagement

During two workshops we engaged key representatives from across the Danube basin, encompassing all major water-related sectors, along with dedicated participants from the Danube Delta. These stakeholders have played an active role in the SOS-Water participatory process and continue to collaborate closely with researchers from IIASA and other partner institutions. Together, we are co-



developing a Safe Operating Space (SOS) framework that reflects the region’s specific challenges, priorities, and opportunities.

During the first workshop, which took place on November 22, 2023, stakeholders were asked to provide their key values of the Danube basin and to participate in developing an objective hierarchy map. The objective hierarchy map provides a structured framework that organizes objectives into a logical sequence, starting from broad, overarching goals, and refining them into specific actionable targets whose degree of success is assessed using measurable indicators.

During the second workshop on March 5, 2025, we gathered feedback on the identified indicators and thresholds used to quantify the fulfilment of the hierarchy’s objectives. Additionally, we shared preliminary modelling results and provided baseline insights into the basin’s future challenges. These insights were used to co-identify possible adaptation options and co-develop adaptation pathways. The pathways will then be simulated across the basin to assess their impacts and trade-offs across various dimensions of the water system to identify the safe operating space for the Danube basin.

3.2.1 Indicators and Threshold

Indicators for the Danube basin have been categorized according to water functions as defined in Falkenmark & Wand-Erlandsson (2021). These water functions (see Table 4) describe the different roles of water in sustaining the social-ecological systems and the Earth system. Unlike ecosystem services, which emphasize the biological benefits that water provides to societies, these functions focus on the systemic roles of water in promoting resilience. Water resilience is defined as the role of water in maintaining a given, desirable state of water-dependent environments, water supply for human society, and moisture feedback to the rest of the Earth Systems.

Table 4. List of Danube basin indicators and their division into water functions as defined by Falkenmark & Wand-Erlandsson, 2021.

Water function	Indicators
Productive	Species Habitat Suitability Number of Navigation Days
Regulatory	Magnitude of Monthly Flow Alteration Connectivity Status Index
State	Aquifer recharge rate
Supply	Water supply reliability for domestic, agricultural and industrial supplies
Carrier	P and N load concentrations



The following table (Table 5) describes the selected indicators and thresholds for the Danube basin case study. A more detailed description of the indicators and their calculation is presented in Appendix A: Danube case study indicators definitions. The stakeholders tentatively validated thresholds based on expert knowledge during the second workshop (Artuso *et al.*, 2025). All indicators are expressed as percentages or ratios, making them dimensionless. The only exceptions are P and N load concentrations, which are measured in milligrams per liter (mg/L).

Table 5. Indicators and thresholds chosen for the Danube River Basin case study.

Indicator	Short description	Threshold
Magnitude of Monthly Flow Alteration (MMFA)	This metric assesses the change in flow magnitude for each month, comparing regulated or altered flow conditions to normal or baseline conditions.	Frequency of MMFA < 0.75. Status: Tentative Source: Expert based on stakeholders' validation.
Connectivity Status Index (CSI)	The Connectivity Status Index (Grill et al., 2019) is a metric used to assess the connectivity status of river reaches, considering pressure factors that can impede or alter the lateral and longitudinal river connectivity.	The river reach is considered free-flowing when the CSI value is greater than 0.95; it is considered in good status when the CSI value is 0.95; and it is considered not free-flowing or impounded when the CSI value is less than 0.95. Status: Final Source: Grill et al. 2019
Aquifer recharge rate (ARR)	It is the ratio of aquifer recharge volume to withdrawals. When this ratio is less than 1, the groundwater pumped is not replenished, therefore its use is unsustainable.	Threshold at ARR > 0.95. Status: Tentative Source: Expert based on stakeholders' validation.
Water supply reliability for domestic, agricultural and industrial supplies	Reliability is defined as the ability of the water supply to meet demand continuously. A reliable water supply can be measured by the	A threshold value is difficult to determine; therefore, using a precautionary approach, the mean reference



	number of deficits (when demand > supply) divided by the time period.	period deficit value is used as a threshold. Status: Tentative Source: Modellers
Species Habitat Suitability	The results of applying Species Distribution Models (SDM) are maps showing the habitat suitability probabilities for the fish species of interest.	Threshold: 5% Status: Tentative Source: Modellers
Number of Navigation Days (NND)	NND is the number of days in a year during which a specific river segment maintains a good navigation status (GNS), meaning it remains between the Low navigable water level (LNWL). LNWL is the water level that is equaled or exceeded on 94% of the days of the year, or 343 days. This value is based on discharge data collected over a 30-year period, excluding times when ice was present.	Threshold: 343 days (94% of days in a year) Status: Final Source: Viadonau, 2024
P and N loads concentrations (NPL)	River concentrations of Total Nitrogen (TN) and Total Phosphorus (TP).	2.5mg/l for TN and 0.05mg/l for TP Status: Final Source: EU Water Framework Directive (WFD)

Due to its extension and diversity, the indicators are evaluated on the subbasin level to better represent the diversity of conditions throughout the entire area. For our analysis, we chose 11 major sub-basins (see Figure 16).

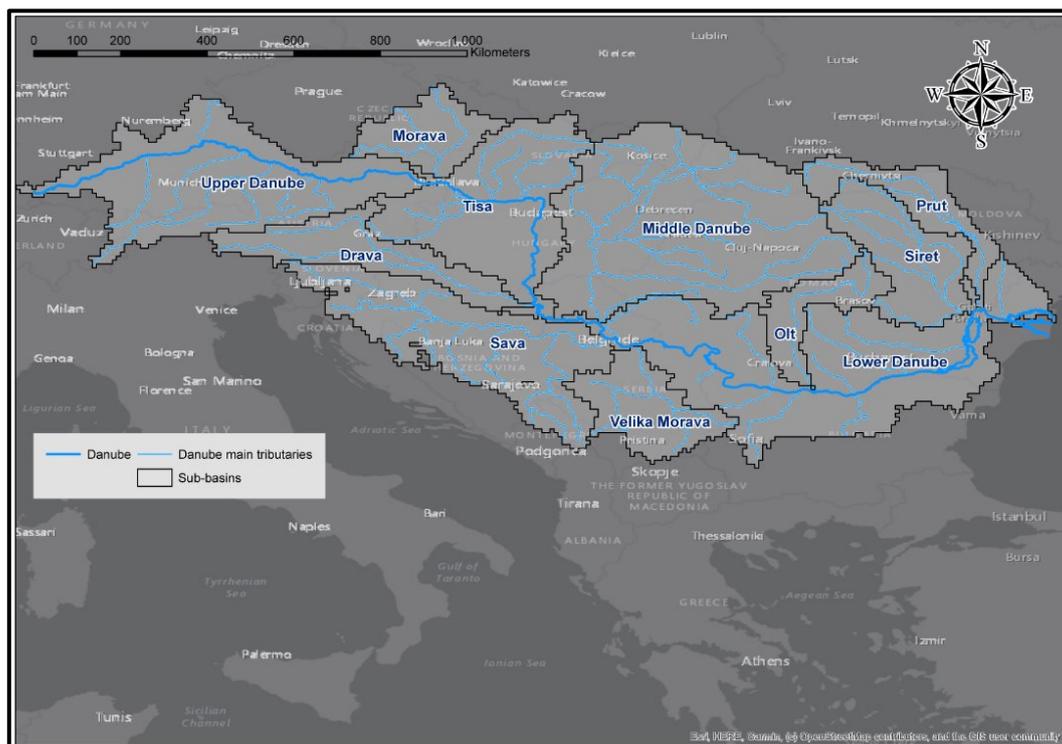


Figure 16. Division of the Danube basin in the 11 major subbasin utilized for the indicators evaluation.

3.2.2 Future Scenarios

As with the other case studies of the SOS-Water project, we selected the following SSP-RCP combinations for modelling future scenarios for the Danube basin case study (see Deliverable 2.1): SSP1-2.6 (sustainable pathways scenario), SSP3-7.0 (regional rivalry scenario), and SSP5-8.5 (fossil fuel-rich development scenario). For our projections, we utilize bias-corrected climate projections from the ISIMIP3b dataset retrieved for the following Global Climate Models (GCMs): GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. The dataset includes daily bias-corrected variables such as precipitation (pr), near-surface air temperature (tas), maximum and minimum air temperature (tasmx, tasmin), and surface downwelling radiation (rsds). The temporal horizons analyzed focus on mid-century (until 2070).

Comparison of temperature and precipitation changes between a historical reference period (1970-2010) and a future projection (2030-2070) for the optimistic scenario SSP-RCP 1.26 (Figure 17) shows warmer summer temperatures (Jun-Aug) across the entire basin, along with decreased precipitation during the same months in most of the basin. For the rest of the year, the lower Danube experiences an increase in precipitation, as does the upper section of the basin in spring (Mar-May).

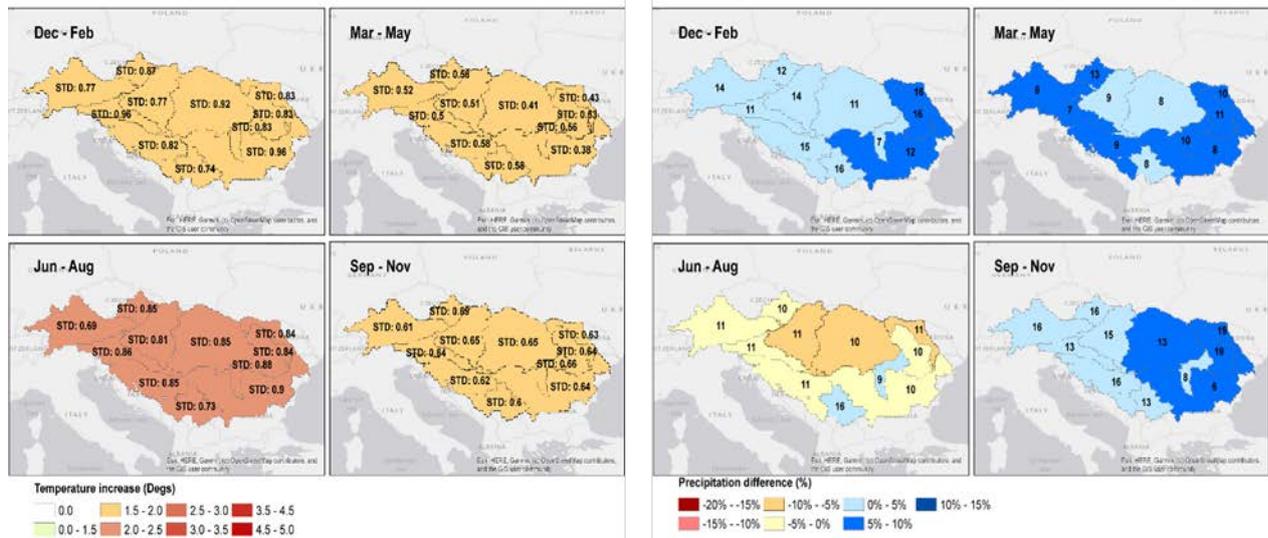


Figure 17. Temperature (degrees) and precipitation (%) change over the entire Danube basin between a historical reference period (1981-2010) and future projections (2030-2070) under the SSP-RCP 1.26 scenario.

The same comparison for the most pessimistic scenario SSP-RCP 5.85 (Figure 18) shows more significant changes, with temperatures rising throughout the entire basin during the entire year, with the greatest increase in summer. Precipitation decreases in the upper basin between September and February, likely indicating a reduction in snowfall, while it increases in the lower basin during winter and spring. The summer months generally exhibit a reduction in precipitation across the whole basin, reaching up to -20%.

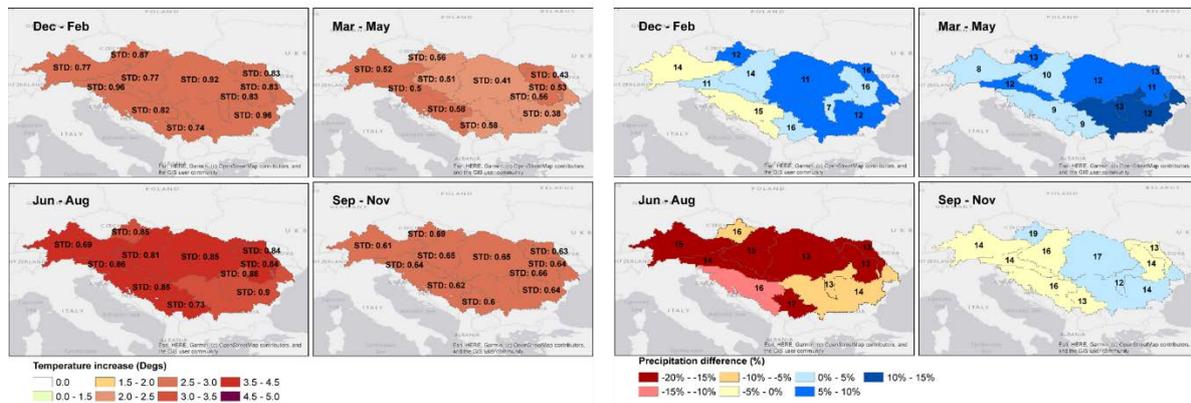


Figure 18. Temperature (degrees) and precipitation (%) change over the entire Danube basin between a historical reference period (1981-2010) and future projections (2030-2070) under the SSP-RCP 5.85 scenario.

The following figure (Figure 19) shows a comparison between historical and projected monthly precipitation (Pr, mm) and reference evapotranspiration (ET_o, mm) for three sections of the Danube (Lower, Middle and Upper; Figure 15) and according to all three scenarios.

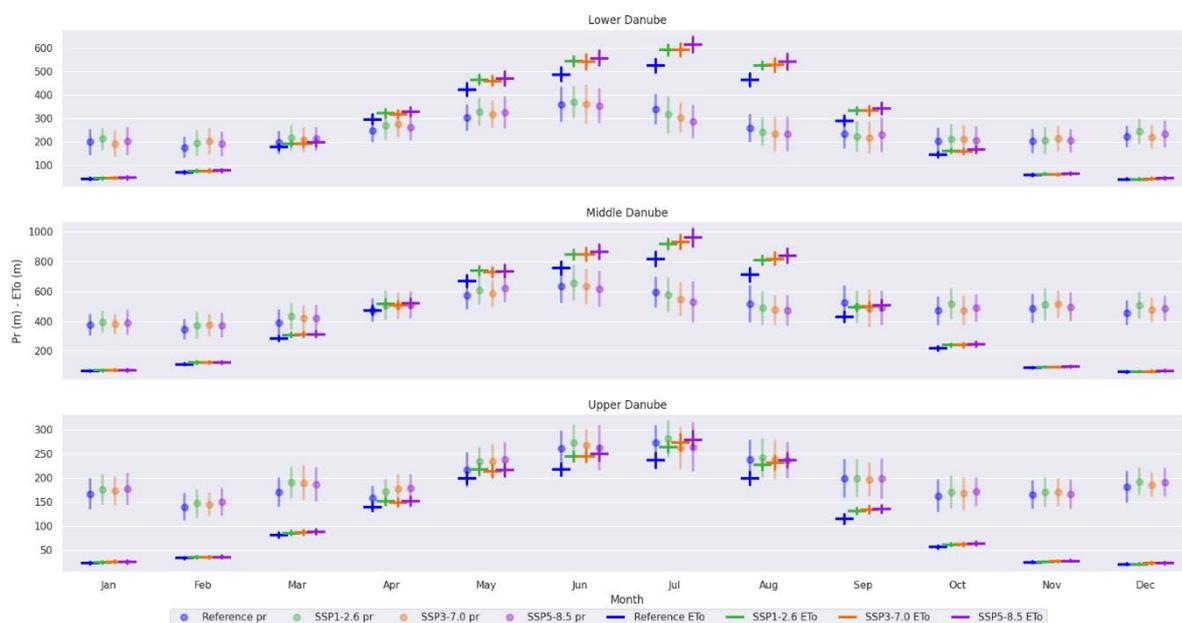


Figure 19. Monthly precipitation (pr , mm) and reference evapotranspiration (ETo , mm) under three future scenarios for three sections of the Danube River basin: Lower Danube, Middle Danube, and Upper Danube (ICPDR). Blue: reference period; Green: SSP1-2.6; Orange: SSP3-7.0; Pink: SSP5-8.5.

Strong seasonality is observed across all regions with distinct summer peaks in both precipitation and Eto. However, changes relative to the historical period are also notable during summer months, characterized by less precipitation (points) and more evapotranspiration (lines), particularly in the Lower and Middle Danube under higher emission scenarios. Additionally, in the upper Danube, summer evapotranspiration increases consistently with the severity of the scenario, while precipitation shows no clear trend across different scenarios.

3.2.3 Integrated Water Modeling System

The modelling components utilized in the Danube River Basin are shown in the figure (Figure 20) below:

- Community Water Model (CWatM; Burek et al., 2020): a large-scale hydrological model used to simulate the water cycle in the Danube basin and produce outputs related to changes in water availability and use. Further descriptions are provided in D2.2, D2.3 and D5.1.
- SWAT+: used to model the water quality indicators, which are total phosphorus (P) and total nitrogen (N) concentrations.
- Species distribution model (SDM): used to assess changes in the distribution and habitat suitability of key fish species in the Danube basin. The model builds on extensive biological datasets and species occurrences (covering 51 fish species) and integrates hydrological, climatic, topographic, and land cover predictors to produce spatially explicit habitat suitability maps under current and future scenarios. The algorithm Random Forest was used as SDM to estimate the habitat suitability predictions.

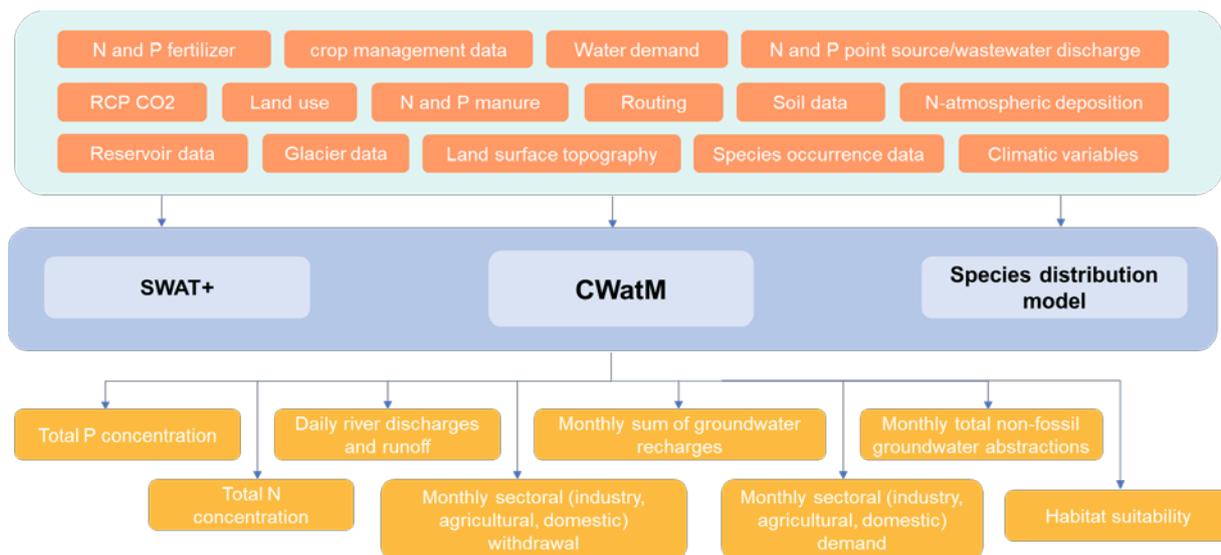


Figure 20. Danube River Basin integrated modelling framework.

The following section describes how the different model outputs were utilized to calculate the final indicators for the Danube Basin.

3.2.4 Multi-Dimensional SOS Assessment Results

Except for the Connectivity Status Index (CSI), all indicators were evaluated for both historical and future scenarios: SSP1-2.6 (sustainable pathways scenario), SSP3-7.0 (regional rivalry scenario), and SSP5-8.5 (fossil fuel-rich development scenario). Each indicator is calculated as an average of five GCMs (see above): GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. CSI was calculated only for the reference period, and its value was also applied to the scenarios. This is because CSI depends on the presence of dams and barriers, and their removal or the construction of new ones involves assumptions that are part of the adaptation pathways yet to be modelled.

For each indicator calculated on a yearly time scale (i.e., all but the SHI and the CSI), once we obtained the indicators' values for each year, we aggregated them across scenarios and time periods by calculating the frequency with which each indicator exceeded its predefined threshold over the evaluation period. This approach was chosen over the mean or median because it provides a more detailed and contextual understanding of how often a variable crosses its threshold, allowing more meaningful comparison between different periods. In contrast, the mean (or median) can smooth out or even hide important information. Moreover, frequency-based measures are more robust against outliers compared to central tendency measures. The use of frequencies is also consistent with the latest iterations of the Water Planetary Boundary framework (Richardson et al., 2023), where blue and green water boundaries are expressed in terms of frequency deviation from pre-industrial times.

Before applying this frequency-based aggregation, we classified years as "wet", "dry", or "normal" to highlight differences in hydrological conditions and potential critical indicator values outside the average. Following, each of the indicators was also classified according to "wet", "dry", or "normal"



conditions (e.g., Domestic Deficit (DmDD) was expanded into DmD-Dry, DmD-Normal and DmD-Wet), and frequencies were then calculated separately for each of those categories.

Years were classified based on the difference between precipitation (Pr) and potential evapotranspiration (ETo). ETo was calculated using CWatM, while Pr was derived from the climatic inputs used in the CWatM calculations (Figure 20). The water balance (WB) between Pr and ETo was assessed at the sub-basin scale using monthly values aggregated to a yearly scale. The difference in water balance indicates whether there is an excess or a deficit of water from precipitation and was used to categorize the years into “wet”, “normal”, and “dry” periods. To do this, we used the following statistical method: first, we calculated the mean (μ) and standard deviation (σ) of the sub-basins' WB for a specified reference period. A year was classified as "normal" if its water balance fell within this range:

$$range = \mu \pm 0.75\sigma$$

Conversely, years with a water balance greater than $\mu + 0.75\sigma$ were classified as "wet," while those with a water balance less than $\mu - 0.75\sigma$ were labelled as "dry." This method provided a solid quantitative foundation for categorizing the time series into distinct hydrological periods. The calculations were conducted separately for each sub-basin and for each GCMs.

Finally, indicators were standardized between 0 and 100, with 0 indicating no threshold exceedance (i.e. indicator consistently within the safe space) and 100 indicating exceedance every year (i.e. indicator consistently unsafe).

Indicators that are not calculated yearly but over the entire time window, namely SHI and CSI, were excluded from this aggregation and are not expressed in terms of frequency. In this case, the standardization was done by simply inverting, if necessary, their values.

Figure 21 illustrates the workflow applied for the evaluation of the indicators, while Table 6 indicates the aggregation and reformulation applied to each of the indicators.

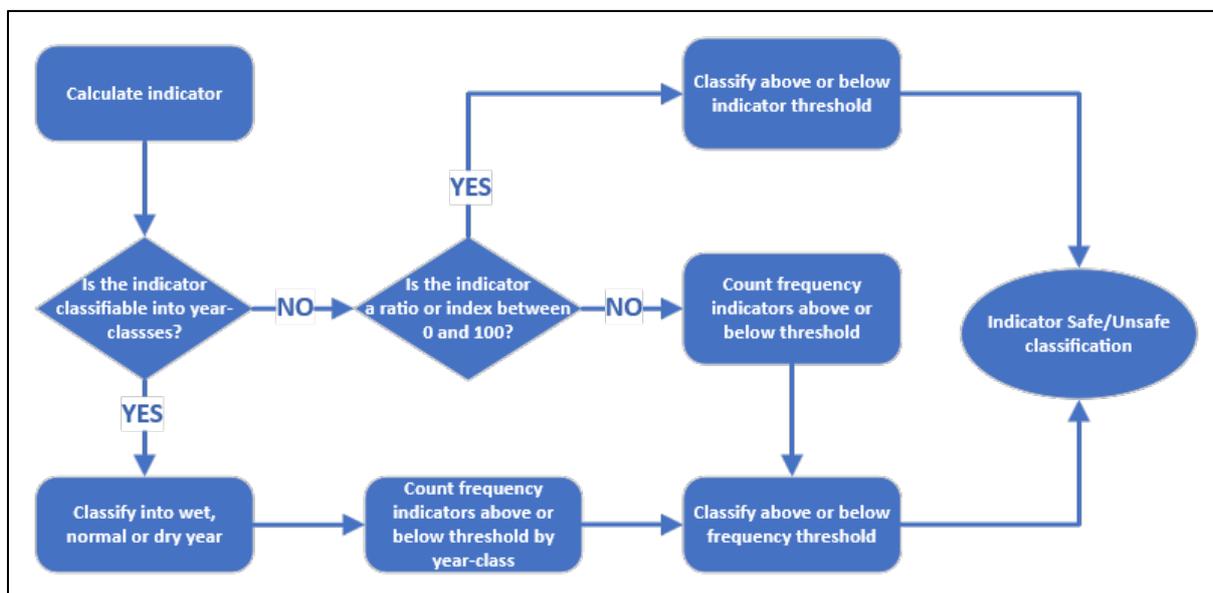


Figure 21. Workflow utilized for the indicator’s evaluation and the multi-dimensional SOS assessment.

Table 6. Reformulation of the indicators according to the aggregation and frequency-based (or other, if needed) transformation performed.

Original index	Reformulation	Definition	Frequency threshold
Species Habitat Index	Habitat Loss Ratio Index (HLR)	Ratio between the reference period habitat availability and a scenario. It indicates the percent of habitat lost compared to the reference period.	2
Number of Navigation Days	Non-Navigable Days-Dry, Normal and Wet (NND-Dry, NND-Nor, NND-Wet)	It indicates the frequency of days in which the outlet of the sub-basin is not navigable. For example, a 10% value indicates that over the scenario period, the fairway will not be navigable for 10% of the time	7



		(roughly 3 days per year).	
Magnitude of Monthly Flow Alteration	Magnitude of Monthly Flow Alteration Dry, Normal and Wet (MMFA-Dry, MMFA-Nor,, MMFA-Wet)	This ratio measures the average difference between the natural flow and the altered flow on a monthly basis. The indicator is calculated as the mean over the scenario period, showing the typical change in flow (discharge) caused by water abstraction, diversion, etc.	25
Connectivity Status Index	Structural Connectivity Alteration Index (SCAI)	Is the inverse (i.e. 100 – CSI) of the Connectivity Status Index (Grill et al. 2019)	5
Aquifer recharge rate	Annual Recharge Rate Loss Dry, Normal and Wet (ARRL-Dry, ARRL-Nor, ARRL-Wet)	It is the inverse of the ratio between the aquifer recharge volume and withdrawals. The higher the value, the greater the percentage of groundwater pumped that is not replenished by recharge.	2
Water supply reliability for domestic, agricultural and industrial supplies	Domestic Deficit (DmD), Irrigation Deficit (IrD), Industry Deficit (InD) Dry, Normal and Wet	The index shows the frequency, i.e., the percentage of time when water cannot be supplied to meet demand.	5 (Domestic), 25 (Irrigation and Industry)



P and N loads concentrations	N-P Load Excess Percent (NPL)	The index shows the frequency, i.e., the percentage of time, Nitrogen and/or Phosphorous concentrations exceed the Water Framework Directive limits.	5
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A matrix containing indicators results for the Danube basin, with indicator values for each scenario and sub-basin, has been deposited in the Utrecht University public repository, Yoda. It can be found at this link:

<https://geo.yoda.uu.nl/research/browse?dir=%2Fresearch-sos-basin-data%2FDanube%2FSOSEvaluation%20>.

Standardizing the indicators with values ranging from 0 to 100 allows us to directly classify their performances into a ‘Safe’ or ‘Unsafe’ space, like in the radial plots below (Figure 22). However, converting the indicator scores into frequencies implied the use of a further frequency-based threshold, i.e. a frequency that is deemed sufficient to consider the indicator within the safe state (the green area in Figure 22). Where literature information was not available for a given indicator, a precautionary, expert-based threshold was assigned (see Table 6).

To evaluate whether each sub-basin was within the SOS for water in the reference period (1970-2010) or is under baseline climate change future scenarios (2030-2070), we separately assessed the performance of each water function using the worst indicator value, assuming that, if one indicator is failing, the function is not supported. The overall SOS was then evaluated considering all functions; if any one function was not supported, the sub-basin was deemed outside the SOS for water. This approach is cautious, and at this stage, it should be considered experimental. Defining an SOS, in fact, is not merely a scientific exercise, but also implies political and normative considerations that reflect the risk-taking attitude of the basin governing bodies (Bierman & Kim, 2020). Adopting a more risk-prone approach to evaluating the SOS for water in the sub-basins should be a topic of discussion with stakeholders during the final stages of the project.

Considering the large number of sub-basins and indicators, only the results aggregated by water functions of the Northern, Central, and Southern Danube sub-basins (see Figure 15) are presented in Figure 22 and Table 7, as they are also representative of the neighboring sub-basins.

Discussion and conclusions

One of the main patterns that emerges from is that the transport function consistently falls outside the safe space for all sub-basins and under all scenarios. However, the NPL index is not representative of reality because nitrogen and phosphorus loads were simulated without considering policy regulations



(Nkwasa et al., 2025). Thus, the transport function was not considered for the final SOS evaluation but is reported as a warning of the risk that relaxing policies on water quality could pose. However, even after excluding the NPL, none of the sub-basins result in a safe state, all having all one or more functions outside the thresholds in all scenarios (see Figure 22 and Table 7). It should be noted, however, that water functions always fail under dry or wet year conditions, indicating that the system performs well under normal circumstances but has low resilience to shocks, especially regarding groundwater depletion (ARRL) in dry years. The poor performance of the water supply function is partly due to the CWatM grid-based model structure and the way it calculates met and unmet demand in each cell. Specifically, CWatM addresses water demand in each cell by supplying water from the cell itself and its neighboring ones, meaning that it does not account for water transfers from distant cells. Consequently, the index should not be interpreted as a lack of water to meet demand per se, but rather as the need to import water from other parts of the basin to fulfil demand. Therefore, it is a measure of how much water can be supplied locally to meet demand or, in other words, a measure of locally sustainable water use. Not surprisingly, the regulatory function fails in all scenarios because it is based on the river's current insufficient connectivity status (see Appendix A: Danube case study indicators for a detailed explanation). This finding aligns with the main pressures identified by ICDPR, which lists hydromorphological alterations as a key pressure on the basin (ICDPR, 2021), with initiatives being undertaken by the EU to achieve the goal of 25000 km of free-flowing rivers in Europe (EU, 2022), such as the EU Mission "Restore our Ocean and Waters".

As a final consideration, it is worth noting that the implemented precautionary approach may lead to conservative evaluations, and using fixed thresholds could potentially cause false positives for values just above the threshold. Employing frequency-based methods can mitigate this risk; however, a thorough assessment of the impacts of threshold uncertainty remains recommended.

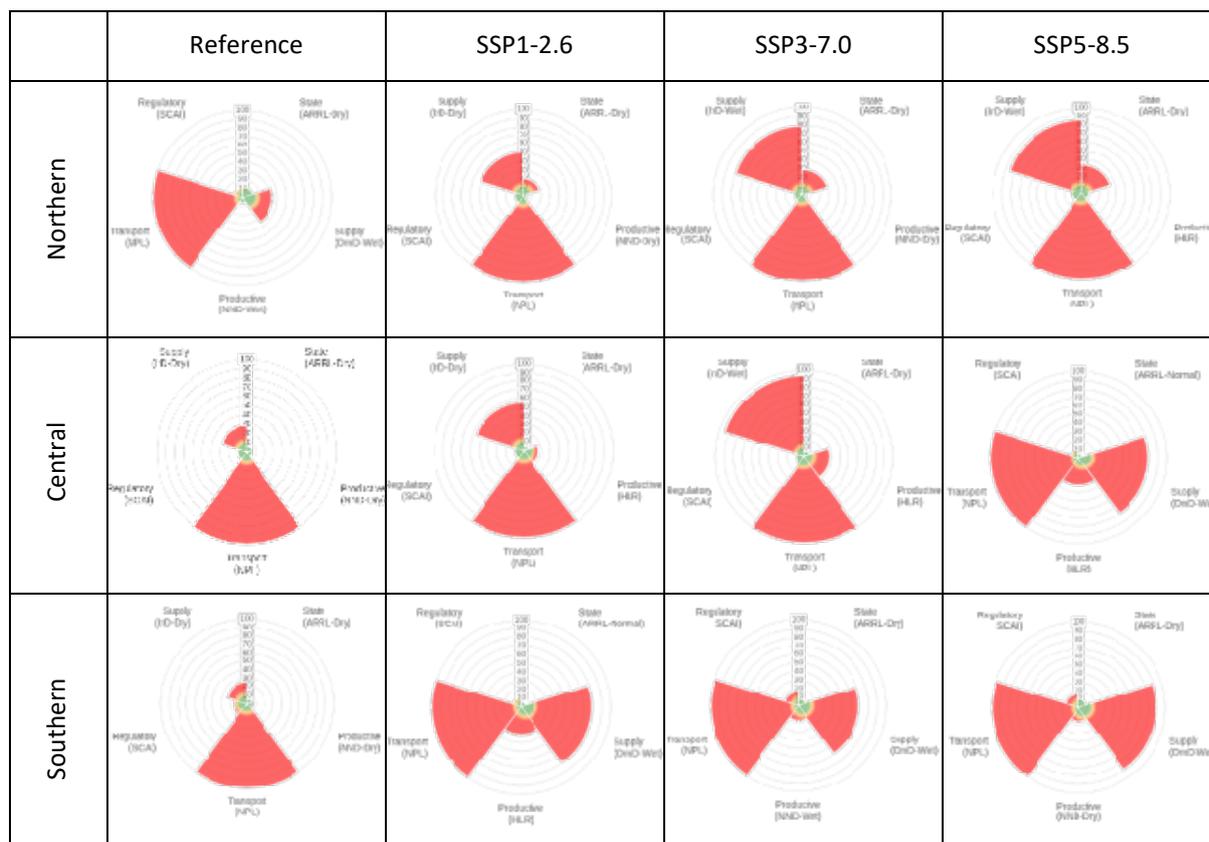


Figure 22. SOS Evaluation by functions of the Northern, Central and Southern Danube sub-basin.

Table 7. Summary of the worst indicators' performance for each water function in the Northern, Central and Southern Danube sub-basins. Colors differentiate among safe (green) and unsafe (red) spaces, following Figure 22.

Sub-basin	Scenario	State	Productive	Transport	Supply	Regulatory	Safe
Northern	Reference	ARRL-Dry	NND-Wet	NPL	DmD-Wet	SCAI	No
Central		ARRL-Dry	NND-Dry	NPL	IrD-Dry	SCAI	No
Southern		ARRL-Dry	NND-Dry	NPL	IrD-Dry	SCAI	No
Northern	SSP1-2.6	ARRL-Dry	NND-Dry	NPL	IrD-Dry	SCAI	No
Central		ARRL-Dry	HLR	NPL	IrD-Dry	SCAI	No
Southern		ARRL-Dry	NND-Dry	NPL	DmD-Wet	SCAI	No
Northern	SSP3-7.0	ARRL-Dry	NND-Dry	NPL	InD-Wet	SCAI	No
Central		ARRL-Dry	HLR	NPL	IrD-Dry	SCAI	No



Southern		ARRL-Dry	NND-Wet	NPL	DmD-Wet	SCAI	No
Northern	SSP5-8.5	ARRL-Dry	HLR	NPL	InD-Dry	SCAI	No
Central		ARRL-Norm.	HLR	NPL	DmD-Wet	SCAI	No
Southern		ARRL-Dry	NND-Dry	NPL	DmD-Wet	SCAI	No

3.3 Rhine Case Study

The Rhine River, spanning a length of approximately 1,230 km, is a major watercourse in Europe. It has a vast drainage area of around 185,000 km², encompassing various sub-basins and tributaries. The source of the Rhine River is in the Swiss Alps in the canton of Graubünden, from which the river flows through diverse landscapes, including mountainous regions, fertile valleys, and urbanized areas. Together with its tributaries, the Rhine forms a diverse range of ecological habitats, including mountain streams, floodplains, wetlands, and estuaries, supporting a rich biodiversity in the region. Moreover, the Rhine plays a crucial role in maintaining ecological connectivity, allowing for the migration and dispersal of species. In addition to serving as an essential navigation route, facilitating trade and commerce within Europe, the Rhine River is also a significant source of water, providing drinking water, supporting industrial processes, and facilitating agriculture in the region. The water flow of the upstream parts of the Rhine is regulated through a system of dams and reservoirs to ensure water availability throughout the year. The lower reaches have no man-made obstacles to enable shipping of large volumes of cargo from Germany to the port of Rotterdam and back. The Rhine-Meuse Delta, also known as the Rhine Delta or the Dutch Delta, is the vast coastal plain formed by the convergence of the Rhine and Meuse rivers in the Netherlands. It extends from the city of Rotterdam to the North Sea and covers an area of approximately 8,000 km². The Delta, with its complex network of channels and wetlands, is a dynamic environment influenced by tidal processes, sediment deposition, and human interventions. The diversity of its habitats supports unique flora and fauna, and serves as an important breeding ground for birds, as well as a stopover site for migratory species.

The Rhine River and its Delta currently face various ecological challenges. Human activities, including land reclamation, urbanization and agriculture have led to habitat loss, fragmentation, pollution, and a reduced water availability in summer. The construction of dams and flood defenses has altered the natural hydrology of the river, affecting fish migration, sediment transport and water quality. Additionally, climate change poses risks such as sea-level rise, increased storm surges, droughts and changes in precipitation patterns, which can impact the stability and biodiversity of the river basin. Regarding the future, the Rhine is expected to deal with challenges related to droughts and floods. With more hydrological extremes it will be more challenging to balance storage of water to mitigate drought and discharging water to increase potential flood volumes.

Stakeholder engagement



The main stakeholders in the Rhine River are the national water authorities of the different countries; they often represent the interests of the more local stakeholders. Other parties involved include nature, shipping, agriculture, industry, local water authorities, hydropower companies, local communities.

In the Rhine River, most activities have been aimed toward summarizing and consolidating existing stakeholder information and engagement. As the Rhine is a mature basin in terms of trans-boundary stakeholder activities, we ensured that this information was used to have thresholds and critical levels reflect current stakeholder knowledge and concerns.

3.3.1 Indicators and Thresholds

For the Rhine River basin, according to the preferences of the stakeholders, most indicators and thresholds were determined based on the river discharge of the Rhine at Lobith (where the river flows into the Dutch delta). This location is frequently used as the outlet of the Rhine, as downstream of Lobith significant alterations to the natural river system make it difficult to evaluate changes in river discharge under “natural” conditions.

The following indicators were evaluated at Lobith, NL.

- Mean annual flow (m^3/s).
- Mean flow of driest month (m^3/s).
- Mean flow of wettest month (m^3/s).
- 1 in 10-year return period for flood and drought (m^3/s).
- Navigability recurrence (number of days under $1000 \text{ m}^3/\text{s}$).
- Average annual water temperature (Kelvin).

For the entire basin, basin specific indicators were developed for both the Meuse and the Rhine basin, namely:

- Reservoir storage fraction (fraction of total stored/max capacity for basin, dimensionless).
- Average water temperature (Kelvin).

These indicators were substituted with additional BioClimatic Indicators (BioClim) that are used for impact modelling (see Section 3.3.). The BioClim indicators calculated for the Rhine and Meuse basin are the following:

- Baseflow index (dimensionless).
- Yearly discharge (m^3/s).
- Discharge wettest month (m^3/s).
- Discharge driest month (m^3/s).
- Discharge driest quarter (m^3/s).
- Monthly standard deviation streamflow (m^3/s).
- Streamflow seasonality (m^3/s).
- Discharge hottest month (m^3/s).
- Discharge wettest season (m^3/s).
- Hydrologic variability index (-).





- Baseflow runoff (m³/s).
- Snow melt (m³/s).
- Water temperature (Kelvin).

These BioClim indicators feed into Species Distribution Model (SDM) that ultimately determines the species occurrence in the Rhine River basin. In replicating the calculation, we refer to the USGS webpage for relevant calculations and definitions (O’ donell and Ignizio, 2012). The output of the SDM is a spatial distribution of species occurrence that can be used to determine the number of species that occur within the basin.

As threshold for the Lobith specific indicators we use the classification provided by the Dutch national water authority: < 1100 m³/s (critical), 1100-4450 m³/s (normal), >4450 m³/s (elevated), >5400 m³/s (high), > 8100 m³/s (flood), >11800 m³/s (extreme flood) (see Table 8 below). For the basin wide indicators, we take the historical baseline and compute the 10-year return period; this is then used as threshold to define safe and unsafe conditions.

Table 8. Given discharge thresholds from the Dutch national water authority that are used to assess the local SOS at Lobith, NL.

Discharge Category	Threshold Range (m ³ /s)	Description
Reduced	< 1,000	Low discharge
Normal	1,000 – 4,450	Typical/normal discharge
Slightly Elevated	> 4,450	Slightly higher discharge
Elevated	> 5,400	Elevated discharge
High	> 8,100	High discharge
Extreme	> 11,800	Extreme discharge

3.3.1 Future Scenarios

As with the other case studies of the SOS-Water project, we selected the following SSP-RCP combinations for modeling future scenarios for the Danube basin case study (see Deliverable 2.1): SSP1-2.6 (sustainable pathways scenario), SSP3-7.0 (regional rivalry scenario) and SSP5-8.5 (fossil fuel-rich development scenario). For our projections, we utilize bias-corrected climate projections from the ISIMIP3b dataset retrieved for the following Global Climate Models (GCMs): GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL. The dataset includes daily bias-corrected variables as precipitation (pr), near-surface air temperature (tas), maximum and minimum air temperature (tasmax, tasmin), and surface downwelling radiation (rsds). The temporal horizons analyzed focus on mid-century (until 2099).

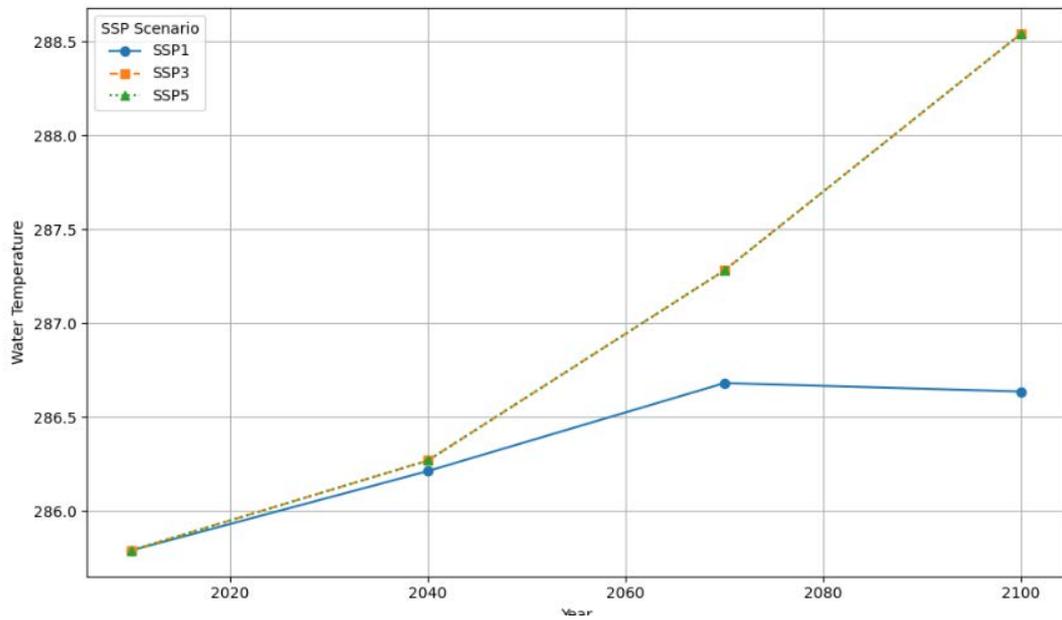


Figure 23. Graph of the changes in water temperature at Lobith, NL across the different scenarios considered.

Indicators over Time by SSP Scenario

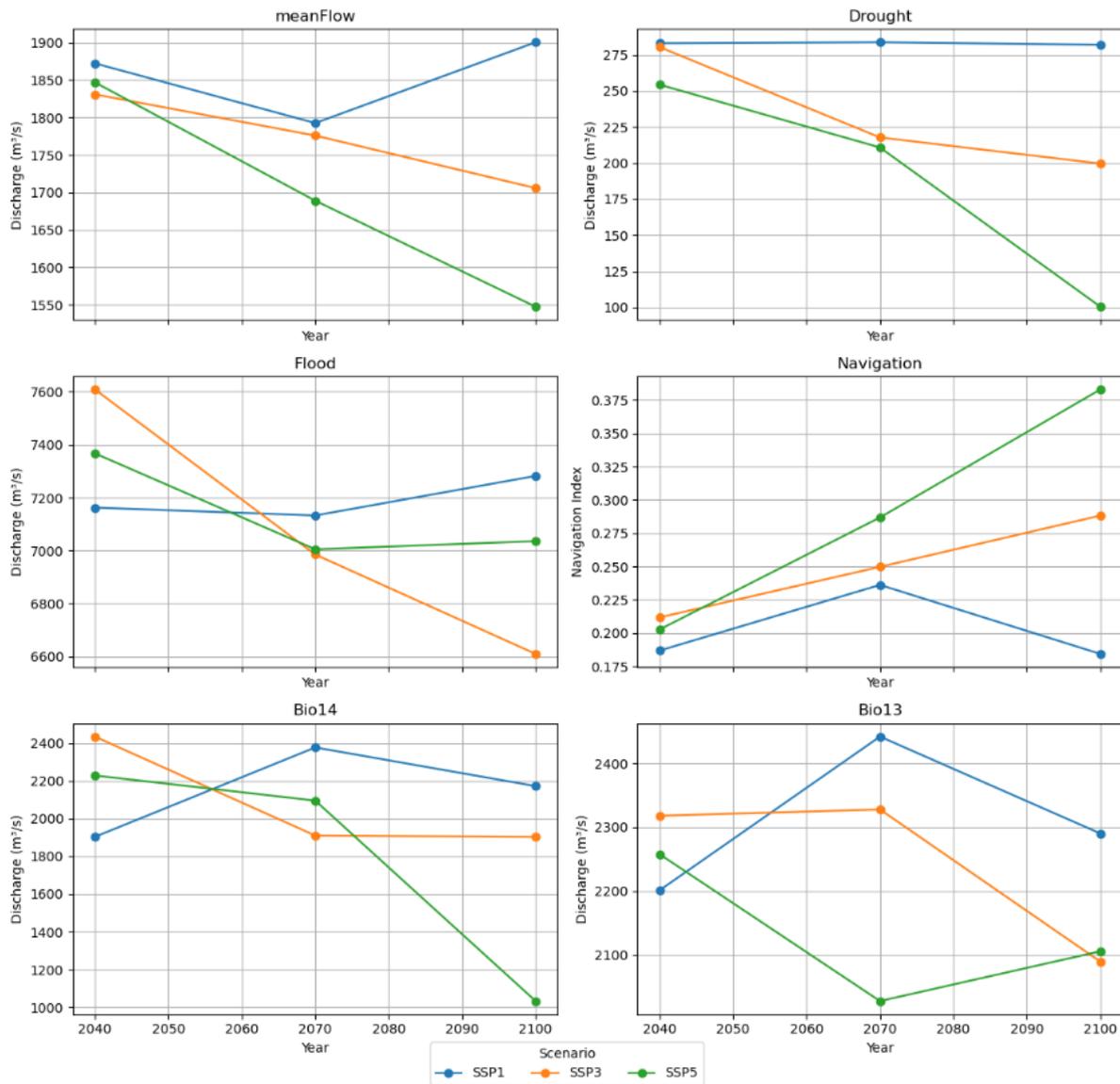


Figure 24. Individual plots of the Lobith specific indicators. Each color corresponds to a different SSP. The drought and flood indices correspond to the 95th percentile of the modelled discharge values. The navigation index corresponds to the number of navigable days across the 30 year period.

To evaluate the potential changes in the river system as they relate to the current group of designated scenarios, we opted to include the above plots that show the changes in the average indicators at Lobith. In all cases except for water temperature (Figure 23), the indicators show significant shifts across the different SSPs (Figure 24). In all instances, SSP5 presents the highest shifts. The lower mean flows, drought index value, Bio14 and Bio13 which both correspond to mean flows of the wettest (bio13) and driest (bio14) months. SSP3 has the lowest value for mean discharge suggesting there is some variability between the indicators at our key location. All the data for these plots is available on the YODA repository under Lobith Indicators.

3.3.2 Integrated Water Modeling System

Future scenarios are used to compute daily hydrological information at a 10 km spatial resolution. More specifically, the hydrological model is driven by future precipitation, evaporation and temperature data. Other factors, such as sectoral water demand, are constrained by the definition of the various SSPs, each corresponding to a different level of economic growth. Water temperature is modelled in combination with the hydrological fluxes.

Output from the hydrological model feeds into the biodiversity model (Figure 25) that classifies habitat suitability based on BioClimatic Indicators (BioClim). These indicators provide a range of suitable habitats for 21 fish species in the Rhine River basin.

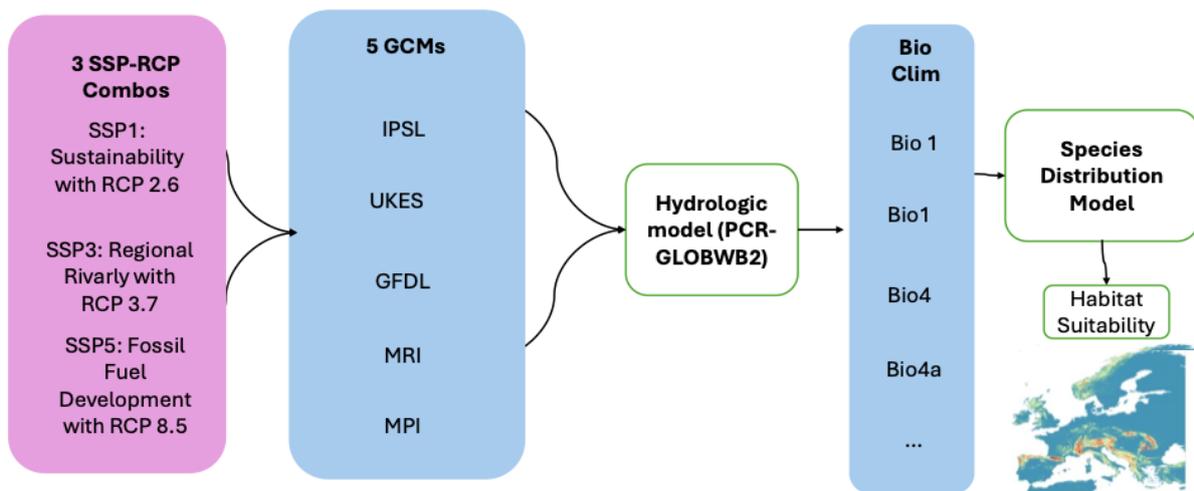


Figure 25. Modelling chain for biodiversity impact modelling in the Rhine River basin.

3.3.3 Multi-Dimensional SOS Assessment Results

The output from the hydrological model is used as input for the indicators’ calculation for different time periods (historic 2010, 2040, 2070). Where the value for 2040 is representative for the period 2010-2040 etc. The hydrological model’s outputs directly translate to inputs for the indicators’ calculation, such as discharge or river stage.

Using information from stakeholders, we make a preliminary classification on safe operating space using Lobith, NL as our evaluation point. To calculate these plots, we take the indicators shown in Figure 24 (mean discharge, navigational days, Bio13, Bio14 and the two quantiles evaluations for extreme droughts and floods) and evaluate them against the thresholds set by the Dutch government. For ease of access, we use all the thresholds to determine what indicators are within the acceptable range and which are outside the safe operating space.

For Lobith, the SOS does not change drastically between the different scenarios or time periods (Figure 26), due in part to the large discharge range from the Dutch national water authority. In general, most of the indicators are within an acceptable range, namely Bio13, Bio14 and navigation, suggesting limited changes to the hydrologic system under these scenarios and, therefore, a relatively safe operating space.



The drought indicator shows large extremes outside of the acceptable range suggesting unsafe conditions in this dimension when moving to the future. The flood indicator shows a moderately unsafe system when looking at future changes. For both of these, the results are due to the values sitting outside the acceptable ranges and are the most impactful on SOS evaluations. Additionally, for these two components, the SOS is exceeded based on the given thresholds. That said, we will need to clarify this in the final assessment, perhaps through normalizing our values or calculating the frequency of occurrence to ensure that we are not placing weight on one specific component of the SOS and rather aggregating the results into specified water functions or water values. All the data for these plots is available on the YODA repository under Lobith Indicators.

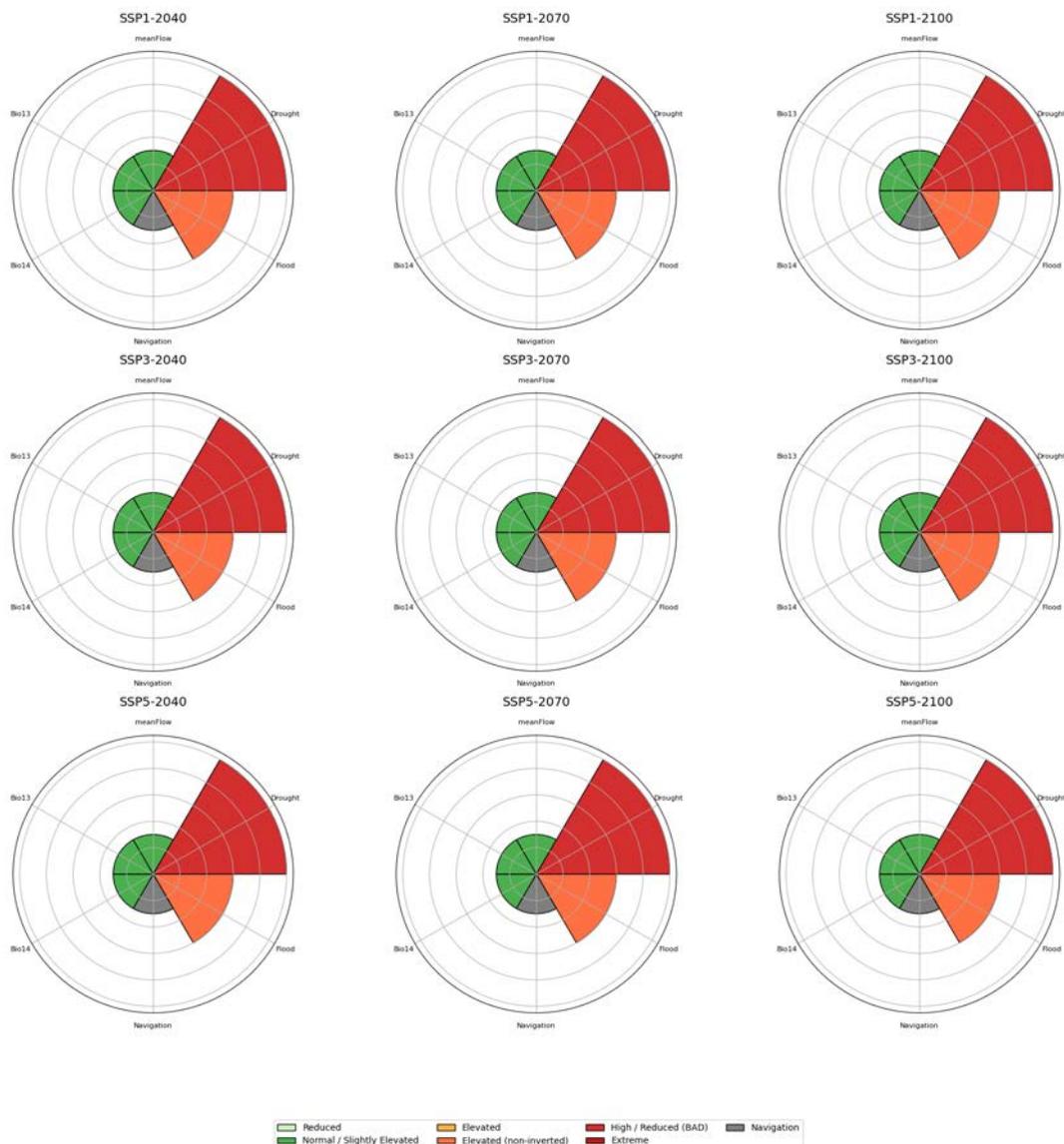


Figure 26. Preliminary evaluation of the SOS for the Rhine basin using Lobith, NL as the evaluation point. The different colors correspond to the threshold levels set by the Dutch national water authority for acceptable



ranges in at Lobith, NL. We plot six indicators and their relative threshold to show where the SOS might be exceeded and where the SOS is still within the limit.

3.4 Upstream Mekong Case Study

The Mekong River stretches nearly 4,800 km, originating in Tibet and flowing through six countries—China, Myanmar, Laos, Thailand, Cambodia, and Vietnam—before forming one of the world’s three largest deltas and flowing into the East Sea. The basin covers an area of approximately 795,000 km², with varying proportions of national territories falling within it: Laos (97%), Cambodia (86%), Thailand (36% in the Northeastern region), and Vietnam (20%, comprising the Central Highlands and the Mekong Delta). The river’s average annual flow is about 475 km³, of which 82% is generated within the four downstream countries—Laos (35%), Thailand (18%), Cambodia (18%), and Vietnam (11%). Although the upstream countries contribute only about 18% annually, their share represents roughly 30% of the dry season flow, making it essential for sustaining low-season water availability. The Mekong is globally significant for its biodiversity—second only to the Amazon—and supports the world’s largest freshwater fishery, yielding around 2.3 million tons of fish annually.

The basin lies in a tropical climate zone with high humidity and abundant rainfall (about 1,600 mm/year on average), though amounts vary by region. Rainfall is concentrated in the wet season (May–October), while November–April constitutes the dry season. Flow variability is high, with wet-season floods exceeding 50,000 m³/s and inundating over 60,000 km², especially in Cambodia and the Mekong Delta. During the dry season, reduced flows (2,000–5,000 m³/s) can cause saltwater intrusion in the Delta.

Since the 1960s, hydropower development—initially on tributaries and later on the mainstem—has altered seasonal flow distribution. Mainstem dams and reservoirs have significantly changed sediment transport, nutrient delivery, and hydrological regimes, producing a range of environmental impacts including:

- Reduced floodplain and coastal productivity due to diminished sediment and nutrient flows.
- Increased bank erosion and delta land subsidence.
- Altered dry season habitats affecting fisheries and local livelihoods.
- Shifts in nutrient dynamics and agricultural runoff patterns.
- Changes in saline intrusion in the Mekong Delta, influenced by both altered flows and sea-level rise.
- Decline in wetland extent and key habitats, with associated biodiversity losses.

These hydrological, ecological, and socio-economic dynamics make the highly transboundary Mekong Basin a complex system, where upstream developments and climate change have profound implications for downstream areas, particularly the Mekong Delta.

For the purpose of this project, as already explained in the introduction, the SOS of the Mekong River basin is assessed by separating the domain into Upstream Mekong and Mekong Delta. The Upstream



Mekong covers the entire area from the Tibetan Plateau (where the river originates) to Stung Treng in Cambodia, a few kilometers upstream of the floodplain and the Delta.

Stakeholder engagement

Since the project is primarily focused on the Mekong Delta, there are no stakeholders directly based in the upstream region. As a result, no stakeholder engagement activities were conducted specifically for this area. Nevertheless, all models developed, indicators selected, thresholds identified, and future scenarios considered for the upstream region were discussed with stakeholders in the Delta. Although not directly involved in upstream management, these stakeholders have an interest in understanding upstream conditions, as such knowledge can help improve the description and assessment of their downstream system.

For this reason, during the second stakeholder workshop, held in May in Ho Chi Minh City, the IWMS, selected indicators, and scenarios used for assessing the SOS under future conditions for the Upstream Mekong were presented to the Delta's stakeholders. Feedback was requested on these elements, although the response was limited, as stakeholders were naturally more knowledgeable about—and primarily interested in—the Delta.

3.4.1 Indicators and Thresholds

In the Upstream Mekong River system, the selection of indicators was primarily based on the variables that the IWMS can reliably represent, given the limited stakeholder participation in this region. Nonetheless, the aim was to develop an integrated model capable of capturing as many relevant dimensions of the basin as possible. These include hydropower development and its sustainability, the reduction of sediment transport, and regional food security—dependent on both fisheries and agriculture, which are themselves reliant on the river's resources.

The final list of indicators considered is as follows:

- **Annual hydropower production.** Based on the output of VICRes, it is possible to calculate the annual hydropower production for each reservoir in the basin. For the time horizons considered under the different scenarios, the following indicators are computed:
 - Mean, maximum, and minimum annual hydropower production for the entire basin, normalized by the total installed capacity of the basin (dimensionless).
 - Mean, maximum, and minimum annual hydropower production of Chinese reservoirs, normalized by the total installed capacity in China (dimensionless).
 - Mean, maximum, and minimum annual hydropower production of Myanmar reservoirs, normalized by the total installed capacity in Myanmar (dimensionless).
 - Mean, maximum, and minimum annual hydropower production of Laos reservoirs, normalized by the total installed capacity in Laos (dimensionless).
 - Mean, maximum, and minimum annual hydropower production of Thai reservoirs, normalized by the total installed capacity in Thailand (dimensionless).
 - Mean, maximum, and minimum annual hydropower production of Cambodian reservoirs, normalized by the total installed capacity in Cambodia (dimensionless).



- Mean, maximum, and minimum annual hydropower production of Vietnamese reservoirs, normalized by the total installed capacity in Vietnam (dimensionless).

These indicators are therefore calculated both at the scale of the entire basin and at the country level. Importantly, to enable comparison of indicator values across different countries—as well as with future hydropower development scenarios—all values are normalized by the respective total installed capacity. Without such normalization, in a management pathway involving the construction of additional reservoirs, the mean, maximum, and minimum annual production would inevitably increase simply due to the higher number of reservoirs. If safety thresholds were defined using historical values, this would result in safe conditions across the scenarios, regardless of actual operational constraints.

- **Annual Stung Treng sediment loads.** Based on the D-CASCADE model output, the annual total sediment load reaching Stung Treng – where the model domain ends – can be estimated. Although the model can compute the same quantities for other upstream stations, the analysis focuses exclusively on Stung Treng, given its proximity to the Delta, where sediment starvation is more critical. For the time horizons considered under the different scenarios, the following indicators are computed:
 - Mean, maximum, and minimum annual sediment loads reaching Stung Treng (Mt/yr). This is a point-specific indicator, calculated for a single location in the basin. However, its value inherently depends on the hydrological and sediment transport conditions across the entire upstream basin.
- **Annual Greenhouse Gas (GHG) emissions from reservoirs.** Using empirical formulas (Tangi et al., 2025) that relate the annual storage volumes of reservoirs (obtained from VICRes outputs) to their corresponding annual GHG emissions, it is possible to estimate the annual GHG emissions for each reservoir in the basin. For the time horizons considered under different scenarios, the following indicator is computed:
 - Mean annual GHG emissions for the entire basin, divided by the total installed capacity of the basin (kg CO₂eq/MW).
 - Mean annual GHG emissions of Chinese reservoirs, divided by the total installed capacity in China (kg CO₂eq/MW).
 - Mean annual GHG emissions of Laos reservoirs, divided by the total installed capacity in Laos (kg CO₂eq/MW).
 - Mean annual GHG emissions of Thai reservoirs, divided by the total installed capacity in Thailand (kg CO₂eq/MW).
 - Mean annual GHG emissions of Cambodian reservoirs, divided by the total installed capacity in Cambodia (kg CO₂eq/MW).
 - Mean annual GHG emissions of Vietnamese reservoirs, divided by the total installed capacity in Vietnam (kg CO₂eq/MW).

As for the hydropower production indicators, a ‘carbon intensity’ approach has been adopted by dividing emissions by the total installed capacity. This normalization ensures that pathways involving the construction of additional reservoirs do not automatically appear to exceed



historical thresholds, which could otherwise classify future conditions as unsafe regardless of actual emissions efficiency.

- **Annual agricultural water deficit south of Stung Treng.** Using discharge data at Stung Treng from VICRes simulations along with monthly potential irrigation water withdrawal data coming from CWatM (Burek et al., 2020), it is possible to calculate the agricultural water deficit in the area south of Stung Treng, which comprises the part of Cambodia out of the model’s domain and the Mekong Delta. For the time horizons considered under the different scenarios, the following indicators are computed:

- Mean, maximum and minimum annual agricultural water deficit south of Stung Treng (m³/year).

This is a lumped indicator, directly calculated considering the outlet section of the model (Stung Treng). However, it is influenced by the variations of upstream hydrological and climatic conditions, as well as by local interventions across the entire basin (e.g. construction and operation of new dams, agricultural expansion, etc.)

- **Annual fish catches in the Dai Fishery.** Using the developed fish catch predictor – based on discharge at Stung Treng (from VICRes outputs), gridded temperature and precipitation data (from downscaled future climate projections), and the Connectivity Index – it is possible to estimate the annual fish catches in the Dai Fishery in the Tonle Sap, Cambodia. For the time horizons considered under the different scenarios, the following indicators are computed:

- Mean, maximum, and minimum annual fish catches in the Dai Fishery (t/year).

This is a lumped indicator, calculated for a single location in the basin. However, it reflects the influence of upstream hydrological and climatic dynamics, as well as connectivity conditions along the river system.

Regarding the thresholds defined for each indicator, in this case study it was challenging to introduce threshold values based on expert judgment, policy standards, or stakeholder input, given the nature of the indicators. Therefore, time series of each indicator were calculated for the historical period (1981–2022), and a statistical analysis was performed on these historical datasets to identify the thresholds. Specifically, thresholds were set at: the 25th percentile of the historical series for indicators representing the mean over the considered time window; the 5th percentile for indicators representing the minimum; and the 95th percentile for indicators representing the maximum over the considered window. Using this approach, the resulting thresholds for each indicator are reported in Table 9. To simplify the visualization, Table 9 only reports the resulting thresholds obtained for the indicators computed over the entire basin, using the mean operator across the considered time windows. The complete set of indicators and their respective thresholds is provided in Appendix B: Complete list of Upper Mekong basin indicators and thresholds.

Table 9. Basin-wide indicators and their thresholds, both in absolute values and normalized between 0 and 1.

Indicator	Threshold	Normalized Threshold
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Mean annual hydropower production for the entire basin, normalized by the total installed capacity of the basin (-)	25 th percentile of the annual historical series (1981-2022) of hydropower production for the entire basin, normalized by the total installed capacity: 0.5177	0.4131
Mean annual sediment loads reaching Stung Treng (Mt/yr)	25 th percentile of the annual historical series (1981-2022) of sediment loads reaching Stung Treng: 79.0043 Mt/yr	0.6728
Mean annual GHG emissions for the entire basin, divided by the total installed capacity of the basin (kg CO ₂ eq/MW)	25 th percentile of the annual historical series (1981-2022) of GHG emissions for the entire basin, normalized by the total installed capacity: 4.2010 kg CO₂eq/MW	0
Mean annual agricultural water deficit south of Stung Treng (m ³ /year).	25 th percentile of the annual historical series (1981-2014) of agricultural water deficit south of Stung Treng: 0 m³/year	0
Mean annual fish catches in the Dai Fishery (t/year)	25 th percentile of the annual historical series (1981-2014) of fish catches in the Dai Fishery: 37252.1589 t/year	0.0579

3.4.2 Future Scenarios

We selected the following SSP-RCP combinations for modeling future scenarios for the Upstream Mekong River System (see Deliverable 2.1): SSP1-2.6 (sustainable pathways scenario), SSP2-4.5 (middle-of-the-road scenario), SSP3-7.0 (regional rivalry scenario) and SSP5-8.5 (fossil fuel-rich development scenario). For our projections, we utilize bias-corrected climate projections from the ISIMIP3b dataset retrieved for the following Global Climate Models (GCMs): GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL. The dataset includes the following daily bias-corrected variables: precipitation (pr), maximum and minimum near-surface air temperature (tasmax, tasmin), and near-surface wind speed (sfcwind). The temporal horizons compared are 2041-2070 and 2071-2100. GFDL-ESM4 outputs are used to illustrate differences between climate projections in the basin. Precipitation and temperature are the variables that most influence the hydrological model’s outcome; therefore, they are the ones presented and analyzed here. The Mekong basin is characterized by a dry

season and a monsoon season, which differ significantly in precipitation patterns; therefore, we analyzed precipitation anomalies separately for the two periods.

Precipitation during the dry season shows a barely noticeable increase across almost the whole basin just for SSP5-8.5 for the mid-century (Figure 27), while for the other scenarios precipitation patterns are expected to remain similar to the baseline. For end-of-century, SSP-1.26 and SSP2-4.5 show a slight increase in precipitation, while SSP-3.70 and SSP-5.85 present almost an opposite trend, with precipitation seemingly diminishing across the basin. All in all, there are not particularly evident trends in precipitation anomaly. During the monsoon season, on the other hand, anomalies become more evident (Figure 28), with a prevalence of dry scenarios for the 2041-2070 period. During the 2071-2100 period, all scenarios but SSP-3.70 appear wetter, with SSP-1.26 displaying the greatest increase in precipitation.

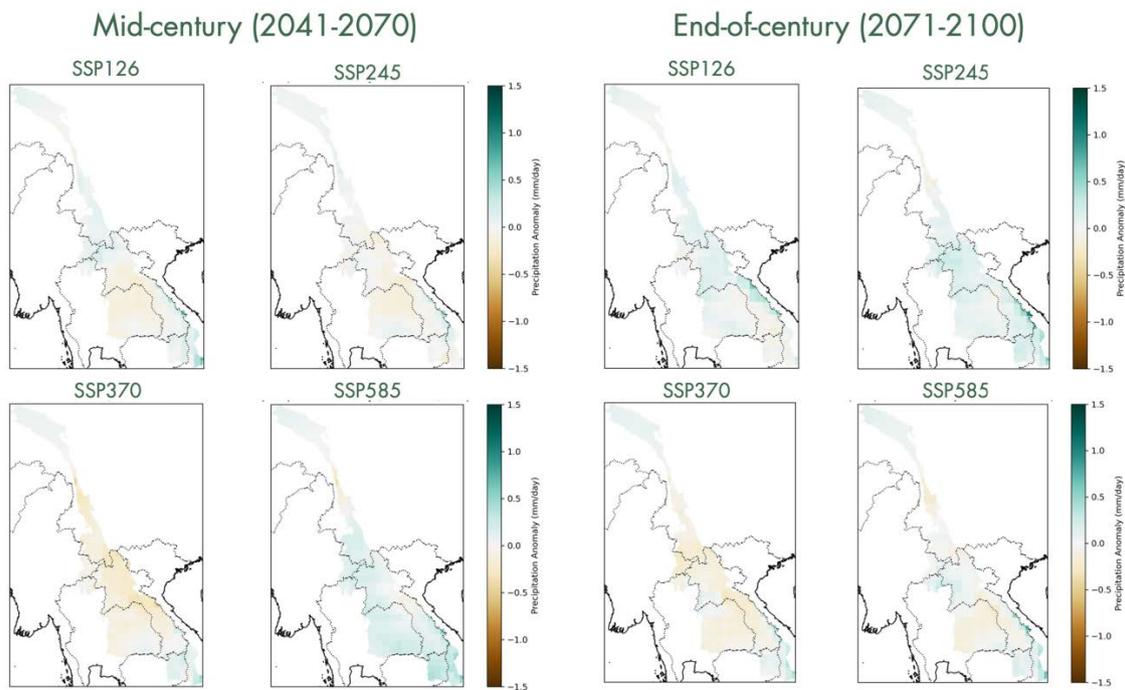


Figure 27. Average daily precipitation anomaly compared to a 1981-2010 baseline (dry season).

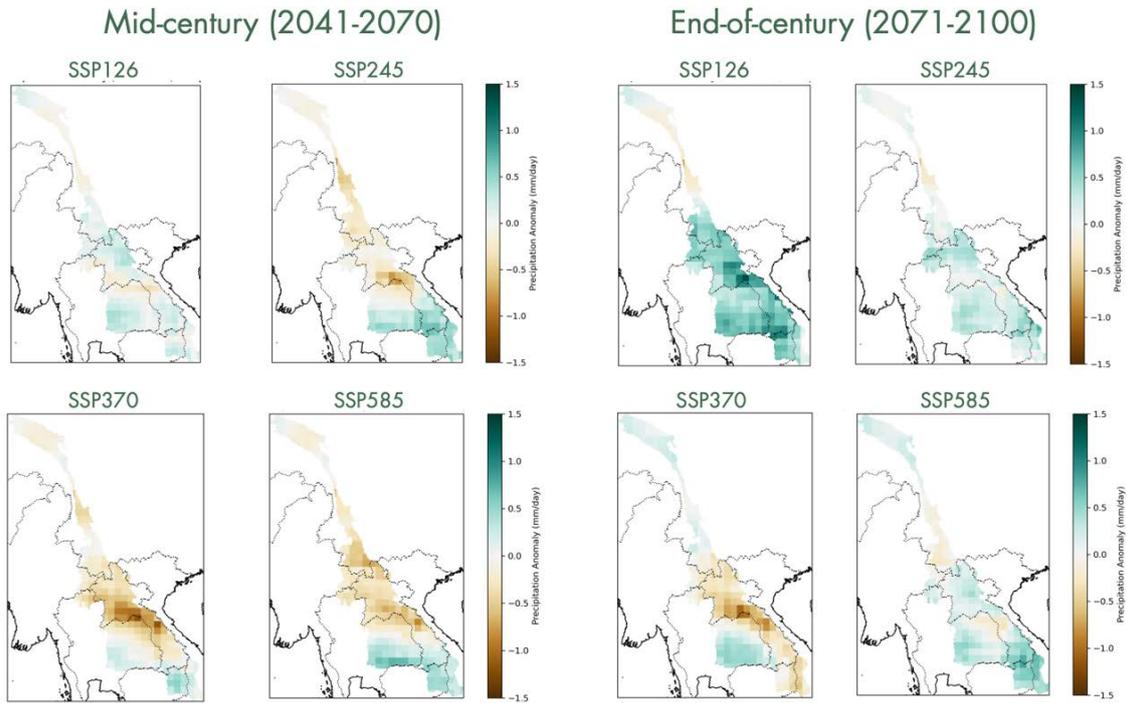


Figure 28. Average daily precipitation anomaly compared to a 1981-2010 baseline (monsoon season).

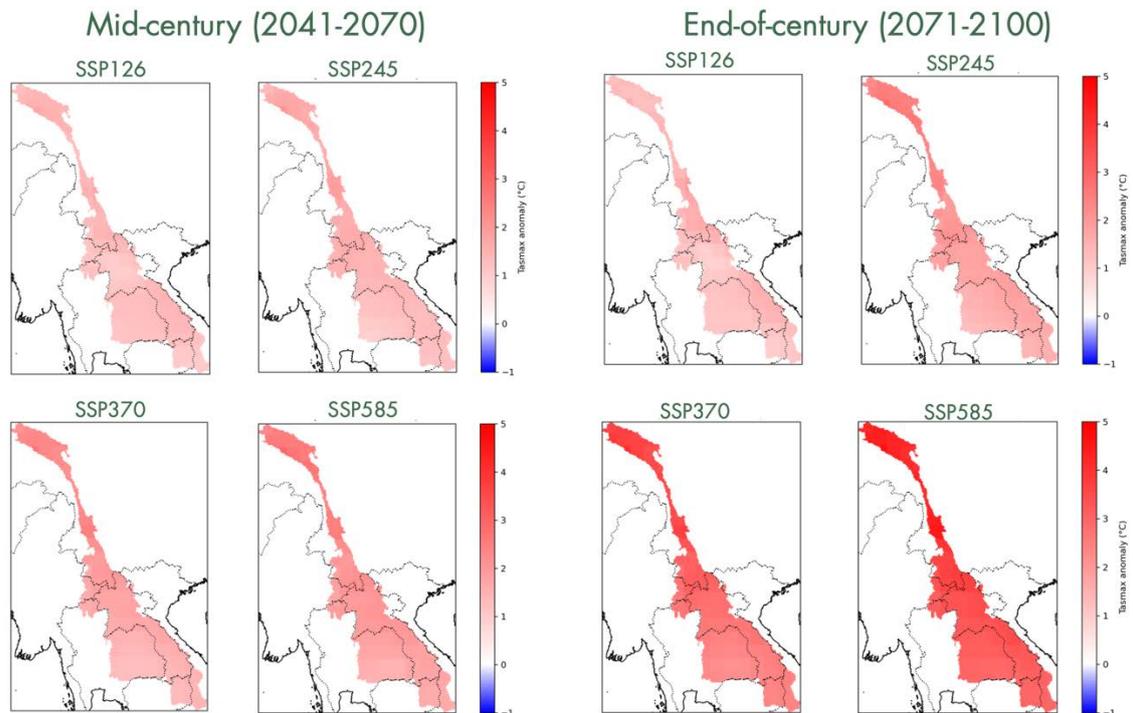


Figure 29. Average maximum daily temperature anomaly compared to a 1981-2010 baseline.

Temperature, on the other hand, always increases independently of time horizon and scenario considered, both when considering maximum and minimum daily temperature (Figure 29 and Figure 30, respectively). In both instances, at the end of the century the difference between scenarios is more marked than for mid-century, with SSP-3.70 and SSP-5.85 registering the greatest increases in temperature. Notably, the most substantial anomalies are expected to interest the upper part of the basin.

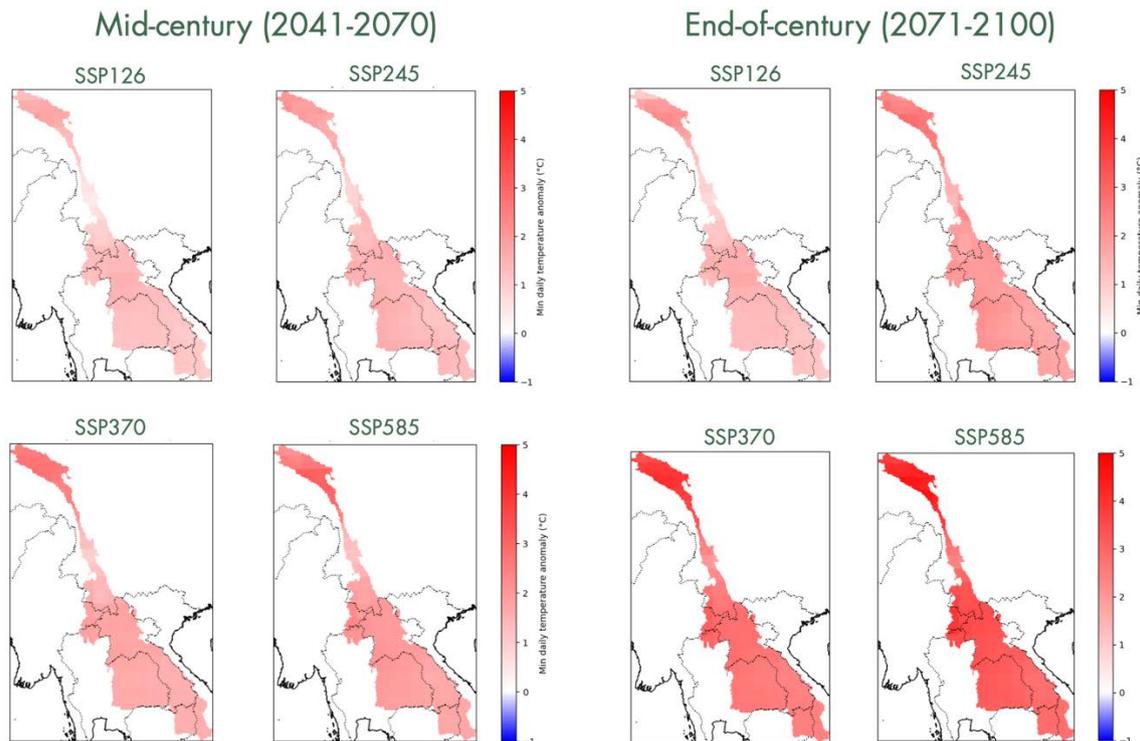


Figure 30. Average minimum daily temperature anomaly compared to a 1981-2010 baseline.

3.4.3 Integrated Water Modeling System

The Integrated Water Modeling System (IWMS) developed for the Upstream Mekong is built around the large-scale hydrological and water management model VIC-Res. A key feature of VIC-Res is its ability to represent water reservoirs and their operations. Each reservoir is modeled with a cell representing the dam location and additional cells representing the water body, where the mass balance is computed. Release decisions follow predefined rule curves, which consider water availability, incoming inflow, and dam design specifications. Using this information, together with hydraulic head and release data, the model calculates daily electricity generation and simulates river discharges along the network. The model domain spans approximately 630,000 km², from the upper reaches of the Lancang in China to the Stung Treng gauging station in Cambodia. In total, 125 dams are represented, each with a storage capacity greater than 1 Mm³ or an installed capacity above 5 MW. The spatial resolution is 0.0625 degrees, selected to ensure that no cell contains more than one dam. The full setup and input data are reported in Eldardiry et al., (2025).



To capture additional system dimensions beyond hydrology and reservoir operations, VIC-Res is coupled with impact models. The first of these is D-CASCADE, a dynamic, one-dimensional network-based sediment connectivity model (Tangi et al., 2022). D-CASCADE conceptualises sediment transport as a series of individual cascades, tracking sediment movement across space and time to assess sediment supply and delivery patterns throughout the basin. D-CASCADE explicitly accounts for hydropower reservoirs and their influence on sediment transport. For each reservoir, daily Trap Efficiency is calculated based on the Brune Curve (Gill, 1979) and the sediment grain size, reducing transported loads accordingly. The coupling between VIC-Res and D-CASCADE is hard-linked, ensuring dynamic feedback between hydrological processes, reservoir operations, and sediment connectivity. This integration required enhancing VIC-Res to simulate sediment management operations in addition to water releases. Two strategies were implemented: drawdown flushing and sluicing. VIC-Res provides D-CASCADE with daily flow data for sediment transport simulations, while D-CASCADE returns daily sediment deposition estimates for each reservoir. These deposition values update VIC-Res's reservoir mass balances, influencing subsequent releases and flow conditions at the next time step. Ultimately, D-CASCADE Mekong is capable of reproducing annual sediment loads at Stung Treng, as well as at other upstream stations when required.

The second impact model linked to the IWMS is a fish catch predictor, designed to estimate the annual fish catches of the Dai Fishery in the Tonle Sap. This model was calibrated using 15 years of historical annual fish catch data through a linear regression approach. The predictors include bioclimatic variables derived from temperature and precipitation data downscaled from global projections, a connectivity index that represents river connectivity based on the number of dams present in the basin, and flow alteration indices at Stung Treng, calculated directly from discharge data produced by VIC-Res. Using these drivers, the model estimates the annual fish catches of the Dai Fishery, which is one of the largest fisheries in the world. This model thus captures the crucial fishery dimension within the Mekong basin.

Furthermore, we introduced a module to estimate greenhouse gas (GHG) emissions from reservoirs, thereby incorporating their sustainability into the SOS assessment for the Mekong River basin. Currently, an empirical formula based on the work of Tangi et al. (2024) has been applied to a subset of reservoirs for which all necessary data were available.

Finally, using discharge data at Stung Treng from VICRes simulations along with monthly potential irrigation water withdrawal data coming from CWatM (Burek et al., 2020), we calculated the annual agricultural water deficit in the area south of Stung Treng.

A comprehensive list of the main inputs required by the various modules, along with the key outputs generated by the IWMS, is presented in Figure 31.

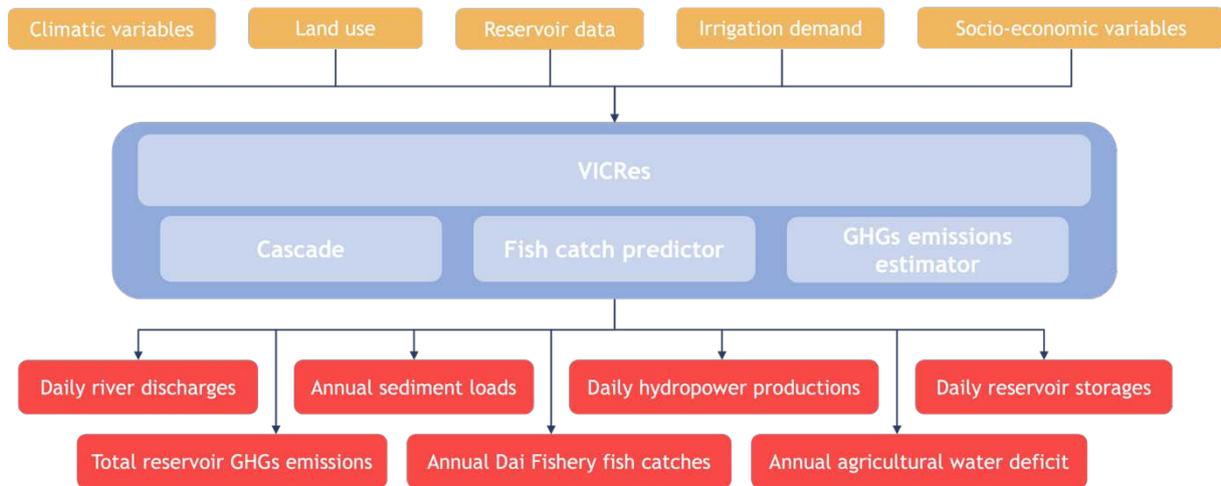


Figure 31. Integrated Water Modeling System (IWMS) for the Upstream Mekong, detailing the inputs needed by the different modules and the outputs they main outputs they produce.

3.4.4 Multi-Dimensional SOS Assessment Results

The IWMS outputs are used to calculate each indicator presented in [Section 3.4.1](#) in the following ways:

- Annual hydropower production.** VICRes provides the daily hydropower production for each reservoir in the basin. We first normalized these values by dividing them by the total installed capacity of each reservoir. The data were then aggregated at the yearly scale to obtain the annual production of each reservoir. Each reservoir was subsequently assigned to the country in which it is located, and by aggregating the production values of all reservoirs within these subsets, we computed the average, minimum, and maximum annual production normalized by the total installed capacity for each country and for the whole basin. These indicators are calculated considering the time windows shown in Figure 32.
- Annual Stung Treng sediment loads.** Using the daily discharges for each D-CASCADE river reach provided by VICRes under different climatological scenarios, we simulated D-CASCADE to estimate the annual total sediment loads reaching Stung Treng – where the model domain ends. From these outputs, we then calculated the average, minimum, and maximum annual sediment loads at Stung Treng over the time windows shown in Figure 32.
- Annual Greenhouse Gas (GHG) emissions from reservoirs.** VICRes also provides as output the daily water volumes of each reservoir in the basin. By aggregating these values, we calculated the average annual water volume of each reservoir. Similarly to the hydropower production indicator, these data were then used to estimate GHG emissions from reservoirs for each country and for the whole basin through an empirical formula. This formula relies on carbon flux data, which are available only for a limited subset of the 125 reservoirs simulated by VICRes. Consequently, the indicator was calculated only for this subset; no data were available for Myanmar, which is therefore not represented. Finally, we computed the average GHG



ORIGINAL INDICATOR MATRIX (BASELINE MANAGEMENT PATHWAYS): UPSTREAM MEKONG BASIN					
Scenarios	Mean Annual hydropower production over total installed capacity	Mean Annual Dai Fishery fish catches	Mean Stung Treng Annual Sediment load	Mean Annual agricultural water deficit	Mean Annual CO2 equivalent emitted by reservoirs over total installed capacity
Historical - (1981 - 2022)	0.42	37647.98	83.58	58698253.54	7.98
Historical - (2001 - 2014)	0.47	38322.37	83.87	63825520.90	4.55
Historical - GFDL-ESM4 (2001 - 2014)	0.36	25223.22	76.24	479034724.11	4.25
SSP1-2.6 - GFDL-ESM4 (2035 - 2050)	0.61	23601.06	75.67	0.00	19.25
SSP1-2.6 - GFDL-ESM4 (2041 - 2050)	0.61	22743.93	77.13	0.00	19.25
SSP1-2.6 - GFDL-ESM4 (2091 - 2100)	0.63	25637.77	81.83	0.00	19.35
SSP1-2.6 - GFDL-ESM4 (2031 - 2100)	0.61	23970.48	80.68	0.00	19.16
SSP2-4.5 - GFDL-ESM4 (2035 - 2050)	0.61	25640.44	78.33	No data	19.29
SSP2-4.5 - GFDL-ESM4 (2041 - 2050)	0.61	25160.41	77.83	No data	19.29
SSP2-4.5 - GFDL-ESM4 (2091 - 2100)	0.63	26421.31	85.86	No data	19.38
SSP2-4.5 - GFDL-ESM4 (2031 - 2100)	0.61	25203.64	80.56	No data	19.05
SSP3-7.0 - GFDL-ESM4 (2035 - 2050)	0.60	27106.18	78.39	0.00	19.27
SSP3-7.0 - GFDL-ESM4 (2041 - 2050)	0.60	31136.99	78.48	0.00	19.26
SSP3-7.0 - GFDL-ESM4 (2091 - 2100)	0.61	19846.92	81.52	0.00	19.28
SSP3-7.0 - GFDL-ESM4 (2031 - 2100)	0.60	20737.63	79.01	0.00	19.05
SSP5-8.5 - GFDL-ESM4 (2035 - 2050)	0.61	24166.57	78.88	0.00	19.29
SSP5-8.5 - GFDL-ESM4 (2041 - 2050)	0.61	24749.15	81.09	0.00	19.34
SSP5-8.5 - GFDL-ESM4 (2091 - 2100)	0.62	21717.17	85.58	0.00	19.33
SSP5-8.5 - GFDL-ESM4 (2031 - 2100)	0.61	22592.81	80.45	0.00	19.08

Figure 32. Upstream Mekong indicator matrix showing the mean values of the basin-wide indicators, calculated over specific time windows for both historical and future periods and under different climate change scenarios.

After normalizing the indicators using their respective minimum and maximum values we performed the final step and derived the SOS evaluation by translating indicator performances into a binary classification of ‘Safe’ or ‘Unsafe’, based on the thresholds defined in [Section 3.4.1](#). The final SOS evaluation for the Upstream Mekong case study is presented in Figure 33. As in the previous case, the figure reports only the indicators aggregated using the mean over the whole basin, while the indicator matrices containing minimum and maximum values are stored in the excel file available on the Yoda portal ([link](#)).



SOS WATER EVALUATION (BASELINE MANAGEMENT PATHWAYS): UPSTREAM MEKONG BASIN					
Scenarios	Mean Annual hydropower production over total installed capacity	Mean Annual Dai Fishery fish catches	Mean Stung Treng Annual Sediment load	Mean Annual Agricultural water deficit	Mean Annual CO2 equivalent emitted by reservoirs over total installed capacity
Historical - (1981 - 2022)	0.76	0.04	0.22	0.12	0.25
Historical - (2001 - 2014)	0.60	0.00	0.20	0.13	0.02
Historical - GFDL-ESM4 (2001 - 2014)	1.00	0.71	0.94	1.00	0.00
SSP1-2.6 - GFDL-ESM4 (2035 - 2050)	0.08	0.80	1.00	0.00	0.99
SSP1-2.6 - GFDL-ESM4 (2041 - 2050)	0.08	0.84	0.86	0.00	0.99
SSP1-2.6 - GFDL-ESM4 (2091 - 2100)	0.00	0.69	0.40	0.00	1.00
SSP1-2.6 - GFDL-ESM4 (2031 - 2100)	0.05	0.78	0.51	0.00	0.99
SSP2-4.5 - GFDL-ESM4 (2035 - 2050)	0.07	0.69	0.74	No data	0.99
SSP2-4.5 - GFDL-ESM4 (2041 - 2050)	0.06	0.71	0.79	No data	0.99
SSP2-4.5 - GFDL-ESM4 (2091 - 2100)	0.01	0.64	0.00	No data	1.00
SSP2-4.5 - GFDL-ESM4 (2031 - 2100)	0.06	0.71	0.52	No data	0.98
SSP3-7.0 - GFDL-ESM4 (2035 - 2050)	0.11	0.61	0.73	0.00	0.99
SSP3-7.0 - GFDL-ESM4 (2041 - 2050)	0.11	0.39	0.72	0.00	0.99
SSP3-7.0 - GFDL-ESM4 (2091 - 2100)	0.08	1.00	0.43	0.00	0.99
SSP3-7.0 - GFDL-ESM4 (2031 - 2100)	0.09	0.95	0.67	0.00	0.98
SSP5-8.5 - GFDL-ESM4 (2035 - 2050)	0.07	0.77	0.68	0.00	0.99
SSP5-8.5 - GFDL-ESM4 (2041 - 2050)	0.06	0.73	0.47	0.00	1.00
SSP5-8.5 - GFDL-ESM4 (2091 - 2100)	0.02	0.90	0.03	0.00	1.00
SSP5-8.5 - GFDL-ESM4 (2031 - 2100)	0.07	0.85	0.53	0.00	0.98

Figure 33. Matrix representing the final SOS evaluation for the Upstream Mekong. Red cells represent unsafe indicators, while green cells safe ones.

To complement the final SOS evaluation, we assessed the performance of each indicator across scenarios, as well as the trade-offs that may emerge among them. Figure 34 presents the distribution of indicator performance across scenarios using violin plots. The color scale of the violins reflects the percentage of safe scenarios for each indicator: red indicates a very low percentage (i.e., the indicator falls in the unsafe space in most scenarios), whereas green indicates a high percentage (i.e., the indicator falls in the safe space in most scenarios). This information is complemented by a parallel coordinate plot, where each line represents a scenario (corresponding to the rows of the matrix shown in Figure 33). Dots represent the performance of each indicator for each scenario, with red denoting unsafe conditions, green denoting safe conditions, and a black star indicating the identified threshold. This visualization allows for a clearer identification of trade-offs across dimensions, which can be recognized when the lines intersect rather than running parallel.

Results show that the hydropower and agriculture dimensions exhibit the highest proportion of safe scenarios in the future. This is likely driven by increased precipitation during the dry season, which enhances overall water availability and consequently improves the performance of these indicators. However, the parallel plot reveals a natural trade-off between these sectors and both the fisheries and GHG emission indicators. In fact, the increase in dry-season water availability—further exacerbated by reservoir operations that store excess wet-season inflows for later release—has negative effects on the Dai fishery in the Tonle Sap. Similarly, higher storage volumes in future scenarios lead to increased GHG emissions per unit of electricity produced, as the mean annual reservoir areas increase, contributing to higher emissions (appearing in the numerator of the empirical equation used for the indicator).

For the sediment-related indicator, performance values are more widely distributed, with roughly half of the scenarios classified as safe and half as unsafe, suggesting a stronger dependence on scenario-specific conditions. However, when this information is cross-checked with the matrix in Figure 33, a clearer temporal pattern emerges: in all near-term scenarios (2035–2050), the sediment indicator consistently falls into the unsafe space. Toward the end of the century, by contrast, the intensification of precipitation and river discharges mobilizes and transports larger amounts of sediment downstream to Stung Treng, bringing the indicator back within the safe operating space.

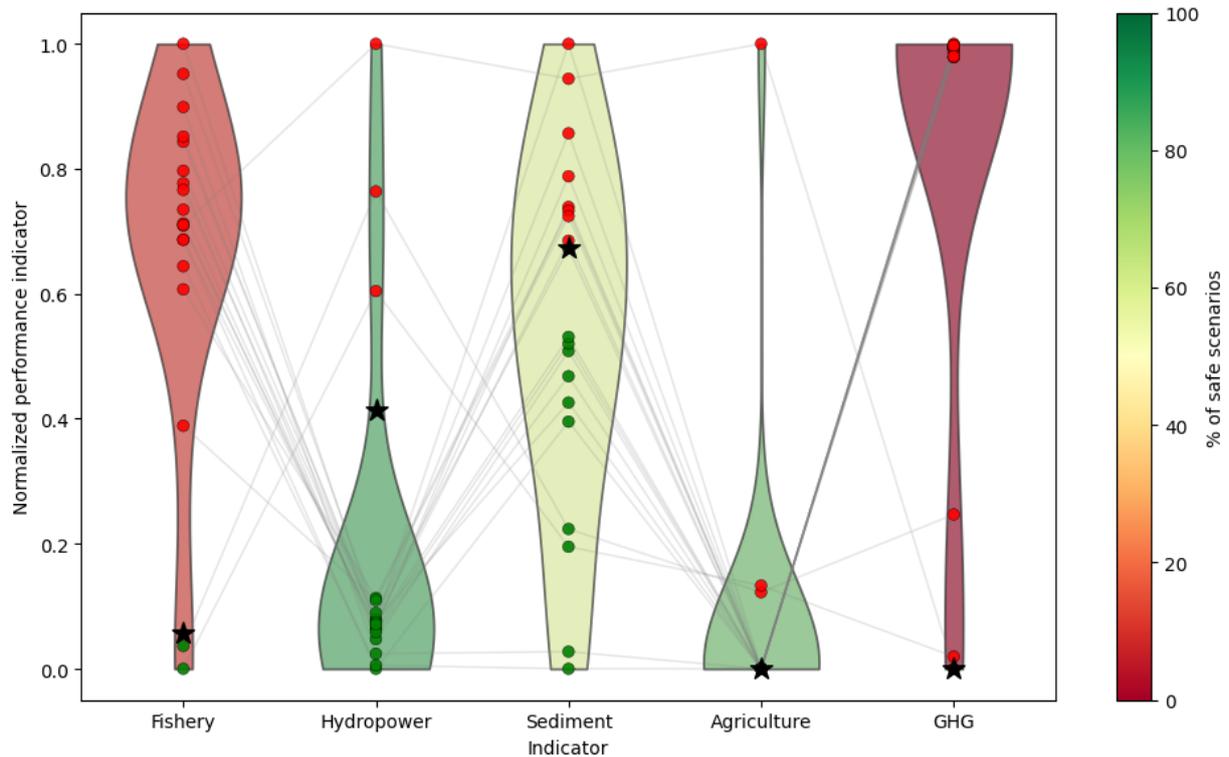


Figure 34. Violin plots representing Upstream Mekong normalized indicators' performance across scenarios.

To conclude the analysis, we focused on the hydropower performance indicator at the country level, carrying out a similar analysis to provide an example of how transboundary trade-offs within a given dimension can be assessed. Figure 35 highlights a marked power asymmetry: China, located upstream, consistently shows higher efficiency compared to downstream countries, with the exception of Cambodia, whose large reservoirs are located on tributaries rather than the mainstem and are thus less affected. The indicator is in fact defined as an efficiency metric (total electricity produced over total installed capacity) and is therefore strongly dependent on upstream water availability. This dependence is further emphasized by the pronounced trade-offs across countries, as evidenced by the frequent intersections of lines in the parallel coordinate plot.

Another key finding is that China, Vietnam, and Cambodia appear relatively insensitive to scenario variability, as indicated by violin plots that are tightly clustered within a narrow performance range. In contrast, the other three countries exhibit much broader distributions, suggesting stronger dependence

on specific future conditions. This pattern is consistent with storage capacity: China, Vietnam, and Cambodia possess the largest reservoirs, enabling them to buffer seasonal variability by storing wet-season inflows and maintaining a production efficiency that is less scenario-dependent.

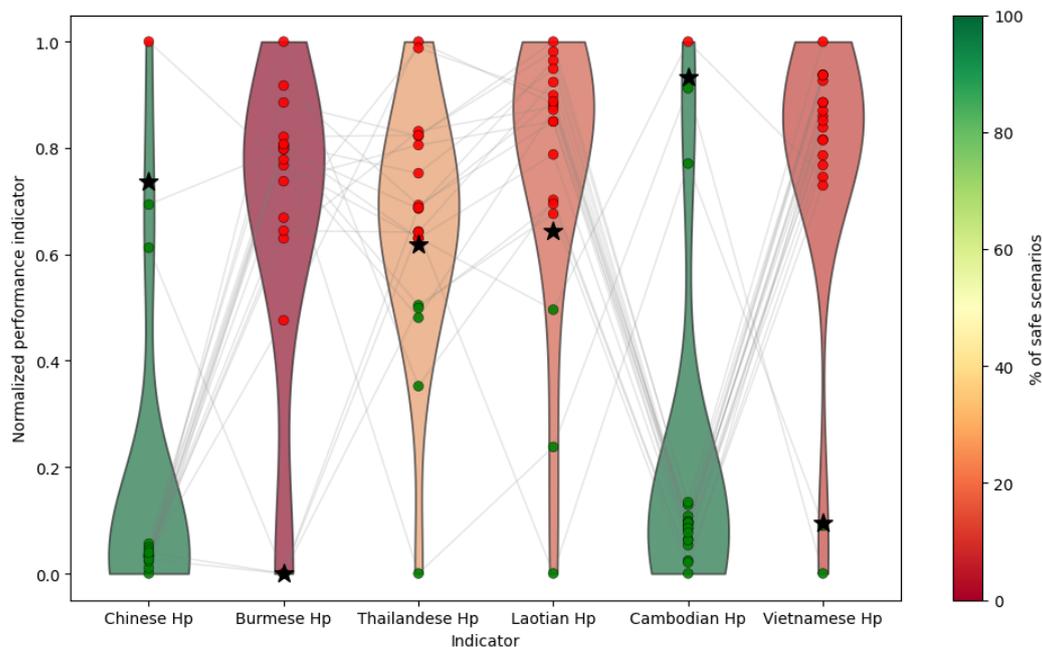


Figure 35. Violin plots representing the performance of the normalized hydropower indicator across scenarios for each country in the Upstream Mekong basin.

3.5 Mekong Delta Case Study

The Mekong Delta of Vietnam (MDV) is the last part of the Mekong River basin, covering the 4 provinces of Dong Thap, Vinh Long, An Giang, Ca Mau and Can Tho city, with a total natural area of about 3.96 million ha, accounting for 79% of the entire Delta, and 5% of the whole Mekong River Basin.

The Mekong Delta has a flat terrain, with an average elevation of +0.7 m to +1.2 m a.s.l. Air temperature is quite high: the average daily temperature throughout the year is about 27 °C, and the average annual temperature range in the region fluctuates between 2-3°C. The average annual rainfall is about 1300-2000 mm and is concentrated in the rainy season from May to October.

The main rivers include two main streams: Tien River and Hau River, distributaries to the sea and adjacent branches such as Vam Co, Giang Thanh, Cai Lon, My Thanh, Ganh Hao, Ong Doc, Bay Hap.

The hydrological regime depends on the tidal regime of the East Sea with a wide range of 3.5-4.0 m, rising and falling twice a day (semi-diurnal tide). The Mekong Delta has 26 irrigation systems with over 90,000 km of canals and nearly 1,000 sluices/dams serving irrigation and drainage for over 1.4 million hectares. Flood control works with a system of dikes and embankments with a total length of about 13,000 km. Coastal salinity and tidal control works include about 450 km of sea dikes and 8,290 km of river dikes and canal banks.



The Mekong Delta plays a very important role in the socio-economic development of Vietnam. With great agricultural potential, over the years the MDV has contributed about 50% of the country's rice output, 70% of the country's fruit output, 90% of rice exports and 60% of fish exports. The MDV water source is considered abundant with a total annual water resource of about 474 billion m³, of which the endogenous water from rain in the MDV is about 30 billion m³ and the water from upstream flowing into the MDV is about 441 billion m³. Currently, the Mekong Delta has been facing many serious challenges, especially the impacts of climate change (CC) such as sea level rise (SLR), drought, increased salinity intrusion, riverbank and coastal erosion, land subsidence, impacts due to exploitation and use of water resources in the upper Mekong. The major problems that the water resources of the Mekong Delta are facing are:

- Limitations of natural conditions: (a) the impact of floods on an area of 1.4-1.9 million hectares in the upstream area; (b) salinity intrusion on an area of 1.2-1.6 million hectares in coastal areas (with salinity of 4 g/l); (c) acid sulfate soils and the spread of acidic water on an area of about 1.2 million hectares in low-lying areas; (d) lack of fresh water and drought affecting production and daily life on an area of about 2.1 million hectares in areas far from rivers and near the sea; and (e) riverbank and coastal erosion occurring in many areas and becoming increasingly serious. Climate change in the past 30 years, and especially during the last decade, has become increasingly complex and unpredictable, causing many losses in all aspects of socioeconomics and national defense and security. The most obvious manifestations of climate change impacts on the Mekong River Delta are sea level rise (about 12-15 cm in the past 30 years), increasingly serious saline intrusion, drought and stream depletion, riverbank and coastal erosion, heavy rain causing flooding, increasing flood differentiation (the number of years with small floods increases, the number of years with large floods decreases) and increasingly complex flood developments.
- Impact of water exploitation and use in the upper reaches of the river: located at the end of the lower reaches of the Mekong River basin, the Mekong Delta is strongly influenced by the process of water exploitation and use of upstream countries, especially the impact of hydropower systems on both the mainstream and tributaries of the Mekong River.
- Combined impacts of climate change and upstream development. The impacts of climate change across the basin can lead to a shortage of annual rainfall in all or part of the basin, causing the total annual flow to decrease accordingly. At the same time, with increased water use and hydropower development, the flood flow is reduced (flood in 2015), the dry flow is even lower (drought and saltwater intrusion in 2016, 2019). Meanwhile, in the MDV, rising sea levels and droughts make water shortages and saltwater intrusion more serious (saltwater intrusion is deeper than average by 20-25 km).
- Unreasonable exploitation and use of water resources in the Mekong Delta: the Mekong Delta is the largest agricultural production area in the country, with a total area of about 3.0 million hectares, of which the rice area is between 1.8-2.0 million hectares, the aquaculture area is between 0.75-0.80 million hectares, and the fruit tree area is between 0.28-0.32 million hectares. To produce agriculture with 2-3 rice crops per year, fruit trees and aquaculture all year round, plus water for daily life for nearly 18 million people, industrial zones, tourism, and



created during the first stakeholder workshop in 2023. Through the research work on the assessment of SOS-Water in the Mekong Delta and based on the available data, the indicators and thresholds were updated and validated during the second stakeholder workshop in 2025.

Threshold values are determined according to legal documents, design standards, historical data and scientific research results.

The final list of recommended indicators and thresholds is reported in Table 10.

Table 10. Mekong Delta indicators and their thresholds.

Indicator	Threshold description	Threshold values
River flow at Kratie	Designed maximum flood and minimum dry flow discharge	1%, 2%, 10%, 50%, 75%, 85%, 95%
Tidal level at coast	Design annual maximum tidal level	10%, 85%
Local rainfall at key stations in Vietnam and Cambodia	Designed annual rainfall	10%, 85%
Flood level at Tan Chau	Flood warning (level 1, 2,3) and historical extreme	+3.5m; +4.0m; +4.5m; +5.1m
Salinity on mainstream at Xuan Hoa most downstream water intake for an irrigation system	High limit of salinity concentration for water use (water supply, irrigation) and historical extreme	1ppt; 4ppt and 5.4ppt
Salinity intrusion length from river mouth	Lower to high potential risk and historical extreme	30km; 50km; 65km and 91km
Water quality index (WQI) on mainstream	Quality level for water supply (class A) and irrigation (class B)	51-75 and >76
Flood and drought events	Historical extreme	Flood 2000, 2011; Drought and salinity 2016, 2020

3.5.2 Future Scenarios

All available output of SSP-RCP combinations and Global Climate Models (GCMs) from modeling future scenarios for the Upstream Mekong River System will be applied for the Mekong delta. Four SSP-RCP are considered, namely SSP1-2.6 (sustainable pathways scenario), SSP2-4.5 (middle-of-the-road



scenario), SSP3-7.0 (regional rivalry scenario) and SSP5-8.5 (fossil fuel-rich development scenario). Additionally, these scenarios are considered along with five GCMs: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL.

The dataset includes the following daily bias-corrected variables: precipitation (pr) at forty sites (rainfall stations) and daily flow discharge at Kratie (upper boundary of the Mekong delta).

The temporal horizons compared are historical 1981-2014, 2031-2050 and 2051-2100.

The data are statistically analyzed to obtain total annual rainfall data and annual maximum and minimum daily flows, which are then evaluated according to the design frequency applied in the country (example in Table 11 and Table 12). The design data are then scaled into daily time series to derive a typical year where daily average of flows and annual rainfall are distributed close to the observed monthly rainfall chart.

Finally, this typical design year is further downscaled to an hourly time step, providing boundary input data for calculations and modeling of the Mekong Delta.

Table 11. Results on the annual maximum daily flow frequency from historical simulations and baseline SSP126 scenarios.

Prob-ability	Historical 1981-2014					SSP126 – in 2031-2050					SSP126 - in 2051-2100				
	GCM1	GCM2	GCM3	GCM4	GCM5	GCM1	GCM2	GCM3	GCM4	GCM5	GCM1	GCM2	GCM3	GCM4	GCM5
P1%	64,035	102,561	39,660	58,058	49,908	52,726	107,096	30,833	59,430	55,602	56,946	92,746	33,836	53,223	50,154
P2%	59,436	89,737	38,004	53,829	47,817	49,335	92,421	29,984	54,270	51,953	53,176	81,965	32,518	50,107	48,447
P5%	53,123	73,025	35,653	48,037	44,746	44,744	73,721	28,739	47,497	47,093	40,098	67,953	30,639	45,768	45,916
P10%	48,076	60,533	33,691	43,452	42,082	41,138	60,161	27,664	42,384	43,355	44,136	57,519	29,066	42,236	43,697
P50%	34,118	31,500	27,690	31,073	33,169	31,558	31,187	24,092	30,192	33,982	33,825	33,514	24,209	32,033	36,101

Note: GCM1, GCM2, GCM3, GCM4, GCM5 are respectively GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 and UKESM1-0-LL

Table 12. Results on the annual minimum daily flow frequency from historical simulations and baseline SSP126 scenarios.

Prob-ability	Historical 1981-2014					SSP126 – in 2031-2050					SSP126 - in 2051-2100				
	GCM1	GCM2	GCM3	GCM4	GCM5	GCM1	GCM2	GCM3	GCM4	GCM5	GCM1	GCM2	GCM3	GCM4	GCM5
P50%	1,388	1,432	1,386	1,407	1,427	2,286	2,367	2,279	2,397	2,454	2,662	2,650	2,663	2,676	2,729
P75%	1,234	1,304	1,270	1,298	1,316	2,027	2,085	2,007	2,111	2,176	2,527	2,494	2,524	2,519	2,568
P85%	1,173	1,240	1,212	1,243	1,260	1,900	1,948	1,875	1,972	2,039	2,461	2,415	2,452	2,438	2,486
P90%	1,140	1,198	1,174	1,207	1,224	1,818	1,860	1,790	1,883	1,952	2,419	2,362	2,404	2,385	2,432
P95%	1,101	1,139	1,120	1,155	1,172	1,704	1,737	1,672	1,758	1,829	2,360	2,286	2,335	2,309	2,354

3.5.3 Integrated Water Modeling System

The 1D hydrodynamic model VRSAP is applied to simulate water resources (water level on the river and on the floodplain cells at the nodes, flow discharge in the river and canal branches, salinity in the river and canal branches) for the entire Mekong delta of Vietnam and Cambodia covering 6.2 million ha (from Kratie to the sea). The model contains a large number of hydraulic units (7002 river sections, 4279 river nodes, 5578 floodplain nodes).

The model was setup since 1990 and was used to successfully simulate flood proofing scenarios for approval of the master plan study in 1999 by the Prime Minister. The model has been updated frequently using topographical survey (river cross-section, dyke & road elevation) data collection (dimension of infrastructures as weirs/gates/dams/bridges), and land elevation (DEM resolution 5x5m).



The input data are hydrological data (daily upstream low discharge at Kratie, hourly tidal level at sea), daily rainfall at several rain gauges, and weekly water demand at 120 irrigation/watersheds. The model was calibrated using observed water level, flow discharge, rainfall data and salinity data of historical years (flood of 1996, 2000, 2001, 2011, 2018; dry year of 2004, 2008, 2016, 2020) and validated frequently most recent years 2020 and 2023. Output data of the model are hourly time series and summary data with geo-reference information for processing output data into chart and maps.

Due to limitations in model capabilities, water quality, sediment and nutrient parameters were not simulated and evaluated; time frame limitations meant that we only selected a few scenarios (RCP4.5 and RCP8.5) and design frequencies (1%, 10%, 85%, 95%) for simulation and evaluation.

3.5.4 Multi-Dimensional SOS Assessment Results

The simulation results of the VRSAP model are used to calculate the flood level indicators and saline intrusion length, as follows:

- The annual maximum flood level at Tan Chau hydrological station on the main river with flood years has a frequency corresponding to the high upstream flow frequency at Kratiè. The threshold values of the flood level indicator are divided into flood warning levels and historical flood level (presented in Table 13). Table 14 represents the indicator matrix of historical observations and historical simulations from 5 GCMs, namely GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL. The Mekong Delta is safe from flood in very dry years (P95%). Under IPSL-CM6A-LR, the flood indicator for the Delta shows more instances of unsafe conditions. In contrast, MPI-ESM1-2-HR simulations project less precipitation in both the Delta and the wider basin, causing the flood indicator to lay in the safe space more often. This highlights the uncertainty associated with the use of different GCMs to evaluate the SOS for the Mekong Delta. On the contrary, considering SSP1-2.6 and looking at the SOS evaluation for the flood indicator under different GCMs we observe small changes in indicator values and no significant change in unsafe flood zones in the future 2031-2050 and 2051-2100 (visualized in Table 15). Finally, considering all SSPs-RCPs and all GCMs, we can generally observe more safe zones for the flood indicator in the future, except for SSP2-4.5 and SSP5-8.5 in the period 2051-2100 (as seen in Table 16).
- The annual minimum saline intrusion length in the Cua Dai river mouth of Mekong mainstream with water years has a frequency corresponding to the low upstream flow frequency at Kratiè. The threshold values of the saline intrusion length indicator are divided using scientific findings and historical saline level (presented in Table 17). The indicator values for historical observations are limited in dry years ($P \geq 50\%$) with safe zones encountered in wet years ($P \leq 5\%$). However, looking at the future projections and considering all the SSPs-RCPs combinations, we can observe that the indicator will always fall in the unsafe space in all the water scenarios (from the driest to the wettest) (visualized in Table 18). This critical result highlights the difficulty to keep the salinity intrusion dimension within its safe space in the Mekong Delta, and the need of identifying measures and local actions to tackle the problem.



Table 13. Application of flood thresholds for SOS-Water evaluation: Mekong delta-flood level at Tan Chau.

Flood thresholds (m)	SOS-Water evaluation
>5,10	Historical extreme 1961
4,51-5,10	High risk (>Flood level 3)
4,01-4,50	Risk (>Flood level 2)
3,50-4,00	Low risk (>Flood level 1)
<3,50	Safe
n/a	Not available, No data

Table 14. Original indicator matrix (historical observation and simulation of GCMs): Mekong delta-flood level at Tan Chau.

Water year	Historical Obs.1985-2008	Historical Simulation 2001-2014				
		GCM1 (GFDL-ESM4)	GCM2 (IPSL-CM6A-LR)	GCM3 (MPI-ESM1-2-HR)	GCM4 (MRI-ESM2-0)	GCM5 (UKESM1-0-LL)
P1%	5,8	6,0	8,2	4,57	5,65	5,18
P10%	4,82	5,07	5,79	4,2	4,79	4,71
P50%	4,03	4,23	4,05	3,8	4,02	4,16
P85%	3,61	n/a	n/a	n/a	n/a	n/a
P95%	3,42	n/a	n/a	n/a	n/a	n/a

Table 15. SOS evaluation for Mekong delta-flood level at Tan Chau (baseline management pathway-SSP1-2.6 and GCMs).

Scenario (Baseline)	Water year	GCM1	GCM2	GCM3	GCM4	GCM5
Historical (2001-2014)	P1%	6,0	8,2	4,57	5,65	5,18
Historical (2001-2014)	P10%	5,07	5,79	4,2	4,79	4,71
Historical (2001-2014)	P50%	4,23	4,05	3,8	4,02	4,16
Historical (2001-2014)	P85%	n/a	n/a	n/a	n/a	n/a
Historical (2001-2014)	P95%	n/a	n/a	n/a	n/a	n/a
SSP1-2.6 (2031-2050)	P1%	5,34	8,46	4,01	5,73	5,51
SSP1-2.6 (2031-2050)	P10%	4,66	4,66	3,8	4,73	4,78
SSP1-2.6 (2031-2050)	P50%	4,06	4,06	3,54	3,97	4,22
SSP1-2.6 (2031-2050)	P85%	n/a	n/a	n/a	n/a	n/a
SSP1-2.6 (2031-2050)	P95%	n/a	n/a	n/a	n/a	n/a
SSP1-2.6 (2051-2100)	P1%	5,59	7,63	4,21	5,37	5,19
SSP1-2.6 (2051-2100)	P10%	4,83	5,62	3,88	4,72	4,8
SSP1-2.6 (2051-2100)	P50%	4,21	4,19	3,54	4,09	4,35
SSP1-2.6 (2051-2100)	P85%	n/a	n/a	n/a	n/a	n/a
SSP1-2.6 (2051-2100)	P95%	n/a	n/a	n/a	n/a	n/a



Table 16. SOS evaluation for Mekong delta-flood level at Tan Chau (baseline management pathway: SSPs-RCPs and GCM1).

Probability	His.Obs. (1985-2008)	His.Sim. (2001-2014)	ssp126 (2031-2050)	ssp126 (2051-2100)	ssp245 (2031-2050)	ssp245 (2051-2100)	ssp370 (2031-2050)	ssp370 (2051-2100)	ssp585 (2031-2050)	ssp585 (2051-2100)
P1%	5,8	6,0	5,34	5,59	5,16	6,11	6,11	5,65	5,3	5,78
P2%	5,51	5,73	5,14	5,37	5,04	5,82	5,77	5,44	5,15	5,58
P5%	5,12	5,37	4,87	4,6	4,7	5,43	5,33	5,15	4,94	5,3
P10%	4,82	5,07	4,66	4,83	4,85	5,13	4,99	4,91	4,75	5,05
P50%	4,03	4,23	4,06	4,21	4,19	4,33	4,17	4,21	4,14	4,32
P75%	3,74	3,87	3,83	3,98	3,93	4,04	3,92	3,92	3,82	3,99
P85%	3,61	3,72	3,74	3,87	3,8	3,92	3,84	3,78	3,66	3,82
P90%	3,42	3,62	3,69	3,83	3,7	3,85	3,8	3,69	3,54	3,72
P95%	3,42	3,49	3,61	3,76	3,57	3,77	3,75	3,57	3,38	3,56

Table 17. Application of salinity thresholds for SOS-Water evaluation: Mekong delta-saline intrusion length in Cua Dai river mouth.

Salinity thresholds (km)	SOS-Water evaluation
>91	Historical extreme 2020
66-91	High risk
51-65	Risk
30-50	Low risk
<30	Safe
n/a	Not available, No data

Table 18. SOS evaluation for Mekong delta-saline intrusion length in Cua Dai river mouth (baseline management pathway: SSPs-RCPs and GCM1).

Probability	His.Obs. (1985-2008)	His.Sim. (2001-2014)	ssp126 (2031-2050)	ssp126 (2051-2100)	ssp245 (2031-2050)	ssp245 (2051-2100)	ssp370 (2031-2050)	ssp370 (2051-2100)	ssp585 (2031-2050)	ssp585 (2051-2100)
P1%	n/a	78.3	72.8	74.1						
P2%	n/a	79.1	73.9	74.5						
P5%	n/a	80.2	75.1	75.2						
P10%	n/a	81.1	76.1	75.7						
P50%	46	84.8	79.1	77.2	79.4	77.6	79.5	77.8	79	77.7
P75%	n/a	87.0	80.3	77.9	80.5	78.5	80.5	78.9	80.5	78.5



P85%	55	88.1	80.9	78.4	81.1	78.9	81.1	79.3	81.4	78.9
P90%	n/a	88.8	81.3	78.6	81.8	79.1	81.7	79.5	82.1	79.1
P95%	80	89.9	81.9	78.8	82.5	79.4	82.4	80	82.4	79.5

4 Conclusions

This deliverable presents the updated SOS-Water evaluation framework and the results of its application across the four case studies of the project. As shown, the framework successfully provides a consistent methodological structure that can be adapted to the specific characteristics and challenges of each river basin. Despite the diversity of contexts, the overall approach remained coherent, while retaining enough flexibility to accommodate local conditions.

Although the evaluations presented here represent the final SOS assessment at this stage, the framework remains open to further refinements during the final phase of the project. In particular, the Integrated Water Modelling Systems (IWMS) developed for each basin may still be improved, both in terms of capturing additional processes and enhancing existing model components. At present, certain dimensions of water systems could not be fully represented due to modelling limitations. The development of new modules or the improvement of existing ones would allow the inclusion of further indicators, or the refinement of current ones, potentially leading to a more comprehensive SOS evaluation in future updates.

Threshold definition also remains a critical challenge. While the thresholds presented in this deliverable represent the best available estimates, in several case studies stakeholder input proved insufficient or inconsistent to robustly characterize them. Future work will therefore explore complementary methods, such as defining thresholds thorough system simulations to detect tipping points in indicator performances. These refinements will not replace the results reported here but will enrich them, thereby complementing them and providing uncertainty ranges around threshold values, allowing for a more nuanced understanding of the SOS and its sensitivity to thresholds uncertainty.

Another important aspect concerns the visualization of the SOS results. In this deliverable, each case study team applied its own approach to represent the SOS, prioritizing clarity and interpretability of the results for their local context. By the end of September, however, a dedicated visualization platform will be released, providing a harmonized way to present and compare results across case studies. This uniform approach will be fully integrated in the next deliverables, ensuring consistency and comparability of SOS visualizations across the project.

Beyond these methodological improvements, important steps remain for consolidating the framework and demonstrating its practical relevance. A key next stage is the integration of locally developed management pathways, which will be addressed in Deliverable 5.5. This will allow the identification of specific actions required to keep each basin within its SOS under current conditions and future scenarios. In addition, uncertainty analysis—covering IWMS, global climate models (GCMs), management pathways, and thresholds—will be a major focus of Deliverable 5.4. For instance, in the Upstream Mekong case study the current evaluation relied on a single GCM (GFDL-ESM4). The





forthcoming analysis will expand on the results by including multiple GCMs, thus enabling a systematic exploration of uncertainty and its implications for the definition of the SOS.

In summary, this deliverable marks a major step forward in operationalizing the SOS-Water framework across diverse contexts. At the same time, it highlights the need for further refinements in indicator thresholds, and uncertainty analysis, as well as the forthcoming integration of management pathways. These steps will ultimately ensure that the SOS concept not only provides a robust scientific framework but also serves as a practical tool for guiding sustainable water management at the basin scale.



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5 Appendix A: Danube case study indicators definitions

5.1 Magnitude of Monthly Flow Alteration (MMFA)

This index is calculated as the absolute difference between the regulated and natural monthly flows, expressed as a percentage of the natural monthly flow.

$$MMFA = \frac{Q_r - Q_n}{Q_n}$$

With Q_r : regulated discharge and Q_n : natural discharge. Daily natural and regulated discharges from CWatM under natural and non-natural conditions are taken at the outlet of the subbasins and aggregated on a monthly basis.

5.2 Connectivity Status Index (CSI)

To compute the CSI of the Danube basin, we used the following key pressure indicators from the original Connectivity Status Index (Grill et al. 2019):

- Degree of Fragmentation (DOF): Measures the degree to which dams and other barriers fragment the longitudinal connectivity of rivers.
- Degree of Regulation (DOR): This measure quantifies how water storage in dams can alter the natural flow regime of downstream river reaches.
- Sediment Trapping Index (SED): Measures the proportion of potential sediment load trapped by dams at any given point in the river system.

These indicators were chosen as they correspond to continuity dimensions relevant to the EU biodiversity strategy (lateral, longitudinal and vertical).

5.3 Aquifer recharge rate (ARR)

This indicator is the ratio between the aquifer recharge volume and withdrawals. It is calculated as:

$$ARR = \frac{GR}{GW}$$

With ARR : Aquifer Recharge Rate, GR : Aquifer recharge volume, GW : Groundwater Withdrawal volume.

To calculate the ARR for the Danube basin, we first aggregated by year the monthly total non-fossil groundwater abstractions and the monthly sum of groundwater recharges from CWatM. These values were then used to calculate the annual recharge rate, first on a grid-based and then averaged across each sub-basin. To allow for some uncertainty in the calculation, the threshold was set as $ARR > 0.95$.



5.4 Water supply reliability

Water supply reliability is calculated separately for **domestic**, **irrigation** and **industrial** supplies, measured by the number of deficits (when demand > supply) divided by the time period:

$$Rel_{time}^i = \frac{No. of times Deficit_t^i = 0}{n}$$

To address uncertainty and variability, the mean reference period deficit value was selected as a precautionary threshold by averaging all deficits for the reference period for each GCM. Since each sub-basin has a different reference value, thresholds are also specific to each sub-basin. Therefore, for each combination of GCM and sub-basin, there is a corresponding reference period threshold.

Demand and supply data were calculated monthly using the total demands and withdrawals for domestic, industrial, and agricultural (irrigation) purposes, as determined by CWatM. To prevent counting minor deficits that do not have a significant impact, only when the ratio between demand and supply exceeds .95 (meaning supply meets less than 95% of demand) the month was classified as a deficit occurrence. Note: Deficit refers to water supplied from within the sub-basin; therefore, when a deficit occurs, it does not necessarily indicate water scarcity but rather that additional water from outside the basin- either through inflow or transfers- must be used to meet demand.

5.5 Species Habitat Suitability

The Species Habitat Suitability (SHS) maps identify areas within the Danube that have the highest likelihood of being suitable habitats for each fish species. The outputs from the SDM models provide habitat suitability probability values, which are then converted into a binary response (suitable habitat/no suitable habitat) using a threshold calculated as the probability where sensitivity (the ability of a test to correctly identify true positives) and specificity (the ability to correctly identify true negatives) are equal. To transform suitability into an index, we calculated the Habitat Loss Ratio (HLR), which represents the habitat loss for each species between the reference and projected scenarios. The species experiencing the greatest habitat loss is used as the index. For this deliverable, we assessed the change in suitable habitat area by comparing the historical area to future projections for two key species in the Danube basin: *Acipenser stellatus* and *Acipenser gueldenstaedtii*. Suitable habitat areas were estimated for both the historical period and future scenarios using species distribution models. A threshold was set at a 5% loss to account for model uncertainty.

5.6 Number of Navigation Days (NND)

NND refers to the number of days in a year when a specific river segment is considered navigable, meaning it has a Good Navigation Status (GNS). The primary indicator to assess the availability of Low Navigable Water Level (LNWL) for safe and efficient navigation is the “number of days per year on which 2.50 m channel depth is available at critical bottlenecks” (Viadonau, 2024). Therefore, water depth, which can be calculated using flow rating curves at specific gauging stations, is a more suitable measure for evaluating GNS. Unfortunately, several countries did not provide information related to the flow rating curves; hence, we relied on computing the index solely from the discharge data simulated with



CWatM. By definition, LNWL is the water level that is equaled or exceeded on 94% of the days in a year, or 343 days. This value is based on discharge data collected over a 30-year period, excluding times when ice was present. Discharge data from CWatM were used to calculate the NND in the Danube basin at the outlet of the 11 major basins using the lower 6th percentile of the discharge as LNWL. In addition to the LNWL, the High Navigable Water Level (HNWL) was estimated as the discharge greater than the 95th percentile. The HNWL marks the discharge at which it is unsafe to navigate because of high water. The 6th and 95th percentiles were calculated for the reference period and for each GCM, thus creating a distinct threshold for each combination of sub-basin and GCM.

5.7 P and N concentrations

River concentrations of Total Nitrogen (TN) and Total Phosphorus (TP), available globally at an annual timestep (Nkwasa et al., 2025), were used as indicators for water quality. The Water Framework Directive recommends thresholds of 2.5mg/l for TN and 0.05mg/l for TP for assessing the chemical status of surface water (Pokaine et al., 2019). Note: Simulations are performed assuming no policies in place to limit nutrient inputs and are therefore a representation of an extreme case.



6 Appendix B: Complete list of Upper Mekong basin indicators and thresholds

Indicator	Threshold	Normalized Threshold
Mean, maximum, and minimum annual hydropower production for the entire basin, normalized by the total installed capacity of the basin (-)	25 th , 95 th , and 5 th percentiles of the annual historical series (1981-2022)	0.4131
	of hydropower production for the entire basin, normalized by the total installed capacity:	0.3715
	0.5177, 0.6016, 0.4862	0.2598
Mean, maximum, and minimum annual Chinese hydropower production, normalized by the total installed capacity of reservoirs in China (-)	25 th , 95 th , and 5 th percentiles of the annual historical series (1981-2022)	0.7359
	of Chinese hydropower production, normalized by its total installed capacity:	0.0298
	0.5357, 0.8414, 0.4577	0.6919
Mean, maximum, and minimum annual Burmese hydropower production, normalized by the total installed capacity of reservoirs in Myanmar (-)	25 th , 95 th , and 5 th percentiles of the annual historical series (1981-2022)	0
	of Burmese hydropower production, normalized by its total installed capacity:	0.1901
	0.5061, 0.5266, 0.4856	0
Mean, maximum, and minimum annual Thai hydropower production, normalized by the total installed capacity of reservoirs in Thailand (-)	25 th , 95 th , and 5 th percentiles of the annual historical series (1981-2022)	0.6427
	of Thai hydropower production, normalized by its total installed capacity:	0.3956
	0.1933, 0.2596 0.1201	0.5113
Mean, maximum, and minimum annual Laotian hydropower production, normalized by the total installed capacity of reservoirs in Laos (-)	25 th , 95 th , and 5 th percentiles of the annual historical series (1981-2022)	0.6194
	of Laotian hydropower production, normalized by its total installed capacity:	0.0304
	0.2615, 0.5136, 0.2265	0
Mean, maximum, and minimum annual Cambodian hydropower production, normalized by the total installed capacity of reservoirs in China (-)	25 th , 95 th , and 5 th percentiles of the annual historical series (1981-2022)	0.9324
	of Cambodian hydropower production, normalized by its total installed capacity:	0.1107
	0.1475, 0.7657, 0.1242	0.8863
Mean, maximum, and minimum annual Vietnamese hydropower production, normalized by the total installed capacity of reservoirs in China (-)	25 th , 95 th , and 5 th percentiles of the annual historical series (1981-2022)	0.0940
	of Vietnamese hydropower production, normalized by its total installed capacity:	0.0207
	0.4655, 0.5503, 0.4021	0.0061



Mean, maximum, and minimum annual sediment loads reaching Stung Treng (Mt/yr)	25 th , 95 th , and 5 th percentile of the annual historical series (1981-2022) of sediment loads reaching Stung Treng: 79.0043, 92.3559, 74.5998 Mt/yr	0.6728 0.7475 0.0464
Mean annual GHG emissions for the entire basin, divided by the total installed capacity of the basin (kg CO ₂ eq/MW)	25 th percentile of the annual historical series (1981-2022) of GHG emissions for the entire basin, normalized by the total installed capacity: 4.2010 kg CO₂eq/MW	0
Mean Chinese annual GHG emissions, divided by the total installed capacity of reservoirs in China (kg CO ₂ eq/MW)	25 th percentile of the annual historical series (1981-2022) of Chinese reservoirs GHG emissions, normalized by its total installed capacity: 1.3617 kg CO₂eq/MW	0.0829
Mean Thai annual GHG emissions, divided by the total installed capacity of reservoirs in Thailand (kg CO ₂ eq/MW)	25 th percentile of the annual historical series (1981-2022) of Thai reservoirs GHG emissions, normalized by its total installed capacity: 20.5439 kg CO₂eq/MW	0.1649
Mean Laotian annual GHG emissions, divided by the total installed capacity of reservoirs in Laos (kg CO ₂ eq/MW)	25 th percentile of the annual historical series (1981-2022) of Laotian reservoirs GHG emissions, normalized by its total installed capacity: 0.9590 kg CO₂eq/MW	0
Mean Cambodian annual GHG emissions, divided by the total installed capacity of reservoirs in Cambodia (kg CO ₂ eq/MW)	25 th percentile of the annual historical series (1981-2022) of Cambodian reservoirs GHG emissions, normalized by its total installed capacity: 0.1606 kg CO₂eq/MW	0.8067
Mean Vietnamese annual GHG emissions, divided by the total installed capacity of reservoirs in Vietnam (kg CO ₂ eq/MW)	25 th percentile of the annual historical series (1981-2022) of Vietnamese reservoirs GHG emissions, normalized by its total installed capacity: 1.3624 kg CO₂eq/MW	0
Mean, maximum, and minimum annual agricultural	25 th , 95 th , and 5 th percentile of the annual historical series (1981-2014) of agricultural water deficit south of Stung Treng: 0, 222022928.6, 0 m³/year	0 0.0602 0



water deficit south of Stung Treng (m ³ /year).		
Mean, maximum, and minimum annual fish catches in the Dai Fishery (t/year)	25 th , 95 th , and 5 th percentile of the annual historical series (1981-2014) of fish catches in the Dai Fishery: 37252.1589, 41426.7633, 30049.5823 t/year	0.0579 0.5746 0.1332



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