SOS-Water deliverable report

D5.1 Preliminary Evaluation of Safe Operating Space

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			PO about Jucar case study threshold		

Publishable Executive Summary

The SOS-Water project aims to establish a comprehensive and participatory assessment framework of the Safe Operating Space (SOS) for entire regional or local water systems, accounting concurrently all relevant water dimensions across multiple sectors (such as agriculture, households, industries, and environment) and spatial scales under the influence of climatic and socio-economic changes. This deliverable presents the established SOS-Water evaluation framework and provides preliminary results from its application in the Jucar River Basin case study (Spain).

The framework involves three stages of SOS-Water evaluation. The first stage focused on assessing the current conditions using indicators and thresholds identified for all natural and socio-economic processes. The second stage evaluates the SOS under co-developed future scenarios using simulations from an integrated water modelling system (IWMS). The last stage investigates SOS changes through the implementation of developed local management pathways. This deliverable describes the components required for the SOS evaluation, including indicators and thresholds, co-developed future scenarios, local management pathways, and IWMs used to calculate the indicator value under future scenarios and local management pathways.

This Deliverable 5.1 also provides an overview of all the five case studies in the SOS-Water project, outlining general case study information, stakeholder lists and urgent water challenges. This information is crucial for the SOS-evaluation process. In this deliverable, we use the Jucar River Basin as an example to demonstrate the SOS-evaluation framework. A more comprehensive SOS evaluation for all case studies will be provided in the coming deliverables.

For the preliminary SOS evaluation in the Jucar River Basin, two indicators were included: the net benefit in terms of hydropower and agricultural benefits, and the availability of fish habitat. The system's performance was assessed under 105 designed climate scenarios, and the impact of implementing efficiency enhancements within the agricultural demand zone of the basin was evaluated. The preliminary result indicates that the increase of the mean annual precipitation and the precipitation variability enhance net benefit and fish habitat performance. Conversely, an increase of mean annual temperature can hurt net benefit and fish habitat performance. These preliminary analyses serve as demonstration examples for the implementation of the SOS-evaluation. The project will continue to evaluate additional indicators, scenarios, and management pathways in subsequent phases. In addition, our preliminary analysis of the multi-dimensional SOS evaluation also underscores challenges in aggregating scenarios and indicators, as well as visualizing the multi-dimensional SOS. In the next step,

methods for the aggregation of indicators, scenarios, and pathways will be developed and the visualization of the multi-dimensional SOS will also be investigated.

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Description of deliverable

1   Introduction

The present Deliverable D5.1 (Preliminary 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 five case studies with various water challenges under different environmental and socio-economic conditions.

The SOS-Water framework established in this deliverable will be used in all five case studies of the project. The SOS-Water produced in T5.1 will be further analyzed in T5.2 (Analysis and synthesis of SOS) to address the challenges associated with the multi-dimensional SOS. The uncertainty propagation in multi-dimensional SOS evaluation will be investigated in T5.3 (Uncertainty and robustness analysis). Outputs from T5.1 will also be used in T5.4 (Reconciling SOS across scale) to comprehend scale discrepancies in the evaluation of the SOS, considering models and indicators operating at different spatial scales.

This deliverable introduces the general SOS-Water evaluation framework and reports some preliminary results of its application in the Jucar River Basin case study (Spain). Given that the Spanish case study is mainly for demonstrative purposes, the preliminary insights recap a few examples for each component of the SOS-Water evaluation framework (e.g., scenarios and pathways, IWMS, and indicators). The complete SOS-Water evaluation results for all case studies will be reported in future deliverables, namely D5.2 (Final Evaluation of Safe Operating Space) and D5.5 (Synthesis of Safe Operating Space).
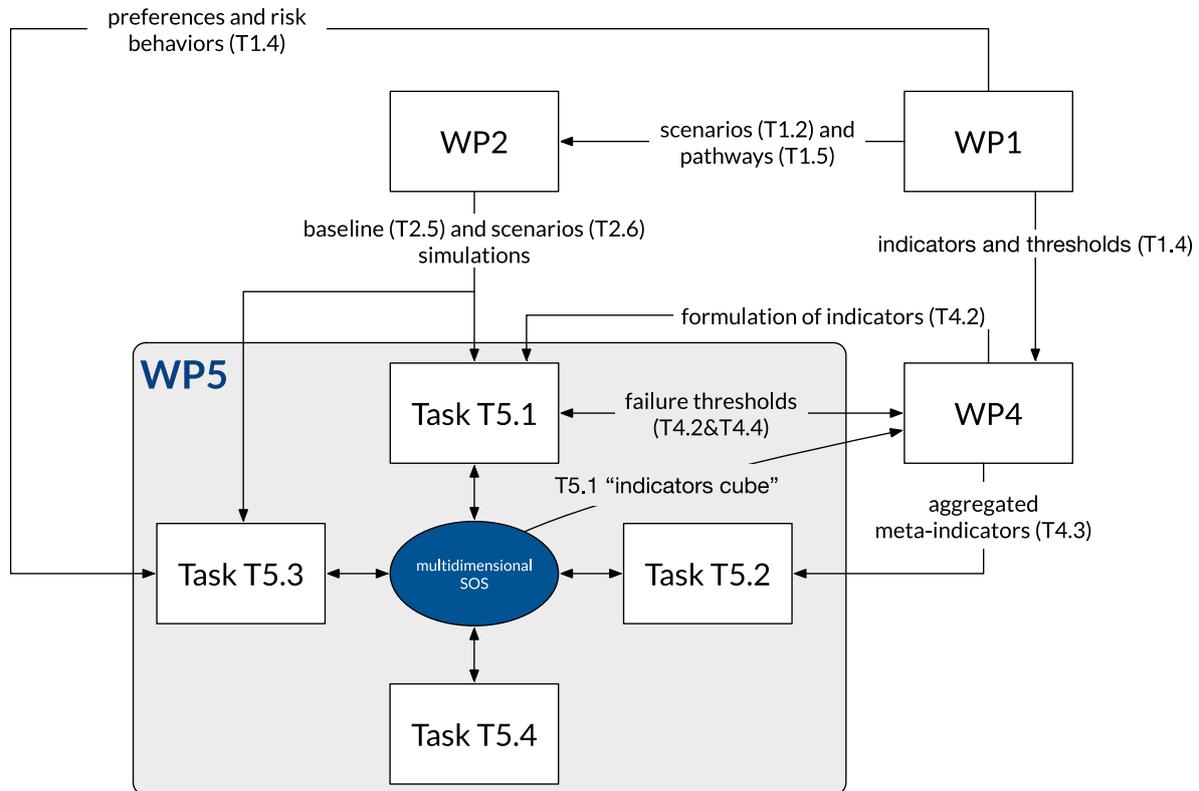
Figure 1 Cross-dependencies between Task T5.1 and other tasks in the SOS-Water project.

The report is structured as follows: Section 2 describes the SOS-Water evaluation framework, which includes the history and concept of SOS-Water and multiple components (e.g., scenarios and pathways, IWMS, and indicators). Section 3 introduces the five case studies in which the SOS-Water evaluation framework will be applied. Finally, Section 4 presents the Jucar case study to demonstrate the SOS-Water evaluation framework.

2   Methods and Frameworks

2.1   SOS-Water concept

The concept of a Safe Operating Space (SOS) for humanity was introduced by Rockström et al. (2009) and consists of a set of nine planetary boundaries (PBs) associated with different Earth-system processes that are critical for maintaining the stability and resilience of the Earth System in the Holocene and for humanity to pursuit of long-term social and economic development. The framework quantifies limits beyond which Earth's systems would collapse and Earth's capability of sustaining human life as we know it, would be lost. The PBs are critical values on the position of control variables that are used as proxies of the underlying process and are set at a "safe" distance from danger levels or thresholds, which, if crossed, could generate catastrophic environmental changes. The SOS concept emphasizes the importance of balancing human activities with Earth's natural systems to ensure a safe and sustainable future for humanity. Since its first introduction, freshwater use has been included in the PBs assessment

together with eight other processes, including climate change, nitrogen and phosphorus cycles, ocean acidification, chemical pollution, atmospheric aerosol pollution, ozone layer depletion, biodiversity loss, and land use change. The anthropogenic perturbations of freshwater cycle affect biodiversity, food, health security and ecological functioning (Rockström et al., 2009) and hence is an important dimension to be assessed in the SOS framework.

In the first attempt at defining the freshwater planetary boundary (WPB), blue water use (i.e., runoff depletion in the form of consumptive runoff) was selected as a proxy for capturing the full complexity of global freshwater boundaries. The WPB was estimated at 4,000 $km^3\,yr^{-1}$ of blue water global consumption, derived from the study of de Fraiture et al. (2001) that assumes water scarcity is encountered when withdrawals surpass 60% of usable water, equating to 6,000 $km^3\,yr^{-1}$. The WPB of 4,000 $km^3\,yr^{-1}$ was proposed by Rockström et al. (2009), following a precautionary approach based on lumped, global estimates of water availability, water stress, and other related-processes, but without considering spatiotemporal patterns.

Some years later, Gerten et al. (2013) proposed a bottom-up, spatially explicit, and context-specific quantification on WPB availability. They defined the WPB by spatially quantifying environmental flows requirements (EFR) in river systems to assess the intensity of freshwater use as a proxy for the integrity of the local biosphere. EFR were calculated using five different hydrological methods, including Smakhtin, Tessmann, Tennant, $Q_{90}\_Q_{50}$, and the variable monthly flow (VMF) methods, which are described in detail in Pastor et al. (2014). Smakhtin's method (Smakhtin et al., 2004) defines Q_{90} (i.e., the flow exceeding 90% of the period of record) as the low flow requirement and an additional percentage of mean annual flow for high flow requirement. In Tessmann's method (Tessmann, 1980), a percentage of mean monthly flow is defined for EFR, ranging from 40% during high flow seasons to 100% during low flow seasons. Tennant's method (Tennant, 1976) allocates 20% of mean annual flow in low flow seasons and 40% in high flow seasons for EFR. The $Q_{90}\_Q_{50}$ method (Pastor et al., 2014) defines the Q_{90} as the low flow requirement and Q_{50}, (i.e., the flow exceeding 50% of the period of record) as the high flow requirement. The VMF method (Pastor et al., 2014) allocates different EFRs for low-, intermediate-, and high-flow months. 60%, 30%, and 45% of mean monthly flow are defined as EFRs for low-, intermediate-, and high-flow months, respectively. The results of the five methods were aggregated considering median and maximum EFR. The resulting WPB was 1,100-4,500 $km^3\,yr^{-1}$, with an average of 2,800 $km^3\,yr^{-1}$. In the revised freshwater use boundary by Steffen et al. (2015), a basin-scale boundary for water was included to complement the global-level blue water use boundary. The basin-scale boundary is based on the concept of environmental water flows (EWF) and accounts for intra-annual variability by classifying flow regimes into high-, intermediate-, and low-flow months and allocating EWF as a percentage of the mean monthly flow.

In a recent work, Rockström et al. (2023) redefined the WPB, segmenting it into two sub-boundaries that address flow alteration and drawdown. These sub-boundaries act as control variables for surface water and groundwater, respectively. The redefinition process involved integrating the bottom-up methodology proposed by Gerten et al. (2013), which underscores the importance of local and spatial considerations. Additionally, the revised WPB incorporates aspects of Earth System functions influenced by groundwater and surface water, while introducing elements of interspecies, intergenerational, and

social justice, as outlined by Gupta et al. (2023). The resulting WPB includes both local and global components. Locally, monthly surface water flow alteration should not exceed 20% of the natural flow regime, and annual groundwater drawdown should not surpass aquifer recharge. Globally, the entire Earth's area must satisfy these local boundaries to uphold the sustainability of the Earth System.

Richardson et al. (2023) further redefined the PB with advanced control and response variables, adopting a novel approach based on Holocene variability as a stable Earth System inter-glacial state. The WPB includes blue and green water, using streamflow as a proxy for blue water and root-soil moisture for green water. Control variables are deviations from preindustrial variability of streamflow and soil moisture over ice-free land. Adopting a precautionary approach, they set the PBs at the 95th percentile of preindustrial time series variability, i.e., 11.1% for green water and 10.2% for blue water. This approach enables better incorporation of disruptions caused by human activities beyond freshwater consumption.

The WPB definitions proposed by Rockström et al. (2009) and Gerten et al. (2013) have been criticized as being too simplistic, not addressing all human effects on the global water cycle, and not practical in the formulation of policies because water is not managed on a global scale (Heistermann, 2017). Gleeson et al. (2020) proposed a qualitative evaluation framework with seven criteria for defining a useful WPB based and evaluated the previously proposed freshwater use planetary boundary. They found that none of the existing versions fully met any of the evaluation criteria and suggested defining the WPB based on functional relationships between water stores and Earth System components. Gleeson et al. (2020) proposed six planetary sub-boundaries for water based on five water stores (i.e., atmospheric water, surface water, soil moisture, groundwater, and frozen water) and four Earth system functions of water (i.e., hydroclimatic and hydroecological regulation, storage, and transport).

As the definition of WPB evolves, attempts have been made to translate and apply it to regional and local scales where water issues and management are most prominent. Previous literature outlines two approaches in sub-global use of the PBs framework: the fair share and local SOS approaches (Zipper et al., 2020). The fair share approach is a top-down method that calculates the local boundary share as a linear proportion of the global boundary, employing different principles such as per capita measures, national water footprint, or environmental and social indicators representative of regional conditions. Different allocation methods can significantly impact the estimated share of global SOS, and the choice of an appropriate approach requires consideration of local contributions to global environmental challenges, the capacity to respond to them, and local stakeholders' definition of a "fair" share.

On the other hand, the local SOS allocation is a bottom-up approach that applies the principles of the PBs framework to define locally relevant control and response variables and associated SOS. It focuses on the local water system, which may entail different variables than the planetary boundary control and response variables. While most of past attempts at local SOS often used consumptive water use as the variable (e.g., Fanning & O'Neill (2016) and Teah et al. (2016)), the development of alternative or additional variables based on local contexts is still necessary. Notably, Dearing et al. (2014) incorporated water quality in their assessment of a local SOS for two regions in China, setting local boundaries based on long-term measurements of regionally relevant environmental processes. Zipper et al. (2020)

recognized both the advantages and shortcomings of downscaling approaches and proposed a rationale based on water stores to harmonize fair shares and local SOS approaches.

Despite the extensive history of the SOS Water concept and various attempts at downscaling, there is a lack of documented application of the SOS Water framework to design basin-scale management plans. Existing studies often focus on individual variables of the water system (Bai et al., 2020; Carpenter et al., 2017; Ofir et al., 2023; Szabó et al., 2020), with no holistic study incorporating all dimensions of the water system at the basin scale. However, to positively impact basin management, it is necessary to focus on how to operationalize the SOS concept in regional or local scales instead of simply downscaling the planetary boundaries.

To help operationalizing the SOS concept to the regional or local scales, the SOS-Water project attempts to establish a holistic and participatory assessment framework of the SOS for entire regional or local water systems, accounting concurrently all relevant water dimensions across multiple sectors (such as agriculture, households, industries, and environment) and spatial scales under the influence of climatic and socio-economic changes. Considering the spatiotemporal complexity of the water systems, SOS-Water will identify all natural and socio-economic processes within water systems and associate each process with an indicator. The indicator for each process can be selected from a set of comprehensive indicators or aggregated from multiple individual indicators. For each indicator, a threshold (i.e., boundary) is defined, beyond which it is considered unsafe. This may manifest as dysfunction in the underlying processes, instability within the water system, and ultimately pose risks to humanity and the environment. With the indicators and thresholds identified, we could compute the value of these indicators and evaluate how many boundaries of associated processes are transgressed, which could give us a comprehensive understanding the water systems' performance in current condition. The SOS evaluation is then extended to future scenarios, considering climate and socio-economic change. The integrated water modelling system will be employed to compute the indicator value under future scenarios. Additionally, the project will also evaluate the SOS of the water system when implementing identified alternative pathways. We could understand if there is any benefit (i.e., bringing certain natural or socio-economic processes within the boundary) by implementing any of these alternative pathways. Throughout each stage of the SOS-Water evaluation process, local stakeholders will be actively involved to ensure the incorporation of their knowledge, water values, visions, and preferences. Consequently, SOS-Water facilitates a deeper understanding of potential system vulnerabilities and ultimately supports water planning and management at local to regional levels.

2.2 SOS-Water implementation framework

Our project aims at addressing the gaps identified in the previous section by developing a framework that comprises three stages of SOS-Water evaluation as illustrated in Figure 2. The first stage is mainly focused on the SOS-Water evaluation for the current condition (i.e., status quo). In 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 the SOS changes by implementing different developed local 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 multiple-dimensional SOS that encapsulates the performance of the entire water system under status quo and co-developed future scenarios and with different local management pathways. The subsequent subsections provide detailed insights into each of these components.
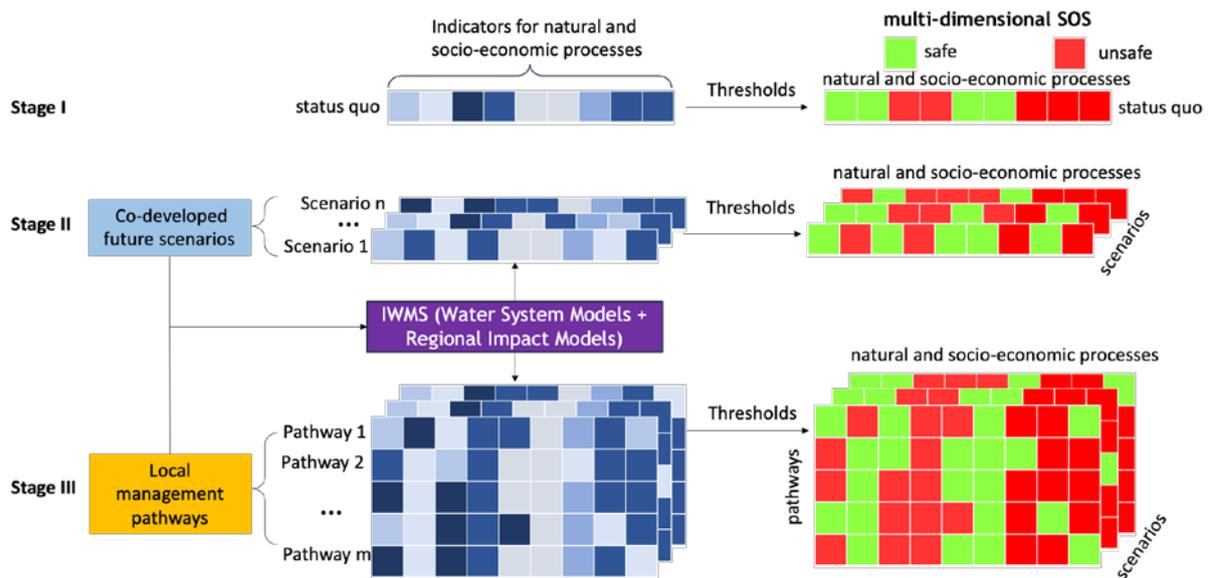
Figure 2 The overview of the SOS-Water evaluation framework. The framework includes three stages: 1) the SOS-Water evaluation under current conditions (Stage I); 2) the SOS-Water evaluation under future scenarios (Stage II); 3) the SOS-Water evaluation with the implementation of local management pathways.

2.2.1 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. These indicators offer valuable information about 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 in SOS-Water project conducted a dedicated review of indicators and identified gaps within the context of water resources systems. The review of the indicators involved collecting and analyzing indicators from four main sources:

- Peer-reviewed scientific papers
- Policy reports and guidelines
- Other outcomes (e.g., deliverables) from research projects
- Legislative documents

Besides the indicators available in literature, innovative water indicators and systems of indicators are under development in WP4 (Indicators and Thresholds). In this section, the set of indicators described is mainly used for demonstration purposes, and a more comprehensive set of indicators will be updated in the upcoming deliverables.

Following D4.1, the indicators are divided into two main categories (as shown in **Figure 3**): 1) water resource indicators that describes the water availability and quality, and 2) water demand indicators that quantify the water required by different sectors for various purposes (e.g., irrigation, urban use, industrial use, and environmental flow).
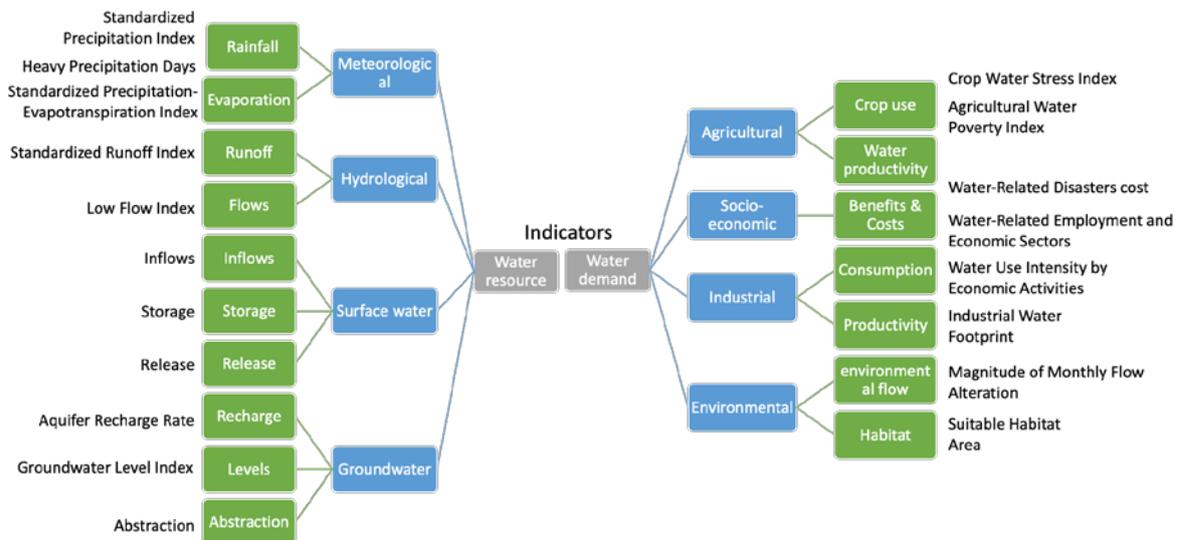
Figure 3 Classification and examples of indicators (adopted from D4.1). The left part are water resources indicators. The right part are water demand indicators.

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. The placement of these boundaries may be situated at a more conservative level on the indicator variables, contingent upon the risk profiles of local stakeholders. Identifying these thresholds and establishing boundaries is a crucial step in shaping the SOS framework for the water system.
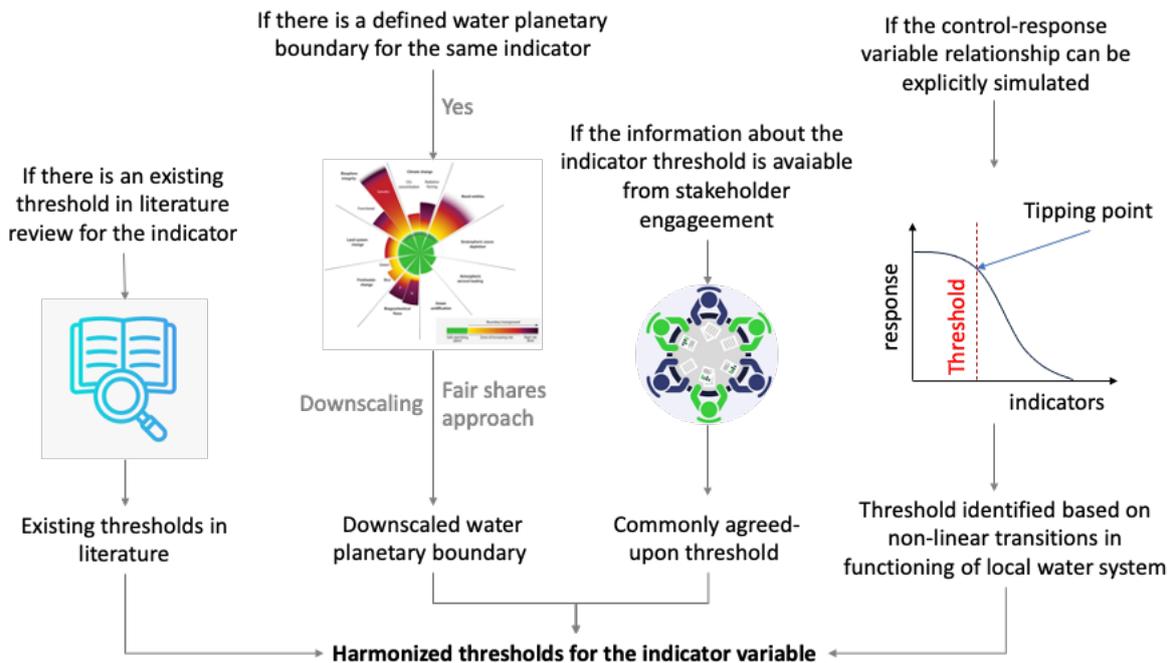
Figure 4 Different approaches for threshold identification of indicator variable.

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 investigated in previous studies related to 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. Downsizing these planetary

boundaries for water resources to a local scale can complement the establishment of SOS boundaries at the local 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, downsizing 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 a threshold is identified, the IWMS output can be utilized to calculate the values of indicators representing various dimensions of the water system. This identified threshold serves as a benchmark to assess whether the local water system operates within the safe operating space under different scenarios and pathways, leading to the multi-dimensional SOS of the local water systems.

2.2.2 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 scenarios, while contributing to developed management pathways to face evolving climate conditions and socio-economic developments. 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 will be 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.
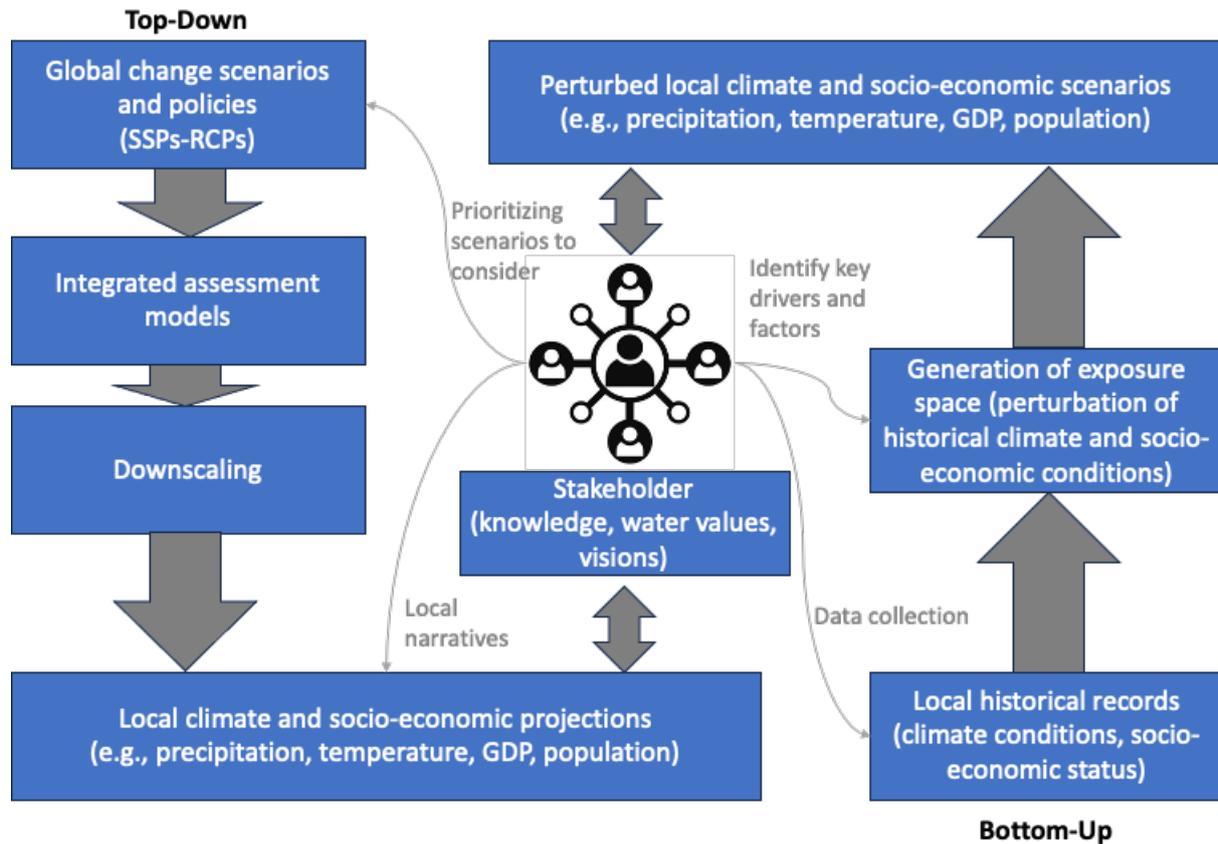
Figure 5 Multiple future change scenarios generation approaches (including Top-Down, Bottom-Up, and Integrated).

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 in 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 (in W/m^2) levels 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 through 2100 was originally identified: RCP2.6 (characterized by peaking and subsequent decline), RCP4.5 and RCP6.0 (representing stabilization pathways), along with 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 a 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 in the literature (van Vuuren et al., 2011), posing a challenge in correlating 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. The 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 (ScenarioMIP6, O'Neill et al. (2016)) combined the SSP narratives with levels of radiative forcing to be achieved by the year 2100 and caused by 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, including unmitigated SSP baseline scenarios and new mitigation pathways (such as those reaching 7.0, 3.4, and below 2.6 W/m^2 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).
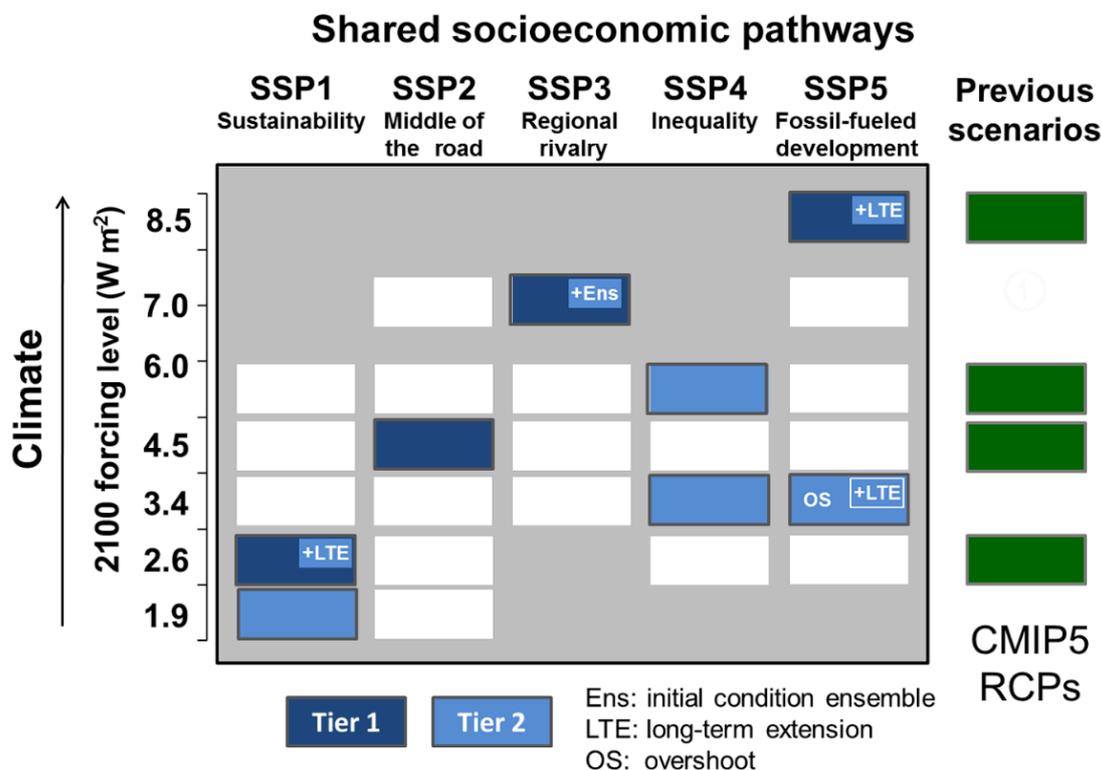
Figure 6 SSPs-RCPs scenario matrix from O'Neill et al. (2016).

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, and 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 considered case study) discussed in Section 2.2.3. 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 polices 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 assessment 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 cascades from one step to the next, considering permutations of emission scenarios, climate models, downscaling, and so on. Although widely used for climate change impact assessment, this approach poses a challenge due to the significantly expanded range of uncertainty at each step, requiring considerable time and effort for characterizing and reducing uncertainty. Despite its utility for decision-makers focusing on climate-related risks on a global scale, a lack of attention to the complex local context creates a communication gap between climate experts and policymakers (Pilli-Sihvola et al., 2015). It is therefore essential to move beyond downscaling by incorporating the perspectives of local and scientific experts in this top-down scenario building approach, to generate practice-oriented and context-dependent scenario design (Swart et al., 2014). For example, the selection of appropriate scenarios and models through engagement with local stakeholders.

On the other hand, "bottom-up" approaches (also known as "scenario-neutral") focus on impact assessment to past and present climate variability (Wilby & Dessai, 2010) and may not necessarily be linked to global scenarios (Nilsson et al., 2017). The "bottom-up" approach takes their starting point from 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, they often begin with factors and conditions that are sensitive for coping with climate-related threats at the local level (e.g., climate conditions or socio-techno-economic factors). A comprehensive exposure space, composited of a wide range of plausible scenarios, is generated based on the perturbation of historical and present climate (e.g., precipitation and temperature), 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" provide two different perspectives on consideration of uncertainty of future conditions in scenario design. The "top-down" approach allows for the impact assessment associated to official projections in global scale but has the issue of uncontrolled expansion of uncertainty. The "bottom-up" approach does not explicitly consider official climate change projections (e.g., SSPs and RCPs) in scenario design and carries the risk of underestimating the potential impacts of global climate change. Therefore, combining these two approaches (i.e., "integrated" approach) for the 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 practices 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 the real-world situations and local context. 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 contrast to 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 stakeholder enables the careful consideration and inclusion of the local communities, preventing the inadvertent exclusion of opportunities for misrecognized and marginalized groups to influence the definition of local SOS-water boundaries, which is essential for the inclusion of justice in define SOS-Water boundaries for social fairness (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, local stakeholders can participate in highly interactive workshops and forums that include local and regional stakeholders, such as planners, public governors, sector representatives, local experts, and researchers. The modeler, for example, can 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 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 ample opportunity for local stakeholder involvement in the bottom-up scenarios design process. Firstly, local stakeholders can be very helpful in historical data collection, ensuring the accuracy and richness of data used for perturbation in bottom-up approaches. Secondly, they can assist in identifying key variables and factors that impact the water system at local level. Their insights and local narratives contribute to a more nuanced bottom-up scenario design. Last, local stakeholders can help to co-construct the future scenarios based on the 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.

2.2.3 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. The non-structural actions either modify the system only functionally or they alter the effects that the system produces. Examples of non-structural actions would be a regulation that sets water quality standards or environmental flows; setting tariffs for water services; an incentive program for farmers to encourage 'virtuous' behavior (e.g. adopting crops that need less water 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 that depends on the characteristics of the case study.

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

Type of local management pathway	Examples **of actions in local water system management pathways**
Structural actions	• Construction of a new dam or reservoir (Planning) • Implementation of a large-scale irrigation system (Planning) • Development of water supply infrastructure for a growing urban area (Planning) • Operation and maintenance of existing dams (Management) • Rehabilitation or retrofitting of aging water infrastructure (Management)
Non-structural actions	• Establishment of water quality standards and regulations (Planning) • Definition of environmental flow requirements for river stretches (Planning) • Implementation of tariffs for water services (Planning) • Introduction of public awareness campaigns to promote water conservation (Management) • Adoption of incentive programs for sustainable farming practices (Management)

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

The determination of which actions to be evaluated in local impact assessment depends on several factors: 1) the technical, institutional, financial, and legal feasibility of the measures at local case study; 2) the preference of the local decision maker to adopt the pathways; 3) the capacity of available models to incorporate the pathways in simulation processes. From the impact assessment perspective, it is also important to consider the lifetime of the pathways, as it can influence the experimental design of future scenarios. If the lifetime of the pathways (actions) is short with 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 dame construction), it is necessary to evaluate 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.

2.2.4   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, agriculture, and energy aspects. The IWMS aims to simulate all relevant information in both the current state and future scenarios developed in Section 2.2.2 and with or without the implementing of local management pathways developed in Section 2.2.3. In this way, the IWMS can be used to evaluate the response of the water system under various conditions and help the stakeholder 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., model that assess the impacts of climate variability and change and human activities on water resources availability) and 2) the local impact models (i.e., models that assess the impact 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 7and its development is carried out in WP2 (Integrated water modelling system). The linkages and test run between global hydrology models and local impact models, and the model calibrations and simulation results will be described in D2.2, D2.3 and D2.4.
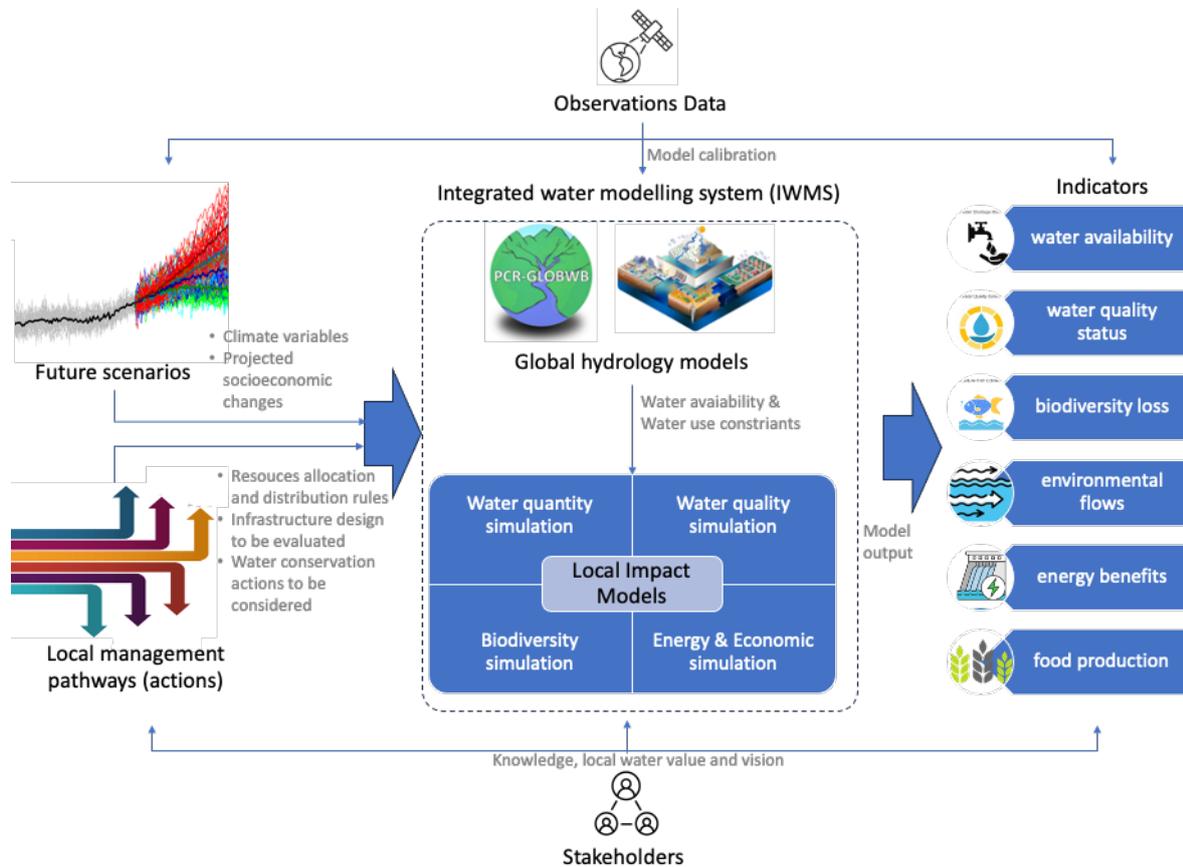
Figure 7 Integrated water modelling system composited of water system models and local impact models and its linkage with other components in SOS-Water project e.g., scenario design, water system status, stakeholders, earth observations.

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 ground water flow. They can calculate state variables that represent certain dimensions of the water systems (such as water availability, and water use at 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 on 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 withdrawal), environmental factors (e.g., water quality), ecological considerations (e.g., biodiversity), and impacts on energy and economics (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 the 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 stakeholder's preference. Examples of these local impact models includes 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. The detailed description of local impact models used will be described in each of the case studies.

3 Case study Descriptions

3.1 Jucar River Basin

The Jucar River Basin (JRB) is a semi-arid area that covers 22,261 Km^2, being one of the most important rivers in Eastern Spain. It starts at the Iberica mountain range, besides the San Felipe hill, at 1,585 m height, flowing through two regions: Castilla – La Mancha and Comunitat Valenciana. The river flows along the Cuenca, Albacete and Valencia provinces until it meets the Mediterranean Sea. For this study, the division of 7 sub-basins shown in **Figure 8** was used.
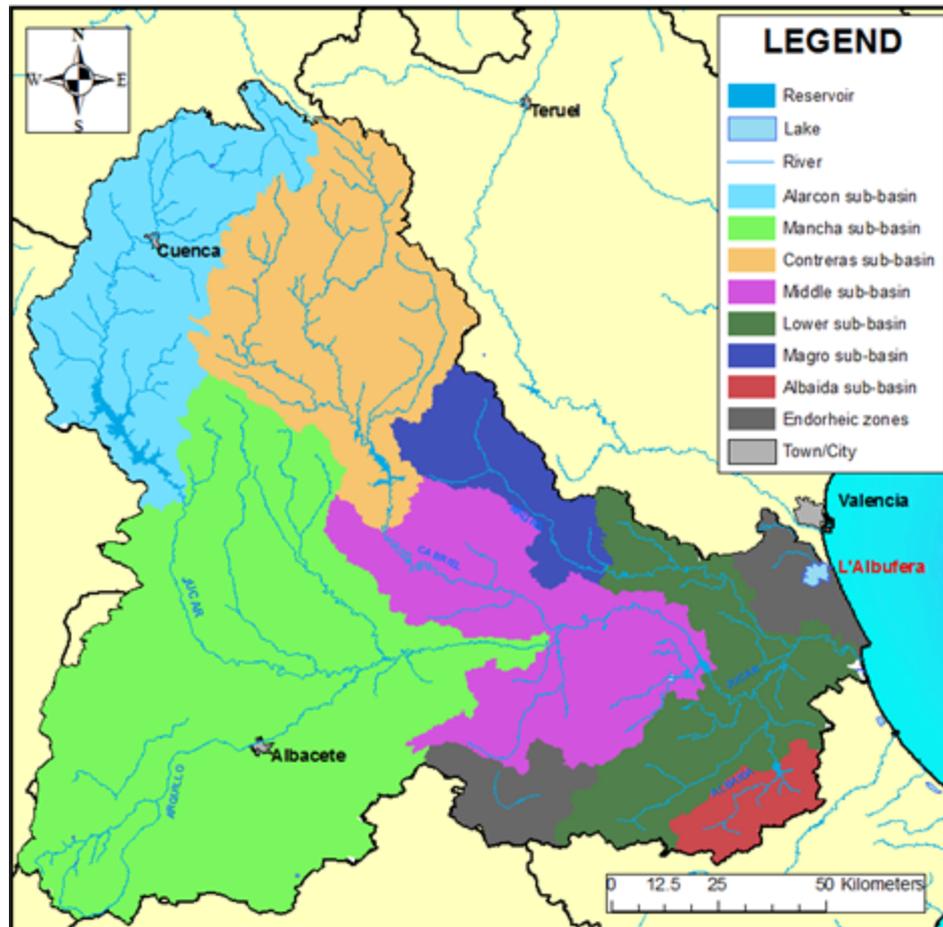
Figure 8 Representation of the sub-basin division of the Júcar River Basin (Macian-Sorribes, 2017)

The annual precipitation ranges between 300 and 820 mm, with an average of 510 mm. Its precipitation pattern is typically Mediterranean: high rainfall in autumn (especially in October), with a second peak in April–May, and very little precipitation during summer. Its mean total annual discharge is 1,455 Mm^3/year, following the same pattern as rainfall (CHJ, 2023). A significant percentage of the total river discharge is provided by groundwater outflow through springs and stream–aquifer interaction. The total available water resources are 1,480 Mm^3/year, mostly from groundwater sources; with the principal uses for water being agricultural use (89%), followed by urban (9%) and industrial uses. Based on data from the river basin agency, the Confederación Hidrográfica del Júcar (CHJ), the population within the JRB is estimated to be approximately one million people. This population figure represents roughly one-fifth of the total inhabitants falling under the jurisdiction of the river basin agency.

The main regulation facilities, which regulate around 75% of the average river flow, are the reservoirs of Alarcon (1,088 Mm^3 useful storage), Contreras (429 Mm^3), and Tous (369 Mm^3). There are eight additional reservoirs with useful storage greater than 1 Mm3, mainly devoted to hydropower (CHJ, 2023) The main aquifers are the Mancha Oriental (located in the surroundings of Albacete), which holds the majority of the groundwater-irrigated demands and shares a strong stream-aquifer interaction with the Jucar river; the Plana de Valencia Sur (in the lower basin of the river), hydraulically connected to the

Jucar river and the l'Albufera lake; and the Hoces del Cabriel (downstream Contreras) which receives the seepage losses from the reservoir and returns them to the Jucar river several kilometers downstream. In the river basin agency's jurisdiction, there are 141 streamflow gauging stations (indicated by dots on **Figure 9**), with 57 of them located within the JRB (highlighted in yellow).

Figure 9 JRB streamflow gauging stations (Own elaboration with data from CHJ, 2023)

Current management issues and water challenges

The primary challenges facing the case study area stem from the anticipated decline in water resources within the Júcar River Basin (JRB). Depending on the source, this reduction could go as high as 40 to 50% of historical levels in certain areas. Particularly, significant decreases are projected in the upper reaches of the JRB, where most reservoirs are located. This situation may result in a considerable reduction in carryover storage, further straining an already delicately balanced resource system. Consequently, the region's resilience to interannual droughts could be significantly compromised. Although there is significant uncertainty regarding the magnitude of the decrease, most CMIP5 projections agreed on predicting a reduction in water resources. This consensus fosters a high degree of confidence in the projections. Moreover, future projections of drought indices indicate a rise in both the frequency and severity of droughts, posing additional challenges to the sustainability of water use within the system.

A reduction in the system would have far-reaching impacts on all water uses, ranging from urban supply to agricultural and industrial demands. Additionally, it would significantly affect the environmental status of ecologically vulnerable areas. With being the main water use, it is set to experience the most significant reductions in water supply compared to urban areas.

Moreover, declining streamflow and competition with agriculture will pose challenges to the environmental health of water and dependent ecosystems. While hydropower production may also experience a notable decrease, it is anticipated to be less severe than in the sectors mentioned earlier.

The main challenges and environmental pressures of the JRB can be summarized as follows:

- Water scarcity:

    o Contamination of aquifers by phytosanitary products and pesticides

    o Significant and prolonged drought episodes and increasing demand

- Energy transition:

    o Decarbonizing the electricity sector and reducing energy demand

    o Rising energy costs directly impact crop profitability

- Food sustainability:

    o Transitioning to a more efficient, ecological, sustainable, and profitable production model

- Environmental sustainability:

    o Protection of the coastal wetlands and other ecosystems in the Jucar Basin

    o Establish an ecological flow adequate to maintain the environmental integrity of the basin

List and role of stakeholders

Key stakeholders within the Júcar River Basin (JRB) encompass several distinct entities:

- Governmental institutions are responsible for formulating the basin's water resource management plans and overseeing the management of various water resource uses (the River Basin Agency Confederación Hidrográfica del Júcar)

- Agricultural user unions primarily advocate for farmers' interests (Jucar Users Union, Acequia Real del Júcar, Canal Júcar-Turia, Junta Central de Regantes de la Mancha Oriental)

- An energy company holds ownership of all the main hydropower facilities in the basin (Iberdrola)

- Local governments and communities play essential roles in the basin's management (City of Valencia, City of Albacete, Government of the Comunitat Valenciana, Government of Castilla – La Mancha)

- NGOs are dedicated to safeguarding the environmental status of ecologically vulnerable areas (Xúquer Viu, AEMS Ríos con Vida)

- Universities are primarily engaged in researching the best practices for managing the water resource system (University of Valencia, Polytechnic University of Valencia)

3.2   Danube Basin

The Danube Basin (DB) is the most international basin in the world, including 19 countries (listed in **Table 2**) home to 79 million people and covering an area of approximately 800,000 km^2, making it the second largest basin in Europe and the 21st in the world. The Danube stretches 2850 km, starting from the Black Forest (Germany) and flowing South through Central Europe to the Romanian shores of the Black Sea. Its exceptional diversity is also reflected in the number of names used to address it. The Danube is called Donau in German, Dunaj in Slovakian, Duna in Hungarian, Istros in Greek, Dunav in Serbian and Bulgarian, Duna in Russian, Dunăre in Romanian, and Danubius in Latin.

*Table 2 Countries of the Danube Basin, their population and area within the basin *EU countries; **EU candidate countries. Data source ICDPR, https://www.icpdr.org/danube-basin/countries accessed 24-1-2024.*

Country	Coverage in DRB (km2)	Share of DRB (%)	Percentage of land territory within the DRB (%)	Population within the DRB (Mio.)
Albania**	126	0.02	0.4	< 0.01
Austria*	80,593	10.03	96.1	8.4
Bosnia and Herzegovina**	38,289	4.77	74.9	3.2
Bulgaria*	47,235	5.88	42.6	3.57
Croatia*	35,111	4.37	62.1	2.9
Czech Republic*	21,681	2.7	27.5	2.7
Germany*	56,250	7	15.7	10.07
Hungary*	93,000	11.58	100	9.8
Italy*	565	0.07	0.2	0.02
Republic of Moldova**	12,505	1.56	36.9	1.1
Montenegro*	7,260	0.9	52.5	0.18
North Macedonia**	109	0.01	0.4	< 0.01
Poland*	430	0.05	0.1	0.04
Romania*	232,193	28.91	97.4	19.5
Serbia**	81,974	10.21	92.6	7
Slovakia*	47,084	5.86	96	5.2
Slovenia*	16,420	2.04	81	1.8
Switzerland	1,809	0.23	4.4	0.02
Ukraine**	30,626	3.81	5.1	3.03

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 10**). 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 between 2 and 2.5 m/s, particularly along the tributaries flowing from the Central European Highlands and the Northern Alps.

The middle basin stretches from the Gate of Devin Castle, near Bratislava, to the Iron Gate Gorge, at the border between Serbia and Romania. The gorge also marks the border between the Southern Carpathian Mountains and the Balkans. 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. There are two narrow stretches at Visegrad (Hungary) and the Iron Gates, where it flows through canyon-like gorges. After the Hungarian Gates Gorge near Bratislava, the river enters the Little Alföld Plain, slowing down significantly and causing deposition of gravel and sand, forming two large islands on the Slovakian and Hungarian sides. The Danube continues through Budapest and the Great Alföld Plain until it reaches the Iron Gate Gorge. Along this stretch, the riverbed is shallow and marshy, with numerous islands formed due to deposition. It is joined by major tributaries, namely the Drava, Tisza, and Sava, significantly increasing its flow.

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. Numerous large islands dot its course, and the current loses its speed. In this stretch, smaller tributaries like the Iskar, Olt, Yantra, Siret, and Prut join the main river, contributing modestly to the overall flow rate. The course of the Danube ends in the Danube Delta, formed by the river splitting into three. The three channels are named Chilla, Sulina and Sfintu Gheorghe (St. George), caring for approximately 63%, 16% and 21% of the discharge, respectively. The delta is the largest in Europe, covering an area of approximately 6000 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 11**).

*Figure 10 Danube Basin states and basin divisions. **The upper, middle, and lower Danube Basin are presented.***
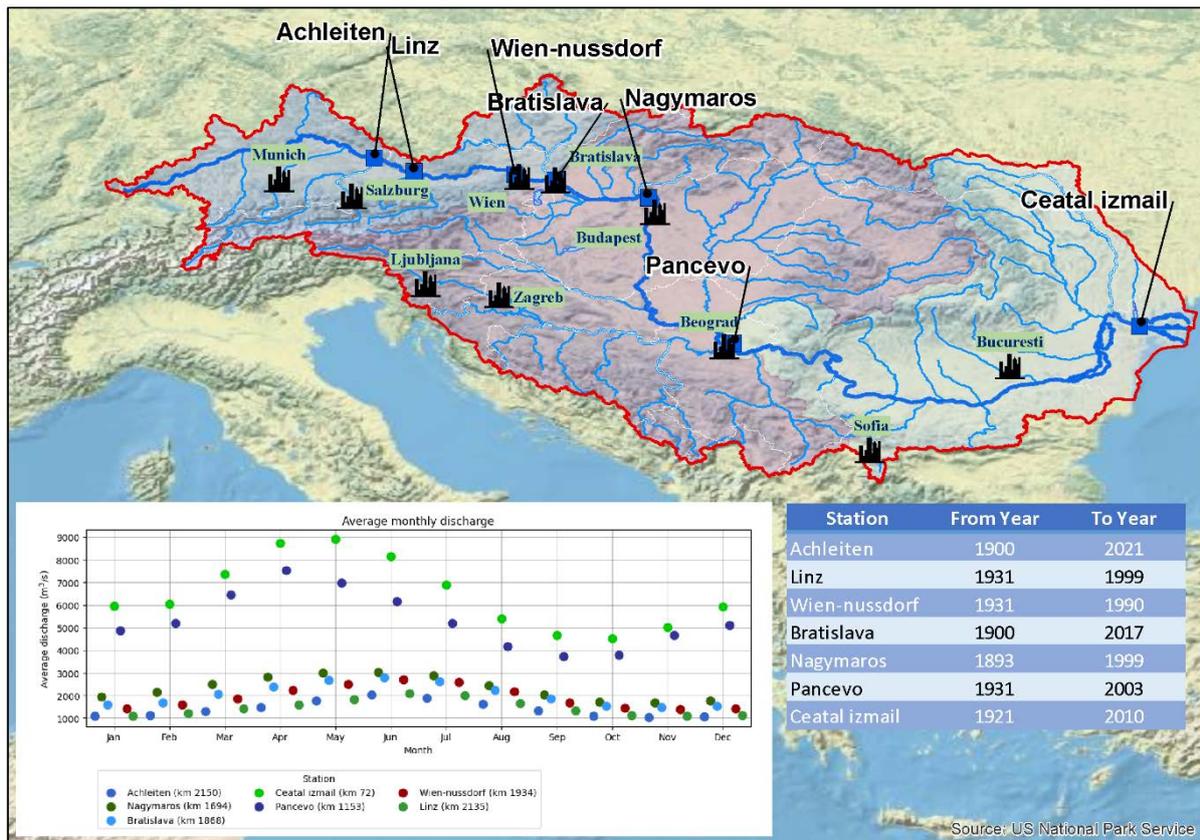
Figure 11 Danube gauging stations maps, average monthly discharge values chart and table of the gauging records temporal availability—data source: Global Runoff Data Centre (GRDC).

Current management issues and water challenges

The large number of people living within the DB inevitably leads to the rise of several environmental management issues in the basin. 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:

1. Organic pollution originating from urban wastewater and industrial emissions. Both sources are decreasing thanks to better water treatment and industrial and technological advancement. However, there is still a margin for substantial improvement by further developing treatment and technologies in non-EU and new EU countries.
2. Nutrient pollution. Agriculture and urban water management are the primary sources of nutrient emissions. Loads are decreasing due to urban wastewater treatment plants and lower agricultural intensity, but they still exceed the long-term historical values.
3. Hazardous substances. 180-point sources from industrial facilities have been recorded to release 32 compounds into surface waters. Other sources are effluents from urban wastewater treatment plant (UWWTP), potentially nearly 500 industrial facilities, and 200 tailings ponds with a significant risk of accidental pollution.

4. Hydromorphological alterations. The three critical hydromorphological alterations in the DRB are I) hydrological, II) interruptions of longitudinal river continuity and sediment balance alterations, and III) morphological alterations. These alterations negatively impact river health and aquatic species, causing many surface water bodies to fail to meet the Water Framework Directive (WFD) objectives.
5. Alien species. The DB is experiencing significant colonisation by invasive species. The biocontamination level is estimated to be moderate to high, with higher levels in the Upper and Middle Danube compared to the Lower Danube.
6. Macro and microplastics. Macro and microplastics are widely recognised issues, but little quantitative data are available for precisely estimating the problem dimension.
7. Pressures on groundwater. Pressures on the chemical status of groundwater are pollution by nutrients and over-abstraction. Since 2015, there has been a decrease in the number of groundwater bodies not achieving good quantitative status, and one groundwater body has improved from poor to good status.

List and role of stakeholders

The main objective of the stakeholder engagement process is to establish an ongoing dialogue with all relevant stakeholders related to freshwater in the Danube River Basin. The role of the stakeholders is to help us jointly identify local water challenges as well as their needs and preferences. The insights gained will allow us to formulate the SOS-Water framework for the Danube basin. During the first workshop, which took place on 22 November 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. Other workshops will follow where stakeholders will help us define objectives and priorities for the Danube basin and discuss the applicability and improvement of the SOS-Water framework.

Stakeholders of the Danube basin represent a wide range of freshwater-related institutions spanning the whole basin, including:

- International Commission for the Protection of the Danube River (ICPDR)
- National Agency for Land Improvements (ANIF)
- International Association for Danube Research (IAD)
- Danube Delta Biosphere Reserve Administration (ARBDD)
- Danube Commission
- Federal Ministry of Agriculture, Forestry, Regions and Water Management (BML)
- Viadonau
- University of Natural Resources and Life Sciences (BOKU)
- Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB)
- International Association of Water Service Companies in the Danube River Catchment Area (IAWD)
- European Landowners' Organization (ELO)
- Verein fur Okologie un Umweltforschung (VÖU) / Tiwag
- Wolff Environmental Consulting (WEC)

- World Bank
- The National Institute for Research and Development of Marine Geology and Geoecology (GeoEcoMar)
- The Danube Civil Society forum

3.3   Rhine River

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 km^2, encompassing various sub-basins and tributaries (as shown in **Figure 12**). The source of the Rhine River is in the Swiss Alps in the canton of Graubünden, from which it flows through diverse landscapes, including mountainous regions, fertile valleys, and urbanised 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 resources, 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 km^2. 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, urbanisation, and agriculture, have led to habitat loss, fragmentation, pollution, and a reduced water availability in summer. The construction of dams and flood defences 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.

With respect to the future, the Rhine is expected to deal with challenges related to drought 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.

The main stakeholders in the Rhine River are the national water authorities of the different countries, they often represent the stakes of the more local stakeholders. Other parties involved include nature, shipping, agriculture, industry, local water authorities, hydropower companies, local communities.
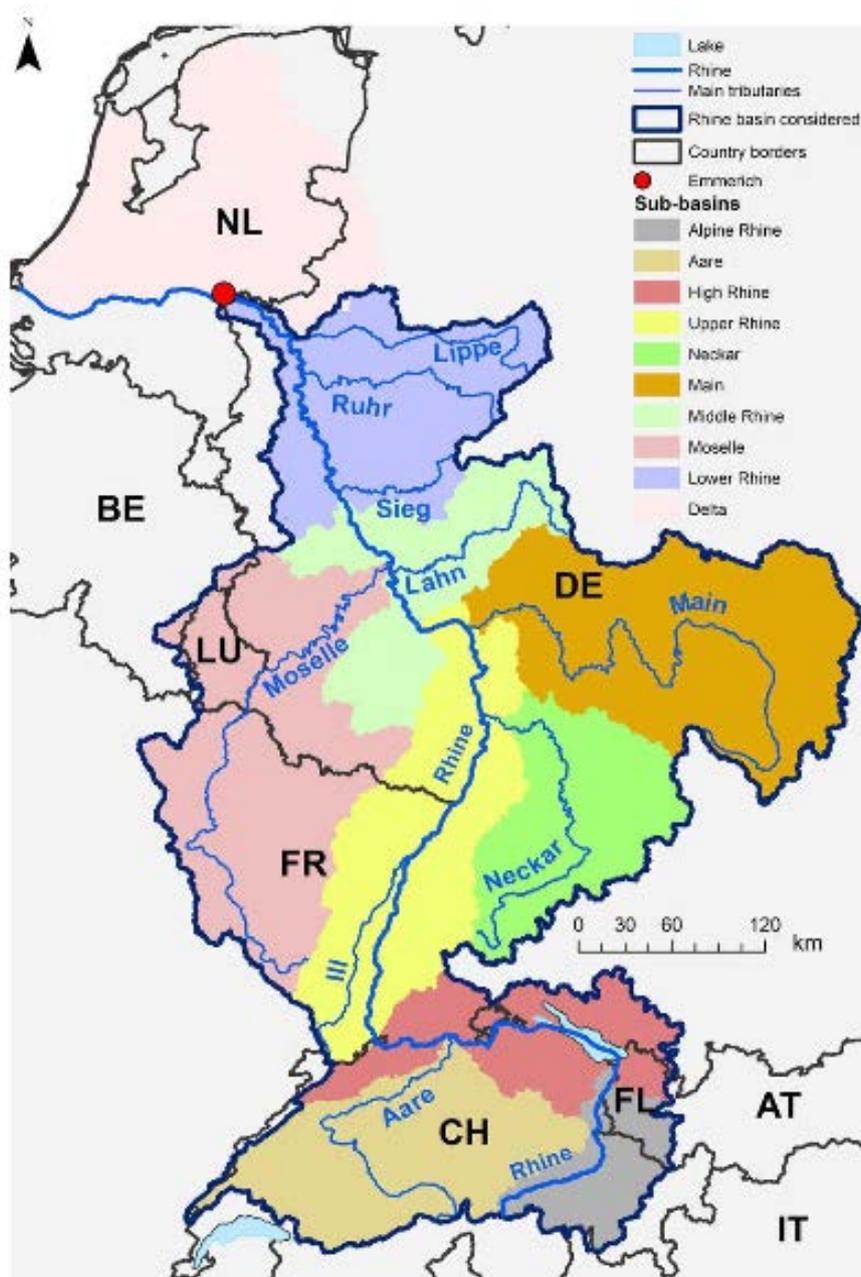
Figure 12 Map of the Rhine catchment obtained from Moser et al. (2018).

3.4 Mekong River Basin

The Mekong River stretches nearly 4,800 km, originates in Tibet and flows through six countries: China, Myanmar, Laos, Thailand, Cambodia and Vietnam, creating a large delta (among the three largest deltas in the world) before flowing into the East Sea. The Mekong River basin has an area of 795,000 km². In particular, the ratio of basin area compared to national area of Laos is 97%, Cambodia is 86%, Thailand is 36% (Northeastern region), Vietnam is 20% (of which 2 main parts are Central Highlands and Mekong Delta).

The average annual flow of the Mekong River is approximately 475 km^3, of which 82% of the total flow is formed from four downstream countries: Laos 35%, Thailand 18%, Cambodia 18% and Vietnam 11%. The flow contribution from the two upstream countries accounts for about 18% of the total yearly flow, however this is an important contribution in the dry season flow (about 30%). Water resources per capita (about 8000 m$^3 \cdot a^{-1}$ per capita) are relatively high compared to most other international river basins (Liu et al., 2022). The Mekong is the river with the second highest biodiversity in the world after the Amazon and has the world's largest freshwater fishing industry with about 2.3 million tons/year.

The Mekong River basin is located in a tropical climate zone, with high air humidity and lots of rain. Rain is the main water-generating factor, with an average annual rainfall in the basin of about 1,600 mm, of which the territory of China and Thailand has a low average rainfall of 1,000 to 1,500 mm, the territory of Laos and the Western region. Vietnam's plateau has a relatively high average rainfall of over 1,600 mm, in some places up to 3,000 mm. Cambodia and the Mekong Delta have an average rainfall of 1,500 mm. The rainy season starts in May and ends in November, rain usually starts earlier in the upstream and ends later in the downstream. However, the main rainy period is from May to October, which is defined as the wet season; from November to April next year is the dry season.

The Mekong has more than 30 main tributaries with a total average annual flow of about 15,000 m^3/s. The average monthly flow changes relatively large, the flood season from May to November has a peak flood flow of over 50,000 m^3/s causing flooding of over 6×10^4 km^2, especially in Cambodia and the Mekong Delta. In the dry season, the average flow is relatively low (about 2000-5000 m^3/s) causing potential saltwater intrusion on about 1.6 - 2.2×10^4 km^2 of land in the Mekong Delta.

In the years from the 1960s to the present, a large number of hydropower dams have been built, first on tributaries and then on the mainstream. By 2013, dams on Lan Thuong River were basically completed with a regulated capacity of about 23 km^3. The reservoir system has participated in regulating flow, causing seasonal flow distribution to change greatly, especially in the period after 2012.

The Great Lake on the Tonle Sap River branch in Cambodia has a large storage capacity, regulates the annual cycle, and plays a very important role in both Cambodia and the Mekong Delta. The lake has a capacity of up to 84 km^3 (approximately 18% of the total annual flow of the basin) corresponding to the flood level elevation of +11m AMSL and an open surface area of 14,000 km^2. In the dry season, the lake surface area is only about 2,300 km^2 with an elevation of +1.6 m AMSL and lake capacity of about 1.4 km^3.

The Mekong Delta of Vietnam (MDV) is the last part of the Mekong river basin, including 13 provinces/cities Long An, Tien Giang, Dong Thap, Vinh Long, Tra Vinh, Hau Giang, Soc Trang, Ben Tre, An Giang, Kien Giang, Bac Lieu, Ca Mau and Can Tho city, with the total natural area of about 39,600 km^2 (not including area of islands), accounting for 79% of the entire Delta, and by 5% of the whole Mekong River Basin.

The Mekong Delta plays an important role in socio-economic development strategy of the country. With a huge agricultural potential, the Mekong Delta in recent years has always contributed over 50% of the total national rice production, deciding to the success of national strategy for food security and a

significant contribution in rice export (more than 90%). Besides, the Mekong Delta also provides about 70% of fruit production, and over 75% of the total fishery production in the country.

However, although located in the lower Mekong River Basin, and inherited many advantages (including geographical location, abundant water resources, natural regulation by the Tonle Sap lake, large coastal region, open sea resources, flat land with fertile alluvial, and abundant, diversity fisheries), the Mekong Delta always faces to the difficulties and impacts of natural conditions, with the frequent and unpredictable effects from climate change, the upstream activities, sea level rise, saltwater intrusion, and above all, the conflict between economic growth and environmental protection issues in this Delta.

In the process of socio-economic development in the Mekong Delta, the limitations of natural conditions are always barriers, especially for agricultural domestic activities of people. The restrictions of natural conditions include (a) the impact of floods on the area from 1.4 to 1.9×10^4 km^2 in the upstream watershed, (b) salt water intrusion in an area of about 1.2 to 1.6×10^4 km^2 in the coastal zone, with salinity of a concentration of 4 g/l; (c) alkaline soil and spread of alum water on an area of about 1.2 to 1.4×10^4 km^2 in the low-lying areas, (d) lack of fresh water for production and living in an area of about 2.1×10^4 km^2 in remote area faraway from rivers and near the sea, and (e) river bank and coastal erosion happening many positions is getting worse. In addition, forest fires often occur, and water pollution is getting worse; the problems of cross-border movement are increasingly complex.

To meet the development needs of the Mekong Delta, many irrigation works have been proposed and built up over 30 years, until now the area affected by salinity is only about 5000 km^2 and the area affected acidic reduces minimum with just lesser 1000 km^2. It should be taken into account that since 1996, after the decision 99-TTg on irrigation development in combination with transportation and residence about the approval of controlled planning and use of flooding of the Prime Minister in 1998, plus Decision 84/TTg on the irrigation portfolio in the period 2005-2015, the initiatives for a series of irrigation projects launched and becomes the driving force and an important lever for the Mekong Delta to have the opportunity and conditions for more rapid growth. Based on the development of strategic water resources, along with the application of technical advances and other development incentives, the Mekong Delta has put rice production from 4.5 million tons in 1976 to 18.3 million tons in 2004, 19.2 million tons in 2007 and 21.3 million tons in 2010, made outstanding changes for socio-economic development.

However, the natural fluctuations and changes of the market in recent years, along with the large-scale and widespread restructuring of crop pattern since 2001, has shown many problems for the irrigation development. The problem is not only related to the irrigation sector, such as flood control, water supply, drainage, salinity control, erosion prevention but also the coordination to solve the problem with multi-purpose water resources for agricultural development, population, transportation, water supply, industrial development and especially for fisheries development (saline, brackish water resources).

In addition, in recent years, the impacts of climate change have increased significantly posing complex challenges, particularly in relation to two key factors: upstream discharge and sea level rise. In 10 years, the Mekong Delta has experienced a series of notable events, including four large floods in the years 2000, 2001, 2002 and 2011 (with the 2000 flood considered a historical flood event). Additionally, the

region has witnessed multiple dry years with low water runoff, leading to severe drought and saltwater intrusion in 2004, 2008, 2010, 2016, and 2020. Typhoons, such as Linda in 1997 and Durian in 2006, have made landfall. Riverbank and coastal erosion occurred at many locations and forest fires occurred with an increasing frequency, for example the forest fire in 2002 in the U Minh Thuong National Park. Typhoons appear more and more commonly; and water resources are increasingly polluted. Therefore, to meet the demand of socio-economic development, various Delta Master Plans on water resources, irrigation and risk reduction are implemented.

Current management issues and water challenges

Due to its geographical location downstream of the Mekong River basin, the MDV depends greatly on changes upstream and the impacts of climate change. Accordingly, the most important issues related to natural resources and water resources include:

- Changing flood season flow and dry season flow of the Mekong River into the delta under the impact of climate change and upstream development.
- Potential impacts of mainstream dams on fish migration behavior and natural fish stocks in the delta.
- Loading and deposition of sediment and nutrients in the flooded areas of the Mekong River and the Mekong Delta under the impact of dam construction and sand mining activities.
- Some other issues include increasingly serious river water pollution due to agricultural and industrial activities in upstream countries and adverse impacts on habitat and biodiversity throughout the lower river basin.

With 11 proposed mainstream dams on the Mekong stream, the major drivers of key impacts of mainstream hydropower development on lower Mekong basin (LMB) natural, social, and economic systems include:

- Changes in the river system flows and LMB flooding patterns, increased irrigation withdrawals, compounded by climate change and sea level rise.
- Changes in sediment flows largely because of trapping within the reservoirs and to a smaller extent due to the changes in stream power and flooding patterns.
- Changes in water quality and nutrient flows largely resulting from the combined effect of altered flows and sediment loadings combined with water quality changes resulting from expanded irrigated agriculture and increases in wastewater discharges from urban and industrial centers.
- Physical fish migration barriers created by the proposed mainstream dams.

In general, hydropower projects alter downstream flow regimes and sediment transport dynamics within riverine systems. In addition, changes could also result in water chemistry; physical habitat; habitat connectivity; and composition, structure, and function of biological communities. Mekong Delta Study (2014) identified the following major impacts that are likely to result in the LMB from changes in Mekong River flow regimes and water quality due to mainstream hydropower development:

- Decrease in flood plain and coastal land productivity because of reduction of flooding, sediment and nutrient flows primarily resulting from increased storage and sediment trapping within the basin.

- Increased risk of bank erosion, which may in part be lessened by reduced wet season flows but aggravated by river regime change as the river system adjusts to new sediment loads.

- Impacts of fluctuating dry season flow depths, compounded by the presence of the proposed new mainstream dams, on riverine habitats including bank-side and exposed riverbed seasonal gardens and deep pools and the consequential impacts on local livelihoods and on fish refuges and spawning areas.

- Changing in natural nutrients driven by increased sediment trapping and modified by changes in flow patterns (particularly regarding the Tonle Sap system, but also the Mekong Delta flood plains) whilst at the same time the likelihood of increased runoff of agricultural input residues due to irrigated agriculture expansion and economic pressures to raise yields.

- Changes in saline intrusion in the Mekong Delta brought about by fluctuations in dry season flows from the increases in storages (especially those in the UMB) and climate change induced sea-level rise.

- Reduction in extent of wetlands and key habitat areas because of modified flow patterns, the reduction of their productivity due to reduced sediment and nutrient flows and the consequential impact of both on the sustainability of various species, some of which are already endangered by human activity.

- Combined effects of the flow, sediment, and water quality alterations on the basin's rich biodiversity including several key rare, threatened and unique wildlife.

List and role of stakeholders

a) Regional level:

- Mekong River Commission (MRC): To promote and co-ordinate sustainable management and development of water and related resources for the countries' mutual benefit and people's well-being by implementing strategic programs and activities and providing scientific information and policy advice.

b) Key national level:

- National Water Resources Council (NWRC): To assist the Prime Minister to urge Ministries, agencies and localities to implement important issues relating to protection, exploitation, use of water resources, prevention against and control of water resources deterioration and pollution.
- MONRE: Water resources management for interprovince rivers and environmental protection (by Departments); Meteo-hydrological monitoring (HydroMet agencies); river basin management and regional coordination (by VNMC).
- MARD: Irrigation management for interprovince systems, risk reduction and rural water supply management (by Departments and IMC);

- DOC: Urban water supply and drainage management for interprovince systems (by Departments);
- MOT: Inland navigation management for interprovince routes;
- MOST: Managing national research study on natural resources & risk reduction (KC.08/21-30 since 2001) and Mekong delta climate change resilience (KC.15/21-30 since 2016).

c) Key local level:

- DONRE: Water resources management for provincial rivers and environmental protection.
- DARD: Irrigation management for provincial systems, risk reduction and rural water supply management (by IMC and districts);
- DOC: Urban water supply and drainage management;
- DOT: Inland navigation management for provincial routes;
- Southern agencies for water resources planning, irrigation and risk reduction (SIWRP), water research (SIWRR), Mekong delta development (Can Tho university).

4 Applications and Assessment of SOS Water – Jucar

In this deliverable we use the Jucar River Basin as an example to demonstrate the SOS-evaluation framework established in Section 2. Since the indicators, scenarios and pathways are under development in other WPs, the SOS-evaluation on Jucar River Basin is preliminary. Hence only a few elements were included in each component (i.e., scenarios, indicators and pathways) of the SOS-evaluation framework. A more comprehensive SOS evaluation for all case studies will be provided in the coming deliverables.

4.1 Indicators and thresholds

4.1.1 Indicators

The indicators for this assessment are one economic indicator, in this case net benefit (hydropower benefit plus agricultural benefit), and an ecological indicator (fish habitat).

The chosen indicator for economic assessment is net benefit, which encompasses both hydropower and agricultural benefits across the entire basin. Agricultural benefit is obtained by multiplying agricultural production by the corresponding crop prices, and hydropower production is estimated with the turbinated streamflow of each reservoir and the corresponding net head for each month. It should be noted that rice crops have been excluded from the economic analysis due to their unique significance in sustaining the l'Albufera wetland. Therefore, attempting to quantify their benefits solely through crop prices would not accurately capture their true value, which, in any case, would be challenging to estimate.

In addition, the evaluation of ecological performance relies on previous scientific studies that have developed a habitat suitability model for a native fish species. This model considers the weighted usable area (WUA) estimated in river reaches using both the habitat suitability model and a hydraulic model. The streams are divided into sections, and the usable area is estimated based on factors such as depth, velocity, and attributes like shelter, which are associated with different streamflow values. The WUA can be calculated for different flow rates, while the target species and size class correspond to the adult

Mediterranean barbel, a native fish species present in a major part of the water bodies of the Júcar River Basin. The indicator consists of the proportion of months above a certain threshold of the WUA in each of the river reaches where a habitat model is available. As a first approximation the threshold of habitat was fixed on 50% of the maximum WUA at each of the river reaches under evaluation, guided by the legal criteria of the fundamental Spanish water planning piece of legislation. An example of a WUA-Flow curve for adult Mediterranean barbel in a river reach is presented in **Figure 13**, with a polynomial adjustment to encompass the inner values of the data points.
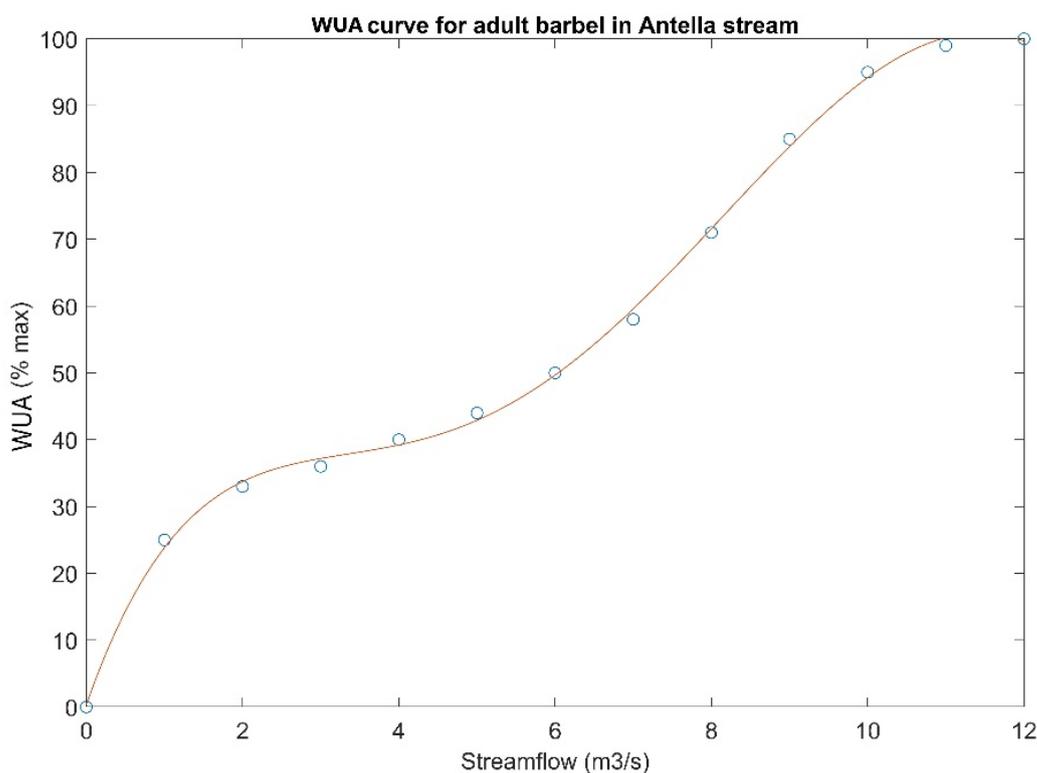
*Figure 13 The **weighted usable area** (WUA) curve for adult barbel in the Antella stream. Each point represents the weighted usable area value for that stream for a given streamflow, as a fraction of the maximum.*

4.1.2 Thresholds

Initially formulated through expert judgment, the threshold values selected for this study were set at 80% of historical net benefit as the success threshold (below which the system is deemed to fail), and 80% of months above the habitat suitability threshold for the ecological indicator (below which the system is considered to fail). With these values, one can evaluate the success or failure of the system under each climatic scenario and develop a climate response map, as outlined by Ray and Brown (2015), to assess system performance across a broad spectrum of climate conditions.

The threshold and indicator values are subject to potential adjustments in the future, guided by expert and stakeholder input. While the selected values were useful as an initial approximation to validate the methodology and simulation streamflow, they should not be regarded as final.

4.2   Global Change Scenarios

For the Global Change scenarios, rather than employing a conventional top-down methodology reliant on assessing system performance through scenarios derived from downscaled global circulation models (GCMs)—which typically yield a limited scope of uncertainty—the approach adopted follows the framework proposed by Brown et al. (2012), known as Decision Scaling. This method involves generating a diverse array of potential climate scenarios independently of GCMs, thus enabling an analysis of system performance across a broader spectrum of possibilities. Subsequently, the results from GCMs can be overlaid onto the resultant climate response map, pinpointing regions with a higher likelihood of projected climate conditions according to the top-down projections.

The different global change scenarios for this case study were produced using a weather generator coded in a MATLAB script, which could be divided into two parts. In the first part, it generates an unperturbed time series aimed at reproducing the main statistics of the historical time series. This consists of an AR(0) autoregressive model for annual precipitation in the Contreras sub-basin, or no autocorrelation, which is downscaled to monthly values via the method of fragments, and then propagated through the basin with linear correlations in the monthly residual series. For temperature, two autoregressive models are used for yearly series: an AR(2) autoregressive model for the Alarcón sub-basin, and an AR(3) autoregressive model for the Contreras sub-basin. As with the precipitation series, the monthly disaggregation is done through the method of fragments, but for interbasin correlation, linear relationships of the monthly series are used in this case.

In the second part, based on the results of the synthetic monthly series for precipitation and temperature, climate change scenarios are generated. For precipitation, a gamma distribution is adjusted to the "base" series, and then the mean and coefficient of variation of this series are changed accordingly. For temperature, simple addition is used on the monthly synthetic series. This consists of dividing the desired increase in temperature for the whole series and adding the corresponding increments to each month of the "base" series.

With this methodology, 105 different climate scenarios are analyzed, which are presented in **Table 3**.

As the climate change scenarios are stochastic series, there is always randomness in the process of generation. Consequently, the generated series will be close to the desired percentage of change, but not the exact value. This aspect must be kept in mind when analyzing the results presented.

Table 3 Climate Scenarios included in the study. Three factors considered in climate scenario design: 1) Precipitation CV change, 2) Annual Precipitation mean change; 3) Temperature increase at year 65. Each scenario is designed based on a combined variation on these three factors.

Factors considered in scenario design	Relative variations compared to historical conditions
Precipitation CV change (%)	-30, 0, 30
Annual Precipitation mean change (%)	-30, -15, 0, 15, 30
T increase at year 65 (ºC)	0, 1, 2, 3, 4, 5, 6

4.3   Local Management Pathways

For these preliminary results, the local management pathway under consideration focuses on enhancing efficiency within the agricultural demand zone of the "Acequia Real del Júcar." This zone is primarily composed of citrus crops, accounting for 51.4% of the total surface area, followed by rice (21.0%), and non-citric fruits (20.1%) (CHJ, 2023). This zone currently operates at a global efficiency level of approximately 0.42. However, it is part of a modernization plan outlined in the hydrological plan published by the river basin authority. The implementation of this plan has led to an increase in efficiency, raising the value to 0.85, aligning it with the higher efficiency standards observed in other agricultural demands within the basin.

Additional management pathways will be evaluated throughout the project, including (but not exclusively) the following preselected options:

- Desalination
- Reutilization
- Repumping

These alternatives will be thoroughly discussed with experts and stakeholders to determine their feasibility.

4.4   Integrated water system modeling

4.4.1   Hydrological model

For conducting hydrological simulations across diverse sub-basins, we employed a previously calibrated conceptual hydrological model. This model, as elucidated by Témez in 1977, operates by intricately balancing water fluxes among distinct processes within the hydrological system throughout various stages of the hydrological cycle. Falling under the category of lumped hydrological models, it globally assesses each sub-basin without factoring in the spatial distribution of variables and parameters involved in calculations, instead opting for average values. Given the basin's division into sub-basins and the monthly analysis timeframe, this level of detail is deemed suitable for the current study. A graphical representation of the model is depicted in **Figure 14**, and the division in sub-basins was shown in the case study description section.
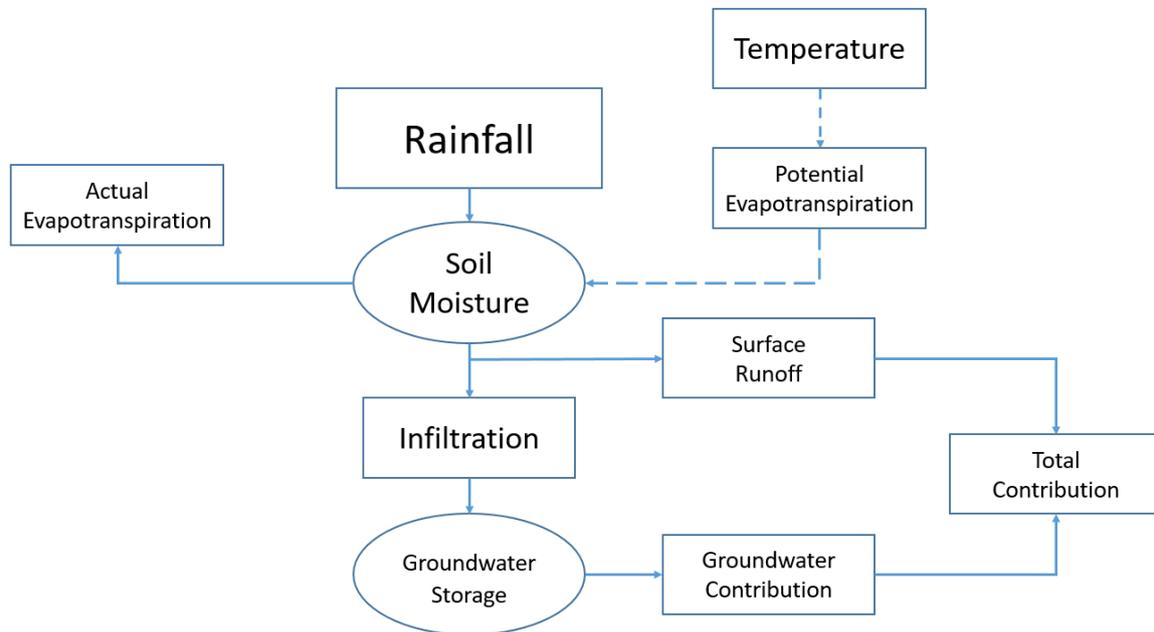
Figure 14 Diagram of the Teméz hydrological model, representing the water fluxes among the different processes.

4.4.2 Hydro-economic model

The hydroeconomic model representing the Jucar River Basin was constructed using the Explicit Stocastic Programing Advanced Tool (ESPAT) developed by Macian-Sorribes et al. 2017. Operating on a monthly time scale, this model employs a simulation methodology to closely emulate the usual reservoir operation and demand priorities that dictate the water resources management in the system. The Júcar River system is represented by 27 nodes, 8 surface reservoirs, 5 groundwater bodies modelled using the Embedded Multireservoir Model (Pulido-Velazquez et al., 2005), 7 sub-basins, 18 consumptive demands, 9 hydropower plants and 6 minimum environmental flows (as described in the hydrological plan). The representation of the system for this model is presented in **Figure 15**, which accurately represents the system in the period ranging from 1998 to 2020, but it may suffer from future modifications.

Figure 15 Hydroeconomic model schematic for the Júcar River Basin (Macian-Sorribes, 2017)

The model's physical attributes, encompassing hydrological sub-basins, reservoir characteristics (capacity, minimum level, storage-head, and storage-surface curves), groundwater dynamics, river reach and canal capacities, prescribed minimum streamflow, water demands, returns, and fish habitat details, were gathered from the Júcar River Basin Agency (RBA). Economic aspects related to water usage, like urban water needs, energy prices, and pumping expenses, were first taken from CHJ (CHJ, 2023) and later updated based on earlier studies (Pulido-Velázquez et al., 2006) within the DMA rollout in the Júcar, part of the EU AQUAMONEY project. These economic factors were compared with other similar models (Kahil et al., 2016). Urban water demand was characterized using demand functions that establish a connection between water supply levels and the marginal utility of water for consumers.

On the other hand, agricultural water demand linked to citrus, orchards, and perennial crops was modeled through an adapted approach to crop yield calculations derived from FAO66 methodologies (FAO, 2012). This method calculates yearly crop yields based on supply-demand ratios and historical data, then estimates total food production from this yield and crop prices. Rice cultivation significantly contributes to maintaining l'Albufera Lake, a vital protected area in the region, and its water supply has been treated as a constraint.

The only industrial water demand from surface water comes from the Cofrentes Nuclear Power Plant. Its benefits per unit of water consumption were assessed employing the alternative cost approach, which factors in the cost of generating equivalent energy via gas minus the operational expenses of the plant, as detailed in Pereira-Cardenal et al. (2014).

The impact of temperature fluctuations on irrigation requirements was assessed by establishing a correlation between the potential evapotranspiration for a specific month and the average evapotranspiration for that month during the historical period. This approach results in increased

irrigation demands during warmer months and decreased demands during colder months compared to the historical baseline. It is important to note that this methodology operates under the assumption that there will be no significant changes to the fields' composition (or at least none that would significantly affect the simulation period).

4.5   Preliminary SOS assessment results

4.5.1   SOS evaluation for future scenarios

1)   Net benefit (hydropower and agricultural benefit)

The SOS assessment of the net benefit indicator across various designed future scenarios is shown in **Figure 16**. The safe and unsafe assessment is determined by the net benefit indicator values computed for each specific scenario. This assessment involves applying a safe threshold for net benefit, defined as values surpassing 80% of historical performance (as described in Section 4.1.2). It is evident from **Figure 16** that the increase of the mean annual precipitation and the precipitation variability enhance net benefit performance. Conversely, an increase of mean annual temperature can hurt net benefit performance but dependent on the precipitation conditions. These trends align with expectations, as the net benefits factor in both hydropower and agricultural advantages. The rise in precipitation within the region contributes to an increased water supply available for hydropower generation and agricultural irrigation. Conversely, the temperature increase has a contrasting effect by elevating the demand for agricultural irrigation, potentially diminishing the amount of water available for hydropower generation. Notably, when mean annual precipitation exceeds 1.1 times the historical average, the system is deemed safe across all scenarios, provided that precipitation variability remains within the range of -30% to 30% and mean annual temperature increase stays below 2.5°C. Additionally, in scenarios where annual precipitation variability increases by 30% compared to historical conditions, nearly all scenarios are considered safe in terms of net benefit, as long as the mean annual precipitation change exceeds 0.8 times the historical mean annual precipitation.
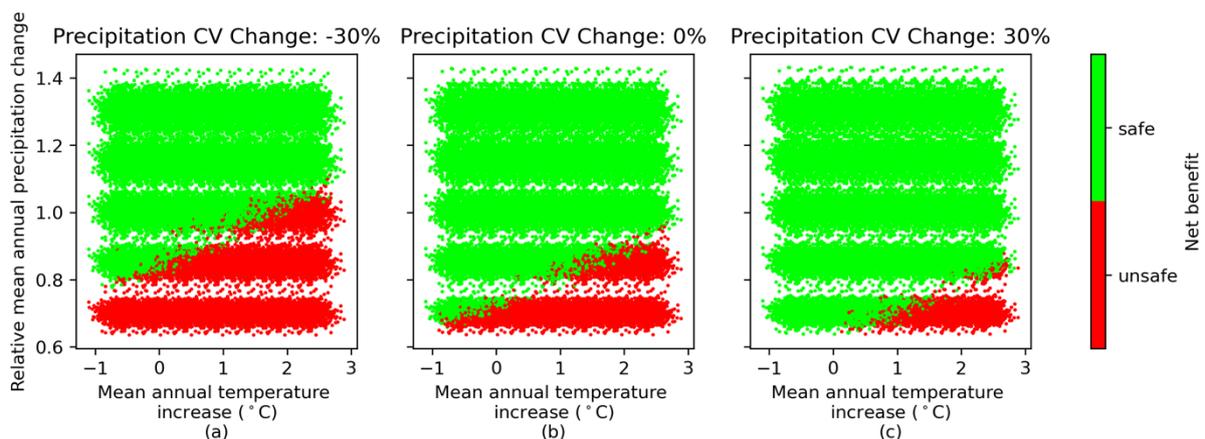

Figure 16 Assessment of Net Benefit indicator across diverse future scenarios. Each data point corresponds to a unique scenario characterized by changes in mean annual precipitation, precipitation coefficient of variances, and mean annual temperature relative to historical conditions. Subplots (a), (b), and (c) show the assessment under scenarios where the change in precipitation coefficient of variances relative to historical conditions is -30%, 0%, and 30%, respectively.

2) Fish habitat

The SOS assessment of the fish habitat indicator across various designed future scenarios is shown in **Figure 17**. Similar to the evolution for net benefit, the safe and unsafe assessment is determined by the fish habitat indicator values computed for each specific scenario and the predefined safe threshold (i.e., over 80% of months the habitat suitability of the river is a above defined habitat suitability threshold). Like the findings in net benefit, **Figure 17** shows that the increase of the mean annual precipitation and the precipitation variability enhance fish habitat performance (i.e., an improved environment for native fish species) while an increase of mean annual temperature decreases fish habitat performance. If mean annual precipitation exceeds 1.1 times the historical average, the system is almost safe across all scenarios, if precipitation variability remains within the range of -30% to 30% and mean annual temperature increase stays below 2.5°C. If annual mean precipitation decreases to a level below 0.8 times of the historical mean annual precipitation, the system is unsafe in all scenarios. If precipitation conditions hold at the historical level (as shown in **Figure 17** (b)), there is a risk of the system not safe when mean annual temperature increase more than 1 °C. of Additionally, in scenarios where annual precipitation variability increases by 30% compared to historical conditions, nearly all scenarios are considered safe in terms of net benefit, as long as the mean annual precipitation change exceeds 0.8 times the historical mean annual precipitation. The increase of mean annual precipitation will lead to an increase of the streamflow, which brings benefits for fish habitat. It is not clear why the increase of the precipitation variability also increases the system's fish habitat performance, which needs further investigation.
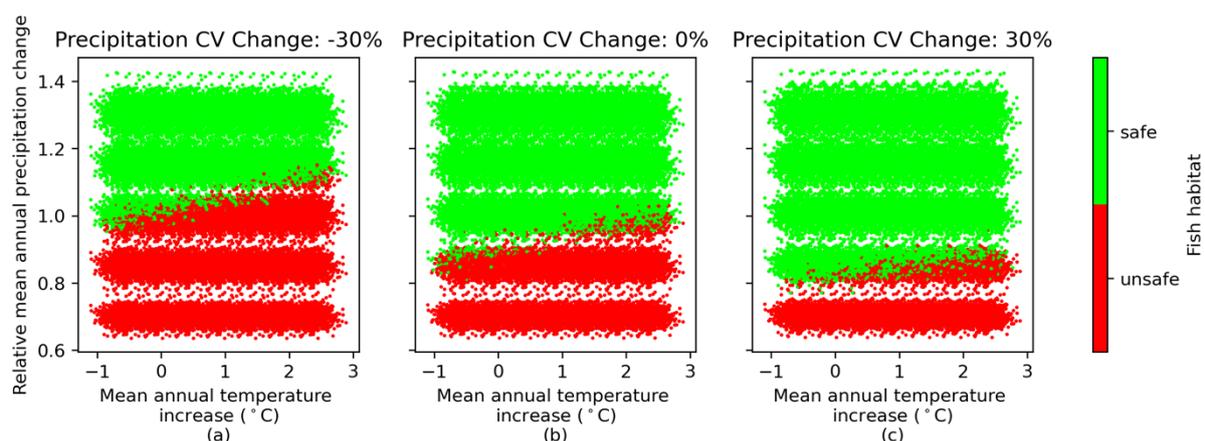

Figure 17 Assessment of Fish habitat indicator across diverse future scenarios. Each data point corresponds to a unique scenario characterized by changes in mean annual precipitation, precipitation coefficient of variances, and mean annual temperature relative to historical conditions. Subplots (a), (b), and (c) show the assessment under scenarios where the change in precipitation coefficient of variances relative to historical conditions is -30%, 0%, and 30%, respectively.

4.5.2 SOS evaluation for future scenarios with pathway implementation

1) Net benefit

Figure 18 compares the system's net benefit performance with and without the implementation of efficiency improvement in the Jucar River basin. The results highlight that thought the enhancing efficiency within the agricultural demand zone, there is an increase of net benefit performance under a few scenarios. For instance, when precipitation variability is reduced by 30% compared to historical conditions, mean annual temperature increased by 0 to 0.5 °C, and mean annual precipitation decreases to 0.8-0.9 times the historical mean, implementing efficiency enhancement shifts the net benefit performance from an unsafe state (as shown in **Figure 18** (a)) to a safe state (as shown in **Figure 18** (d)). However, for the majority of scenarios initially deemed unsafe in baseline condition, the implementation of efficiency enhancement fails to restore net benefit performance to a safe status. This suggests the need to explore additional action options to ensure the system operates safely in these challenging scenarios.
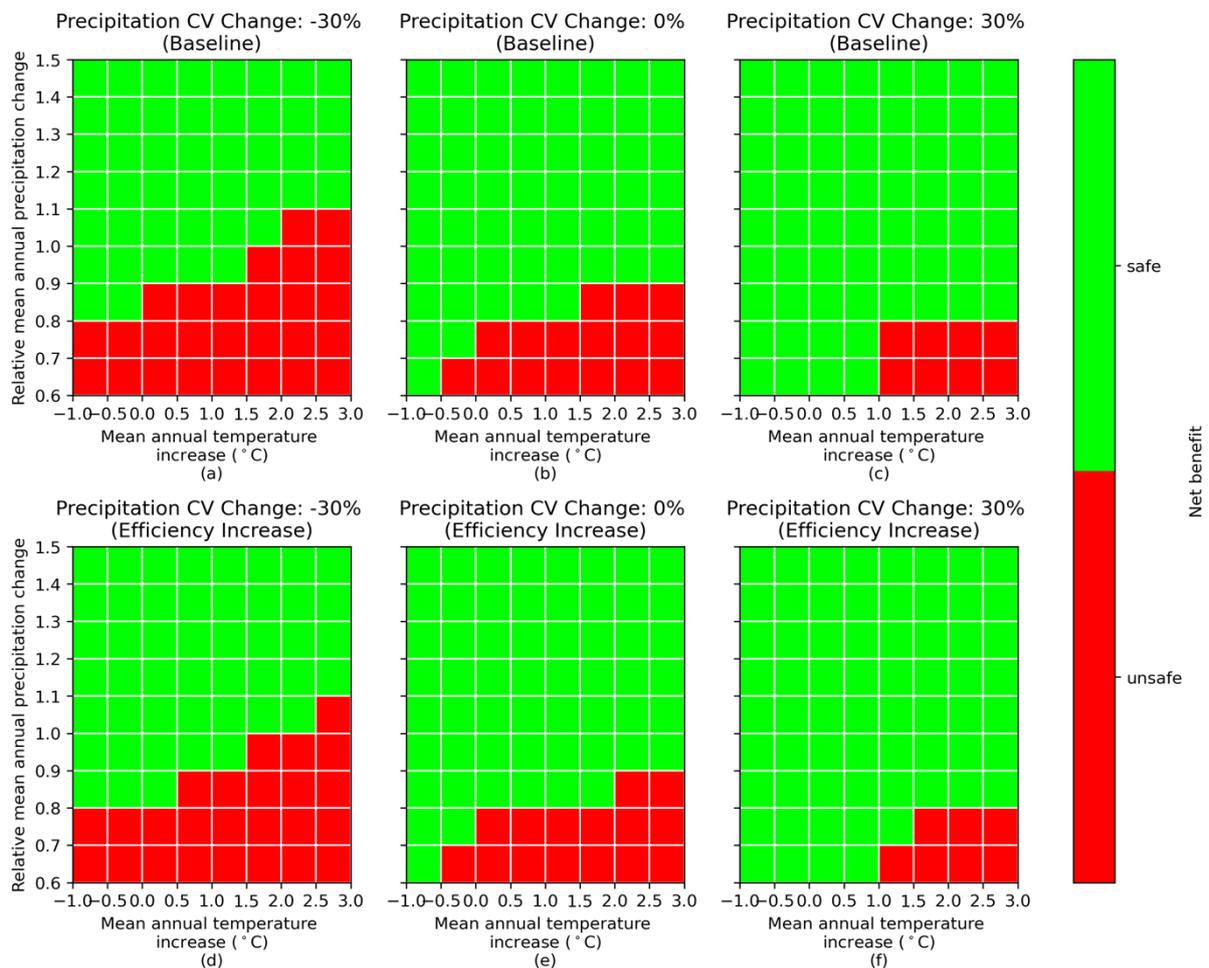

Figure 18 Assessment of the Net Benefit indicator across various future scenarios, comparing the results with and without efficiency improvements from the baseline case. Subplots (a), (b), and (c) depict the assessment under scenarios where the change in precipitation coefficient of variances relative to historical conditions is -30%, 0%, and 30%, respectively (derived from Figure 16 by consolidating the performance for scenarios falling within the same specified intervals). Subplots (d), (e), and (f) illustrate the performance with the incorporation of efficiency enhancements.

2) Fish habitat

The impact of implementing the efficiency enhancement on fish habitat performance is shown in **Figure 19**. The introduction of efficiency enhancements proves effective in restoring fish habitat performance in a subset of scenarios, as evidenced by the reduction of unsafe zones in **Figure 19** (d), (e), and (f) compared to **Figure 19** (a), (b), and (c), respectively. However, akin to the findings in the net benefit performance analysis, for most scenarios initially classified as unsafe, the implementation of efficiency enhancements does not lead to an improvement in fish habitat performance.
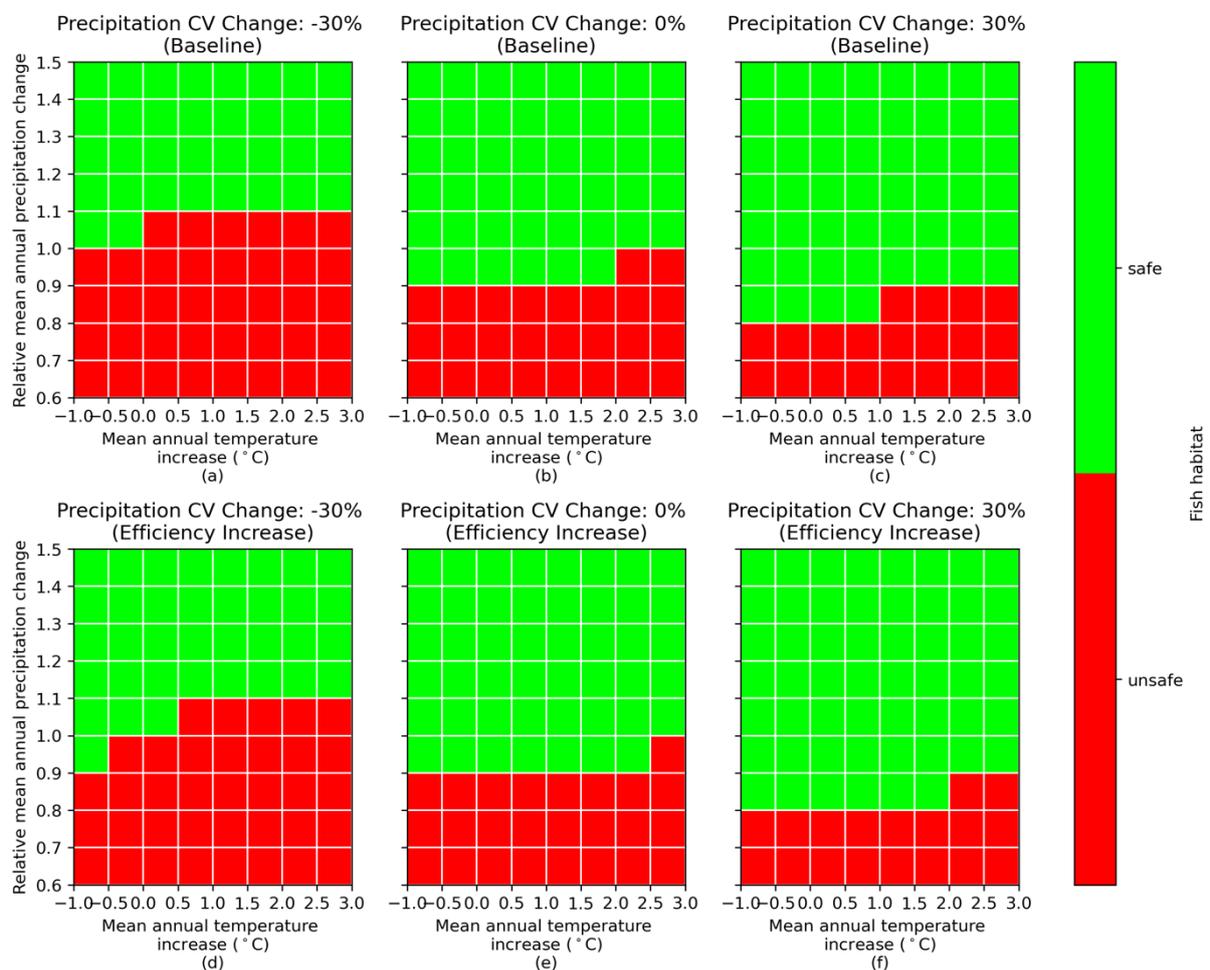

Figure 19 Assessment of the fish habitat indicator across various future scenarios, comparing the results with and without efficiency improvements from the baseline case. Subplots (a), (b), and (c) depict the assessment under scenarios where the change in precipitation coefficient of variances relative to historical conditions is -30%, 0%, and 30%, respectively (derived from Figure 17 by consolidating the performance for scenarios falling within the same specified intervals). Subplots (d), (e), and (f) illustrate the performance with the incorporation of efficiency enhancements.

4.5.3 Multi-dimensional SOS evaluation

The SOS-Water aims to generate a comprehensive, multi-dimensional SOS evaluation that captures the performance of the entire water system across various indicators, both in the current state and in co-developed future scenarios, considering diverse local management pathways. This extensive evaluation allows decision-makers and stakeholders to assess the system's safety concerning specific indicators, given distinct scenarios and the implementation of particular pathways. **Figure 20** gives as an illustrative example of the multi-dimensional SOS evaluation, offering a glimpse into the system's performance under different conditions. Given the preliminary nature of this analysis, a limited number of examples have been included in each dimension (i.e., indicators, pathways, scenarios) to showcase the multi-dimensional SOS results.

It is important to acknowledge the existence of visualization challenges when presenting multi-dimensional SOS. As the number of elements in each dimension (such as indicators, pathways, and scenarios) increases, there arises a difficulty in effectively visualizing and communicating the multi-dimensional SOS with decision makers or stakeholders. In **Figure 20**, for instance, identifying specific scenarios becomes challenging due to the growing number of elements. This challenge is expected to intensify in the future as more indicators and pathways are considered in the SOS analysis.

To address this issue, careful consideration must be given to the aggregation of indicators, scenarios, and pathways, or alternatively, the selection of representative elements. This strategic approach is essential to prevent the final multi-dimensional SOS from becoming overly intricate and challenging for stakeholders and decision-makers to visualize and comprehend. Striking the right balance in complexity is crucial for facilitating effective communication of the multi-dimensional SOS results with stakeholders and decision-makers. **Figure 21**and **Figure 22** give examples of the aggregation in terms of scenarios. **Figure 21** shows the assessment of Net Benefit and Fish habitat indicators across a spectrum of mean annual precipitation change. For each mean annual precipitation change scenario, the safety assessment is based on the indicator value averaged from multiple simulation results, accounting for variations in mean annual temperature ranging from -0.5 °C to 2.5 °C above historical conditions and precipitation variation range from −30% to 30%. In **Figure 22**, the outcomes are presented when the 105 scenarios are aggregated based on mean annual temperature change. This aggregation of scenarios in specific climate variables provides insights into how the system performs in response to changes in that variable. This approach enables us to draw more concise and summative conclusions from the multi-dimensional SOS, enhancing our understanding of system dynamics. Although we highlight these challenges, it is not our goal to address these challenges in this report. The aggregation of indicators and visualization of multi-dimensional SOS will be explored in another task of the project.
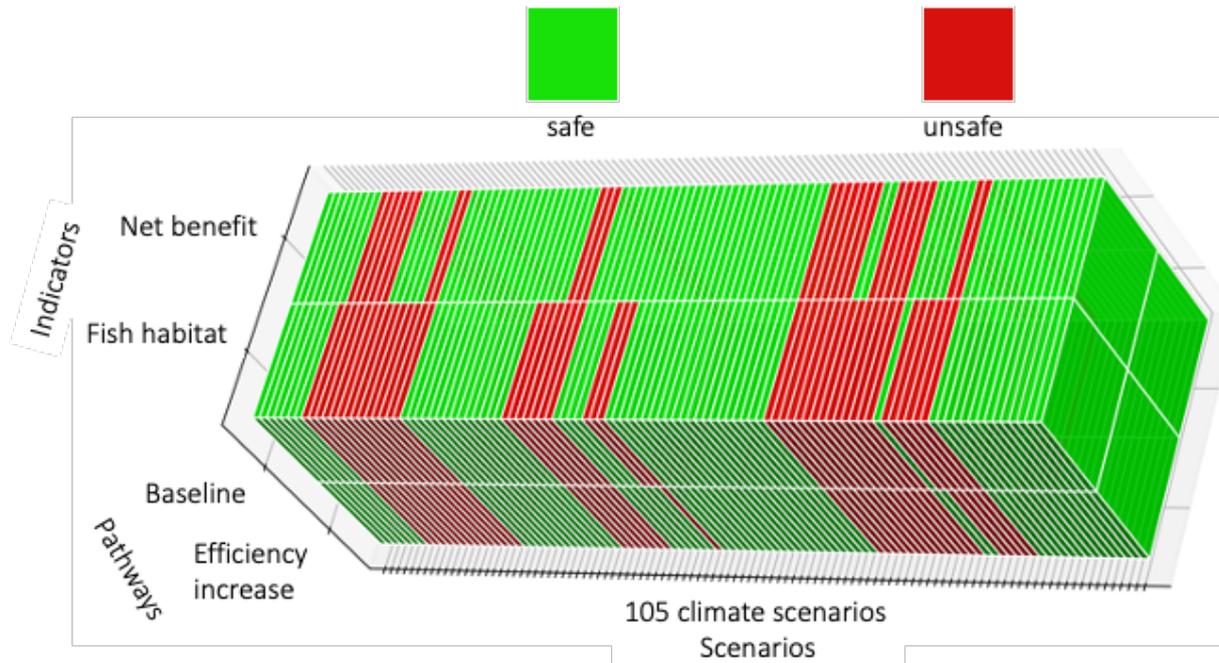
Figure 20 The multi-dimensional SOS evaluation, representing safety assessments for different scenarios (105 climate scenarios as discussed in Section 4.2) and pathways (i.e., Baseline and with the implementation of efficiency increase) across multiple indicator dimensions (i.e., Net benefit and Fish habitat).
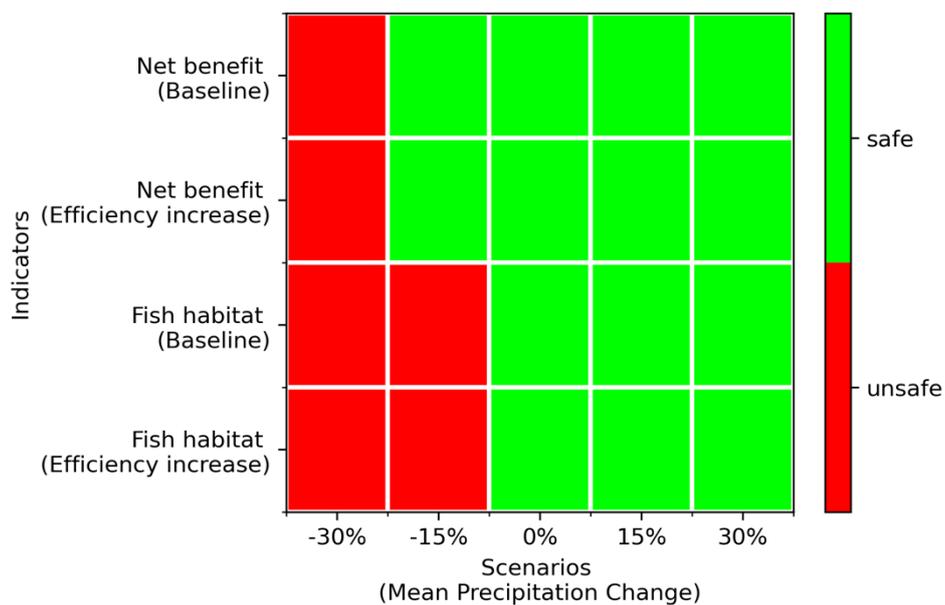

Figure 21 Assessment of net benefit and fish habitat indicators across a spectrum of mean annual precipitation change, ranging from -30% to 30% change of historical mean annual precipitation, both in baseline condition and with the implementation of efficiency increase. For each scenario, the safety assessment is based on the indicator value averaged from multiple simulation results, accounting for variations in mean annual temperature ranging from -0.5 °C to 2.5 °C above historical conditions and precipitation variation range from −30% to 30%.
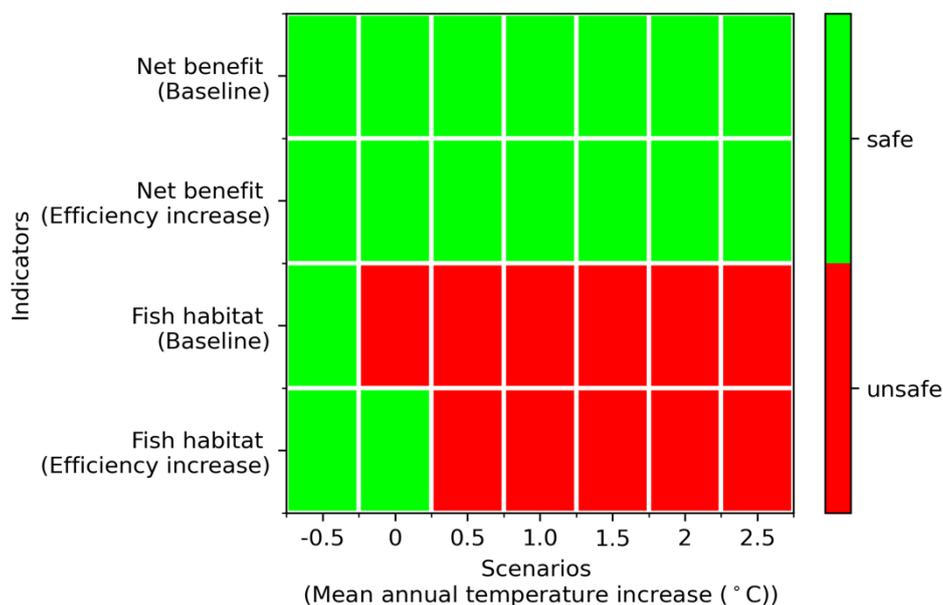
Figure 22 Assessment of net benefit and fish habitat indicators across a spectrum of mean annual temperature change, ranging from -0.5 ℃ to 2.5 ℃ increase of historical mean annual temperature, both in baseline condition and with the implementation of efficiency increase. For each scenario, the safety assessment is based on the indicator value averaged from multiple simulation results, accounting for variations in mean annual precipitation and precipitation variation ranging from -30% to 30% change of historical conditions.

Conclusions

This deliverable presents the established SOS-Water evaluation framework and provides preliminary results from its application in the Jucar River basin case study (Spain).

The framework unfolds in three stages: the first stage focuses on assessing the current condition using indicators and thresholds identified for all natural and socio-economic processes. The second stage evaluates the SOS under co-developed future scenarios using simulations from integrated water modelling system. The last stage investigates SOS changes through the implementation of developed local management pathways. The SOS evaluation requires multiple components that are developed in other WPs: 1) indicators and thresholds (in WP4), 2) co-developed future scenarios (in WP1), 3) local management pathways (in WP1), and 4) integrated water modelling system (IWMS, in WP2). Ultimately, the SOS-Water framework yields a multiple-dimensional SOS that encapsulates the performance of the entire water system under both status quo and co-developed future scenarios, along with different local management pathways.

This report provides an overview of all the case studies in the SOS-Water project, including details on general case study information, stakeholder lists and urgent water challenges that are crucial for the SOS-evaluation process. We use Jucar as an example to demonstrate the SOS-evaluation framework. For the preliminary SOS evaluation in Jucar case study, two indicators were included: the net benefit

(hydropower benefit and agricultural benefit) and fish habitat. The system's performance was assessed under 105 designed climate scenarios, and the impact of implementing efficiency enhancements within the agricultural demand zone of the basin was evaluated. The preliminary result indicates that climate conditions (such as the mean annual precipitation, precipitation variability, and mean annual temperature) have a significant impact on the system's performance on net benefit and fish habitat. Specifically, the increase of the mean annual precipitation and the precipitation variability enhance net benefit and fish habitat performance. Conversely, an increase of mean annual temperature can hurt net benefit and fish habitat performance. The implementation of efficiency enhancements proves effective in restoring net benefit and fish habitat performance under certain future scenarios. More indicators, pathways, and future scenarios will be considered in the final SOS evolution.

The framework introduced in this report will be applied for all case studies for a comprehensive SOS evaluation, the final evaluation results will be included in D5.2 (Final Evaluation of Safe Operating Space) and D5.5 (Synthesis of Safe Operating Space). In addition, our preliminary analysis of the multi-dimensional SOS evaluation also underscores challenges in aggregating scenarios and indicators, as well as visualizing the multi-dimensional SOS. Indicator aggregation will be conducted in T4.3 of WP4 and the visualization of multi-dimensional SOS will be investigated in T5.2 of WP5.

Bibliography

Brown, C., Ghile, Y., Laverty, M., & Li, K. (2012). Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. Water Resources Research, 48(9). https://doi.org/10.1029/2011WR011212

Bai, J., Guan, Y., Liu, P., Zhang, L., Cui, B., Li, X., & Liu, X. (2020). Assessing the safe operating space of aquatic macrophyte biomass to control the terrestrialisation of a grass-type shallow lake in China. *Journal of Environmental Management*, *266*(February), 110479. https://doi.org/10.1016/j.jenvman.2020.110479

Bhave, A. G., Mishra, A., & Raghuwanshi, N. S. (2013). A combined bottom-up and top-down approach for assessment of climate change adaptation options. *Journal of Hydrology*, *518*(PA), 150–161. https://doi.org/10.1016/j.jhydrol.2013.08.039

Burek, P., Satoh, Y., Kahil, T., Tang, T., Greve, P., Smilovic, M., Guillaumot, L., Zhao, F., & Wada, Y. (2020). Development of the Community Water Model (CWatM v1.04) - A high-resolution hydrological model for global and regional assessment of integrated water resources management. *Geoscientific Model Development*, *13*(7), 3267–3298. https://doi.org/10.5194/gmd-13-3267-2020

Carpenter, S. R., Brock, W. A., Hansen, G. J. A., Hansen, J. F., Hennessy, J. M., Isermann, D. A., Pedersen, E. J., Perales, K. M., Rypel, A. L., Sass, G. G., Tunney, T. D., & Vander Zanden, M. J. (2017). Defining a Safe Operating Space for inland recreational fisheries. *Fish and Fisheries*, *18*(6), 1150–1160. https://doi.org/10.1111/faf.12230

CHJ. (2023). Plan hidrológico cuenca. Ciclo 2022-2027. Confederación Hidrográfica del Júcar. https://www.chj.es/es-es/medioambiente/planificacionhidrologica/Paginas/PHC-2022-2027-Plan-Hidrologico-cuenca.aspx

De Fraiture, C., Molden, D., Amarasinghe, U., & Makin, I. (2001). PODIUM: Projecting water supply and demand for food production in 2025. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, *26*(11), 869–876. https://doi.org/https://doi.org/10.1016/S1464-1909(01)00099-5

Dearing, J. A., Wang, R., Zhang, K., Dyke, J. G., Haberl, H., Hossain, M. S., Langdon, P. G., Lenton, T. M., Raworth, K., Brown, S., Carstensen, J., Cole, M. J., Cornell, S. E., Dawson, T. P., Doncaster, C. P., Eigenbrod, F., Flörke, M., Jeffers, E., Mackay, A. W., … Poppy, G. M. (2014). Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, *28*(1), 227–238. https://doi.org/10.1016/j.gloenvcha.2014.06.012

Fanning, A. L., & O'Neill, D. W. (2016). Tracking resource use relative to planetary boundaries in a steady-state framework: A case study of Canada and Spain. *Ecological Indicators*, *69*, 836–849. https://doi.org/10.1016/j.ecolind.2016.04.034

FAO (2012) Crop yield response to water. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/i2800e/i2800e.pdf

Gerten, D., Hoff, H., Rockström, J., Jägermeyr, J., Kummu, M., & Pastor, A. V. (2013). Towards a revised planetary boundary for consumptive freshwater use: Role of environmental flow requirements. *Current Opinion in Environmental Sustainability*, *5*(6), 551–558. https://doi.org/10.1016/j.cosust.2013.11.001

Girard, C., Pulido-Velazquez, M., Rinaudo, J. D., Pagé, C., & Caballero, Y. (2015). Integrating top-down and bottom-up approaches to design global change adaptation at the river basin scale. *Global Environmental Change*, *34*, 132–146. https://doi.org/10.1016/j.gloenvcha.2015.07.002

Gleeson, T., Wang-Erlandsson, L., Zipper, S. C., Porkka, M., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S. E., Piemontese, L., Gordon, L. J., Rockström, J., Oki, T., Sivapalan, M., Wada, Y., Brauman, K. A., Flörke, M., Bierkens, M. F. P., Lehner, B., Keys, P., … Famiglietti, J. S. (2020). The Water Planetary Boundary: Interrogation and Revision. In *One Earth* (Vol. 2, Issue 3, pp. 223–234). Cell Press. https://doi.org/10.1016/j.oneear.2020.02.009

Gupta, J., Liverman, D., Prodani, K., Aldunce, P., Bai, X., Broadgate, W., Ciobanu, D., Gifford, L., Gordon, C., Hurlbert, M., Inoue, C. Y. A., Jacobson, L., Kanie, N., Lade, S. J., Lenton, T. M., Obura, D., Okereke, C., Otto, I. M., Pereira, L., … Verburg, P. H. (2023). Earth system justice needed to identify and live within Earth system boundaries. *Nature Sustainability*, *6*(6), 630–638. https://doi.org/10.1038/s41893-023-01064-1

Haasnoot, M., Middelkoop, H., Offermans, A., van Beek, E., & van Deursen, W. P. A. (2012). Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change*, *115*(3–4), 795–819. https://doi.org/10.1007/s10584-012-0444-2

Heistermann, M. (2017). HESS Opinions: A planetary boundary on freshwater use is misleading. *Hydrology and Earth System Sciences*, *21*(7), 3455–3461. https://doi.org/10.5194/hess-21-3455-2017

Hoef, J. M. Ver, Peterson, E. E., Clifford, D., & Shah, R. (2014). on Stream Networks. *Submitted to Journal of …, 56*(3). ftp://sunsite2.icm.edu.pl/packages/cran/web/packages/SSN/vignettes/SSN.pdf%0Apapers3://publication/uuid/EEF33D01-D2EF-4967-99B7-C3ADF58B4183

IPCC. (2013). *IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)].*

IPCC. (2021). *IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157896

Kahil, M. T., Ward, F. A., Albiac, J., Eggleston, J., & Sanz, D. (2016). Hydro-economic modeling with aquifer–river interactions to guide sustainable basin management. Journal of Hydrology, 539, 510–524.

Liu, J., Chen, D., Mao, G., Irannezhad, M., & Pokhrel, Y. (2022). Past and future changes in climate and water resources in the lancang–mekong River Basin: Current understanding and future research directions. *Engineering*, *13*, 144-152.

Long, D., Yang, W., Scanlon, B. R., Zhao, J., Liu, D., Burek, P., ... & Wada, Y. (2020). South-to-North Water Diversion stabilizing Beijing's groundwater levels. *Nature Communications*, *11*(1), 3665.

Macian-Sorribes, H., Tilmant, A., & Pulido-Velazquez, M. (2017). Improving operating policies of large-scale surface-groundwater systems through stochastic programming. *Water Resources Research*, *53*(2), 1407–1423. https://doi.org/10.1002/2016WR019573

Macian-Sorribes, H., Tilmant, A., & Pulido-Velazquez, M. (2017). Improving operating policies of large-scale surface-groundwater systems through stochastic programming. Water Resources Research, 53(2), 1407–1423.

Mastrandrea, M. D., Heller, N. E., Root, T. L., & Schneider, S. H. (2010). Bridging the gap: Linking climate-impacts research with adaptation planning and management. *Climatic Change*, *100*(1), 87–101. https://doi.org/10.1007/s10584-010-9827-4

Moser, A., Wemyss, D., Scheidegger, R., Fenicia, F., Honti, M., & Stamm, C. (2018). Modelling biocide and herbicide concentrations in catchments of the Rhine basin. *Hydrology and Earth System Sciences*, *22*(8), 4229–4249. https://doi.org/10.5194/hess-22-4229-2018

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., & Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. In *Nature* (Vol. 463, Issue 7282, pp. 747–756). https://doi.org/10.1038/nature08823

Nilsson, A. E., Bay-Larsen, I., Carlsen, H., van Oort, B., Bjørkan, M., Jylhä, K., Klyuchnikova, E., Masloboev, V., & van der Watt, L. M. (2017). Towards extended shared socio-economic pathways: A combined participatory bottom-up and top-down methodology with results from the Barents region. *Global Environmental Change*, *45*, 124–132. https://doi.org/10.1016/j.gloenvcha.2017.06.001

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W. (2017). The roads ahead: Narratives for shared socio-economic pathways describing world futures in the 21st century. *Global Environmental Change*, *42*, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Ofir, E., Silver, T., Steenbeek, J. G., Shachar, N., & Gal, G. (2023). Applying the Safe Operating Space (SOS) Approach to Sustainable Commercial Fishing under Varying Lake Levels and Littoral Zone Conditions. *Fisheries*, *48*(3), 107–120. https://doi.org/10.1002/fsh.10869

Pastor, A. V., Ludwig, F., Biemans, H., Hoff, H., & Kabat, P. (2014). Accounting for environmental flow requirements in global water assessments. *Hydrology and earth system sciences*, *18*(12), 5041-5059.

Pereira-Cardenal, S. J., Madsen, H., Arnbjerg-Nielsen, K., Riegels, N., Jensen, R., Mo, B., Wangensteen, I., & Bauer-Gottwein, P. (2014). Assessing climate change impacts on the Iberian power system using a coupled water-power model. Climatic Change, 126(3–4), 351–364.

Phong, N. D., Hoanh, C. T., Tuong, T. P., Malano, H., & Weaver, T. (n.d.). *Modelling Acidity Propagation in a Coastal Zone with Acid Sulphate Soils*.

Pilli-Sihvola, K., van Oort, B., Hanssen-Bauer, I., Ollikainen, M., Rummukainen, M., & Tuomenvirta, H. (2015). Communication and use of climate scenarios for climate change adaptation in Finland, Sweden and Norway. *Local Environment*, *20*(4), 510–524. https://doi.org/10.1080/13549839.2014.967757

Pulido-Velazquez, M. A., Sahuquillo-Herraiz, A., Camilo Ochoa-Rivera, J., & Pulido-Velazquez, D. (2005). Modeling of stream–aquifer interaction: the embedded multireservoir model. Journal of Hydrology, 313(3–4), 166–181.

Pulido-Velázquez, M., Andreu, J., & Sahuquillo, A. (2006). Economic Optimization of Conjunctive Use of Surface Water and Groundwater at the Basin Scale. Journal of Water Resources Planning and Management, 132(6), 454–467.

Ray, P. & Brown, C. (2015) Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework. Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/516801467986326382/Confronting-climate-uncertainty-in-water-resources-planning-and-project-design-the-decision-tree-framework

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., KC, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The Shared Socio-economic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., Von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., … Rockström, J. (2023). *Earth beyond six of nine planetary boundaries*. https://www.science.org

Rockström, J., Gupta, J., Qin, D., Lade, S. J., Abrams, J. F., Andersen, L. S., Armstrong McKay, D. I., Bai, X., Bala, G., Bunn, S. E., Ciobanu, D., DeClerck, F., Ebi, K., Gifford, L., Gordon, C., Hasan, S., Kanie, N., Lenton, T. M., Loriani, S., … Zhang, X. (2023). Safe and just Earth system boundaries. *Nature*, *619*(7968), 102–111. https://doi.org/10.1038/s41586-023-06083-8

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., De Wit, C. A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. A. (2009). A safe operating space for humanity. *Nature*, *461*(7263), 472–475. https://doi.org/10.1038/461472a

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin,

S., Snyder, P. K., Costanza, R., Svedin, U., … Foley, J. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2). https://doi.org/10.5751/ES-03180-140232

Schmitt, R. J. P., Bizzi, S., Castelletti, A., & Kondolf, G. M. (2018). Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong. *Nature Sustainability*, *February*. https://doi.org/10.1038/s41893-018-0022-3

Schmitt, R. J. P., Bizzi, S., Castelletti, A., Opperman, J. J., & Kondolf, G. M. (2019). Planning dam portfolios for low sediment trapping shows limits for sustainable hydropower in the Mekong. *Science Advances*, *5*(10). https://doi.org/10.1126/sciadv.aaw2175

Smakhtin, V., Revenga, C., & Döll, P. (2004). A pilot global assessment of environmental water requirements and scarcity. *Water international*, *29*(3), 307-317.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223). https://doi.org/10.1126/science.1259855

Sutanudjaja, E. H., Van Beek, R., Wanders, N., Wada, Y., Bosmans, J. H. C., Drost, N., Van Der Ent, R. J., De Graaf, I. E. M., Hoch, J. M., De Jong, K., Karssenberg, D., López López, P., Peßenteiner, S., Schmitz, O., Straatsma, M. W., Vannametee, E., Wisser, D., & Bierkens, M. F. P. (2018). PCR-GLOBWB 2: A 5 arcmin global hydrological and water resources model. *Geoscientific Model Development*, *11*(6), 2429–2453. https://doi.org/10.5194/gmd-11-2429-2018

Swart, R., Biesbroek, R., & Lourenço, T. C. (2014). Science of adaptation to climate change and science for adaptation. In *Frontiers in Environmental Science* (Vol. 2, Issue JUL). Frontiers Media S.A. https://doi.org/10.3389/fenvs.2014.00029

Szabó, Z., Buczkó, K., Haliuc, A., Pál, I., L. Korponai, J., Begy, R. C., Veres, D., Luoto, T. P., Zsigmond, A. R., & Magyari, E. K. (2020). Ecosystem shift of a mountain lake under climate and human pressure: A move out from the safe operating space. *Science of the Total Environment*, *743*, 1–17. https://doi.org/10.1016/j.scitotenv.2020.140584

Tangi, M., Schmitt, R., Bizzi, S., & Castelletti, A. (2019). The CASCADE toolbox for analysing river sediment connectivity and management. *Environmental Modelling and Software*, *119*(April), 400–406. https://doi.org/10.1016/j.envsoft.2019.07.008

Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. In *Bulletin of the American Meteorological Society* (Vol. 93, Issue 4, pp. 485–498). https://doi.org/10.1175/BAMS-D-11-00094.1

Teah, H. Y., Akiyama, T., Carlos, R. S., Rayo, O. V., Khew, Y. T. J., Zhao, S., Zheng, L., & Onuki, M. (2016). Assessment of downscaling planetary boundaries to semi-arid ecosystems with a local perception: A case study in the middle reaches of Heihe River. *Sustainability (Switzerland)*, *8*(12), 1–11. https://doi.org/10.3390/su8121233

Témez, J. R. (1977). Modelo Matemático de transformación "precipitación-escorrentía". Asociación de Investigación Industrial Eléctrica. ASINEL. Madrid 39 pp.

Tennant, D. L. (1976). Instream flow regimens for fish, wildlife, recreation and related environmental resources. *Fisheries*, *1*(4), 6-10.

Tessmann, S. (1980). Environmental assessment, technical appendix E in environmental use sector reconnaissance elements of the Western Dakotas region of South Dakota study. *Water resources research institute, South dakota state university, Brookings, SD*.

van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J. F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1), 5–31. https://doi.org/10.1007/s10584-011-0148-z

Wilby, R. L., & Dessai, S. (2010). Robust adaptation to climate change. *Weather*, *65*(7), 180–185. https://doi.org/10.1002/wea.504

Zipper, S. C., Jaramillo, F., Wang-Erlandsson, L., Cornell, S. E., Gleeson, T., Porkka, M., Häyhä, T., Crépin, A. S., Fetzer, I., Gerten, D., Hoff, H., Matthews, N., Ricaurte-Villota, C., Kummu, M., Wada, Y., & Gordon, L. (2020). Integrating the Water Planetary Boundary With Water Management From Local to Global Scales. *Earth's Future*, *8*(2). https://doi.org/10.1029/2019EF001377

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