



STARS 4 Water

Synthesis report for guidance to river basin management practitioners on STARS4Water data and model innovations

Deliverable: D5.4

September 2026

Synthesis report for guidance to river basin management practitioners on STARS4Water data and model innovations

Work Package	5: Upscale and uptake for preparedness
Due date	September 2026 (Month 48)
Submission date	September 2026
Lead beneficiary	Deltares
Lead author(s)	Judith ter Maat
Contributions from (alphabetic order)	Aguilera, H., Avila, L., Duel, H., Graf, T., Glas, M., Baron, H., Collignan, J., De la Hera-Portillo, A., Hegdahl, T. J., Hisdal, H., Keller, V., Kossida, M., Fotopoulos, F., Laize, C., Martínez-Santos, P., Miaari, S., Ramos, M.-H., Rickards, N.

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

Version log			
Version	Date	Released by	Nature of Change
0.0	08.04.2026	Judith ter Maat	Outline and raw material for input
0.1	16.06.2026	Judith ter Maat	First version for review and contributions from partners
0.2	10.07.2026	Judith ter Maat	Partner contributions added
0.3	13.07.2026	Judith ter Maat	Updated version for review and contributions from partners
0.6	15.07.2026	Judith ter Maat	Feedback from review incorporated
0.8	21.09.2026	Judith ter Maat	Final draft version for review
0.9	23.09.2026	Judith ter Maat	Feedback from review incorporated
1.0	30.09.2026	Harm Duel	Final version accepted

Citation

Ter Maat, G.J. et al. (2026): Synthesis report for guidance to river basin management practitioners on new STARS4Water data and model innovations - Deliverable 5.4 (D5.4). Horizon Europe project STARS4Water. Grant Agreement No 101059372.



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

Disclaimer

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

Summary

This report presents an overview of the novel data services, next generation modelling instruments and new co-created decision-support and communication tools developed and delivered within the STARS4Water project. It also provides guidance on the selection and application of such data and modelling tools and further uptake, discussing key takeaways and lessons learned from the project. The synthesis at the start of the report captures the conceptual pathway from STARS4Water - from innovations to sustainable uptake – highlighting important principles that have emerged during the co-design, development and application process of data and tools in STARS4Water.

STARS4Water did not develop a single unified modelling framework across all river basins. Instead, existing models were improved, integrated, and complemented with new data services and data-driven models, creating the new generation modelling framework tailored for each river basin. The collected and derived new global to local data sets are stored in Zenodo archive and the Metadata portal. Scenarios are presented in stakeholder-oriented dashboards and in Story Maps.

These developments respond directly to stakeholder needs to better understand and project current and future water system behaviour and water availability and use, while using both proven and new data technologies. Results support informed decision-making on river basin management and planning in an operational manner for river basin practitioners and stakeholders due to the co-creation approach and stakeholders needs-driven way of working in the project.

The document is meant for stakeholders in the 7 river basins hubs of the project in Europe, viz. Danube, Drammen, Duero, East Anglia, Messara, Rhine, and Seine. But, also beyond these STARS4Water basins, for river basin management practitioners that work on water resources availability planning and operations addressing the main stakeholder's concerns in their river basin: water for water supply, agriculture, hydropower, navigation, ecological flows, as well as risks for low flows, drought extremes and water scarcity, and water reservoir filling/release conditions.

Table of contents

Summary	ii
1. Introduction	1
1.1. STARS4Water project	1
1.2. Uptake and upscale	2
1.3. Guidance to practitioners on data services, modelling and decision support tools	3
1.4. This report	3
2. Synthesis - from innovation outputs to sustainable uptake	5
2.1. Introduction	5
2.2. The STARS4Water conceptual pathway	5
2.3. Sustainable uptake of STARS4Water innovation outputs	7
3. STARS4Water key advancements	10
3.1. Introduction	10
3.2. A summary of the key advancements in all STARS4Water river basin hubs	10
3.3. Key advancements in the Drammen basin	11
3.4. Key advancements in the Danube basin	12
3.5. Key advancements in the Duero basin	13
3.6. Key advancements in the East Anglia basin	14
3.7. Key advancements in the Messara basin	15
3.8. Key advancements in the Rhine basin	15
3.9. Key advancements in the Seine basin	16
4. Novel data services for river basin management	18
4.1. Introduction	18
4.2. Metadata Portal	18
4.3. Derived datasets based on global data and tier 1 indicators	19
4.4. Derived water demand projection datasets based on global and regional data and tier 2 indicators	20
4.5. Derived water availability projection datasets based on tier 3 indicators	21
4.6. Key takeaways on data services	22
5. Next generation modelling frameworks – part 1: process-based and integrating hydrological, water allocation, reservoir and environmental flow models	23
5.1. Introduction	23
5.2. Improved models for better understanding of (geo-)hydrological processes in the basins	24
5.3. Improved models for better understanding of water allocation in the basins	28
5.4. Key takeaways on integrated modelling frameworks	30

6.	Next generation modelling framework - part 2: Innovative data-driven modelling tools and machine learning applications	31
6.1.	Introducing ML models for better understanding of (geo-)hydrology and water use in river basins	31
6.2.	ML snow water equivalent	32
6.3.	DL water table depth	32
6.4.	ML predictive mapping of groundwater quality	33
6.5.	ML groundwater storage changes	34
6.6.	RF-LSTM Groundwater Monitoring model	34
6.7.	ML water table depth prediction and uncertainty quantification	35
6.8.	RF reservoir storage modelling	35
6.9.	ML irrigated agricultural area and demand	36
6.10.	Key takeaways on data-driven modelling and machine learning	37
7.	New co-created decision support and communication tools	38
7.1.	Introduction	38
7.2.	Impact Reporter Tool	38
7.3.	Story Maps Tool	39
7.4.	STARS4Water's river basins generic dashboard	40
7.5.	River basin tailored dashboard – the Drammen case	41
7.6.	Key takeaways	41
8.	Guidance on selecting data services and modelling approaches	43
8.1.	Introduction	43
8.2.	Detailed overview of delivered modelling frameworks in the 7 river basins	43
8.3.	Some reflections on the delivered frameworks, their applicability and conditions for use	44
8.4.	Support for selecting suitable modelling approaches	45
8.5.	Crosscutting lessons for uptake, transferability and long-term sustainability	47
8.6.	Conclusions	48
	References	50
	ANNEX A - Danube river basin – Integrated water resources management modelling framework	53
	ANNEX B – Drammen river basin – Integrated modelling framework	59
	ANNEX C – Duero river basin – Groundwater modelling framework	62
	ANNEX D – East Anglia river basin – Environmental flow modelling framework	64
	ANNEX E – Messina river basin – Integrated water resources management modelling framework ...	67
	ANNEX F – Rhine river basin – Integrated water resources management modelling framework	73
	ANNEX G – Seine river basin – Hydrological and reservoir modelling framework	79

1. Introduction

1.1. STARS4Water project

STARS4Water (Supporting Stakeholders for Adaptive, Resilient and Sustainable Water Management) is a four-year Horizon Europe research project that contributes to the implementation of the European Water Resilience Strategy and broader EU water policies. The project seeks to improve understanding of how climate change affects water resources and related vulnerabilities across ecosystems, communities, and economic sectors at the river basin scale. To ensure that project outcomes respond to real-world needs, STARS4Water applies a stakeholder-driven co-creation approach. Working closely with river basin organisations and other key actors in seven European river basins, namely the Rhine, Danube, Messara (Crete), Duero, Seine, East Anglia, and Drammen (Norway) (Figure 1), the project co-designs data services, assessment methods, and decision-support tools tailored to stakeholder requirements. Central to this approach is the establishment of dedicated stakeholder communities within each river basin. These communities provide a platform for dialogue, knowledge exchange, and collaborative development, ensuring that STARS4Water solutions are relevant, usable, and capable of supporting climate-resilient and sustainable water management. STARS4Water integrates new datasets and models into their existing river basin management planning processes, improving projections and decision-making for more resilient water policies.

The ambitions of STARS4Water are:

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

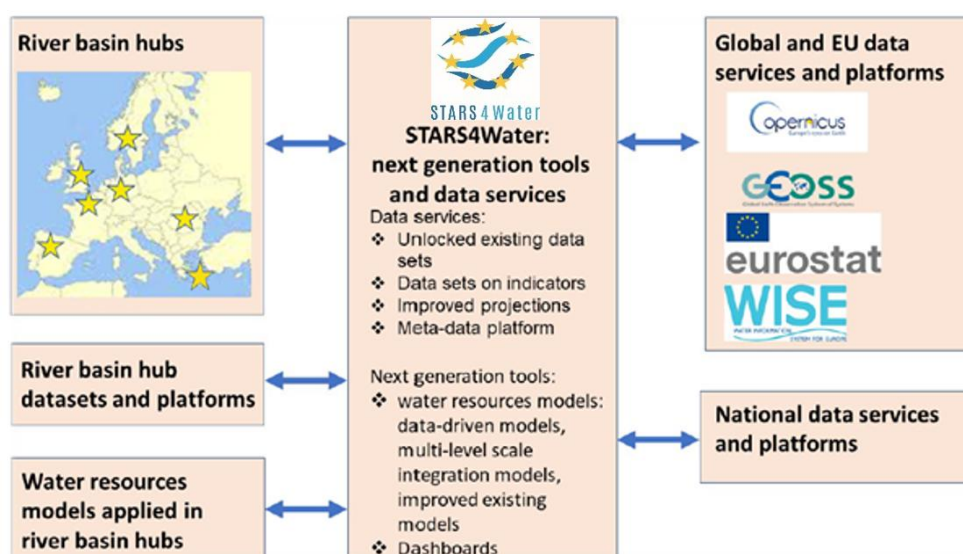


Figure 1. Overview of STARS4Water activities within the context of stakeholders and data providers.

1.2. Uptake and upscale

This report is specifically associated with Work package 5 (WP5) of the STARS4Water project. WP5 focuses on maximizing the uptake and scaling of data services, tools, and approaches that support the assessment of future water resources and flow regimes. Its objective is to strengthen preparedness and support climate-resilient water resources management across Europe and beyond. Figure 2 illustrates the role of WP5 within the overall STARS4Water framework.

WP5 builds on the outcomes of the other project work packages of the project. Its activities are guided by the stakeholder co-design process undertaken in WP1, draw on the data services developed in WP2 and the modelling innovations developed in WP3, and are informed by the integrated assessments of future water resources conducted in the river basin hubs under WP4. Together, these components provide the knowledge base needed to support the wider adoption and application of STARS4Water solutions.

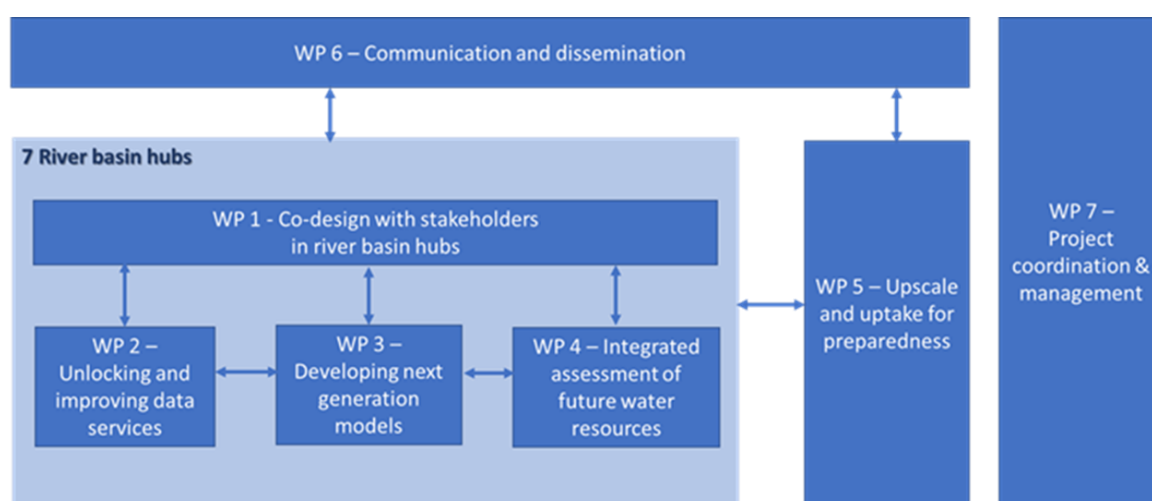


Figure 2. Work package structure of the STARS4Water project: the development of the next generation models (WP3) through a co-creation approach (WP1), benefitting from data sources available (WP2) and integrated Safe-Operating-Space assessments activities in WP4 to explore future water resources availability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

WP5 consists of the following tasks:

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

This report presents the results of task 5.3.

1.3. Guidance to practitioners on data services, modelling and decision support tools

This report consolidates and synthesises the key achievements of the project to support the development, uptake and scaling of water availability projections for water resources management within the STARS4Water river basin hubs and beyond.

It presents the data services, modelling frameworks, decision-support tools, and communication instruments that were developed or enhanced and used during the project, together with guidance for their future application. For stakeholders in the STARS4Water hubs, the report documents the modelling frameworks and tools now available for assessing water availability and climate change impacts. For practitioners in other river basins, it captures lessons learned on selecting appropriate datasets, models, and approaches for different management contexts. Rather than providing technical guidance on model operation, the report focuses on helping users identify suitable tools and inspiring approaches based on practical experiences gained across the seven river basin hubs.

The report highlights the key data services delivered through Work Package 2 and the modelling and decision-support frameworks developed in Work Package 1, 3 and 6 and applied in Work Package 4 to generate water resources availability projections and assess Safe-Operating-Spaces (SOS) within the selected river basins (Ramos, 2026). It describes their main characteristics, applications, findings, opportunities, limitations, and implications for water resources management in an accessible manner, while detailed basin-specific information is provided in the Annexes.

Complementary a synthesis of STARS4Water approach and outcomes are reported in Deliverable 5.2, Guidance to practitioners to river basin management practitioners (Duel et al., 2026). That report introduces the STARS4Water guiding principles for building water resilience at river basin level and presents the key findings from stakeholder engagement activities conducted across the project's river basin hubs.

1.4. This report

This report is structured as follows:

- **Chapter 2 – From STARS4Water innovation to sustainable uptake.** This chapter is a synthesis of the journey in STARS4Water and presents the key lessons and insights from the STARS4Water data and tool development and delivering process, highlighting important principles that have emerged during the co-design, development and application process of STARS4Water.
- **Chapter 3 – STARS4Water key advancements.** This chapter summarizes the main innovations in data services, modelling frameworks, data-driven models, and decision-support tools developed across the seven river basin hubs, after introducing the stakeholders' needs first. It provides an overview per river basin hub.
- **Chapter 4 – Novel data services for river basin management.** This chapter presents the metadata portal and new datasets developed within STARS4Water. For each data service, it describes its purpose, key functionalities, and contribution to river basin management. At the end it discusses key takeaways based on experiences, insights and lessons learned from project implementation.

- **Chapter 5 – Next generation modelling frameworks – part 1: process-based and integrating hydrological, water allocation, reservoir and environmental flow models.** This chapter provides an overview of the building blocks delivered and enhanced in the seven river basin hubs and integrated in their next generation integrated modelling framework, simulating river basin processes and management scenarios. These building blocks are process-based hydrological models, water allocation models, reservoir models and environmental flow models. In some river basins these models were combined with machine learning technologies (see next chapter). Key takeaways based on experiences, insights and lessons learned from STARS4Water are also discussed. The integrated modelling frameworks per river basin are describe in the Annexes A-G.
- **Chapter 6 – Next generation modelling framework - part 2: Innovative data-driven modelling tools and machine learning applications.** This chapter presents the innovative data-driven modelling approaches explored in STARS4Water. It describes the machine learning models developed and tested, their potential applications for river basin management, and the key takeaways identified during their development, testing and application. Some of these applications are applied at the European level, while others became part of the next generation modelling framework of the river basins.
- **Chapter 7 – New co-created decision support and communication tools.** This chapter describes the solutions developed in the project to stimulate further use and uptake of modelling results and support informed decision making. These tools include co-designed dashboards, both generic and basin-specific versions, and Story Maps. It highlights their contribution to stakeholder engagement, communication, visualisation and decision-making, and discusses key takeaways.
- **Chapter 8 – Guidance on selecting data services and modelling approaches.** This chapter synthesizes the experiences gained throughout STARS4Water on the tools and provides guidance for selecting and applying modelling frameworks, including data sets and data-driven tools. The guidance is intended to support the river basin stakeholders and the wider community seeking to develop or improve their water resources management and assessment capabilities. The chapter starts with an overview of the improved river basin modelling framework per river basin, consisting of data, process-based and integrated models, data-driven components and/or dashboards; the delivered composition of the workflow or model chain configuring various modules was based on the stakeholders needs, local basin context and data availability.
- **Chapter 9 – References.** This chapter provides the bibliography that underpins this project and/or lists the key references cited throughout the report.
- **Annexes – Modelling framework per STARS4Water river basin.** The annexes provide detailed descriptions of the state-of-the-art integrated modelling frameworks developed and applied in each of the seven STARS4Water river basin hubs based on chains of improved models or new modules/components, datasets and dashboards. These annexes serve as technical reference material for the basin authorities and other interested stakeholders.

2. Synthesis - from innovation outputs to sustainable uptake

2.1. Introduction

This chapter reports a synthesis of the 4-years conceptual pathway in the STARS4Water project by presenting the framework that have emerged during the execution of the project. It captures its pathway and highlights important lessons learned and principles that have emerged during the data services and modelling tools co-design, development and delivering process of STARS4Water. The pathway is summarized in a generalized way to make it relevant for both water management practitioners in the 7 river basin hubs and beyond.

2.2. The STARS4Water conceptual pathway

Figure 3 shows how STARS4Water innovations can progress to sustained use in river basin management. The framework consists of five connected layers, moving from co-creation and stakeholder engagement at the base to adaptive and resilient water management at the top. Each layer builds on the foundations provided by the layer below. Innovations in data services, models and decision-support tools (layer 2, 3 resp. 4) become valuable when they address relevant management questions, are credible and understandable to users (layer 1 and 5), and have ownership and can be maintained within the organisations expected to use them for example better decisions on adaptive and resilient water management and planning. The figure also reports success factors, risks and cross-cutting principles that were identified during the project.

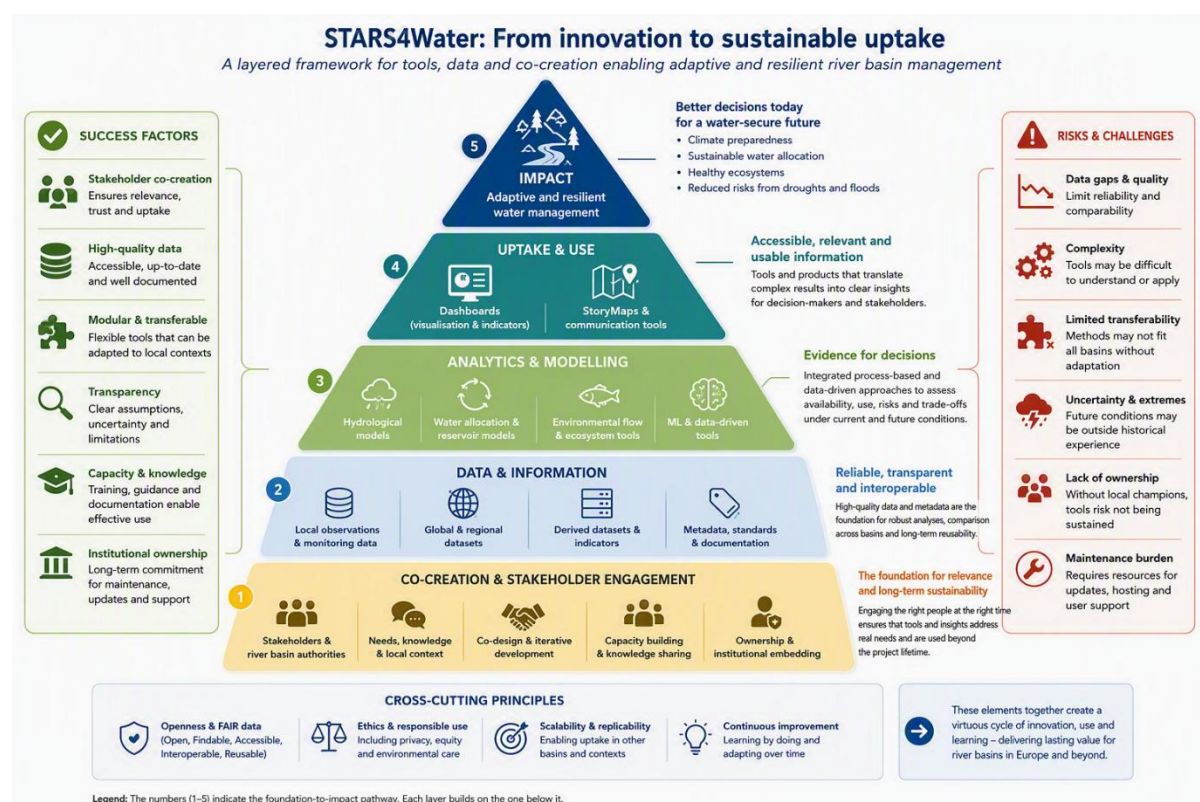


Figure 3. The STARS4Water conceptual pathway - from stakeholder engagement to lasting impact (Hegdahl – design assistance copilot).

Layer 1: Co-creation and stakeholder engagement

The first layer, co-creation and stakeholder engagement, forms the foundation for relevance and long-term sustainability and serves as the starting point for the STARS4Water project. River basin managers and other stakeholders contribute knowledge of local conditions, management priorities and practical constraints and share the water-related decisions that they have to make. Their involvement helps define the issues to be addressed through data and modelling activities and to identify appropriate indicators and scenarios. Co-design and iterative development allow for the assessment, validation and refinement of intermediate results. Capacity building, knowledge sharing and institutional embedding are also part of this stage, because successful uptake depends on whether organisations feel ownership and possess the knowledge, resources and responsibility required to continue using the outputs after the project. STARS4Water confirms that the most usable outputs were those developed through dialogue with basin experts, both river basin commissions and stakeholders (in reservoir operation, water use, etc.), and in response to clearly identified needs. STARS4Water Deliverable 5.2 describes this in greater depth and outlines STARS4Water’s lessons learned in this regard.

Layer 2: Data and information

The second layer concerns data and information. Local observations and monitoring data are combined, where appropriate, with regional and global datasets, derived indicators, metadata, standards and documentation. These different sources play complementary roles. Global and regional datasets can support initial screening, comparison and assessment where local information is limited. Local observations and basin-specific knowledge remain essential for detailed interpretation, validation and calibration and application in operational and strategic water management. Datasets in transboundary river basin context often require aggregation and further harmonisation before it can be applied on the transboundary level. Transparent metadata, clear protocols and formats for data exchange and documentation make datasets easier to find, understand, compare and reuse, while also providing insight into their origin, assumptions and limitations. Layer two is discussed in more detail in Chapter 3 of this report.

Layer 3: Analytics and modelling

The third layer, analytics and modelling, transforms data into evidence-based information for decision-making. The framework includes process-based hydrological models, water allocation and reservoir models and environmental flow tools, and machine-learning and other data-driven approaches. Connecting these models, as modules or components in a model chain or workflow, makes it possible to investigate interactions between natural processes, human water use, infrastructure and ecosystems, under current and future conditions. Machine-learning applications can complement process-based models by filling monitoring or modelling gaps and enabling rapid exploration, but their credibility depends on the quality of the training data, appropriate validation, transparent handling of uncertainty and expert interpretation. Together, as a hybrid modelling approach, they enable a more holistic approach to comprehensive water system modelling and are the “next generation integrated modelling framework for river basin management”. The various components are discussed in Chapter 4 (hydrology, water allocation, reservoirs and e-flow models) and Chapter 5 (ML and data-driven models).

Layer 4: Uptake and use

The fourth layer represents uptake and applications or making informed decisions. Dashboards translate datasets, indicators and model results into accessible visualisations, while Story Maps and other communication tools place results within a recognisable basin context and explanatory narrative. Such products can help decision-makers and stakeholders explore scenarios, understand trade-offs and discuss possible responses. Their effectiveness depends both on its (technical) functionalities and on a clear connection with the decisions users need to make and the information or evidence they require. The STARS4Water report therefore mentions these products as both communication instruments and decision-support tools. The different products from STARS4Water are presented in Chapter 6.

Layer 5: Impact through water management and planning

The four supporting layers collectively contribute to the fifth layer on top: impact through adaptive and resilient water management and planning. Intended outcomes include improved climate preparedness, more sustainable water allocation and use, healthier ecosystems and reduced risks associated with droughts and water scarcity. These outcomes emerge when relevant stakeholder questions, reliable data, scientific-evidence analyses based on pre-defined relevant indicators and accessible products, including models and tools, are integrated into a coherent and repeatable process.

Success, risks and cross-cutting principles

The figure also illustrates success factors, risks and cross-cutting principles that were identified during the project. Success is fostered by stakeholder co-creation, high-quality data, modular and transferable tools, transparency, sufficient capacity and institutional ownership. Uptake can be constrained by data gaps, technical complexity, limited transferability, uncertainty about future extremes, unclear ownership and the burden of maintenance.

Openness and FAIR (findable, accessible, interoperable and reproducible) data, ethical and responsible use, scalability and continuous improvement therefore apply across all five layers. Sustainable uptake should be viewed as an iterative cycle of development, application, learning and adaptation, rather than as the final transfer of a completed technical product.

Successful application in another basin will usually require adjustment to the composition of the stakeholder and research community members for co-creation and their local data, expert knowledge, management and operation questions and decisions, governance arrangements and user capacity. STARS4Water Deliverable 5.2 addresses this in more detail.

2.3. Sustainable uptake of STARS4Water innovation outputs

The STARS4Water project has developed a diverse set of tools to support river basin management, ranging from novel data services and next generation modelling frameworks to innovative ML applications and co-created decision-support products. Figure 4 provides a synthesis of these tools, assessing them across four practical dimensions that are important for implementation and sustainable uptake: added value, transferability, operational readiness, and maintenance needs.

Dimension 1: Added value

All tool categories deliver substantial added value for river basin management. The delivered data services provide a strong foundation of global and regional datasets, indicators, and metadata that support basin screening, comparison and knowledge development. Comprehensive modelling frameworks offer deep insights into hydrological processes and integrated water resources management system understanding, making them particularly valuable for decision support and scenario analysis. Machine learning and other data-driven tools help fill data gaps and enable rapid assessments. Meanwhile, decision-support and communication tools such as dashboards and Story Maps translate technical information into accessible information and visualisations that support stakeholder engagement and informed decision-making.

Dimension 2: Transferability

The assessment also highlights that most STARS4Water tools are highly transferable. Data services and machine learning methods can generally be applied across different river basins, while modelling frameworks and decision-support tools can also be adapted to new contexts provided that local data, policies, and management questions are considered. This means that project results have relevance well beyond the case study basins in which they were originally developed.

Dimension 3: Operational readiness

In terms of operational readiness, many of the tools are already mature enough to support practical basin management. Data services, modelling frameworks, and decision-support products are largely ready for operational use, although their successful application depends on the availability of local data, technical capacity, and validation efforts. Machine learning approaches show considerable promise but often require further testing, uncertainty assessment, and integration with other methods before routine implementation.

Dimension 4: Ownership and maintenance

An important message from the synthesis is that long-term maintenance should not be underestimated. While data services and machine learning tools generally require moderate effort to remain up to date, modelling frameworks and decision-support platforms often require significant ongoing investment in data collection, calibration, software maintenance, user support, and content updates. Sustainable impact therefore depends not only on the technical quality of the tools but also on clear ownership, governance arrangements, and long-term resources.

In conclusion, Figures 3 and 4 together demonstrate that no single tool can address all river basin management challenges. The greatest benefits are achieved by combining complementary approaches and tools and acting across the different conceptual layers. STARS4Water shows that effective river basin management requires a balance between globally consistent data and locally relevant knowledge and credibility, the integration of process-based models with data-driven techniques i.e. hybrid approach, transparent communication of the results in terms of transparency on uncertainties, assumptions and limitations, and sustained investment to secure long-term ownership, operational deployment and maintenance for the benefit of better decisions today for adaptive and resilient river basin management.

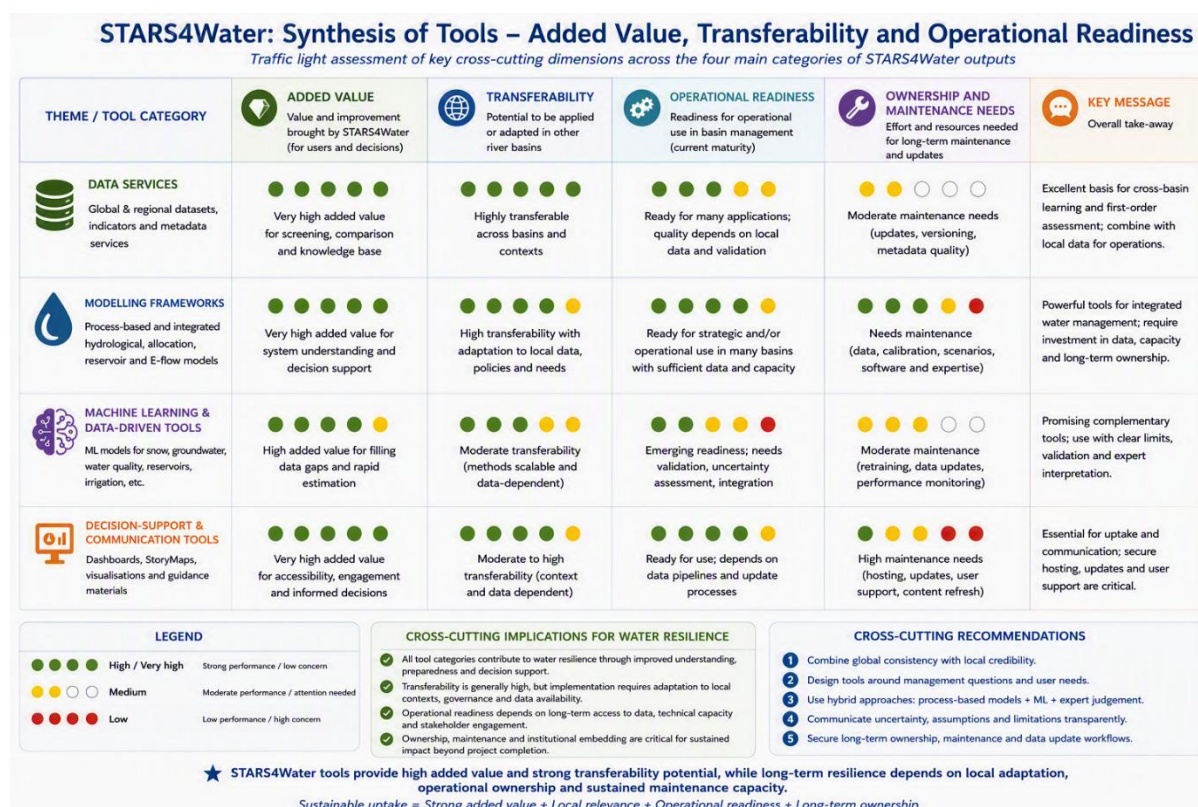


Figure 4. The STARS4Water Synthesis of Tools – Added value, transferability and operational readiness (Hegdahl – design assistance copilot)

3. STARS4Water key advancements

3.1. Introduction

In this chapter we present a brief overview of the innovations in the STARS4Water developed and delivered in the river basins of the project: Danube, Drammen, Duero, East Anglia, Messara, Rhine and Seine. These are key advancements in the field of data services, integrated and/or data-driven modelling and decision support and communication tools.

Although all innovations are tailored to stakeholder needs which address issues in local contexts, together they present a valuable suite of tools with high potential for use by water practitioners managing the water availability, supply and demand in river basins across Europe, and potentially across the world. Therefore, in principle, the findings in the river basins are described in more general terms to make them relevant for a broader audience. Where applicable, e.g. a detailed model is developed for one river basin only, a more in-depth description can be given. In the text it is described if a tool is applied in one basin only or multiple basins. Some tools are developed as model software packages that enable to build own model applications, while others are programmed specifically to address a dedicated need.

The work builds on achievements from several of the project's work packages, for which the results were reported in previous deliverables of the project: stakeholder co-creation of narratives and what-if scenarios of local interest (deliverable D1.2), indicators and model developments (deliverables D2.1, D3.1 and D3.2), model calibration/validation (deliverable D4.1) and model application to improve projects on water resources availability and risks (deliverable D4.2). All reports are available on the project's website¹.

3.2. A summary of the key advancements in all STARS4Water river basin hubs

It is important to note that each deliverable in STARS4Water is the result of an integrated effort to improve the understanding of the water resources availability, supply and demand to support local concerns of stakeholders on water availability and management at the river (sub)basin scale. That implies that most tools relate to water for fresh water supply, agriculture, hydropower, navigation, ecological flows, as well as risks for hydrological extremes (floods, droughts), glacier melt and water reservoir filling/release conditions.

Table 1 presents a general overview of new data, models and tools available for the river basins. More details are described per river basin hub in the following sections.

¹ <https://stars4water.eu/output/public-deliverables/>

Table 1. New data, models and tools available for all STARS4Water river basins.

Category	New data, models and tools available to support the stakeholders in the river basin
Data and portals	• Accessibility of local data sets through the Metadata Portal, • Global data sets used for improving understanding and made available through generic dashboard, • Local and global data sets collected and used for developing data-driven models, • Data sets on socio-economic scenarios and water use, • Data sets generated on future water resources availability (water resources projections) and impacts on ecological flows. • New local project output datasets uploaded to Zenodo, and visible products available in generic and tailor-made dashboard, available data described in Metadata portal (?)
Integrated river basin management modelling framework	• Advancements in process-based and integrated (geo-) hydrological, allocation, reservoir and e-flow modelling (selected components differ per river basin depending on stakeholders needs)
ML and data-driven models	• Multiple river basins (East Anglia, Duero, Drammen, Rhine and Seine) experimented with ML and data-driven tools e.g. for estimating snow water equivalent, estimating irrigated area, groundwater and reservoir modelling, as complements/modules in the integrated modelling framework.
Decision support and communication tool	• Generic dashboard showing information for all river basin hubs, • Tailored dashboard for the Drammen river basin, • Impact reporter for all river basins, • Story Maps for each river basin hub.

3.3. Key advancements in the Drammen basin

In the Drammen River Basin (Norway), the STARS4Water project has implemented a suite of tools to support adaptive water management under climate change (Table 2). These tools range from advanced multiple hydrological models, both process-based and machine learning, as well as a reservoir, water allocation and use model. Main objective was to provide projections relevant for water supply, ecology, and hydropower production and thereby identify the Safe-Operating-Space. The findings are presented in a stakeholder-oriented tailored dashboard and Story Map for decision support and communication. Below is an overview of the key tools applied in the project.

Table 2. New data, models and tools available for the Drammen river basin.

Category	New data, models and tools available to support the stakeholders in the river basin
Data and portals	New local project output datasets uploaded to Zenodo, and visible products available in generic and tailored dashboard, available data described in Metadata portal
Integrated river basin management modelling framework	Advancements in hydrological modelling Lisflood, HBV and Wflow_sbm modelling, linked with new set-up of reservoirs, water allocation and use model using Ribasim2025 beta software version, aligned with EOPS model for hydropower production modelling.
	Complemented by a machine learning model, in particular for estimating snow water equivalent.
Decision support and communication tool	Generic and Drammen tailored dashboard, impact reporter, Drammen Story Map

3.4. Key advancements in the Danube basin

In the Danube Basin, which is the largest basin in Europe and that includes 19 countries, the STARS4Water project has implemented a new integrated river basin management model to support low water management under climate change (Table 3). The decision to proceed with this initiative was made after a gap analysis of modelling tools and stakeholder interaction. This analysis revealed the necessity for a water allocation model encompassing the entire Danube Basin (Rickards & Keller, 2024). This model consists of a new established water allocation and use model that is linked to a hydrological model that was already established in the EU DOORS project. Various scenarios were developed and assessed with a focus on the impact of climate change, socio-economic projections and the effect of intensified and additional abstractions from the main Danube River (flowing through 10 countries). Main objective was to provide projections for public water supply, ecology, navigation, cooling water for nuclear power plants and hydropower to identify the Safe-Operating-Space. The findings are presented in a stakeholder-oriented Story Map. Below is an overview of the key tools applied in the project.

Table 3. New data, models and tools available for the Danube river basin.

Category	STARS4Water deliverables to the stakeholders in the basin
Data and portals	New local project output datasets have been uploaded to STARS4Water Zenodo repository.
Integrated river basin management modelling framework	Wflow (developed in the DOORS project) – no new developments, used for projections of hydrology under climate change - connected with a new developed model dedicated to the Danube main river, using Ribasim8 model software version, to assess impact of climate change and water abstractions assessed following the SOS approach to study impact on water supply, ecology, hydropower and navigation, Fairway/ecological discharge thresholds identified for critical locations. Local socio-economic and water use data.
Decision support and communication tool	Generic dashboard, impact reporter, Danube Story Map

3.5. Key advancements in the Duero basin

The Duero basin is Spain's second largest catchment. It is best described as a rural region where agriculture accounts for most of the existing water uses. Suitably, agrochemical contamination and intensive groundwater extractions have been identified by STARS4Water stakeholders as major issues in the basin. Several tools have been developed to support groundwater management (Table 4).

Nitrate contamination is of particular concern, as this species consistently exceeds 50 mg/l in many monitoring boreholes across the central part of the catchment. This poses a threat to drinking supplies in rural areas and to ecosystem health. Predicting groundwater contamination is crucial to underpin decision making. In the context of Stars4Water, this was achieved through the development of a data-driven tool (MLMapper) that was subsequently exported to the East Anglia hub.

Furthermore, the Duero basin is subject to emerging water scarcity pressures due to severe droughts and increasing groundwater abstraction. This was tackled from two different perspectives. The first one consists of the expansion of an existing process-based model (Modflow) whose purpose was to simulate future scenarios in the face of uncertainty. This was complemented by a second data-driven approach focusing on the prediction of storage changes across the basin.

Table 4. New data, models and tools available for the Duero river basin.

Category	STARS4Water deliverables to the stakeholders in the basin
Data and portals	New local project output datasets have been uploaded to STARS4Water Zenodo repository.
Groundwater flow model	Extending the existing MODFLOW model to cater to the whole central part of the basin was used to provide meaningful predictions for groundwater management purposes; to serve as a baseline for performance, providing a common ground for comparison between traditional and data-driven tools; and to provide inputs to data-driven approaches in order to explore different means to improve predictive mapping.
Data-driven tools to assess groundwater contamination	A data-driven predictive mapping tool for groundwater contamination was developed and applied to the Duero and East Anglia hubs. Outcomes may be used to delineate the areas affected by contamination at the basin scale. These can also be useful in terms of explaining trends in groundwater contamination as well as deciding where to locate new monitoring boreholes.
Data-driven tools to assess groundwater storage changes	A machine learning model for groundwater storage changes estimation was developed for the Duero and transferred to the Seine. The model is a hybrid spatio-temporal deep-learning architecture that predicts monthly variations in total groundwater storage using a combination of static catchment descriptors, dynamic climatic and land-cover drivers, and the recent history of the target variable itself. The model can be used to simulate climate change and water management scenarios for future water resources, as shown by the application to RCP4.5 and RCP8.5 scenarios from three EURO CORDEX CMIP5 regionalized members.
Decision support and communication tool	Generic dashboard, impact reporter, Duero Story Map

3.6. Key advancements in the East Anglia basin

The East Anglia Basin is situated in the Eastern part of the United Kingdom. To fulfil the demands of the stakeholders, the STARS4Water project has explored new machine learning technologies for groundwater contamination assessment similar to what has originally been developed for the Duero basin. STARS4Water also advanced and implemented an environmental flow modelling tool to assess the impact of climate change on ecology considering alterations in the hydrological cycle due to climate change and changes in water use. Various scenarios were developed and assessed using the tool. New insights are reported in a stakeholder-oriented Story Map which explores changes in E-flow whilst adopting the Safe-Operating-Space concept. An overview of key advancements is listed in Table 5.

Table 5. New data, models and tools available for the East Anglia river basin.

Category	STARS4Water deliverables to the stakeholders in the basin
Data and portals	New local project output datasets have been uploaded to STARS4Water Zenodo repository. New datasets are for example, E-flow data sets for change in hydrological regimes.
Data-driven reservoir storage model	Forecasting reservoir storage on a monthly timestep in the East Anglia, Seine and Duero RBHs, to address the need for better quantitative assessments of water resources, and to support decision making for reservoir operation and water resources management.
Data-driven groundwater contamination model	A data-driven predictive mapping tool for groundwater contamination – ML Mapper – was developed and applied to the Duero and East Anglia hubs. The outputs from the tool can be used to delineate the areas affected by nitrate contamination at the basin scale. These can also be useful in terms of explaining trends in groundwater contamination, as well as a siting tool in deciding where to locate new monitoring boreholes in East Anglia.
E-flows risk indicator tool	The STARS4Water <i>ERFA tool</i> was developed to give a custom implementation of the Ecological Risk due to Flow Alteration (ERFA) method – a hydrology-based environmental flows screening approach originally developed for European rivers. The method compares a set of hydrological indicators across user defined time periods to highlight future risk to E-flows as a result of flow alteration due for example to climate and/or anthropogenic influences.
Decision support and communication tool	Generic dashboard, impact reporter. A Story Map focussing on the key challenges to water resources management in East Anglia, and how these are likely to change in the future. Alongside a general narrative on the region and its water resources, the Story Map also highlights the impact of drought and the changing demands of water users on E-flows in the region and placed in the context of the SOS risk framework.

3.7. Key advancements in the Messara basin

The Messara Basin is the largest and most intensively cultivated agricultural region in central-south Crete in Greece. The stakeholders expressed the need for a significant update of their integrated river basin model up to latest standards and at a disaggregated sub-catchment level, and the needs to fill the current data gaps of in-situ precipitation and streamflow measurements. STARS4Water developed a new integrated river basin management model suite to simulate river streamflow and water budget and assess the impact of climate and irrigation water use at sub-catchment level under various scenarios (Table 6). Various scenarios were co-designed with stakeholders and assessed using the tool. New insights are reported in a stakeholder-oriented Story Map corresponding the Safe-Operating-Space concept.

Table 6. New data, models and tools available for the Messara river basin.

Category	STARS4Water deliverables to the stakeholders in the basin
Data and portals	ERA5 downscaled bias-corrected climate data for 1950-2022, Stochastic future climate data for 5yrs and 7yrs prolonged droughts, Specific narrative for the Messara river basin under the SSP2 scenario for 2040, Calibrated streamflow data for 1989-2022, Metadata for the Sacramento model simulation, Local water use data 1989-2022, Monthly water budgets at sub-catchment level and per water user node, Assessment of water supply reliability under different scenarios. New local project output datasets have been uploaded to STARS4Water Zenodo repository.
Integrated river basin management modelling framework	A new developed model dedicated to the Messara basin representing the balance between the water availability and water use(rs) disaggregated at sub-catchment level using Ribasim8 model software version. Datasets from Sacramento rainfall-runoff model and Modflow groundwater model were used as data input for hydrological boundary conditions. Thresholds for the Safe-Operating-Space based on the unmet demand and water supply reliability
Decision support and communication tool	Generic dashboard, impact reporter, Messara Story Map

3.8. Key advancements in the Rhine basin

Flora, fauna, and approximately twenty million people within the Rhine Basin depend on the river's water availability to sustain biodiversity, secure drinking-water supplies, support heavy industry and agriculture, and facilitate inland navigation. The Rhine river basin commissions (CHR, ICPR and CCNR) as key stakeholders expressed the need for advancing their integrated river basin model suite, especially on water use and low water impact assessments (Table 7). STARS4Water co-designed Rhine basin specific socio-economic scenarios, and by combining them with existing KNMI'23 climate change scenarios, fulfilled a model-based analyses of the Safe-Operating-Space for water supply, inland navigation and environmental flows under uncertain futures. New insights are reported in a stakeholders' workshops from the Rhine commissions and a Story Map to communicate results.

Table 7. New data, models and tools available for the Rhine river basin.

Category	STARS4Water deliverables to the stakeholders in the basin
Data services and portals	Local socio-economic and water use data from various sources (literature, modelled, monitored, etc.) have been collected for updating the models and validation according to three socio-economic scenarios. New local project output datasets have been uploaded to STARS4Water Zenodo repository.
Integrated river basin management modelling framework suite	An advance integrated river basin model for modelling water availability, water allocation and water use(rs) using Wflow_sbm software and Ribasim8 software. Dedicated ML module to irrigated agricultural area assessment based on EO data. Thresholds for the Safe-Operating-Space based on the unmet demand and water supply reliability and minimum flows for inland navigation and e-flows at various locations.
Decision support and communication tool	Generic dashboard, impact reporter and Rhine Story Map

3.9. Key advancements in the Seine basin

The Seine river basin is one of the largest and most densely populated catchments in France, as it includes the Paris region. The river flow regime shows an important interannual variation, with high flows in winter and low flows in summer. This variability is controlled by four reservoirs located upstream on the Seine River and its major tributaries, the Marne, Aube, and Yonne rivers. Overall, the reservoirs are managed to be filled up during the wet season up to summer (November to June) and to release water to sustain low flows during the summer period (July to October). Freshwater resources are used for domestic drinking supply and economic purposes (agriculture, industry, leisure, navigation, and cooling systems for power plants).

The catchment lies at a climatic boundary in Europe: to the north, precipitation is projected to increase, whereas to the south, it is expected to decrease. As a result, future precipitation trends over the area remain highly uncertain. In STARS4Water, stakeholders responsible for the management of the four upstream reservoirs, among other water infrastructures, expressed their needs toward modelling tools that could be easily used operationally to simulate their management practices and evaluate the impact of future climate and water availability on low flow management, in particular. Modelling tools were also a concern in terms of supporting a better understanding of interactions between groundwater and surface water within the river basin, and of how the management of the upstream reservoirs might interact with this process (Table 8).

In STARS4Water, we co-designed management scenarios and evaluated their effect on low flows when combined with climate scenarios. We integrated reservoir operations in the framework of the GRSD hydrological model, a semi-distributed model based on the family of GR models, which are largely used in operational settings in France. We explored the links between water quantity and water quality by investigating ecological flows and fish species indicators, as well as the interplay between chloride transport dynamics and hydrologic model parameters. Findings are reported to the stakeholders in the Safe-Operating-Space framework, tailored to the river basin, and in a Story Map.

Table 8. New data, models and tools available for the Seine river basin.

Category	STARS4Water deliverables to the stakeholders in the basin
Data and portals	Climate and reservoir management scenarios, ecological flow indicators, and model output data for water availability/low flow assessment. Downscaled Monthly Water Table Depth Anomalies from ML and global models. New local project output datasets have been uploaded to STARS4Water Zenodo repository.
Next generation hydrological model	Semi-distributed hydrological model with explicit incorporation of the influence of reservoir management. Model calibrated and validated using observed discharges and estimated long-term average evapotranspiration for more robust assessments under climate changing conditions.
Decision support and communication tool	Generic dashboard, impact reporter and Seine Story Map

4. Novel data services for river basin management

4.1. Introduction

The STARS4Water project has conducted several activities (under work package 1 and 2) aimed at provisioning stakeholders with data for better understanding climate change impacts in their own river basins as well as in other river basins. These novel data services for river basin management are:

1. The project created a Metadata Portal (<https://stars4water.openearth.eu/>) that captures close to 500 existing datasets that can support river basin management. The metadata portal follows the FAIR data guiding principles: it supports findability, accessibility, interoperability, and reusability of digital assets and scientific data. In this context, the project team did an extensive data inventory to collected global, regional and local datasets in cooperation with stakeholders.
2. Furthermore, the project developed new data services based on a three-tiered indicator approach:
 - a. Tier-1 indicators efficiently translate readily available global data into river catchment scales to show projected relative changes through 2050 against a historical baseline. The data is unlocked to the river basin management practitioners and wider audience by the generic dashboard (see chapter 6).
 - b. Tier-2 indicators combine global data with auxiliary sources to yield practical management metrics, such as precipitation deficits for agricultural drought monitoring or estimating current and future water demand.
 - c. Tier-3 indicators utilize advanced numerical or ML and data-driven models to precisely capture local hydrology per river basin.

All new datasets are stored in the Metadata portal (see Figure 5) and [Zenodo archive](#). Shorts movies in the STARS4Water Academy ([The STARS4Water Academy – STARS4Water](#)) will guide end-users on how to navigate those.

4.2. Metadata Portal

Alongside delivering datasets (see section 4.3-4.5) and modelling tools (described in chapter 5), the project established a [Metadata Portal](#) (see Figure 5) for STARS4Water from the beginning of the project. The Metadata portal supports more integrated and data-wise (and data-efficient) river basin management. The metadata portal is essentially a catalogue of data sets and data services compiled or generated, in and outside STARS4Water that have relevance for river basin management. This portal indexes datasets such as climate inputs, hydrological observations, model outputs, socio-economic data, etc., making them findable and accessible to project members and stakeholders. For the STARS4Water basins, this would mean that various data – from local reservoir statistics provided by a river basin stakeholder or local datasets collected by one STARS4Water research partner to global reanalysis data generated by another STARS4Water research partner, to data that was used in modelling by the river basin hubs partners – are documented in one place. The portal doesn't host the actual data, but it provides information on the data, i.e. the metadata (descriptions, sources, how to access them) ensuring transparency and reusability. Additionally, the project developed *data services* (APIs or pipelines) to deliver certain global datasets and datasets derived from global models (like updated climate indicators for Tier 1 and 2 of the dashboard) to all basins. This enables a comparison

climate change between the basins. The results should be presented with cautions zooming in towards the local level, since global models are often inaccurate and lack the precision that local managers can achieve with their local models to meet the local operational needs. At the same time these STARS4Water data services created are particularly important to provide the pipelines to extract data from global model anywhere these data are lacking. In sum, the Metadata Portal and associated data services form the backbone of information management for river basin analyses, within and beyond STARS4Water project, supporting traceability and consistency of the data used across tools.

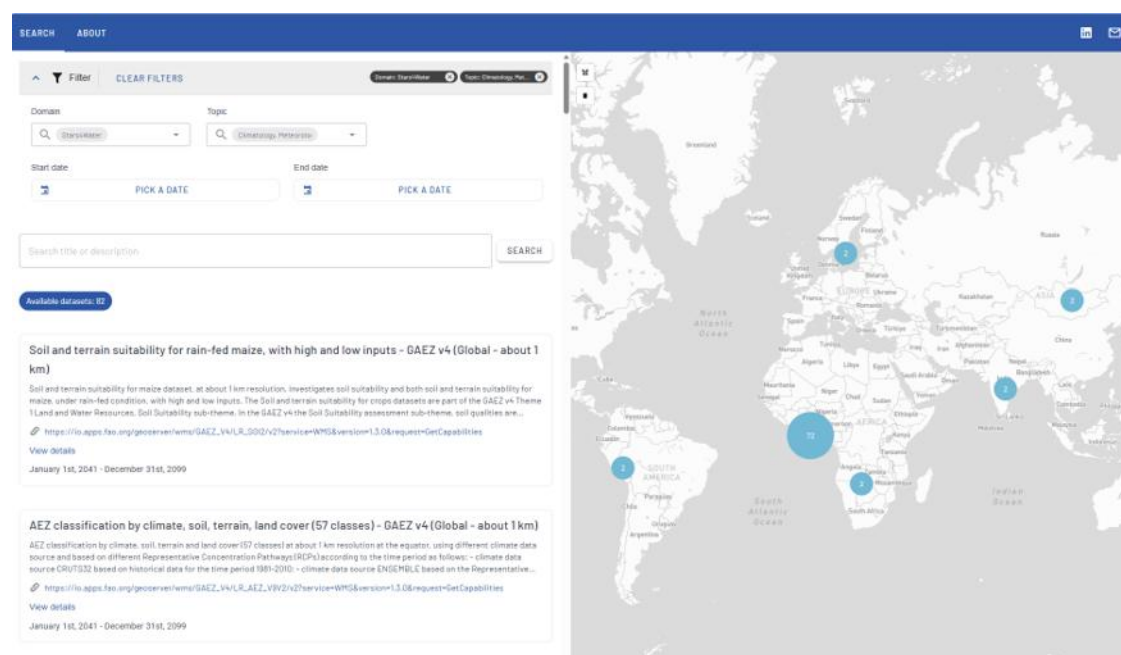


Figure 5. The user interface of the STARS4Water Metadata Portal - accessible via the project's OpenEarth site: stars4water.openearth.eu.

4.3. Derived datasets based on global data and tier 1 indicators

Work Package 2 (WP2) of the STARS4Water project, titled "unlocking and improving data-services," focused on generating several novel datasets indicative of climate change to support water resources management and climate risk assessment at the river basin level. These datasets were either directly derived from freely available global datasets (tier-1) or combined or augmented with local data with minimal processing (tier-2). The climate indicators from global datasets thus provide an efficient method to assess impacts for a basin, whereas deriving data directly from specialized local model calculations is far more laborious.

The set of tier-1 climate indicators was designed to evaluate integrated water resource systems across European river basins, indicating relative changes in mean annual, summer, and winter values for air temperature, precipitation, potential evapotranspiration, soil moisture, snow water equivalent, groundwater recharge, and river discharge, alongside socio-economic metrics tracking total population and fractions of land use classes. They were derived from readily available global datasets.

The tier-1 indicators were used as a basis for a generic dashboard that displayed the expected changes in the seven river basins as a result of climate change. All generated data have also been uploaded to the Zenodo repository with persistent digital object identifiers (DOIs), and their corresponding

descriptive information has been documented in the publicly accessible STARS4Water Metadata Portal (see section 4.2).

4.4. Derived water demand projection datasets based on global and regional data and tier 2 indicators

The tier-2 datasets and indicators were also based on global and regional data, however with more processing, combination with local measurement data and/or existing model calculations. Some examples of these tier-2 datasets are the water demand projections and the ecological flow scenarios.

To address the needs of stakeholders for better understanding of historical and future water demand for both domestic households and industrial sectors, as well as distinct projections for agricultural irrigation water demand under varying future socio-economic and climate scenarios, water demand scenarios and accompanying datasets were created. The water demand scenarios project water utilization trends from 2020 to 2050 by integrating historical data with future Shared Socioeconomic Pathways (SSPs) across distinct socioeconomic and environmental sectors. For domestic and industrial sectors, future scenarios span SSP1 through SSP5, utilizing population growth and Gross Domestic Product (GDP) as primary macro-drivers to model spatial and economic shifts. This methodology applies a flexible downscaling framework that disaggregates data to a fine 1 km resolution, allowing researchers to evaluate both gross withdrawals and net consumption. Net domestic demand is adjusted based on urban-rural demographic proportions and urban recycling rates, while net industrial demand specifically filters out the significant return flows typically associated with thermoelectric and nuclear power plant cooling systems. Under the specific "Middle of the Road" SSP2 scenario framework, both domestic and industrial water demands are projected to steadily rise across all studied European river basins by the year 2050, with industrial data missing only for the Messara basin due to local input data limitations.

In contrast, agricultural irrigation water demand scenarios were modelled using the field-scale AquaCrop simulator over a spatial resolution of 0.5 degrees to evaluate European biomass and soil water balances. These scenarios combine five different General Circulation Models (GCMs) with three specific emissions pathways: SSP1-2.6 representing low emissions with strong mitigation, SSP3-7.0 representing high emissions, and SSP5-8.5 representing extreme, unmitigated climate conditions, yielding a total of 15 distinct scenario combinations. To isolate the variables most consistent with the narrative core of the overarching STARS4Water project, the analysis focuses on the near-future horizon spanning 2031 to 2060 under the high-emissions SSP3 narrative. The modelling underlying these scenarios operates under several strict parameters: it evaluates net irrigation requirements specifically during the peak summer months of June, July, and August, assumes well-managed fields with near-optimal soil fertility, and ignores changes in actual irrigated surface boundaries by normalizing values directly against grid cell areas. Averaging the ensemble results of these climate pathways indicates a universal increase in summer net irrigation demand across all studied river basins when moving from the historical baseline to the near-future timeline. The absolute scale of this increase varies dramatically by geography; for instance, the Messara basin is projected to experience a minor increase from 585 mm/year to 593 mm/year, whereas the Rhine basin faces a massive projected surge in irrigation requirements, escalating from a baseline of 696 mm/year to an ensemble mean of 1100 mm/year.

Similar to the tier 1 datasets, all generated tier 2 data have been uploaded to the Zenodo repository with persistent digital object identifiers (DOIs), and their corresponding descriptive information has been documented in the publicly accessible STARS4Water Metadata Portal (see section 4.2).

4.5. Derived water availability projection datasets based on tier 3 indicators

As part of WP3, the STARS4Water initiative generated several high-resolution, data-driven water availability and storage datasets to address identified stakeholder modelling gaps across various European river basins. These tier-3 datasets and indicators primarily focus on optimizing the monitoring and quantitative estimation of surface reservoirs and groundwater systems as well as the irrigation area in a basin. ML technologies and data-driven models (see Chapter 6 for more information on these) were used to produce the datasets:

- **High-Resolution Irrigated Area Maps:** Annual gridded maps mapping the spatial distribution and inter-annual variability of irrigated cropland to serve as the critical first step for calculating agricultural water demand. These were produced at a fine 1 km spatial resolution spanning 2010–2019 across the Rhine River Basin via a Random Forest classification model. The model identifies irrigation signatures by analysing land surface temperature differences between actual MODIS satellite observations and non-irrigated simulations from the wflow_sbm hydrological model.
- **Daily Reservoir Inflow and Storage Simulations:** Daily time series predicting reservoir inflows and storage volumes were sourced globally using the Caravan community dataset but applied locally over case study reservoirs in the Duero and Seine basins. They were generated using a Long Short-Term Memory (LSTM) network designed under a Multi-Task Learning (MTL) framework to simulate streamflow and historical volumes simultaneously.
- **Monthly Seasonal Reservoir Storage Forecasts:** Coarse monthly-scale datasets providing sub-seasonal to seasonal reservoir storage forecasts up to 1 to 3 months ahead. These were generated for Duero basin reservoirs and across the UK (including the Anglian region). They were built using tree-based machine learning algorithms (specifically an Extra Trees Regressor global model) that utilize historical storage patterns, meteorological inputs, and localized catchment characteristics from HydroAtlas and CAMELS datasets.
- **Downscaled Monthly Water Table Depth Anomalies (WTDA):** A continuous spatial grid mapping localized monthly groundwater depth variations across the Seine River Basin. These were generated at a refined 9 km (0.11 degree) spatial resolution by using Random Forest and LSTM architectures to downscale coarse global satellite observations from NASA's GRACE project, blending them with ERA5-Land reanalysis data and Terrestrial Systems Modelling Platform (TSMP) simulations.
- **Quantitative Groundwater Storage Changes (GWSC):** Fine spatiotemporal scale grids estimating changes in groundwater storage to improve real-time monitoring and drought/low-flow tracking across the Duero River Basin. They were created at an 11 km resolution spanning 2013–2022 using a Spatiotemporal Transformer (STT) neural network and an XGBoost ensemble. Because raw process-model simulations contained high uncertainties, simulated Total Water Storage from the TSMP and Community Land Model (CLM) were first corrected by assimilating in-situ piezometer data from the Duero River Basin Authority via linear regressions and spatiotemporal kriging.

Also, tier3 data have been uploaded to the Zenodo repository with persistent digital object identifiers (DOIs), and their corresponding descriptive information has been documented in the publicly accessible STARS4Water Metadata Portal (see section 4.2).

4.6. Key takeaways on data services

The new data services in STARS4Water delivered a comprehensive overview of metadata, a consistent indicators, metadata and accessible datasets.

The project team and the stakeholders identified the following key strengths of STARS4Water products:

- Open and accessible datasets and metadata.
- Consistent indicators across river basin.
- Supports cross-basin comparison and screening.
- Strong foundation for transparency and re-use.

Based on experiences during project execution and feedback from stakeholders, the main limitations are:

- Global datasets may not capture local conditions.
- Advanced indicators (tier 3 and partly tier 2) depend on local data availability.
- Different datasets have varying uncertainties.
- Long-term updates require maintenance.

The above results in the following recommendations from the STARS4Water project for further use and uptake:

- Combine global and local information.
- Clearly communicate uncertainty and assumptions.
- Use global indicators for screening, not replacement.
- Maintain metadata, provenance and version control.

5. Next generation modelling frameworks – part 1: process-based and integrating hydrological, water allocation, reservoir and environmental flow models

5.1. Introduction

STARS4Water have taken existing models and modelling framework as the starting point of the project and contributed to bring those to a next level. The stakeholders expressed their needs for improving hydrological and water allocation models or in some cases adding new ones to their modelling frameworks. Depending on their needs for better describing water resources availability and related risks (droughts, reservoirs operations, etc.) (see also Chapter 2) we have further developed those modelling instruments. These developments showed a wide diversity: building model applications from scratch using well-established model software packages, upgrading user interfaces and calculation cores by transferring to new model version releases, improving reliability of the model by incorporating new collected data, or extension of models or model suites with new functionalities covering new thematic areas (like coupling with e-flow module).

In this chapter, we provide an overview of hydrological models and water allocation models that are used in practice for river basin management by (at least) the river basins in this project (Figure 6 shows an example). At the end of the chapter, we reflect on the improvements based on experiences, findings and observations in the project by sharing key takeaways. This way we want to support the continued process of model improvements to support river basin management in the 7 river basin hubs and beyond.

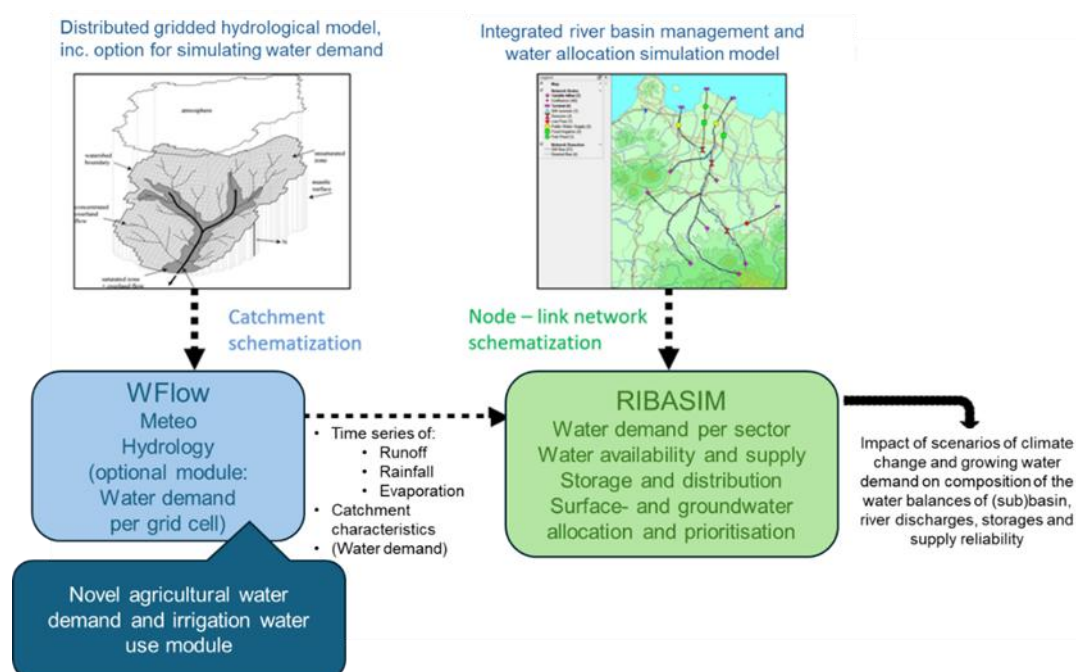


Figure 6. The structure of the next generation modelling framework for the Rhine River basin: wflow for grid-based hydrological modelling and water demand modelling connected with the network-based RIBASIM water balance modelling for water management and water allocation simulation. The framework enables scenario analysis in drought and low flow conditions, water infrastructure and water supply for various water use(rs). (Maat, J. ter, et al, 2025).

5.2. Improved models for better understanding of (geo-)hydrological processes in the basins

LISFLOOD Hydrological Model

LISFLOOD is a grid-based and physically based hydrological model initially developed for pan-European flood forecasting. It is designed to simulate rainfall-runoff-routing processes across large river basins at regional, continental, and global scales (Burek et al 2013). It plays a crucial role in applications such as flood forecasting, water resource management, and climate change impact assessments. The model accounts for various hydrological processes, including surface and subsurface water flow, groundwater storage, and interactions with lakes and reservoirs. It transports water both horizontally and vertically through the landscape and soil, making it suitable for complex hydrological studies. *LISFLOOD* serves as the core model for operational flood and drought forecasting systems, including the European Flood Awareness System (EFAS), the Global Flood Awareness System (GloFAS), and the European Drought Observatory (EDO) and it also integrates water demand from multiple sectors, including irrigated agriculture, and is being further developed to incorporate crop yield and energy production.

In Drammen, it has been customised to include all 54 reservoirs in the basin. This model simulates river flow on a grid and accounts for land use and water demand changes, providing a foundation for flood and drought analysis under current and future conditions. In the STARS4Water project, *LISFLOOD* serves as one of three core models for the Drammen in an ensemble, often supplying inflows to the reservoir operations tool (EOPS) and then receiving adjusted flows back to evaluate regulated river impacts. It underwent local calibration with Norwegian data, achieving performance (Kling–Gupta Efficiency >0.7 at most gauges) that indicates reliable reproduction of observed streamflow.

HBV (Hydrologiska Byråns Vattenbalansavdelning) Model

HBV is a conceptual rainfall–runoff model widely used in Scandinavia for water balance and flood forecasting. For Drammen, a gridded *HBV* model at 1 km resolution was developed to provide high-precision simulation of runoff and soil moisture across the basin. This model is relatively lightweight and can capture snow accumulation and melt – a key factor in Norway – through calibrated snow and soil parameters. In *STARS4Water*, *HBV* is part of the Drammen model ensemble, offering a different perspective alongside *LISFLOOD*. It was also locally calibrated (rather than using generic Norwegian settings), improving its fit to Drammen’s conditions. While simpler than *LISFLOOD*, *HBV* provides quick insights into water balance changes and complements the more complex models.

Sacramento Rainfall-Runoff Model

Sacramento Soil Moisture Accounting Model (SAC-SMA) is a conceptual hydrologic model that simulates continuous streamflow by tracking water movement through distinct soil layers. The *SAC-SMA* uses up to 16 conceptual parameters to estimate various hydrological responses (surface runoff, percolation, interflow, baseflow, etc.). It is utilized for river forecasting, water supply planning, and climate change assessments. It requires inputs of precipitation and potential evapotranspiration.

In the Messara basin in-situ streamflow data at the Geropotamos river outlet and at Anapodaris outlet were not available after 2003. A Sacramento Rainfall-Runoff Model (*SAC-SMA*) was developed to simulate streamflows until 2022 using the *HydromadR* package and calibrated with 13 parameters. This was coupled with Exponential Hydrograph Routing model (3 parameters). The model accurately

captured a significant regime change in the Anapodaris river around 1989, as well as the intermittent behaviour of the Geropotamos river. Records of groundwater licences were also considered during this process, adding an additional layer of precision to the model. The Nash–Sutcliffe efficiency (NSE) was used as a performance indicator to evaluate the model's accuracy, with results showing good to very good performance in predicting monthly streamflow. The output of the model was also used as an input to the RIBASIM water allocation model.

Wflow_sbm Hydrological Model

Wflow_sbm, developed by Deltares, is an open-source tool for distributed hydrological modelling (Van Verseveld et al, 2024). Its soil structure is built on the concept of the *topog_sbm* (soil bucket model) (Vertessy et al, 1999). *Wflow_sbm* aims to bridge the gap between conceptual hydrological models, which are simpler and faster but lower in resolution, and physics-based models, which offer higher resolution and complexity. It achieves this balance by utilizing parameters grounded in physical processes while maintaining efficient computational performance. The model incorporates a range of hydrological processes, including glacier and snow dynamics, lakes and reservoir operations, evapotranspiration, the behaviour of the unsaturated zone, lateral subsurface flow, and multiple surface flow routing methods. With the Python-based HydroMT-Wflow tool, creating and parameterizing *wflow_sbm* models for any catchment area becomes straightforward (Eilander et al, 2023). This tool leverages globally available datasets to extract river morphology (such as river networks, flow directions, and river width) and uses (pedo)transfer functions and scaling rules to derive parameter values (Imhoff et al., 2020).

In Drammen, *wflow_sbm* was tailored with local data and global datasets to represent both large-scale patterns and fine details (including reservoirs). It runs at a high spatial resolution (1 km) like LISFLOOD/HBV and is linked to the RIBASIM water allocation model (see section 5.3.2) in one of the Drammen modelling chains and in the workflows of the Rhine and Danube. For the Rhine basin and Danube, we have made use of models that have been created in previous projects. For the Danube this was the EU DOORS project.

The *wflow* model brings the advantage of flexible open-source code and an easy integration with water management, water demand and groundwater modules. As such the *wflow*-Ribasim integrated application of *wflow_sbm* and Ribasim, applied in the STARS4Water project for the Rhine and Danube basin (see in the Appendices for more details) together is essentially part of a novel approach to combine hydrology with water allocation and use, enabling simulation of natural flows and human impacts in one framework.

GRSD Hydrological Model – extended with the influence of Reservoir Management

The STARS4Water team implemented the *GRSD hydrological model* to enhance its capabilities to simulate the Seine's hydrology influenced by reservoir operations and to enhance model robustness through a multi-variate calibration strategy that provided more spatially coherent simulations under climate change. The GRSD model is originally a semi-distributed rainfall–runoff model and is built on INRAE's GR4J model. Crucially, in the STARS4Water project, the model was adapted to include the four major reservoirs that regulate the Seine, Marne, Aube, and Yonne rivers. As such, the new GRSD modelling framework allows users to directly simulate the influence of different strategies for reservoir management on river flows downstream, with focus on the impacts during low flow periods. Historical reservoir operation data (filling curves, release rules) were considered within the model structure: for example, when reservoir storage nears capacity, the model increases downstream flows (simulating controlled releases or overflows), and when reservoirs are low, it limits outflows to mimic real low-

flow augmentation policies. The modelling approach was co-designed with stakeholders from EPTB Seine Grands Lacs to ensure it captured actual operations. A multi-criteria calibration was performed using observed flows at key points (including Paris and other downstream river sections of each reservoir) to fine-tune both natural hydrological parameters and operational behaviour. It comprised a multi-variate calibration strategy with an extra constraint on evapotranspiration, highlighting its effect on reducing biases in the flow regime toward the end of the dry season. The advantages of a model with higher spatial robustness and more coherent flux patterns for simulations under contrasted hydroclimatic conditions were demonstrated. In essence, the GRSD model provides a one-stop simulation tool for exploring the Seine's water cycle under human influences from reservoir management, enabling analysis of scenarios such as "How would a half full water reservoir storage in the beginning of the summer period, due to a drier winter/spring season, for instance, affect reservoir releases up to Paris during the summer low flow period?" The model is setup to run on a daily timestep at sub-catchment scale, covering the ~43,800 km² basin up to the Seine River in Paris. It has been validated against historic data, giving stakeholders confidence to use it for forward-looking planning and as the basis for further modelling improvements.

MODFLOW groundwater model

MODFLOW is a widely used, open-source computer code developed by the U.S. Geological Survey that uses the finite-difference method to simulate and predict groundwater flow in aquifers. An updated MODFLOW model was developed to cater to all groundwater bodies in the central part of the Duero basin. This represented an improvement over the existing models, which only covered individual groundwater bodies in an unintegrated manner, even though there is existing hydraulic connectivity among them. The updated model was intended to provide inputs for data-driven tools as well as to act as a baseline to validate machine learning models for long-term aquifer evolution.

The groundwater model follows a conventional approach based on the development of a conceptual hydrogeological model and calibration/validation under steady- and transient-state conditions. Historical data from the 1990s to present was used to this purpose. The enhanced MODFLOW groundwater model thus captures long-term aquifer dynamics and fluctuations. Long-term calibration contributes reliable simulation and improved predictive accuracy for future groundwater management scenarios.

An additional methodological contribution of the model relates to the participation of stakeholders in the development of modelling scenarios and predictions. To ground the model in realistic future conditions, stakeholders were first presented with targeted questionnaires designed to capture their primary concerns and regional insights. Following this initial data collection, stakeholders participated in a collaborative workshop to directly evaluate and rank the likely drivers for change, such as socio-economic developments, land-use shifts, and climate impacts. The qualitative insights gathered from these discussions were subsequently translated into quantitative, spatially distributed hydrological stress parameters—specifically pumping rates and aquifer recharge values. This systematic translation of stakeholder input allowed for the development of a comprehensive envelope of plausible what-if scenarios, ensuring that the resulting MODFLOW model serves as a robust, socially validated decision support tool.

Other hydrological models

The following models are mostly in the scientific research domain and not used by river basin organisations for their planning or water management. Instead, the models were used in STARS4Water analyses at the EU level and for ML model development (see Chapter 5) and analyses purposes.

LISFLOOD-EUROPE

LISFLOOD is a grid-based hydrological model designed to simulate rainfall-runoff-routing processes across large river basins at regional, continental, and global scales (Burek et al 2013). The model accounts for various hydrological processes, including surface and subsurface water flow, groundwater storage, and interactions with lakes and reservoirs. It transports water both horizontally and vertically through the landscape and soil, making it suitable for complex hydrological studies. LISFLOOD serves as the core model for operational flood and drought forecasting systems, including the European Flood Awareness System (EFAS), the Global Flood Awareness System (GloFAS), and the European Drought Observatory (EDO) and it also integrates water demand from multiple sectors, including irrigated agriculture, and is being further developed to incorporate crop yield and energy production.

Model outputs from the LISFLOOD-Europe model, including simulated snow water equivalent (SWE), were used as the input dataset to validate the transfer learning and upscaling process of the ML models developed in WP4 (Task 4.4). We applied a fine-tuning process to the ConvLSTM model trained over the Drammen River Basin to predict daily SWE in the Alps region. In addition, the outputs from LISFLOOD-Europe were used to perform an inter-comparison of multiple large-scale models (WP3 – Task 3.3) to assess model strengths and limitations in simulating different hydrological variables over Europe.

Community Land Model (CLM)

The *Community Land Model* (CLM) is a physical land surface model that simulates the hydrological cycle over land by considering interception of water by plants, throughfall, infiltration, runoff, soil water and accumulation and melting of snow (Kollet and Maxwell, 2006; Maxwell, 2013). The CLM is available through the National Centre of Atmospheric Research (NCAR) as part of the Community Climate System Model (CCSM). The CLM version 3.5, used in this study, considers an update surface dataset (Lawrence and Chase, 2007), an improved canopy, integration scheme, scale canopy interception, a simplified TOPMODEL-based runoff model, a groundwater model and a new frozen soil scheme. Given that CLM is a physical-based model, no calibration procedure is necessary to reproduce hydrological patterns in a river basin. However, errors associated with the modelling process can be handled with data assimilation procedures. For instance, Naz et al. (2018, 2020) developed a 3km spatially and temporal reanalysis to 2000 to 2015 over Europe, using data assimilation techniques to correct soil moisture data.

CLM model outputs were not used to develop any ML model in WP4 and WP5. Instead, this model was considered in the inter-comparison of large-scale models performed in (WP3 – Task3.3)

Parflow

Parflow is a parallel fully coupled model that uses partial differential equations (PDE) to simulate variably saturated groundwater flow and overland flow (Kollet and Maxwell, 2006; Maxwell, 2013). The variably saturated subsurface flow is calculated with the Richards equation, and the kinematic wave equation is applied to calculate overland flow. Parflow can be integrated with the Common Land Model (CLM) to represent land-surface processes like evaporation and transpiration (Dai et al., 2003). This last version is the so-called Parflow-CLM model. Considering that Parflow-CLM is a fully physical model, no calibration is required. Instead, a spin-up process is prior performed to set up the initial

condition and states into a dynamic equilibrium. Parflow-CLM has been applied from test sites to the continental scale, from sub-daily to climate time scales, and ranges from scientific research to quasi-operational use around the world (Kuffour et al., 2020; Belleflame et al., 2023).

Model outputs from Parflow, including water table depth (WTD) and soil moisture, were used to develop a ConvLSTM model to estimate daily WTD over Central Europe. The results and details about this modelling process are described in WP4 (Task 4.4). In addition, the outputs from LISFLOOD-Europe were used to perform an inter-comparison of multiple large-scale models (WP3 – Task 3.3) to assess model strengths and limitations in simulating different hydrological variables over Europe.

Terrestrial Systems Modelling Platform (TSMP)

TSMP is a fully coupled terrestrial model closing the water and energy cycle from groundwater across the land surface to the top of the atmosphere (Gasper et al., 2014; Shrestha et al., 2014). *TSMP* comprises the hydrologic model Parflow for variably saturated groundwater and surface water flow, CLM for land surface processes and the numerical weather prediction model COSMO (Baldauf et al., 2011). The models are externally coupled via the Ocean Atmosphere Sea Ice Soil (OASIS3), allowing *TSMP* to run in fully coupled mode (Parflow-CLM-COSMO) or in hydrologic offline mode (Parflow-CLM).

Model outputs from the *TSMP*, including water table depth (WTD) and soil moisture, were used as input to validate the transfer learning and upscaling process of the ML models developed in WP4 (Task 4.4). We applied a fine-tuning process to the ConvLSTM model, initially trained over Central Europe, with the objective to estimate daily WTD over the full Europe domain at a spatial resolution of 0.11 degrees. In addition, the outputs from LISFLOOD-Europe were used to perform an inter-comparison of multiple large-scale models (WP3 – Task 3.3) to assess model strengths and limitations in simulating different hydrological variables over Europe.

5.3. Improved models for better understanding of water allocation in the basins

EOPS Reservoir Operations Simulator

EOPS is a reservoir management simulation tool used in the Drammen basin to model hydropower reservoir operations. It is widely used by local stakeholders (like NVE and hydropower companies) to calculate reservoir water levels, releases, and hydropower production. In the STARS4Water project, *EOPS* is incorporated in the first Drammen modelling chain: hydrological models (LISFLOOD or HBV) feed *EOPS* with inflows, *EOPS* simulates reservoir regulation (on a weekly time-step), and then outputs (e.g. outflows) are fed back into LISFLOOD to assess downstream flow impacts. By including *EOPS*, the modelling captures realistic operational decisions – something pure hydrology models struggle with. Notably, comparisons show *EOPS* reproduces the seasonal pattern of reservoir filling more accurately than the simplified reservoir algorithms in LISFLOOD or wflow. This makes it a crucial tool for reflecting how Drammen's reservoirs are managed under various conditions.

RIBASIM Water Allocation Model

RIBASIM (River Basin Simulation) is a water allocation and planning model software package dedicated to Integrated Water Resources Management and Integrated River Basin Planning simulations developed and maintained by Deltares. The package is under continuous further development and maintenance according to official software development approaches, quality standards and testing protocols, etc. The software package can be used to build one's own model, based on a node-link network schematisation tailored to the key water features in its own water system.

In Drammen, RIBASIM is used to simulate how water is distributed and used across part of the basin, especially under scenarios of changing demands or operations. It forms the core of the Rhine, Danube and Messara modelling chain, linked with a hydrological model (in case of the Rhine and Danube with `wflow_sbm` and in case of Messara with Sacramento): the hydrological model provides natural inflows (runoff in the watershed), and RIBASIM routes these through the network of rivers, reservoirs, and demand points (such as abstractions) to evaluate outcomes. This approach is well-suited to balancing water supply, hydropower, and environmental flow needs and examining multipurpose reservoir management impacts for instance. RIBASIM requires a schematisation of the Drammen basin (river reaches, reservoir nodes, demand nodes) and can simulate operations based on rules or optimisation of demands. While still under development for Drammen (as of project year 3, reservoir simulation in RIBASIM was continuing), it represents a forward-looking tool to test various water management scenarios in an integrated way.

Ecological Risk due to Flow Alteration (ERFA) tool for better understanding of environmental flow and ecological risks in the basins

Environmental flows or e-flows refer to the quantity, timing, and quality of water required to sustain river ecosystems and the services they provide. In practice however, e-flow assessments often primarily focus on water quantity. They used to be primarily thought of as the minimum river flow necessary to sustain the river ecosystems but now it is accepted that a wider range of flow characteristics are required (e.g. minimum river discharge, flood or freshet timing, duration and timing of the low flow conditions).

The STARS4Water *ERFA tool* is a customised implementation of the Ecological Risk due to Flow Alteration (ERFA) method – a hydrology-based environmental flows screening approach originally developed for European rivers. This tool was built as an interactive R Shiny application that takes in river flow time-series for a baseline (current flow regime) and one or more scenarios (e.g. altered flows under increased abstraction or climate change). It then computes a comprehensive set of 70 flow indicators (covering high flows, low flows, flow variability, seasonal timing, and stream intermittency) for each scenario and compares them to baseline. If a scenarios indicator deviates from baseline by more than a threshold (default 30%), that signals a significant hydrological alteration. The ERFA tool summarizes results in a simple “traffic-light” risk classification: it assigns each scenario an overall ecological risk class (Low/Medium/High) based on how many indicators changed beyond the threshold and risk classes in sub-categories (high-flow, low-flow, etc.). The output is visualised in a user-friendly dashboard format – for each river site, a table shows coloured ratings for the scenario’s impact overall and per flow component (blue = no change, green = low risk, amber = medium, red = high risk). Crucially, the ERFA tool in STARS4Water operates at a daily time step (versus monthly in earlier versions) and includes new metrics to handle intermittent rivers (i.e. frequency and duration of zero-flow periods), a key need in East Anglia where many chalk streams and fenland drains cease to flow in dry months. In practice, the East Anglia team is using the ERFA tool to screen how future scenarios (like climate-driven drought or increased irrigation abstraction) might alter the natural flow regime and thus pose ecological risks to rivers such as the River Wensum or the Bedford Ouse. Also, the Drammen, Rhine and Seine basins experimented with the tool. The ERFA tool enables regulators and planners to quickly flag “hotspots” of flow alteration requiring attention – essentially providing a science-based health check of river flows under different conditions.

5.4. Key takeaways on integrated modelling frameworks

The new data services in STARS4Water delivered integrated river basin management modelling frameworks that focus on low flows, water scarcity and droughts and integrate hydrology, water allocation and use, reservoirs and ecological flow assessment.

The project team and the stakeholders identified the following key strengths of STARS4Water products:

- Captures interactions across the holistic water system.
- Supports scenario and trade-offs analysis.
- Strong stakeholder relevance.
- Many workflows transferable to other basins.

Based on experiences during project execution and feedback from stakeholders, the main limitations are:

- Medium to high data requirements.
- Significant validation and/or calibration effort.
- Cross-boundary data harmonization is challenging.
- Long-term maintenance requires expertise.

The above results in the following recommendations from the STARS4Water project for further use and uptake:

- Develop modular model chains.
- Document assumptions and validation and calibration strategies.
- Prioritize stakeholder-driven use cases.
- Plan for long-term ownership and training.

6. Next generation modelling framework - part 2: Innovative data-driven modelling tools and machine learning applications

6.1. Introducing ML models for better understanding of (geo-)hydrology and water use in river basins

Over the past ten years, the use of artificial intelligence (AI) has increased dramatically due to notable advancements in machine learning techniques. AI is becoming increasingly essential to complicated fields like water availability evaluations and analysis, where the difficulties of data intensity, system complexity, and decision uncertainty call for innovative solutions, as computational processing capability continues to advance. To bring this to the attention of river basin managers, STARS4water explored and demonstrated how different machine learning approaches, such as Long Short-Term Memory (LSTM) networks and Random Forest (RF), can exploit outputs from physically based models (see section 4.2) to downscale water table depth anomalies (WTDA), estimate snow water equivalent (SWE), and predict groundwater storage changes (GWSC), in the Seine, Drammen and Duero River Basin, respectively. For the Rhine basin a data-driven model was developed to identify the irrigated area of the Rhine basin leveraging earth observation land surface temperature data combined with hydrological modelling. Using observed data, LSTM and RF type models were developed to predict reservoir variables at daily and monthly timesteps in the Duero, Seine and East Anglian basins.

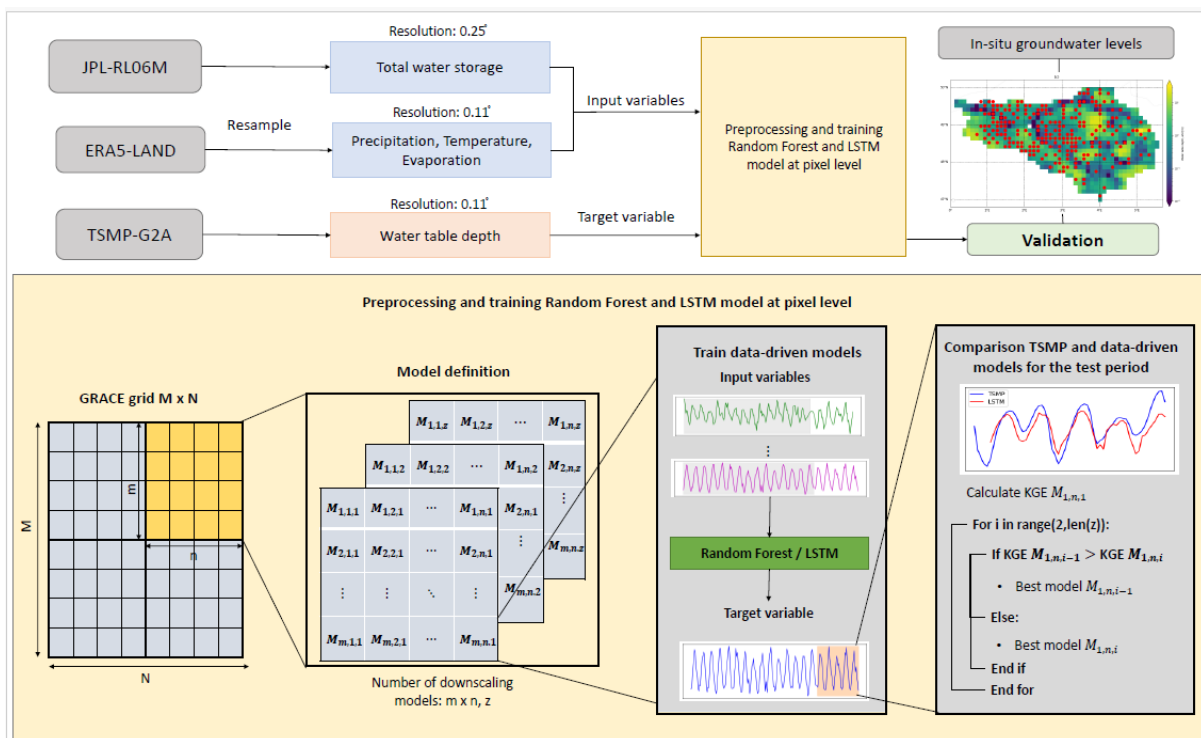


Figure 7. Framework of GRACE TWSA downscaling based on Terrestrial Systems Modelling Platform (TSMP) and Long Short-Term Memory (LSTM) network. The model considers Jet Propulsion Laboratory Release 06 (JPL-RL06M) of the GRACE data processing and ERA5-Land data to obtain the main meteorological variables. (Avila et al., 2025).

These new innovative data-driven models (an example is given in Figure 7) provide a way to bridge the gap between observational limitations and high-resolution process simulations, offering scalable solutions for water resources management. To support this process, this chapter ends with a SWOT analysis to reflect on the new data-driven models based on experiences, findings and observations in the project.

6.2. ML snow water equivalent

In the Drammen River Basin, STARS4Water developed a machine-learning (ML)–based tool to estimate *Snow Water Equivalent* (SWE), addressing the critical role of snowpack as a natural water reservoir in snow-dominated river basins. Accurate SWE estimation is essential for hydropower production, reservoir operation, and seasonal water availability forecasting, especially under changing climate conditions.

The ML approach builds on a Convolutional Long Short-Term Memory (ConvLSTM) framework, which is well suited to capturing spatio-temporal dependencies in gridded hydro-meteorological data. The model integrates spatial information (such as elevation and topography) with temporal drivers including temperature, precipitation, and observed or simulated SWE, allowing it to learn both seasonal snow accumulation and melt dynamics. This enables estimation of SWE at finer spatial detail while preserving physically meaningful patterns across the basin.

Application in Drammen showed that the ML-based SWE tool can reproduce seasonal snow dynamics and broad spatial patterns, with stronger performance in mid-elevation zones and lower accuracy in highly mountainous areas where snow processes are more complex. While peak SWE values in high-altitude regions tend to be underestimated, the tool consistently captures the timing of accumulation and melt, which is particularly relevant for operational water management.

The SWE ML tool is positioned as a supportive forecasting and diagnostic instrument that could be used in other basins as well. It complements hydrological models by providing rapid, spatially explicit insight into snow storage dynamics, supporting scenario exploration, seasonal outlooks, and dialogue with hydropower and water managers. The approach is especially valuable where observational coverage is limited or where rapid assessment of multiple future conditions is required.

The trained ConvLSTM model was also transferred and upscaled to other regions, including Norway, Alps and the Rocky Mountains (US). The objective of this transfer and upscaling was to assess the model's ability to generalize beyond the Drammen River Basin and to produce reliable daily SWE estimates in regions with different climatic conditions. More details about the upscaling process are described in WP4 (Task4.4) and WP5 (Task5.2), respectively.

6.3. DL water table depth

Within STARS4Water, a deep learning (DL)–based tool was developed to estimate *water table depth* complementing the physically based hydrological and land surface models applied in work package 3 of the STARS4Water project. Rather than simulating absolute groundwater levels, the tool can be also used to estimate deviations from long-term mean conditions, allowing a consistent comparison of dry and wet periods across spatial scales. For this case, a ConvLSTM model was trained to estimate water table depth and water table depth anomalies over Central Europe.

The ConvLSTM tool is trained using outputs from Parflow model described in work package 3 from STARS4Water, capturing non-linear relationships between climatic drivers, surface hydrology, and subsurface water storage dynamics. This enables efficient estimation of water table anomalies under historical and scenario conditions, particularly in regions where explicit groundwater model representations remain highly uncertain or data-intensive.

By design, the tool does not replace process-based groundwater modelling. Instead, it provides a computationally efficient layer that supports rapid diagnostics of groundwater stress, spatial pattern analysis, and cross-model consistency checks within the multi-scale modelling framework of STARS4Water.

The ConvLSTM model was later upscaled to other regions including full Europe and United States, using simulated data derived from TSMP and Parflow-CONUS, respectively. The results indicate that the proposed data-driven approach can well generalize the estimation of water table depth over different climatological and geographical conditions, with a reduce computational costs compared with the simulation process of pure physical and large-scale models.

6.4. ML predictive mapping of groundwater quality

MLMapper, a machine learning tool, was developed within Stars4Water for the predictive mapping of groundwater contamination. This was developed as a QGIS plugin first by the Universidad Complutense Madrid, in the context of the Duero basin, and subsequently improved by adding new regression-based functionalities in collaboration with the UK Centre for Ecology and Hydrology and project stakeholder Anglian Water in the East Anglia basin.

MLMapper provides a spatial prediction of groundwater quality variables based on a series of predictors and a ground truth database. By leveraging machine learning, the tool allows users to match known outcomes to multiple predictors simultaneously, thus providing a significant improvement on traditional approaches such as geostatistics. The identification of contamination markers allows for the delineation of affected areas at the basin scale, explain contamination trends across different boreholes, and optimize the placement of future monitoring sites. Some of these outcomes can be used as inputs for certain data-driven and process-based models.

Predictive mapping in MLMapper operates by inferring target variables, such as groundwater contamination, from indirect environmental indicators like lithology, land use, rainfall, and topography within a GIS environment. The modelling suite is rather flexible, allowing users to establish any spatially-distributed target variable—i.e. not only groundwater contamination—and any set of predictor variables. Because machine learning algorithms are highly complex, the software tests multiple supervised classification methods from the SciKit-Learn toolbox simultaneously to identify and carry out an ensemble of the best performers.

6.5. ML groundwater storage changes

In the Duero river basin, STARS4Water explored a machine-learning (ML)–based approach to estimate *groundwater storage changes* (GWSC) at spatial and temporal resolutions not readily achievable with existing process-based hydrogeological models. The motivation for this work arose from stakeholder concerns regarding the limited ability of current models to capture groundwater dynamics at sub-basin and groundwater-body scales, particularly under changing abstraction patterns and climate conditions.

Conventional process-based groundwater models in the Duero are constrained by coarse spatial resolution, structural uncertainty, and computational limitations, making them less suitable for large ensemble scenario analyses. To address these challenges, STARS4Water investigated the use of data-driven emulators that integrate information from land-surface and hydrological model outputs, local and global datasets, and local groundwater observations.

The ML workflow combines simulated total water storage components from large-scale models (notably TSMP) with in-situ groundwater level observations from the Duero monitoring network, together with static catchment descriptors, and dynamic climatic, land-cover, and socio-economic drivers. These datasets are harmonised in space and time and used to train deep-learning models capable of estimating groundwater storage changes. By focusing on relative changes, the approach supports consistent comparison across regions and scenarios, even where hydrogeological properties vary strongly.

The resulting GWSC estimates provide a spatially distributed picture of groundwater depletion and recovery patterns, supporting assessment of long-term trends and responses to climate variability and water use. The model was applied to simulate RCP4.5 and RCP8.5 regionalized climate change scenarios, showing a progressive reduction in mean storage levels, with the magnitude of the impact sensitive to the emission pathway. During the project, the model has also been successfully implemented in the Seine basin, with the aims of testing its transposability. In general, and for wider uptake, the ML-based GWSC tool is intended as a screening and exploration instrument that complements detailed hydrogeological studies. It is particularly valuable in regions where groundwater observations are sparse or where rapid evaluation of multiple future scenarios is needed to inform preparedness and adaptation planning.

6.6. RF-LSTM Groundwater Monitoring model

A data-driven groundwater monitoring tool was developed to improve the assessment of groundwater dynamics and support water resources management under changing climatic conditions. The tool focuses on estimating monthly water table depth anomalies, providing a consistent indicator of groundwater status across the basin.

The approach compares two machine learning techniques, namely including Random Forest (RF) and Long Short-Term Memory (LSTM) network. Both models are trained using satellite observations, climate reanalysis data and outputs from large-scale hydrological simulations. Inputs include GRACE-derived terrestrial water storage anomalies and ERA5-Land climate variables, while simulated water table depth from the TSMP modelling framework is used as the target variable for training. By learning the relationships between climate conditions, water storage and groundwater behaviour, the models can estimate groundwater anomalies without requiring new computationally intensive simulations.

An application in the Seine basin demonstrated that both RF and LSTM approaches can reproduce the main spatial and temporal patterns of groundwater variability. Validation against nearly 500 groundwater monitoring wells showed particularly good performance in the upper basin, where groundwater dynamics are closely linked to precipitation and surface water processes. The RF model performed slightly better overall and requires less computational effort, making it attractive for operational applications, despite the well-known low extrapolation capacity of RF models.

Within WP5, the *RF–LSTM groundwater monitoring model* is positioned as a complementary tool to process-based hydrological and groundwater models. It supports rapid assessment of groundwater stress, drought impacts and long-term changes in water availability, while providing a transferable methodology that can be applied in other river basins where satellite observations and climate datasets are available.

6.7. ML water table depth prediction and uncertainty quantification

STARS4Water also developed a machine-learning (ML)–based approach to predict Water Table Depth (WTD) at continental scale, together with a novel approach for assessing uncertainties in non-monitoring regions. The development of this study is motivated by the uneven distribution of groundwater and hydrometeorological monitoring across Europe, which limits the calibration and validation of process-based models and leaves many sub-basins and groundwater bodies without reliable estimates of groundwater dynamics, particularly under changing climate and abstraction pressures.

The proposed approach combines a set of Long Short-Term Memory (LSTM) neural networks to construct an ensemble estimation with a transfer-learning strategy that extends predictions to locations without training data, together with an ensemble-based method for quantifying prediction uncertainty.

Models were trained using hydrometeorological inputs, such as precipitation, vapor pressure deficit, and soil moisture, together with static catchment attributes such as location, slope, and soil type. Ensemble learning was implemented through bootstrap sampling of grid cells across the TSMP domain. Each sample is used to train an independent LSTM model. This design allows the spread across ensemble members to be interpreted as an indicator of confidence in areas without observations, providing a way to flag where transferred predictions are likely reliable rather than relying solely on model output.

The model was developed and tested using the TSMP dataset across continental Europe, with part of the domain deliberately withheld from training to evaluate transferability to unseen locations. Within STARS4Water, the tool is intended as a scalable screening instrument that complements process-based groundwater modelling, supporting groundwater monitoring, confidence assessment, and water management planning in regions where observations are sparse or unavailable.

6.8. RF reservoir storage modelling

Data-driven methods were used to develop reservoir storage models for predicting storage at a monthly to seasonal timestep. This was a requirement as requested by stakeholders across a few river basin hubs in STARS4Water to better assess water availability in reservoirs, and therefore allow for planning around water allocations, flood mitigation and drought planning. (Deliverable 3.1)

Ensemble-tree models were explored as an option for predicting reservoir storage in both simulation and forecasting modes. The models were applied to reservoirs in the Duero basin and reservoirs across the UK, including in East Anglia, and was later extended to include reservoirs in the Seine. The approach was implemented in two ways; firstly, by building individual models for each reservoir using timeseries data specific to that reservoir, and secondly, by building a multi-reservoir model which uses timeseries data for all the reservoirs included (including those received from stakeholders), as well as reservoir and catchment characteristics.

Both the individual and multi-reservoir models showed potential for predicting reservoir storage at a monthly timestep. The multi-reservoir model generally simulates reservoir storage well across a range of reservoirs at 1 and 3 months. Initial analysis of the multi-reservoir model in forecast mode was undertaken, with promising results shown for reservoirs in the UK driven by the Met Office's Historical Weather Analogue ensemble forecast. As such, both models support the management of water across monthly to seasonal timescales, providing a state-of-the-art approach to aid reservoir storage management.

6.9. ML irrigated agricultural area and demand

STARS4Water also developed a machine-learning (ML)–based tool to improve the estimation of irrigated agricultural areas and associated irrigation water demand. The development was motivated by stakeholder needs in the Rhine_river_basin, where reliable spatial information on irrigation is often scarce, while irrigation is becoming an increasingly important component of summer water demand. The tool supports improved quantification of agricultural water use and provides input for integrated water resources management assessments.

The approach combines distributed hydrological modelling with Earth Observation data. Estimates of actual evapotranspiration generated by the wflow_sbm model are linked to MODIS land surface temperature (LST) observations. Irrigation affects the surface energy balance through additional evapotranspiration, which influences land surface temperature. Differences between modelled and observed LST therefore provide an indicator for irrigation activity. A Random Forest classifier is subsequently applied to identify irrigated areas at a spatial resolution of 1 km.

The model was applied across the Rhine basin for the period 2010–2019. Irrigation hotspots were identified in the Alsace region, the Lower Rhine near Düsseldorf, and the Main region around Darmstadt and Rheinhessen-Pfalz. The resulting irrigated-area maps were used to estimate irrigation water withdrawals from surface water and groundwater sources, as well as consumptive water use through evapotranspiration.

Validation against agricultural statistics showed good agreement with observed irrigation patterns, with coefficients of determination (R^2) ranging between 0.79 and 0.90. The approach was found to perform particularly well in temperate regions because it explicitly combines hydrological processes with satellite observations. Within STARS4Water, the tool complements process-based hydrological and water allocation models by providing spatially explicit information on agricultural water demand, supporting water resources assessments under current and future conditions. The tool is available for upscaling to other basins.

6.10. Key takeaways on data-driven modelling and machine learning

An important finding from researchers and stakeholders in the STARS4Water project is that the new machine learning approaches and data-driven model have proven to be fast, scalable tools complementing process-based understanding.

The project team and the stakeholders identified that the STARS4Water tools have the following key strengths:

- Fills monitoring and modelling gaps
- Computationally efficient
- Suitable for rapid scenario exploration
- Highly transferable between regions.

Based on experiences during project execution and feedback from stakeholders, the main limitations of the tools are:

- Performance depends on training data
- Less robust outside historical conditions
- Can be difficult to interpret
- Validation remains essential

The above results in the following recommendations from the STARS4Water project for further use and uptake:

- Use ML alongside process-based modelling
- Quantify and communicate uncertainty
- Apply explainable AI approaches
- Provide guidance and user training

7. New co-created decision support and communication tools

7.1. Introduction

Co-created decision support and communication tools were developed to support the presentation and dissemination of information of projects on policymakers, stakeholders and the wider public:

1. Impact Reporter Tool for narrating historic events to policy makers and the wider public and structuring unstructured information on the impacts of historical extreme events and related response measures aimed as a source for scientific analyses (<https://ir.stars4water.eu/>).
2. Story Maps Tool for communicating future scenarios to that combines maps, model results and explanatory narratives to present basin-specific future climate and water-related risks in an accessible format for policymakers, stakeholders and the wider public.
3. Dashboards – two level of dashboards were developed to present and explore the project results.
 - a. STARS4Water’s river basins generic dashboard provides basic, practical information on the seven river basin hubs and the expected water-related changes in each basin, while also enabling cross-basin comparison across the basins. General indicators (Tier 1 and Tier 2) are based on global data sets and did not specifically require indicators that are based on combining local datasets or local modelling results. Their needs would be met by being able to display more global data with a lower specificity, as often other information systems already exist in these river basins, and the dashboard would just need to support these existing systems (bit.ly/stars4water-tier1).
 - b. River basin tailored dashboard designed and developed based on the stakeholder needs in the selected river basin in a co-creation process with stakeholders and research focal points of the consortium for the basin. The dashboard contains river basin specific indicators (Tier 3), which are generated from local datasets and local modelling results. To co-create the tailor-made river basin, a co-creation workshop with the stakeholders will take place to co-design the dashboard considering the specific needs of the stakeholders. The tailor-made dashboard is developed for Drammen (<https://bit.ly/nve-stars4water>). This process and product are leading examples for other basins.

7.2. Impact Reporter Tool

The [STARS4Water Impact Reporter](#) is an interactive web-based platform designed to document, analyse and share information on the impacts of historic extreme events, including floods, droughts, storms and heatwaves. It is a simple repository of events and impacts for future analysis. Rather than focusing on future scenarios, the platform captures real-world experiences from past events, providing a structured documentation of knowledge on their consequences and the measures implemented in response.

The platform enables users to report and explore a wide range of impacts, including biophysical, social and cultural, economic, and health-related effects, alongside information on emergency response, mitigation and long-term adaptation measures. Users can search and compare events through interactive maps, filters, analytics and event fact sheets, allowing them to identify common patterns, assess vulnerabilities and examine how different management approaches have performed under similar conditions.

More than a database, the Impact Reporter functions as a collaborative knowledge-sharing platform that supports vulnerability and risk assessments by making impact information accessible, structured and comparable. By enabling stakeholders to learn from previous events and exchange experiences across river basins, it contributes to evidence-based planning, strengthens the STARS4Water Community of Practice and beyond, and supports the development of more resilient and adaptive water management strategies.

7.3. Story Maps Tool

A *Story Map* is an interactive web-based narrative communication tool, combining maps, text, images, and other media to tell a story based on the co-creation journey of the basin within the STARS4Water project (Figure 8). For example, in the Danube basin, the project is using the Story Map to present the narrative of drought and low flows under various scenarios. This means distilling the complex model results and risk analyses into a more story-like format that can be browsed by stakeholders and the general public. The Story Map walks the reader through the basin's context, the challenges of water scarcity, how climate change and water demand scenarios could alter snowmelt, droughts, flows and riverbed erosion. It also indicates what the implications are for people and ecosystems, all illustrated with maps, tables and charts, modelling results and alongside explanatory text based on indicators that have interest of stakeholders. The Story Maps incorporate results of the risk assessments and analyses done in STARS4Water under work package 4, effectively humanising the data to ensure they are accessible for non-technical stakeholders. Created with a common methodology each STARS4Water river basin has a Story Map tailored to its key issues, ensuring local relevance while following a coherent approach. The aim is to provide an accessible, engaging summary of “what might happen” supporting awareness and discussion beyond the technical community (Klösch et al., 2026).

- **[Danube](#) – Drought water conditions under climate change:** discover how drier conditions and glacier retreat could affect navigation, ecosystems, hydropower and other water uses, and how targeted management measures could strengthen resilience.
- **[Drammen](#) – Balancing future water, energy and ecosystems:** explore how changing runoff and seasonality could reshape hydropower production, ecological conditions and the trade-offs between different water-management objectives.
- **[Duero](#) – Groundwater beneath your fields:** see how climate and human pressures are affecting groundwater in this agriculturally important basin and how improved data and modelling can support more adaptive management.
- **[East Anglia](#) – Drier future for wildlife, but action can help:** examine the growing pressures on water for wetlands and rivers and the measures that could help protect environmental water requirements.
- **[Messara](#) – Basin under water pressure:** explore how groundwater over-abstraction, high irrigation demand and climate change are shaping water scarcity in Crete's largest agricultural plain—and the alternative pathways that could improve its resilience.
- **[Rhine](#) – Navigating water scarcity in a changing climate:** explore how climate and socio-economic change could intensify summer water scarcity and trade-offs among domestic, industrial and agricultural water uses.
- **[Seine](#) – The future of low-flow management:** discover how climate change and different reservoir management strategies could influence low flows and water availability along the Seine.

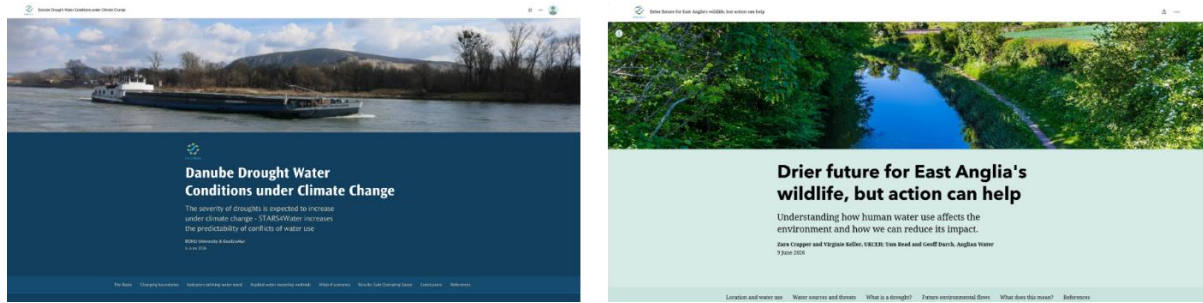


Figure 8. Story Maps delivered by STARS4Water – examples of the Danube and East-Anglia river basins (Klösch et al., 2026).

7.4. STARS4Water's river basins generic dashboard

The [STARS4Water's river basins generic dashboard](#) is an interactive web-based platform designed to make complex data and model outputs accessible to stakeholders (Figure 9). This dashboard was co-developed between Deltares and research representatives for the 7 river basin hubs in a series of workshops. It features a two-tier structure: Tier 1 and Tier 2 present high-level indicators using global and regional datasets for context (comparing the individual basins among each other). (See Section 4.3). Through the dashboard, users can visualize current conditions, trends, and future projections (e.g. modelled river flows, reservoir levels, drought indices) via maps, graphs, and charts. The co-development approach, which included prototyping and validation workshops, ensures the interface and content support in leveraging the datasets from the metadata portal. The dashboard is not just a technical tool to make datasets from the metadata portal visual accessible, but it is also a decision-support platform aiming to foster a shared understanding among stakeholders by presenting data in an intuitive way and make benchmarking of own river basin against other river basins possible based on same identical global to European datasets.



The collaborative project funded under the Horizon Europe Framework Programme that aims to improve the understanding of climate change impacts on water resources availability and the vulnerabilities for ecosystems, society and the economy at river basin scale. STARS4Water will develop and deliver new data services and data driven models for better decision-making support on planning actions for adaptive, resilient and sustainable management of fresh water resources, which will be co-designed with stakeholders to meet their needs, ensuring their relevance and uptake beyond the lifetime of the project.

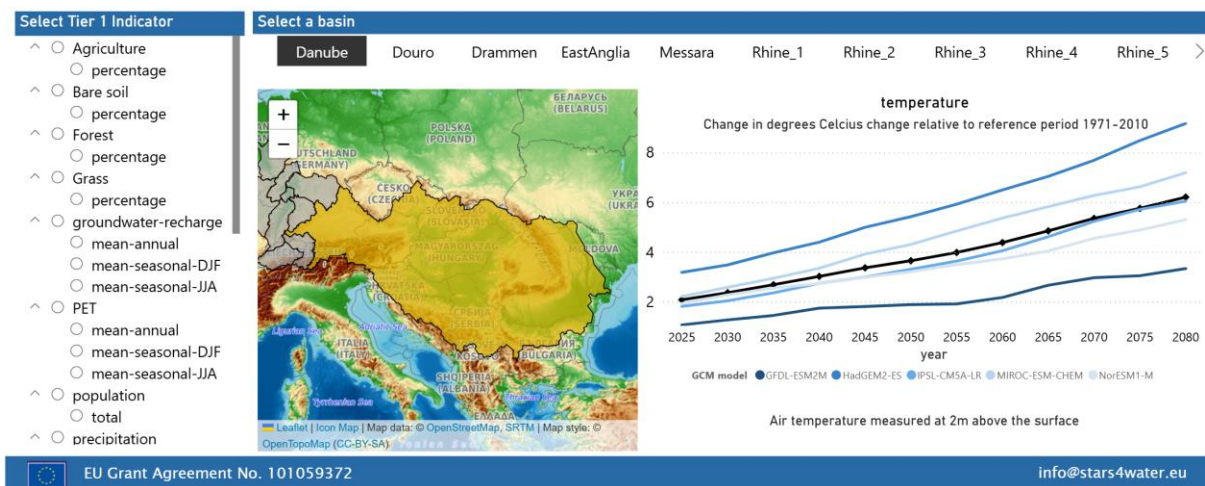


Figure 9. Generic dashboard delivered by STARS4Water (Edler & Mes, 2024)

7.5. River basin tailored dashboard – the Drammen case

The [STARS4Water Dashboard for Drammen](#) is an interactive web-based platform designed to make complex data and model outputs accessible to stakeholders (Figure 10). This dashboard was co-developed between the Drammen team and Deltares in a series of workshops. It features a three-tier structure: Tier 1 and Tier 2 present high-level indicators using global and regional datasets for context (comparing the Drammen basin with broader benchmarks), while Tier 3 zooms into detailed, local results driven by the institutionalized models for Norway. Through the dashboard, users can visualize current conditions, trends, and future projections (e.g. modelled river flows, reservoir levels, drought indices) via summary table, maps, graphs, and charts. The co-development approach — including prototyping and validation workshops — ensures the interface and content meet local needs and preferences. The dashboard is not just a technical tool, but a decision-support platform aiming to foster a shared understanding among stakeholders by presenting data in an intuitive way.

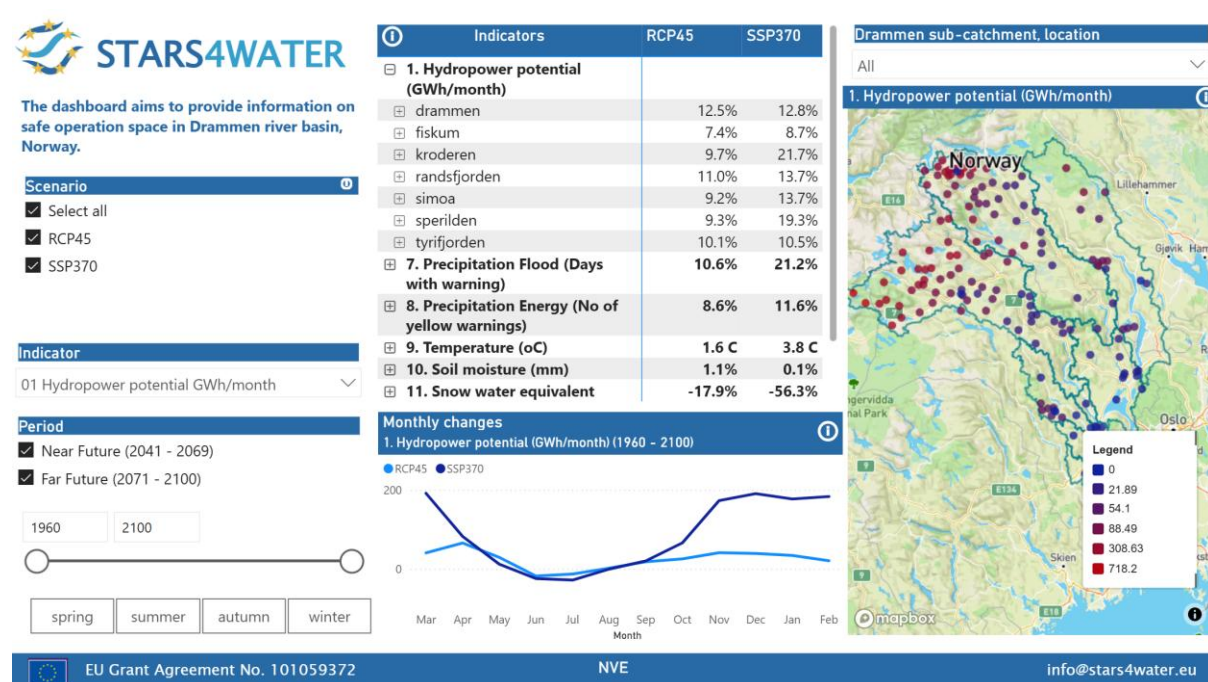


Figure 10. Tailor-made dashboard for the Drammen River Basin delivered by STARS4Water (Hermawan et al., 2026).

7.6. Key takeaways

STARS4Water delivered dashboards, Story Maps, an impact reporter tool and accompanying guidance material (for example in the STARS4Water academy and reports) to support decision-making and communication on the results of the project.

The project team and the stakeholders identified the following key strengths of STARS4Water products:

- Supports stakeholder engagement.
- Makes complex results accessible.
- Facilitates evidence-based dialogue.
- Balances basin-specific and generic insights.

Based on experiences during project execution and feedback from stakeholders, the main limitations are:

- Resource-intensive development process.
- Dependence on underlying data quality.
- Risk of oversimplification.
- Maintenance and updates are required.

The above results in the following recommendations from the STARS4Water project for further use and uptake of STARS4Water products and methods:

- Design around user needs and decisions.
- Clearly explain assumptions and limitations.
- Establish ownership before project closure.
- Include training and supporting guidance.

8. Guidance on selecting data services and modelling approaches

8.1. Introduction

This chapter synthesizes the experiences gained and lessons learned throughout STARS4Water on the tools developed, and provides guidance for selecting appropriate modelling frameworks, including datasets and data-driven components. The guidance is intended to support the river basin stakeholders involved in the project but also the wider community seeking to develop or improve their water resources management and assessment capabilities. The chapter introduces the delivered modelling frameworks first and then reflects on the experiences gained for further applicability and use, arriving at a framework that can support practitioners and stakeholders in other basins that are in the process of improving their modelling frameworks. The chapter ends with some general cross-cutting lessons for uptake, transferability and long-term sustainability, as well as final remarks.

8.2. Detailed overview of delivered modelling frameworks in the 7 river basins

For each river basin hub in the STARS4Water project, the project upgraded the modelling framework in the river basin, with a focus on an update of the model data input and a more holistic scope. The new frameworks were designed around stakeholders' needs and their water management decisions, such as drought preparedness, reservoir operations, protect nature, navigation, groundwater management and/or water supply, rather than from the technical model side itself. Modelling chains were extended, adapted or replaced for hydrology, water allocation and use, reservoir management and/or ecological flow modelling and combined with ML and data-driven components and/or a dashboard. The adjustments in practice depended on basin context and data availability and covered various modules (with crossovers between basins).

In the ANNEXES, detailed presentations of these delivered frameworks are presented per river basin, describing:

- What are the target water types and water bodies?
- What are the novel digital methods, tools and solutions?
- What is the geographical coverage / implementation of the solution?
- What are the main findings about enabling conditions or limiting factors related to deployment, scaling, or uptake of these tools/methods?
- What re-usable modules/tools, guidance, open-source solutions will remain after the project ends?
- What data collected and generated by the project?
- What has been reported by the modelling framework in the project?
- What are relevant references to literature?

During the execution of the project the frameworks are employed to generate projections of water resource availability and to support Safe-Operating-Space assessments for each STARS4Water's River Basin Hub (RBH), using the analytical framework described in Deliverable 5.2. The outcomes of these assessments are presented in Deliverable 4.2. The resulting new datasets are archived on Zenodo.

In many instances, the frameworks are also presented in a scientific context through publication in peer-reviewed journals. One such outlet is the STARS4Water special issue of the *International Journal of River Basin Management* (IRBM) (Martínez-Santos, 2026).

Long-term sustainability of these frameworks requires clear agreements on hosting, data updates, technical maintenance, licences, documentation, user training and institutional responsibility. The STARS4Water exploitation plan (separate deliverable under WP6) addresses this further.

8.3. Some reflections on the delivered frameworks, their applicability and conditions for use

A key requirement of the developed and enhanced data-services and tools in STARS4Water was that they should have the potential to be applied outside of the river basin hubs of the project, therefore providing a suite of tools supported by new data services for use by water practitioners managing the supply and demand in river basins across Europe, and potentially across the world.

Fulfilling this requirement has already been demonstrated within the project; the development and application of a Ribasim water allocation model in the Rhine, Danube, and Messara basins not only highlights the usefulness of open model software packages and the versatility of the model being modified, but also how the application of such models can be successful in terms of better understanding dependencies across watersheds and international borders. The Ribasim Rhine model updates have also led to transfer and uptake of the modelling approach, along with wflow_sbm or Sacramento, in the Danube and Messara basins, respectively, where a basin-wide water resources model within a new modelling framework was requested by stakeholders. As indicated by the Story Map for the Meuse River basin, built to showcase transferability of the STARS4Water approach to river basins other than the ones in the project, it is clear that developments can also be picked up by other river basins outside of STARS4Water.

The environmental flows tools that have been developed in the project were an advancement on work already applied internationally. A further refinement, developed using the East Anglian as the development case, has expanded its scope in meeting key indicators across different climatic zones, and for different aquatic species. Special focus has been given to better capture the impact of intermittent streams on riverine ecology due to requests from stakeholders in East Anglia. This is especially pertinent given the magnitude and global extent of alteration to natural flow regimes and the implementation of riverine infrastructure. The new generation EFRA tool has already been applied for assessments in the Seine, Drammen and Rhine rivers in addition to East Anglia within the project.

New data services and global to local data collection supported the improvement of the data input for (new) hydrological and environmental flow models, that are interlinked with the water allocation models. The improved accuracy of the models, as developed within STARS4Water, expands its scope and applicability to users with different needs and priorities around understanding the hydrological cycle and water resources management.

Similarly, the data-driven model developments in the Duero and Seine have driven forward innovative ML approaches in better understanding interactions of groundwater and surface water (GW/SW), a key area if water resources are to be accurately quantified and forecast. The approaches are applicable to other basins where groundwater/surface water interactions were flagged as priority topics, with the potential to supplement their current modelling frameworks.

Furthermore, data-driven modelling tools for groundwater quality assessment developed and validated in the Duero basin have been successfully transferred and applied to the East Anglia aquifer system, demonstrating their portability and methodological robustness across distinct hydrogeological settings. The transferability assessment focused on nitrate as the target groundwater quality indicator, employing both regression and classification machine learning approaches to predict nitrate

concentrations and identify areas at risk of exceeding regulatory thresholds. The models were trained and validated using basin-specific datasets while maintaining a common methodological framework, enabling the evaluation of their generalisation capability under different environmental and hydrogeological conditions. Successful implementation in the East Anglia case study confirms the scalability of the developed data-driven methodologies and their potential for application in diverse groundwater management contexts, supporting evidence-based assessment of groundwater quality and nitrate pollution risk.

Beyond the basin-specific applications, Task 4.4 and Task 5.2 demonstrated that the machine learning tools developed within STARS4Water can be transferred and upscaled to pan-European and even global domains. Different machine learning and deep learning approaches demonstrated good performance when they are transferred and validated to other regions over Europe, even without require additional training process. These main implication of those results at the European level indicate that STARS4Water's data-driven tools are not limited to the seven river basin hubs but can provide a scalable, and general tools to support water resources assessments, including basins with sparse monitoring networks or without existing process-based models. This is particularly relevant for supporting pan-European policy frameworks, where consistent, comparable indicators across basins and member states are needed.

As demonstrated from the examples here, the modelling frameworks, data services and tools developed hold relevance for river basins outside of STARS4Water and at EU level. The improvements in modelling chains, model functionality and process representation described in this report are largely transferable in scope and nature, and it is hoped that their implementation through STARS4Water and this guidance will encourage the uptake of these tools by other river basins and researchers alike. To support further uptake, we provide support for selecting suitable STARS4Water products in the next section.

8.4. Support for selecting suitable modelling approaches

The STARS4Water results confirm that no single model, data service or modelling framework is suitable for all river basin contexts. The selection and combination of appropriate modules and tools depend on the characteristics of the water resources system, the management question, data availability and quality, and the institutional setting.

The guidance in the table below is intended to support river basin managers, modellers and other practitioners when establishing, improving or adopting an integrated modelling framework for their own basin. Table 9 mentions 7 evaluation criteria; each criterion is accompanied by a guiding question that can help structure the decision-making process and identify suitable data services, models or frameworks developed in projects like the STARS4Water project. It also summarises points to consider during the process of answering these questions.

It is not intended as a prescriptive checklist, but as a practical source of inspiration to support reflection, comparison and informed decision-making when exploring the most suitable approach for a specific river basin context.

Table 9. Guidance for selecting a suitable modelling approach.

Criterion	Key decision question	Things to consider
1. Problem relevance	Does it solve my core problem in my basin?	- Key local issues: e.g. drought, flood, water scarcity, groundwater, glacier melt, ecology - Problem–solution match - Basin characteristics: size, climate, socio-economic conditions
2. System coverage	Does it include the relevant processes and sectors in my basin?	- Natural processes: runoff, groundwater, snow, etc. - Management processes: water allocation, reservoirs, abstraction - Sectoral relevance: agriculture, hydropower, navigation, ecosystems, and/or other
3. Integration	Does it capture the system (physical aspects and operations) and its interactions in a sufficient holistically way for my basin?	- Integration of: * Hydrology + water use + infrastructure * Surface water + groundwater - Coupling of multiple models or tools - Ability to represent interdependencies across sectors
4. Scenario capability	Can it support my future operations and strategic planning?	- Ability to run: * Climate scenarios * Socio-economic/water demand scenarios * Management strategies - Support for risk assessment and planning, operational or strategically - Alignment with Safe-Operating-Space (SOS) or similar concepts
5. Data and capacity feasibility	Can I run it with available data and capacities in my basin?	- Data needs (climate, hydrological, socio-economic) - Dependence on local vs global datasets - Complexity of data preparation and processing - Availability of supporting data platforms (e.g. makes use of STARS4Water metadata portal, STARS4Water Zenodo, Github, etc.)
6. Robustness & credibility	Does it produce robust, reliable and scientifically credible results for decision-making?	- Calibration and validation performed - Reported model performance - Handling of uncertainty (scenarios, limitations) - Transparency about strengths/weaknesses
7. Usability & uptake	Can we (easily) adopt and sustain it?	- Ease of use for practitioners (interfaces, documentation) - Availability of: * Guidance * Training (e.g. STARS4Water Academy-type support) * Decision support tools (dashboards, Story Maps) - Transferability to other basins (flexibility vs bespoke design) - Maintenance, help desk support and operational, governance and financial embedding

8.5. Crosscutting lessons for uptake, transferability and long-term sustainability

As presented in this report, STARS4Water project has delivered a diverse portfolio of data services, modelling frameworks, data-driven tools and decision-support products across seven river basin hubs. The main categories are mentioned in Figure 3, while the details are described in the chapters 3-5. Although these developments differ in technical scope, maturity and basin-specific application, several common lessons emerge. These lessons can be particularly relevant for river basin organisations, stakeholders, practitioners and researchers seeking to apply, adapt or upscale STARS4Water outputs beyond the project's original case-study basins.

Lesson 1: For successful uptake of technical innovations, continuous co-creation is a necessity

Across the project, the most usable outputs were those that responded to clearly identified stakeholder needs based on management questions and decisions and continuously engaged stakeholders in the tools that were developed through iterative dialogue and co-design with basin experts. This was particularly evident for the tailored Drammen dashboard and the Messara water allocation model, where stakeholders were encouraged to discuss current and future trade-offs, in the Rhine, the Seine and the Danube integrated modelling frameworks, where stakeholders wanted to get a better understanding on the impact of water use and regulation, besides climate change, on the low flows in the rivers, and in the Duero and the East Anglia data-driven tools for better understanding of groundwater behaviour and environmental flow impacts. In all cases, stakeholder involvement helped define relevant questions to be answered, indicators, appropriate spatial and temporal scales, and meaningful scenarios to be explored. Altogether, they embraced a variety of holistic situations in water management, related to drought preparedness, reservoir and environmental flows operation, navigation risks, groundwater management or water allocation trade-offs, rather than narrowing the focus only on the technical tools.

Lesson 2: Combine global consistency with local credibility

Global, regional and local datasets serve different but complementary purposes. Global datasets and Tier 1 indicators are valuable for screening, comparison and rapid assessment, especially where local data are scarce and/or at the start of a project. However, they cannot replace locally calibrated models, basin-specific observations or stakeholder knowledge. Their greatest value is therefore as a first-order diagnostic layer, a reference tool, or a trigger for further investigation when global and local signals diverge. This can path the way for tier 2 and 3 indicator analyses that require more active involvement from stakeholders, regional and local data collection, basin-specific models and expert judgement for operational interpretation.

Lesson 3: Integrated modelling chains are key to supporting Safe-Operating-Space assessments and more holistic river basin planning

STARS4Water applications demonstrated the importance of integrated modelling chains and the added value of linking hydrological models with water allocation models, reservoir operation tools, ecological flow assessments, and decision-support or other user interfaces, in different combinations. Such integration makes it possible to assess present and future climate impacts on water availability, as well as the consequences for water use, environmental flows, hydropower, navigation, and reservoir management, depending on stakeholders' needs towards more holistic river basin planning. In this context, it is recommended to promote modular and transferable modelling chains, where components can be adapted or replaced depending on the basin's context and data availability. Workflows are designed based on local contexts and specific Safe-Operating-Space dialogue and discussions are setup to support impact assessments and decision-making in this regard.

Lesson 4: ML and data-driven models cannot alone replace process-based models

Machine learning and data-driven tools are most useful when positioned as complements to process-based understanding and models, the so called ‘hybrid’ approach in workflows or modelling chains. The ML applications developed in STARS4Water show strong potential for estimating snow water equivalent, groundwater storage changes, groundwater contamination risk, irrigated areas and reservoir storage. Their advantages include computational efficiency, flexibility and the ability to exploit heterogeneous datasets. Their credibility depends on data quality, careful validation, uncertainty communication and expert interpretation. They should therefore be framed as diagnostic, screening or complementary tools for a hybrid modelling approach rather than stand-alone replacements for physically- or process-based models.

Lesson 5: STARS4Water has offered proof that products can be successful transferred to other basins

A fifth lesson from the project is that methods and approaches in STARS4Water can be successful transferred to other basins, by taking problem-solving capacity, local data, expert knowledge, management and operation questions and decisions, as well as governance arrangements and user capacity into account. Several modelling approaches or model software codes delivered in the STARS4Water project were exchanged and applied in multiple basins. Transferability is never an easy endeavour in hydrology and water resources management, as it must preserve generality of the transferred tools while guaranteeing also sufficient local representativeness. Despite the challenges, the STARS4Water project has shown that product transfer should not be neglected and, importantly, it can be beneficial in the development cycle of decision-support tools.

Taken together, these lessons suggest that the sustainable uptake of STARS4Water outputs depends on a combination of scientific robustness, stakeholder relevance and added-value, transparent communication, methodological and technical transferability, operational readiness and institutional commitment (ownership, maintenance and capacity). For this, science-stakeholder partnerships must be not only encouraged, but also supported by authorities and policy agendas at different levels, from local to national and EU levels.

8.6. Conclusions

The STARS4Water river basin hubs demonstrated the power of combining technical innovation with stakeholder knowledge. By developing sophisticated next generation integrated modelling frameworks supported by novel data services and ensuring local experts steered its use, the project provided with its water resources availability and use projections a nuanced preview of the river basins water future in Europe.

The main takeaway is that, while the river basins will face tough water resilience challenges in coming decades, such as more frequent low-flow and drought crises as already experienced in 2026, there are also clear pathways to address them.

Ensuring a river basin remains within a “Safe-Operating-Space” will hinge on early planning, such as investing in efficient irrigation, updating navigation regulations, and formalising drought-response agreements among water users and in transboundary cases even between countries. The STARS4Water project’s collaborative approach has already laid groundwork for such actions. In practical terms, seven river basin stakeholders now have a set of modelling frameworks, including datasets and interactive dashboards and Story Maps developed alongside models, and a shared set of scenario insights to inform their strategies. This means the river basins are better equipped to answer

pivotal questions like, *“How much can we abstract, and how should we adapt, so that even in a dry 2050 we don’t cross the red line for our river?”*

While uncertainties remain a bottleneck in river basin management under a global, including climate, changing future, the project has helped transform climate projections that are often scientifically-sound but yet abstract to real-life operations, into concrete, area-specific water-related information for enhanced operations and planning, at least for the seven river basin hubs. This is a critical step towards adaptive, resilient and sustainable water management in Europe. Further upscaling the experiences from the seven selected river basin hubs of STARS4Water to the policy level will further contribute to achieve this

References

- Avila, L., S. Kollet (2025) Improving existing models based on multi-scale model integration. Horizon Europe project STARS4Water. Deliverable 3.3.
- Avila, L., de Lavenne, A., Ramos, MH. *et al.* (2025). Estimation of Monthly Water Table Depth Anomalies Based on the Integration of GRACE and ERA5-Land with Large-Scale Simulations Using Random Forest and LSTM Networks. *Water Resource Management* 39, 2899–2918.. <https://doi.org/10.1007/s11269-025-04097-7>
- Baron, H. & V. Keller (2026). Data-driven water resources modelling tools. STARS4Water. Deliverable D3.4.
- Beckers, J. (2023). Review of existing observational systems. Horizon Europe project STARS4Water. Deliverable D2.1.
- Beckers, J. et al (2023). Design of indicators for assessing climate risks. Horizon Europe project STARS4Water. Deliverable D2.3.
- Beckers, J. (2025). Next generation data services. STARS4Water Deliverable D2.4.
- Beckers, J., M. Grady, C. Laize and S. Szporak-Wasilewska (2025). Next generation water resources data services. Horizon Europe project STARS4Water. Deliverable D2.6.
- Beckers, J., Schotmeijer, G.J., & G. Hendriksen (2025). STARS4Water Metadata Portal: third release Horizon Europe project STARS4Water. Deliverable D2.7
- Blind, M. (2025). Workshop report on capacity building for using the models, services and dashboards. STARS4Water. Deliverable D5.1.
- Duel, H., N. Cremers, J. ter Maat, T. Jahr Hegdahl, V. Keller, M.H. Ramos, M. Kossida, A. de la Hera Portillo, H. Habersack & A. Scriciu (2026). Synthesis report for guidance to river basin management practitioners. Horizon Europe project STARS4Water. Deliverable D5.2.
- Edler, T. & Mes, E.M. (2024): Dashboard to support decision-making on water resources management at river basin level: prototype. Horizon Europe project STARS4Water. Deliverable 1.4.
- Eilander, D., van Verseveld, W., Yamazaki, D., Weerts, A., Winsemius, H. C., and Ward, P. J. (2021). A hydrography upscaling method for scale-invariant parametrization of distributed hydrological models, *Hydrol. Earth Syst. Sci.*, 25, 5287–5313, <https://doi.org/10.5194/hess-25-5287-2021>, 2021.
- Habersack, H., M. Glas, T. Graf, M. Klösch & M. Prieml (2026). Added value of next generation modelling frameworks. STARS4Water. Deliverable 4.1.
- Hegdahl, T.J., J. ter Maat, J. Kruijshoop & H. Hisdal (2023). Stakeholder engagement plan. STARS4Water. Deliverable D1.1.
- Hegdahl, T.J., H. Hisdal, J. ter Maat & J. Kruijshoop (2023). Assessment of the needs on data services and modelling tools of stakeholders in selected European river basins. Horizon Europe project STARS4Water. Deliverable D1.2

- Hermawan, T, Ter Maat, J., Monji, F., Huang, S. & T. Jahr Hegdahl (2026) Co-designed dashboard to support decision-making on water resources management in the Drammen river basin. Horizon Europe project STARS4Water. Deliverable 1.8
- Imhoff, R. O., van Verseveld, W. J., van Osnabrugge, B., & Weerts, A. H. (2020). Scaling point-scale (pedo)transfer functions to seamless large-domain parameter estimates for high-resolution distributed hydrologic modeling: An example for the Rhine River. *Water Resources Research*, 56, e2019WR026807. <https://doi.org/10.1029/2019WR026807>
- Klösch, M.; Graf, T.; Glas, M.; Preiml, M.; Habersack, H.; Aguilera, H.; Collignan, J.; Crapper, Z.; Cremers, N.; Correa, D.; Darch, G.; De la Hera-Portillo, A.; Duel, H.; Edler, T.; Engeland, K.; Fotopoulos, F.; García, O.; Gelati, E.; Gómez-Escalonilla, V.; Hegdahl, T. J.; Hisdal, H.; Huang, S.; Keller, V.; Kossida, M.; Laize, C.; Martínez-Santos, P.; Moreno, L.; Prieto, A.; Ramos, M.-H.; Read, T.; Rickards, N.; Rodríguez del Rosario, M.; Ter Maat, J.; Veie, C. A.; Werner, M. (2026). Web-based Story Maps on water resources availability in river basin hubs. Horizon Europe project STARS4Water. Deliverable 4.3 (D4.3).
- Maat, J. ter, E. Mes, T. Edler, F. Schasfoort, J. Buitink, B. Dalmijn, F. Monji, F. Sperna Weiland (2025). Impact of changing water demand on the transboundary Rhine River basin water balance and flow under climate change. CHR Report I-29. October 2025.
- Martínez-Santos P. (coord.) (2026). Manuscripts on Stars4Water results for special issue in peer-reviewed journal. Horizon Europe project STARS4Water. Deliverable 6.9.
- Mes, E. & T. Edler (2024). Dashboard to support decision making on water resources management at river basin level: prototype. STARS4Water. Deliverable D1.4.
- Okruszko, T., Gietczewski, M., Piniewski M., Habersack, H., Kloesch, M., Glas, M., Preiml, M., Scricciu, A., Toma, A., Hegdahl, T.J., Huang, S., Hisdal, H., Martinez Santos, P., de la Hera Portillo, A., Keller, V., Rickards, N., Rees, G., Kossida, M., Monokrousou, K., Kritsotakis, M., Pantazoglou, F., ter Maat, J., Edler, T., Schasfoort, F., Duel, H., Mes, E., Kruishoop, J., Ramos, M.H., de Lavenne, A. (2024). Water scenarios for river basin hubs. Horizon Europe project STARS4Water. Deliverable D1.5.
- Piniewski, M., Szporak-Wasilewski, S., Gietczewski, M., Okruszko, T., Sperna Weiland, F., Ter Maat, J., Beckers, J. (2024). Data Sets on Scenario Narratives. Horizon Europe project STARS4Water. Deliverable D2.5.
- Ramos, M.H. (eds.) (2026). Improved projections on water resources availability and risks in selected river basins. STARS4Water Deliverable D4.2.
- Rickards, N., S. Kollet & V. Keller (2023). Gap analysis of existing tools in the river basins. STARS4Water Deliverable D3.1.
- Rickards, N.J. & Keller, V.D.J. (eds.) (2024). Improved modelling frameworks for better understanding of water resources at the river basin scale. Horizon Europe project STARS4Water. Deliverable 3.2 (D3.2).
- Schotmeijer, G.J., J. Beckers & G. Hendriksen (2023). First release of the STARS4Water Metadata Portal. Horizon Europe project STARS4Water. Deliverable D2.2
- van Verseveld, W. J., Weerts, A. H., Visser, M., Buitink, J., Imhoff, R. O., Boisgontier, H., Bouaziz, L., Eilander, D., Hegnauer, M., ten Velden, C., and Russell, B. (2024). Wflow_sbm v0.7.3, a spatially

distributed hydrological model: from global data to local applications, *Geosci. Model Dev.*, 17, 3199–3234, <https://doi.org/10.5194/gmd-17-3199-2024>, 2024.

Vertessy, R. A., & Elsenbeer, H. (1999). Distributed modeling of storm flow generation in an Amazonian rain forest catchment: Effects of model parameterization. *Water Resources Research*, 35(7), 2173–2187. <https://doi.org/10.1029/1999WR900051>

Websites:

STARS4Water project website: [STARS4Water](#)

STARS4Water Academy website: [The STARS4Water Academy – STARS4Water](#)

ANNEX A - Danube river basin – Integrated water resources management modelling framework

Authors: Glas M., Graf T., Monji F., Klösch M., Preiml M., Toma A., Scrieciu A., ter Maat J. and Habersack H.

A.1. Target water types and water bodies

Target water types

The integrated modelling framework developed for the Danube River basin addresses multiple water types, with a strong focus on mostly surface freshwater resources under low flow and drought conditions:

- Danube mainstem (Upper, Middle, Lower Danube) under low-flow and drought conditions
- Side channels and lateral floodplain systems (ecological connectivity under low flow)
- Run-of-river (RoR) hydropower impoundments and free-flowing reaches (navigation bottlenecks)
- Cooling and public supply abstractions from the river (nuclear power plant cooling, drinking water)

Target water bodies and systems

- Entire Danube River Basin (~801,463 km²), basin partitioned into Upper, Middle, Lower Danube
- Focus in the Danube mainstem and surface water:
 - Critical shallow navigation sections in the Upper and Lower Danube (thresholds based on RNQ/ENR - characteristic discharges indicating the 94% probability of exceedance derived from daily discharge measurements of the previous 30 years)
 - A side-channel case study in the Upper Danube (lateral connectivity)
 - RoR hydropower plants (9 Upper Danube; 1 Lower Danube case)
 - Nuclear power plants (NPP) (3)
 - Major cities (10) abstracting for drinking and industrial water from the mainstem or hydraulically connected alluvial aquifers
 - A key Lower Danube bifurcation (Old Danube vs. higher-discharge side channel)
- Sub-basins and inflow nodes (Variable Inflow Areas) receiving hydrology from wflow_sbm

A.2. Novel digital methods / tools / solutions

An integrated, stakeholder-informed modelling framework quantifies local Safe-Operating-Space (SOS) for low-flow water allocation and climate change along the Danube by linking basin hydrology to local operations in navigation, ecology, run-of-river hydropower, drinking water and nuclear power plant (NPP) cooling.

Core components (dynamically linked, basin-to-local):

a) Hydrological model (supply side)

- wflow_sbm (v0.7.3; distributed, grid-based; SBM vertical scheme; 1D floodplain routing), forced by ERA5; outputs spatial runoff and routed daily discharge (2010–2020) at sub-basin outlets.
- Danube wflow_sbm model originally developed in the DOORS Black Sea project.

b) Water allocation model (management side)

- RIBASIM (v7.01.25) node-link allocation model, time step of “decades” (~10 days; 1st/11th/21st of each month).
- Network emphasizes the mainstem and low-flow-sensitive nodes:
 - Explicit demand nodes for irrigation and NPP cooling (with seasonal time series and return flows where applicable), major cities (drinking and industrial supply), ecological needs via connectivity thresholds, and navigation RNQ/ENR thresholds.
 - Bifurcation settings in the Lower Danube simplified but informed by literature.
 - Explicit abstractions prioritized over remote-sensing estimates where available.

c) Local hydrodynamics at critical sites

- RSim-3D (finite-volume RANS, standard k-ε) applied on an Upper Danube reach (8.3 km) including two critical navigation bottlenecks and a side channel (for local water levels/depths under low flow and to evaluate connectivity thresholds).

Temporal scale

wflow_sbm (daily) → RIBASIM (decadal) with developed “what-if” scenarios; RSim-3D used for selected scenarios and characteristic discharges (e.g., RNQ).

Scenario design (“what-if”)

- Climate change:
 - GR (glacier retreat, seasonally shaped August peak loss, distributed by glacierized areas)
 - CC1 (more pessimistic discharge changes to mid-century, based on Stagl & Hattermann 2016, adjusted to baseline)
 - CC2 (less extreme/optimistic changes, based on Probst & Mauser 2023, adjusted consistently)
 - CC1+GR (combined)
- Water allocation and socio-economy:
 - IR1, IR2 (Upper Danube surface-water irrigation abstractions), IR3 (IR1+IR2)
 - LN (diversion from the Danube to augment a nearby endorheic lake; worst-case 4 m³/s; no return)
 - POP (city demands scaled to 2050 per Eurostat/Serbia statistics)
- Combination: Worst-Case (WCS, combination of GR + CC1 + IR3 + LN + POP)

Indicators and thresholds for Safe-Operating-Space

- Navigation: low-flow occurrence I_N = days/year with $Q < \text{RNQ/ENR}$; legal minimum fairway depth target 2.5 m; classes Risk (≤ 22 d/a below RNQ) vs Crisis (> 22 d/a).
- Ecology: side-channel connectivity I_E = days/year without upstream surface connection to mainstem; threshold discharge Q_{Cd} from rating curves and culvert invert elevations (historical and actual KWDs; future bed-degradation variants).
- Hydropower: $I_{HPP} = \left(\frac{E_{ann,S}}{E_{ann,REF}} - 1 \right) \times 100(\%)$, with decadal energy $E_{i,S} = \eta_c \rho g Q_{T,i,S} H_i \Delta t_i$.
- Drinking water: I_D = demand as % of Q_{95} (low-flow quantile) to represent high priority of public supply.
- NPP cooling: I_{NPP} = days/year with Q below cooling demand (m³/s) at plant intake.

Calibration, validation and robustness

- Hydrology (wflow_sbm): calibrated/validated in Danube headwaters and selected tributaries within DOORS
- RIBASIM (driven by wflow_sbm) vs observed decadal Q on mainstem nodes (2010–2020):
 - NSE_{In} : 0.52–0.70 (satisfactory–good); KGE : 0.60–0.78; r : 0.84–0.87; $nRMSE$: 0.24–0.31; small positive bias (6–13%).
- Navigation indicator (IN): validated against fairway authority data; hydrology-based IN explains interruptions but local morphology and dredging strongly affect the real fairway depths.
- Ecology (IE): average modeled connectivity 163 d/a (2010–2020), comparable to the connectivity reported by the related stakeholder.
- Hydropower (IHPP): decadal energy proxy calibrated/validated with daily national energy data (2015–2020); post-calibration fits excellent ($KGE \approx 1$, low bias) for considered plants.
- RSim-3D: water-level validation at RNQ with $NSE = 0.997$; max deviation ≈ 0.07 m.

Improved capabilities

- Basin-to-local integration (hydrology $\rightarrow$ allocation $\rightarrow$ local 3D hydraulics) under a coherent SOS concept.
- Explicit mainstem demands and fairway/ecological thresholds at critical locations.
- Cross-sector, upstream–downstream trade-off analysis under climate and water management scenarios.
- Decadal time step allows low-flow allocation analysis over long periods; local 3D model resolves fairway depth/connectivity at bottlenecks.

Main improvements and added value

- Jointly considers climate change, glacier retreat, water allocation, and socio-economy for low-flow SOS.
- Moves from climate-only or use-only analyses to integrated allocation with explicit demands on the mainstem.
- Quantifies:
 - Navigation interruptions (I_N ; days/year)
 - Ecological lateral connectivity losses (I_E ; days/year)
 - Hydropower production changes (I_{HPP} ; %)
 - Drinking-water quantity pressure (I_D ; % of Q_{95})
 - NPP cooling-water reliability (I_{NPP} ; days/year)
- Evaluates effectiveness of river restoration (side-channel reconnection) and sensitivity to bed degradation.

Reveals upstream–downstream propagation of small abstractions during low flow (e.g., IR3 and LN signals at Lower Danube nodes).

A.3. Geographical coverage / implementation

- Entire Danube Basin, with emphasis on mainstem nodes in the Upper and Lower Danube.
- Local case studies:
 - Upper Danube: two critical shallow navigation sections and one restored side channel; 3D hydrodynamics applied on an 8.3 km reach.

- Lower Danube: two critical navigation sections (including the Old Danube branch influenced by a bifurcation), NPP and city nodes.
- Developed within STARS4Water (Horizon Europe) and leveraging DOORS Black Sea hydrology;
- RIBASIM schematization informed by local expertise and published datasets (e.g., Viadonau, national agencies).
- Commission: ICPDR

A.4. Enabling conditions and limiting factors

Enabling conditions

- Availability of ERA5 forcing and an existing wflow_sbm Danube setup from DOORS.
- Mature open/established tools (wflow_sbm, RIBASIM, RSim-3D) and well-defined operational thresholds:
 - Navigation: RNQ/ENR and fairway depth target (2.5 m)
 - Ecology: connectivity thresholds from KWD rating curves and culvert elevations
- Published climate-change discharge projections to define CC scenarios (pessimistic vs optimistic) and documented glacier-melt seasonality.
- Explicit demand data assembled from official sources (cities, NPPs), and literature-based abstractions for irrigation and diversions.
- Validation using observed flow (national hydrological services, GRDC) and published energy/fairway datasets.

Limiting factors

- Limited, spatially incomplete data for direct abstractions (locations/volumes); presence of unmetered withdrawals.
- Decadal time step may smooth short low-flow pulses affecting local impacts.
- Morpho-dynamics strongly affect fairway depth and connectivity; representation is simplified in basin allocation and time-invariant at the bifurcation.
- Slight positive discharge bias and occasional under/over-prediction of low-flow indicators.
- Groundwater not dynamically coupled (drinking water impacts via alluvial systems not simulated with models like MODFLOW).
- Water temperature and thermal constraints (relevant for NPP/ecology) not modelled.

A.5. Re usable tools and outputs

Assets after STARS4Water

- Integrated wflow_sbm → RIBASIM modelling chain for low-flow allocation on the Danube mainstem.
- Local 3D hydrodynamic model (RSim-3D) of an Upper Danube reach, validated for RNQ water levels.
- Indicator set and workflows for SOS: definitions and thresholds in A.2.
 - Navigation I_N (RNQ/ENR thresholds; 2.5 m depth target at bottlenecks)
 - Ecology I_E (lateral connectivity duration; Q_{Cd} from KWD rating curves; bed-degradation variants)
 - Hydropower I_{HPP} (annual energy change, seasonal diagnostics)

- Drinking water I_D (demand as % of Q_{95})
 - NPP cooling I_{NPP} (days below cooling demand)
- Scenario library and implementation approach:
 - GR, CC1, CC2, CC1+GR; IR1/IR2/IR3; LN; POP; WCS (combination).
 - Method: apply relative seasonal changes and explicit abstractions to the 2010–2020 reference.
- Data inputs curated from official sources (ERA5; hydrometric agencies; Viadonau KWD and fairway targets; EurEau/Eurostat; OVF; GRDC; national statistics; published NPP reports).

Transferability and scaling

- Blueprint for large, transboundary basins where mainstem demands, navigation, ecology, hydropower and cooling water interact under low flows.
- Scaling requires explicit local demand data, reach-scale hydraulic/morphological knowledge, and engagement with waterway/energy/utilities authorities to define thresholds and operations.

A.6. Data collection, platforms and maintenance

Data collected

- Hydrometeorology and hydrology: ERA5; wflow_sbm outputs; observed discharges for validation (national services; GRDC).
- Sectoral demands:
 - Cities: EurEau and Eurostat (and national statistics) for baseline and POP scenario.
 - NPP cooling: OVF (2015–2019) and Romanian NPP studies; seasonal demand and return flow percentages.
 - Irrigation and diversion nodes (IR1/IR2; LN) as explicit abstractions from literature and project inputs.
- Navigation and morphology:
 - RNQ/ENR thresholds and characteristic water levels (KWD 1996/2010/2020, Viadonau)
 - Dredging/maintenance records (Fairway Danube)
 - Bed-degradation prognosis variants (literature)

Platforms and tools

- Hydrology: wflow_sbm v0.7.3 (Deltares)
- Allocation: RIBASIM v7.01.25 (Deltares)
- Hydrodynamics: RSim-3D (finite-volume RANS, Michael Tritthart, BOKU University, Institute of Hydraulic Engineering and River Research)

Maintenance and availability

- Models, indicators and scenarios documented in STARS4Water outputs; data available on request from the authors.

A.7. Key deliverables

- Deliverable 4.1: Added value of next generation tools.
- Deliverable 4.2: Improved projections on water resources availability and risks in selected river basins

A.8. Notes on key findings

- Navigation: climate and allocation scenarios can add up to +40 crisis days/year at critical sections; fairway depth at bottlenecks is highly sensitive to low-flow levels and morphology; WCS reduces RNQ water level at the Upper Danube site by ~0.34 m in August in the 3D model.
- Ecology: side-channel crisis days increase up to +40 d/a (WCS) relative to REF; reconnection dramatically reduces crisis days and increases resilience; bed degradation can negate gains if unmanaged.
- Hydropower: annual production changes range from about –6.2% (Upper Danube, CC1+GR) to –15.5% (Lower Danube, WCS), with winter increases mitigating seasonal “energy droughts.”
- Drinking water: $I_D \ll 1\%$ of Q_{95} for all cities (REF and POP); quantity not a mainstem limitation under modeled scenarios.
- NPP cooling: Lower Danube NPP case shows crisis decades in a dry year (2011) under REF, extended by CC1/WCS; Upper Danube NPP not flow-limited in modelled dry years.

ANNEX B – Drammen river basin – Integrated modelling framework

Authors: *Trine Jahr Hegdahl*

The main methodological output from Drammen is a modular, basin-scale modelling chain that explicitly links climate scenarios, hydrology, reservoir operations, energy production, and ecological impacts. The modelling framework consists of:

- The hydrological models: LISFLOOD, HBV and wflow
- The reservoir operation model: EOPS
- Water resources allocation model: RIBASIM
- Ecological hydrological flows assessment model: EFRA

The full climate–hydrology–reservoir–energy market coupling where explicit energy narratives are integrated into water management modelling facilitates:

- Realistic handling of licensed hydropower constraints.
- Indicators derived from altered flow regimes (high flows, low flows, rate of change). Used to assess ecological risks of alternative reservoir operation strategies, including energy-driven scenarios (ERFA method used and tested for different basins within Stars4Water).
- Combination of operational relevance and research innovation.

B.1. Target water types and water bodies

Rivers and hydropower reservoirs.

B.2. Novel digital methods / tools / solutions

STARS4Water has developed modelling chain for the Drammen river basin using existing modelling frameworks to address the water challenges in a complex system of hydropower reservoirs and hydroelectric power generation plants. The Drammen stakeholders have pointed out the need for a complete watershed model chain that also includes the reservoir operations. The modelling framework addresses the challenges related to low flows, droughts, and floods for current and future climates and how water allocation strategies could be used to mitigate severe effects.

B.3. Geographical coverage / implementation

Drammen basin, including multiple reservoirs.

B.4 Enabling conditions and limiting factors

Enabling conditions

The modelling framework builds on existing, well-established models and datasets already used by river basin managers, hydropower operators, and water authorities. The availability of long-term hydro-meteorological observations, reservoir information, climate projections, and hydropower operation data has enabled the development and calibration of the integrated model chain. The framework further benefits from stakeholder involvement throughout the STARS4Water co-design process, ensuring that model outputs, indicators, and scenarios address real management needs.

Limiting factors

The framework requires detailed information on reservoir characteristics, operating rules, water demands, and hydropower infrastructure, which may not always be available in other basins.

Uncertainties in climate projections, bias-correction methods, hydrological model structure, and future energy market assumptions propagate through the modelling chain and influence projected outcomes. Model transferability may therefore require local calibration and adaptation to basin-specific hydrological and operational conditions.

B.5. Reusable tools and outputs

This framework is suitable for use in other (Norwegian) basins with significant hydropower activity and competing water uses. The modular design allows individual components to be adapted or replaced depending on available data and local management objectives.

Tools

- Climate scenario processing and bias-correction workflow.
- Hydrological model setups using HBV, LISFLOOD and wflow.
- Reservoir operation modelling using EOPS.
- Water allocation modelling using RIBASIM.
- Ecological Risk due to Flow Alteration (ERFA) assessment framework.
- Integrated dashboard and visualisation framework for scenario exploration and stakeholder dialogue.

Outputs

- Climate change impact assessments for water availability, floods and droughts.
- Reservoir operation scenarios under alternative climate and energy futures.
- Hydropower production and water value assessments.
- Ecological flow indicators and flow alteration risk assessments.
- Safe-Operating-Space (SOS) indicators supporting integrated river basin management.
- Interactive dashboard, Story Map and communication products for decision support and stakeholder engagement.

B.6 Data collection, platforms and maintenance

The framework combines climate, hydrological, reservoir, water allocation, ecological and hydropower datasets collected and processed within the STARS4Water project. Data sources include observed hydro-meteorological records, climate projections, reservoir and hydropower system information, river basin characteristics, ecological indicators, and stakeholder-defined management scenarios.

The modelling chain is implemented through a combination of established modelling platforms, including HBV, LISFLOOD, wflow, EOPS, RIBASIM and ERFA. Data exchange protocols enable information transfer between model components, allowing climate scenarios to be propagated through hydrological, reservoir operation, energy production, water allocation and ecological assessments.

Resulting datasets and indicators are made available through the STARS4Water Drammen dashboard and presented in the Drammen Story Map. The dashboard infrastructure was developed jointly by Deltares and NVE, with maintenance and further development expected to continue beyond the project period through NVE. New indicators, scenarios and datasets can be integrated as they become available.

B.7. Links to information sources / Key deliverables for the above theme

- Deliverable 1.8:
- Deliverable 4.1: Added value of next generation tools.
- Deliverable 4.2: Improved projections on water resources availability and risks in selected river basins
- Webinar: Lisflood and Dashboard

[Future water availability and energy potential](#) ArcGIS Story Map presenting the Drammen river basin hub. Key messages on future water availability and energy potential. Provides an accessible, map-based overview to support stakeholder dialogue and communication of results.

- Hegdahl Trine Jahr^{a*}, C. A. Veie^a, K. Engeland^a, S. Huang^a, S. Gulaker^b, E. Gelati^a, C. L. R. Laizé^c (2026) Water availability, energy production, and ecological flows defining the ‘safe operating space’ for the Drammen basin.
- Engeland Kolbjørn, N. Ayrault, E. Gelati, T. J. Hegdahl, S. Huang and C. A. Veie (2026) Climate change impacts on river discharge, reservoir operations, energy production and water availability – a case study from Drammen river basin in Norway

ANNEX C – Duero river basin – Groundwater modelling framework

Authors: *Martinez-Santos P, Aguilera H, De la Hera-Portillo A, Gómez-Escalonilla V, Rodríguez del Rosario M, Díaz-Alcaide S*

The Duero data-driven groundwater modelling framework provides critical insights and projections for groundwater sustainability, ecosystem protection, and agricultural water use, making it highly relevant for climate adaptation in semi-arid river basins. Data-driven tools include classification and regression approaches to predict groundwater quantity and quality in the Duero basin.

The models have been calibrated, validated, and demonstrated using real groundwater datasets from the Duero River Basin under representative operational conditions. Their performance has been successfully evaluated through realistic application scenarios, demonstrating the capability to reproduce the targeted processes and provide robust outputs within the intended domain of application. Although the models have reached a high level of technical maturity through testing in a relevant environment, they have not yet been deployed for routine operational use or integrated into an operational decision-support workflow. Consequently, their current maturity is consistent with TRL-6, with operational implementation and long-term deployment remaining as subsequent development stages.

C.1. Target water types and water bodies

Groundwater aquifers and associated ecosystems.

C.2. Novel digital methods / tools / solutions

STARS4Water has developed data-driven tools to evaluate some of the major challenges in groundwater management in the Duero basin, including groundwater quality and groundwater storage. This was done in close collaboration with the stakeholders, who established the need to tackle these two issues in the early stages of the project. The modelling approach thus focuses on spatial prediction of groundwater contamination due to agrochemicals, as well as on the prediction of storage changes under different scenarios.

C.3. Geographical coverage / implementation

The models cover the whole of the Duero basin. In the context of Stars4Water, these have been successfully exported to evaluate groundwater quality in the chalk aquifer units of East Anglia, and the groundwater storage in the Seine, demonstrating the flexibility of this approach.

C.4. Enabling / limiting factors

Enabling conditions: The tools are highly flexible and are specifically designed to run with the outcomes of spatial databases. For the groundwater quality model, users provide a series of spatially distributed inputs and a spatially distributed set of ground-truth examples as target. The tool identifies the patterns leading to ground truth values and develops predictions based on these. For the groundwater storage model, a combination of static catchment descriptors, dynamic climatic and land-cover drivers from multi-source satellite data, and socio-economic factors are used. The models

present relatively modest running requirements, which makes them suitable to be run locally. Python knowledge is required.

Limiting factors: Data needs to be provided in spatially distributed form.

C.5. Re-usable tools

The framework is highly flexible and replicable, as both target and predictor variables can be tailored to any geographical setting. In the Stars4Water context, the Duero's groundwater quality model has been successfully exported to the East Anglia case study. It has also been replicated with different targets and predictor variables in non-European basins, including the Aconcagua basin in Chile, the East-Ouaddai region of Chad, and the groundwater aquifers of southern Madagascar. The data-driven groundwater storage model has been successfully tested on the Seine river basin.

C.6. Data collection, platforms and maintenance

Data collection: These data-driven models typically rely on readily available datasets. As anything spatially distributed can be used as an input variable, official data repositories and GIS databases such as those maintained by river basin authorities, and platforms like NASA's EarthExplorer or Copernicus, are habitual sources of information.

In the case of the models developed by Stars4Water, most data come from the internal databases of the Duero River Basin Authority (Duero case study) and Anglian Water (East Anglia case study). Institutions like the Geological Survey of Spain and the British Geological Survey contributed additional datasets.

Platforms and maintenance: Output datasets are available through Stars4Water Zenodo platform. An open-access version of the python code is available through the website of the Environmental Hydrogeology research group of the Universidad Complutense de Madrid (<https://www.ucm.es/hidrogeologia/programas-software>).

C.7. Key deliverables for the above theme

Deliverable 3.2: Improved modelling frameworks for better understanding of water resources at the river basin scale

Deliverable 4.1: Added value of next generation tools.

Deliverable 4.2: Improved projections on water resources availability and risks in selected river basins

Deliverable 4.4: Upscaling of basin-wide assessment of climate change risks and impacts to EU-level

ANNEX D – East Anglia river basin – Environmental flow modelling framework

Authors: Cedric Laize, Virginie Keller, Zara Crapper and Nathan Rickards

D.1. Target water types and water bodies

- Surface water: rivers

D.2. Novel digital methods / tools / solutions

STARS4Water delivered a bespoke implementation application of the Ecological Risk due to Flow Alteration (ERFA) screening method (Laizé et al., 2014), referred to as STARS4Water ERFA (“S4W ERFA”). ERFA was developed for Europe as part of the EU FP6 project “water SCenarios for Europe and NEighbouring States (SCENES)”. The core assumption of the method is that river ecosystems are adapted to current (baseline/pre-impact) conditions, so that any aspect of flow alteration (magnitude, duration, timing, frequency and rate of change) can lead to a risk of ecological impact. The more post-impact conditions differ from pre-impact conditions, the higher the ecological risk.

Within S4W ERFA, two main methodological developments were implemented: (i) based on the original ERFA concepts, the method was further developed to analyse flow series at the daily time step; (ii) indicators were added to capture flow intermittency to address the need identified in the literature review presented above. From a software perspective, we developed a new version of the ERFA R shiny app, able to process daily time-steps, whilst also adding functionality to display multiple-site results. The app runs in R (or R Studio) and provides a user-friendly web-style front end (no R coding is needed although users need to install R/ R Studio and to be able to run R scripts).

D.3. Geographical coverage / implementation

As this is a screening tool, it is relatively easy to implement across the world. Within STARS4Water, S4W ERFA was implemented in the following river basins:

- East Anglia, UK
- Drammen, Norway
- Rhine
- Seine
- Danube
- Messara
- Duero

D.4. Enabling / limiting factors

Enabling conditions

This is a screening tool that requires minimal input data. Users provide one baseline flow series and scenario flow series as .csv files with a very simple format. Input files are therefore generated outside the app, and they can be anything the users want (e.g. climate change, abstraction, a combination of several drivers).

This model also requires minimal computation; it is therefore easily transferable to any region of the world.

Limiting factors

This method is not species or 2 dimensional (e.g. information floodplains for connectivity) specific, which can be considered as a downside. However, hydrological indicators are important starting point grouped in categories, namely: High Flows, Monthly Flows, Low Flows, Rate of Flow Changes and Intermittent Flows. Therefore, the user could target some of these groups to tailor the screening assessment, should it be necessary.

D.5. Re-usable tools

After Stars4Water, the following assets remain:

- STARS4Water ERFA shiny app STARS4Water GitHub
(<https://github.com/openearth/stars4water>)
- Generated indicators outputs from the river basin hubs application: East Anglia, Seine, Drammen, Danube, Duero, Messara and Rhine

D.6. Data collection, platforms and maintenance

Multiple datasets were used as input to develop this data-driven model, most of the datasets are open-access.

Data collected:

- Modelled current and future flows (natural and artificially influenced) for 14 gauging stations in East Anglia were sourced from: CS-NOW: Gridded future projections of natural and artificially influenced river flows (1980 to 2080) (available at: <https://catalogue.ceda.ac.uk/uuid/cf66055440344d7eb9b6f834e81736c6/>)
- Observed flow and future estimated flows for 14 gauging stations in East Anglia were sourced from: Hydrological projections for the UK, based on UK Climate Projections 2018 (UKCP18) data, from the Enhanced Future Flows and Groundwater (eFLaG) project (available at: <https://catalogue.ceh.ac.uk/documents/1bb90673-ad37-4679-90b9-0126109639a9>)
- Modelled current and future flows for the Rhine river, using the wflow hydrological model connected with a weather generator tool. The wflow model was connected with the ERFA tool.
- Modelled current and future flows for the Seine river, using the GRSD hydrological and data on the management of upstream reservoirs to take into account their influence on river flows. Data is available here: <https://zenodo.org/records/17632107>. The model output data were used in the ERFA tool to derive the indicators.
- Modelled historic and future flows for Drammen River basin, and 7 subbasins. Based on 6 different climate projections (GCM-RCM combinations) and two emission scenarios (CMIP5 RCP45 and CMIP6 SSP370). Data period 1961-2100. The streamflow data provided by a local Lisflood model with simple reservoir handling was used to assess ERFA indicators for different periods.

Platform and tools:

- Shiny app developed in R.

D.7. Key deliverables

Deliverable 3.2: Improved modelling frameworks for better understanding of water resources at the river basin scale

Deliverable 4.2: Improved projections on water resources availability and risks in selected river basins

ANNEX E – Messara river basin – Integrated water resources management modelling framework

Authors: *Maggie Kossida, Fotis Fotopoulos, Ioannis Tsoukalas*

E.1. Target water types and water bodies

The integrated modelling framework developed for the Messara basin addresses multiple water types, with a strong focus on freshwater resources under water scarcity conditions.

Target water types:

- Surface water: ephemeral rivers (Geropotamos, Anapodaris), reservoirs (Faneromeni, Gergeri)
- Groundwater: alluvial and karstic aquifers (primary water supply source)
- Agricultural water use: irrigation (dominant demand component)
- Domestic and industrial water supply (domestic is the priority 1 water use)
- Environmental flows (implicitly represented through allocation constraints)

Target water bodies and systems:

- Messara river basin (~600 km²)
- Nine groundwater districts (hydrogeological sub-basins)
- Central alluvial aquifer system (core water supply system)
- Reservoir infrastructure and conveyance systems
- Groundwater abstraction network (~1,300 wells)

These components are jointly simulated to assess water availability, allocation, deficits, and groundwater sustainability.

E.2. Novel digital methods / tools / solutions

STARS4Water developed for Messara a fully integrated modelling framework combining hydrological simulation and water allocation modelling at the disaggregated node level, tailored to groundwater-dominated Mediterranean basins.

The Messara modelling suite consists of two dynamically linked components:

- a. Hydrological model (supply side): A Sacramento Rainfall-Runoff Model (SAC-SMA) has been developed using the HydromadR package and calibrated with 13 parameters. This is coupled with Exponential Hydrograph Routing model (3 parameters). Monthly timestep simulations were applied to generate surface runoff, recharge signals and inflows to rivers and reservoirs.
- b. Water allocation model (management side): A RIBASIM (River Basin Simulation Model) model has been developed using a node-based architecture. The basic management units are the groundwater districts (nine in total), each one linked with the relevant water demand nodes (irrigation, domestic, industrial water users). By integrating water demand priorities and water availability at the disaggregated groundwater district level, the model provides a robust framework for evaluating various management scenarios and alternative future conditions.

Both models operate at monthly timestep and are integrated to simulate the full water cycle from climate forcing to allocation decisions. This integration of the two models enables the evaluation of a broad spectrum of scenarios, encompassing infrastructure development, operational strategies, and demand management. Operating at a highly detailed spatial scale, this modelling suite provides stakeholders a comprehensive tool to make informed decisions regarding water allocation within a Safe-Operating-Space and a nuanced approach to sustainable water resource.

Calibration, validation and robustness:

- The hydrological model calibrated and validated using **30-year streamflow records (1989–2003)**. It can capture regime changed (post-1989) and intermittent river behaviour. Extended simulations have been run to produce output until 2022 using ERA5 input data
- The RIBASIM model has been validated through continuous stakeholder **engagement**, including:
 - Model schematisation (groundwater districts and demand nodes)
 - Physical realism of flow and availability
 - Allocation rules and priorities
 - Scenario simulation capability

Modelling suite improved capabilities:

- Spatial disaggregation into 9 groundwater districts, reflecting hydrogeological behaviour
- Explicit representation of:
 - Groundwater storage and lateral flows
 - Water demand per sector and location
 - Allocation priorities and constraints
- Integration of:
 - ERA5 climate data (bias-corrected)
 - Land use and crop-specific water demand
 - Groundwater abstraction capacity (well data)

Main improvements over previous solutions and added value:

- Coupling of hydrological processes and water allocation (previously disconnected analyses)
- Transition from static balances to dynamic system simulation
- Explicit modelling of:
 - Groundwater abstraction vs recharge
 - Sectoral water competition
 - Spatial heterogeneity of deficits
- High-resolution representation at sub-catchment level and per node (user)
- The integrated framework enables quantification of water deficits (absolute and %), supply reliability per user, groundwater overexploitation (abstraction vs recharge)
- Scenario-based analysis of:
 - Infrastructure (e.g. reservoirs, transfers)
 - Demand management (irrigation strategies)
 - Policy interventions (abstraction caps, allocation rules)

- The model directly supports decision-making by answering key stakeholder questions such as:
 - o Where are water stress hotspots?
 - o Who experiences shortages under drought conditions?
 - o What abstraction limits are needed for sustainability?
 - o Which measures improve equity and efficiency?

D.3. Geographical coverage / implementation

The modelling framework covers the entire Messara River Basin in Southern Crete (Greece):

- Nine groundwater districts
- Main hydrological systems (Geropotamos and Anapodaris)
- Agricultural areas (~77% of land use)
- Reservoir and groundwater abstraction systems

The modelling framework has been developed in collaboration with the Region of Crete (main end-user) and other local stakeholders (TOEBs, water authorities, experts). The Messara case represents a Mediterranean showcase for groundwater-stressed agricultural basins.

E.4. Enabling conditions and limiting factors

Enabling conditions:

- Strong stakeholder co-development and validation process
- Availability of satellite ERA5 meteorological data and historical in-situ data for bias-correction
- Use of established modelling tools (SAC-SMA in HydromadR, RIBASIM)
- Clear policy relevance: the applied tools directly address issues of groundwater overexploitation, irrigation efficiency and water allocation conflicts. The outputs are aligned with the needs of River Basin Management Plans and EU directives (WFD, agricultural policies). The output data can be used as quantitative indicators usable for policy (e.g. reliability, deficits, abstraction vs recharge)

Limiting factors:

- Uncertainty in actual groundwater abstraction (unregistered wells)
- Variability in irrigation practices (irrigation practices vary significantly across farmers, while over-irrigation or deficit irrigation are not consistently documented)
- Limited recent in-situ monitoring data (post-2010)
- Sensitivity to crop coefficients and irrigated area estimates

These have been partially mitigated through the bias-corrected ERA5 datasets, the extended stakeholder validation processes and the scenario-based analysis

D.5. Re-usable tools and outputs

After STARS4Water, the following assets remain:

- Integrated SAC-SMA – RIBASIM modelling framework
- Transferable methodology for:
 - o Groundwater-dependent basins
 - o Water allocation under scarcity conditions

- Semi-arid regions with strong seasonal demand
- Spatial datasets:
 - Land use and irrigation demand
 - Groundwater abstraction capacity
- Scenario workflows for:
 - Infrastructure planning
 - Demand management
 - Policy testing
- The Messara model serves as a replicable blueprint for Mediterranean water-scarce regions. While the framework is transferable, scaling requires detailed local hydrogeological knowledge, stakeholder engagement processes, data harmonisation. Without this, deployment in other basins may face high setup costs and reduced reliability.

D.6. Data collection, platforms and maintenance

Data collected:

- Hydro-meteorological data (ERA5 precipitation, temperature)
- Streamflow observations (historical)
- Land use and crop distribution
- Irrigation water demand coefficients
- Groundwater abstraction data
- Reservoir data

Platforms and tools:

- Hydrological modelling: HydromadR (SAC-SMA)
- Allocation modelling: RIBASIM

Maintenance:

- Continued use and updating by local stakeholders (i.e. the Region of Crete)
- Integration into water planning processes

D.7. Key deliverables for the above theme

Deliverable 4.1: Added value of the next generation tools

Deliverable 4.2: Improved projections on water resources availability and risks in selected river basins

D.8. Status and further outlook

The developed SACRAMENTO-RIBASIM model suite has reached **TRL 6 (Technology demonstrated in a relevant environment)**. The model has been configured for the Messara River Basin using real hydrological, groundwater, infrastructure and water demand data, and has been applied to evaluate water allocation under current and future climate and management scenarios. It supports stakeholder engagement by enabling transparent assessment of allocation policies, groundwater abstraction strategies and adaptation measures. The model has been demonstrated in a relevant operational environment, but it has not yet become part of routine operational water management.

At TRL 6 the model suite has:

- been implemented for a **real river basin** rather than as a theoretical prototype;
- represents the actual water resources system, including reservoirs, groundwater abstractions, irrigation demand, river reaches, and allocation rules;
- uses observed data for setup, calibration, and validation;
- can evaluate management interventions and climate change scenarios;
- is intended to support stakeholder discussions and water allocation planning.

What would be needed to reach higher TRLs?

TRL 7	- Pilot implementation with the regional water authority or river basin organization. - Stakeholders use the model during actual planning exercises or drought management. - Model outputs influence real management decisions.
TRL 8	- Fully operational decision-support system. - Standard operating procedures established. - Regular updates with monitoring data. - Maintenance and user support framework.
TRL 9	- Routine operational use over multiple years. - Institutional adoption by the competent authority. - Used for official water allocation planning, drought management, or implementation of basin management plans.

ANNEX F – Rhine river basin – Integrated water resources management modelling framework

Authors: *Judith ter Maat, Devi Purnamasari, Esmée Mes, Tatjana Edler, Umi Taner and Albrecht Weerts*

The advancement in the Rhine consists of several components:

- I. Wflow-Ribasim model framework
- II. ML irrigated agricultural area and demand modelling tool

STARS4Water advanced the Integrated River Basin Management (IRBM) modelling instrument for the Rhine river basin, aligned with the principles of Integrated Water Resources Management (IWRM), with a focus on advancements in simulating water demand and water allocation. The updated framework comprises integrated hydrological and water allocation models developed using the Wflow and Ribasim model software packages. These internationally applied modelling tools support tailored representations of water resources systems, integrating land use and land cover, socio-economic drivers, ecological processes and water governance across spatial scales from local to global.

In addition, a dedicated tool has been delivered to assess the irrigated agricultural area and demand in the basin.

F.I. Wflow-Ribasim model framework

F.I.1. Target water types and water bodies

The integrated river basin modelling framework developed in STARS4Water for the Rhine river basin addresses multiple water types and water bodies, with a strong focus on freshwater resources and their allocation under climate and socio-economic change.

Target water types:

- Surface water (primary focus): rivers, tributaries, lakes, reservoirs and canals
- Groundwater–surface water interactions (implicitly represented via hydrological processes)
- Drinking water use (public water supply abstractions)
- Hydropower
- Agricultural water use (irrigation demand)
- Industrial water use (including cooling water for power plants)
- Environmental flows supporting aquatic ecosystems
- Minimum flow addressing inland navigation requirements

Target water bodies and systems:

- The transboundary Rhine River, it's main river and major tributaries
- Catchment and sub-basin systems across the full Rhine basin
- Large lakes and reservoirs: most reservoirs are German and Alpine storage, including Lake Constance
- Water demand at sub-basin level and main water infrastructure

These water types and bodies are jointly simulated to assess water availability, allocation, shortages, low-flow risks and supply reliability under present and future conditions.

F.1.2. Novel digital methods, tools and solutions

STARS4Water has delivered significant improvements to the Rhine modelling capacity by coupling advanced hydrological and integrated water resources management tools.

Key digital innovation

The Integrated Rhine River Basin Model Suite consists of a workflow using the Wflow and the Ribasim open state-of-the-art model software packages to build the Rhine model applications. The FEWS platform is used for the model workflow, data storage and handling, visualization and analyses. All packages are developed and maintained by Deltares, following strict software development protocols and combining expertise from various field disciplines (software architects, hydrologists, groundwater experts, database experts, mathematicians, EO and global data specialists, etc.).

The integrated river basin wflow–Ribasim framework with a FEWS user interface consists of:

- wflow_sbm provides high-resolution, spatially distributed hydrological simulations (runoff, soil moisture, evaporation, snow processes). An integrated water demand module provides water demand estimates.
- Ribasim simulates integrated river basin management, water allocation, storage and prioritisation across sectors.
- The two models are dynamically linked via the FEWS platform, enabling consistent, time-step based data exchange of flows and demands.

Main improvements over previous solutions

Main improvements achieved in the EU STARS4Water project were:

- Updated software and workflows: migration of the legacy Rhine Ribasim model application to the latest software version and protocols with new computational workflows and FEWS interface.
- Enhanced spatial and sectoral detail for the Rhine basin: Grid-based, daily water demand modelling (domestic, industrial, agricultural) and minimum flow modelling for ecology and inland navigation.
- Explicit inclusion of irrigation water demand as a new module leveraging EO data and Machine learning technologies.

Expanded parameter and scenario coverage

The project enabled the expansion of the model application, by:

- the use of the IPCC AR6–consistent climate data, including KNMI’23 regional scenarios.
- integration of socio-economic futures, co-designed with Rhine basin stakeholders.

This way it is possible to explore the current situation in flows, water balances, etc. in the basin for the current situation as well as under socio-economic and/or climate change situations, according to latest scientific and stakeholders’ insights.

Performance gains

Basin-wide coverage in a single, coherent framework enables faster exploration of “what-if” scenarios compared to fragmented national studies and promote a joint understanding of the system and promote transboundary dialogues on plausible future changes. Ongoing improved calibration and validation, now at multiple locations across the basin rather than a single control point (e.g. Lobith), will further improve the performance of the model. Together, these advances allow quantitative assessment of water balances, low-flow risks, unmet demand and allocation trade-offs at sub-basin to basin scale, ultimately supporting informed decision-making on water security and resilience between the Rhine countries and stakeholders.

F.I.3. Geographical coverage / implementation of the solutions

The integrated model covers the entire transboundary Rhine River Basin, including:

- Switzerland
- Liechtenstein
- Italy (only hydrology of the Rhine catchment)
- Austria
- France
- Luxembourg
- Germany
- The Netherlands

The framework explicitly supports transboundary analysis and is jointly developed with and applied for the three Rhine basin commissions:

- CHR
- ICPR
- CCNR

This ensures that regional and national datasets are embedded in a consistent basin-wide assessment context.

As stated before, similar models have been developed for the Danube river basin, Drammen river basin, Messara river basin and Meuse river basin (as a replicator case of the Rhine) and working with and adopted by river basin organisations in those basins.

F.I.4. Findings about enabling conditions or limiting factors related to deployment, scaling, or uptake of these tools/methods**Enabling conditions**

As key enabling conditions can be mentioned:

- Strong co-development with river basin commissions, ensuring relevance, credibility and uptake. During the development and application of the models (running scenarios) STARS4Water consortium researchers participated in regular meetings with stakeholders to discuss data collection, simulation results and findings.
- Availability of open hydrological models (wflow) and established basin planning tools (Ribasim), that have track records in other basins around the world.
- Alignment with RBOs and EU policy needs (Water Framework Directive, drought management, navigation, etc.). The findings are directly relevant and fed into their process, e.g. the Rhine2040 climate adaptation plan.

Limiting factors

Some limiting factors were:

- Data heterogeneity across countries represents the current situation, requiring further detailed understanding and harmonisation of water use, abstraction and socio-economic datasets.
- Remaining uncertainties in future water demand and adaptation behaviour, especially feedback loops with climate change impacts.
- Computational and organisational effort needed to maintain up-to-date transboundary datasets.

These factors influence deployment speed and scaling but are mitigated through following a step-wise approach (several simulation rounds over years tuned with the ongoing policy process), iterative stakeholder engagement and scenario-based approaches.

F.I.5. What re-usable tools, guidance, open-source solutions will remain after the project ends

After STARS4Water, several assets will remain available:

- Open-source hydrological model (wflow) tailored for the Rhine basin.
- Updated water allocation and use model schematisation compatible with the latest Ribasim software version.
- A comprehensive dataset for indicating water demand for households, industry and irrigated agriculture in the Rhine basin for the current situation and under various future scenarios.
- Scenario workflows and indicators (e.g. unmet demand, environmental flow alteration, risks for inland navigation, based on “Safe-Operating-Space” concepts).
- Guidance and documentation on integrated modelling for transboundary river basins, illustrated by the Rhine case.
- A proven, transferable “Rhine showcase” (and “Danube showcase”, “Messara showcase”) that can be adapted to other European river basins (e.g. the Meuse case). (The Drammen river basin is a showcase for the newest Ribasim software version (2026; with lower TLR level).)

These outputs provide a sustainable foundation for continued basin-scale assessment, management and planning.

The needs and feedback from stakeholders collected are also highly relevant input for the Deltares research agenda and roadmap for the continuous improvement of the Wflow and Ribasim model software packages based on scientific state-of-the-art concepts as part of the Digital Critical Infrastructure and Transformation Strategy and performed in projects like for the Dutch National Hydrological Instrument or the flood early warning system (FEWS) projects worldwide.

F.I.6. Data collected and generated by the project

The following data has been collected, as part of ongoing Rhine projects (like the CHR SES and Rheinblick2027 projects, the Dutch water model instrument project, etc.) and/or as part of the local data collection” activity in the STARS4 water project.

- Hydro-meteorological data (precipitation, temperature, evaporation)
- River discharge time series
- Grid-based water demand and abstraction data (domestic, industry, agriculture)
- Reservoirs and lakes datasets
- Socio-economic drivers and scenario assumptions
- Climate scenario datasets (IPCC AR6 / KNMI’23)

Regarding platforms and maintenance, we would like to mention that:

- Data ingestion, processing and exchange are handled via the FEWS platform.
- Model input and output datasets are stored in STARS4Water project-managed repositories and/or linked to stakeholder institutions, e.g. the Information System of the CHR that is under development, or the STARS4Water Metadata portal and Zenodo.
- Continued maintenance is foreseen through basin commissions and research partners, ensuring datasets remain usable beyond the project life cycle.

F.I.7. Reports

- **Deliverable 3.2:** Improved modelling frameworks for better understanding of water resources at the river basin scale
- **Deliverable 4.2:** Improved projections on water resources availability and risks in selected river basins
- Impact of changing water demand on the transboundary Rhine River basin water balance and flow under climate change (Ter Maat et al, 2025) - CHR report I-29, Deltares report 11211521-015.

F.II. ML irrigated agricultural area and demand modelling tool**F.II.1 Target water types and water bodies**

The modelling tool is developed for identifying irrigated area for the whole area of the Rhine basin. The result of the model is used to derive estimation of irrigation water withdrawal from the surface and groundwater surfaces and consumptive water use (actual evapotranspiration) from irrigation.

F.II.2 Novel digital methods, tools and solutions

A novel modelling tool combining estimates of actual evapotranspiration from the wflow_sbm spatially distributed hydrological model with MODIS satellite land surface temperature (LST) observations was developed. This was done by linking the water balance (actual evapotranspiration) to the surface energy balance to enable a comparison between the modelled and observed LST from MODIS. The differences between modelled and observed LST reflect the actual evapotranspiration from irrigation. A random forest classifier was used to classify irrigated areas from the annual statistical summaries of land surface temperature differences at 1 km spatial resolution. The results were validated against NUTS level 2 administrative regions using data from the Eurostat Farm Structure Survey statistics (2013, 2016) and German Federal Statistics (2019).

F.II.3 Geographical coverage / implementation of the solutions

The modelling tool was applied across the entire Rhine basin that largely covers parts of Germany, France, and Switzerland at 1 km from 2010-2019. The key irrigated hotspots were identified in Alsace, Lower Rhine near Düsseldorf and the Main region near Darmstadt and Rheinhessen-Pfalz.

F.II.4 Findings about enabling conditions or limiting factors related to deployment, scaling, or uptake of these tools/methods

Enabling conditions:

- The method performs well in drier sub-regions where the irrigation signal in LST is more pronounced.
- The framework works without requiring pre-existing irrigation maps as input.

Limiting factors:

- Cloud covers cause data gaps in daily MODIS LST which does not allow for sub-seasonal mapping.
- Performance deteriorates in humid regions and in areas with small, fragmented agricultural holdings (<1 km²) due to mixed pixel effects.
- The classifier is year-specific due to interannual variability in meteorological conditions, requires annual retraining.

- A spatial resolution mismatch between the 1 km mapping unit and actual plot sizes that leads to over- or underestimation in heterogeneous landscapes.

F.II.5. What re-usable tools, guidance, open-source solutions will remain after the project ends

- Irrigation maps of the Rhine basin (2010–2019) published openly via the 4TU.ResearchData repository (DOI: 10.4121/66647538-ed17-4dd2-9af8-962ed0c61177.v2)
- The LST module (linking wflow_sbm ET outputs to land surface temperature) is transferable and described fully in the paper (see Purnamasari et. al, 2025)
- The overall methodological framework is designed to be transferable to other temperate river basins with available hydrological model setups and MODIS data.

F.II.6. Data collected and generated by the project

- Ten annual irrigated area maps (2010–2019) of the Rhine basin at 1 km resolution, including irrigation frequency maps.
- Estimated average irrigated area: ~159,000 ha/year, with spatial extent covering up to 370,000 ha across the basin.

F.II.7. Reports

- The combined LST–hydrological modelling approach can approximate irrigated areas with R^2 of an 0.79–0.90, depending on region and year.
- The Alsace region (Rhine valley, France) consistently shows the highest irrigation extent that expands during dry years.
- Despite covering only ~2% of the basin, irrigation peaks in summer months when precipitation deficits are highest.
- The method outperforms vegetation index-based approaches in temperate humid regions by explicitly accounting for precipitation-driven ET through hydrological modelling.

References

Purnamasari, D., Teuling, A. J., & Weerts, A. H. (2025). Identifying irrigated areas using land surface temperature and hydrological modelling: application to the Rhine basin. *Hydrology and Earth System Sciences*, 29(6), 1483–1503. <https://doi.org/10.5194/hess-29-1483-2025>

ANNEX G – Seine river basin – Hydrological and reservoir modelling framework

Authors: Helena Ramos (INRAE), Julie Collignan (INRAE), Alban de Lavenne (INRAE), Helen Baron (CEH), Leandro Avila (Juelich)

The modelling framework in the Seine consists of several components:

- I. GRSD Hydrological model, including reservoir modelling
- II. ML reservoir storage forecasting model
- III. Data-Driven Groundwater Monitoring (RF – LSTM) model

G.I. GRSD Hydrological model, including reservoir modelling

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

G.I.1. Target water types and water bodies

The GRSD semi-distributed rainfall-runoff model is based on the GR5J lumped model, developed at INRAE in Antony. It has five free parameters to calibrate, and the main components of the model are two stores: a production store (maximum capacity parameter $X1$ [mm]) and a routing store (maximum capacity parameter $X3$ [mm]), which is filled by the output of a unit hydrograph (time base parameter $X4$ [day]). Two other parameters, the groundwater exchange coefficient ($X2$ [mm/day]) and the threshold for groundwater exchange ($X5$ [—]), are used to quantify the inter-catchment groundwater flows (IGFs). To account for snow accumulation and melt, the model is combined with the degree-day CemaNeige snow module, which contains two additional parameters (CTG [—] and K_f [mm · °C⁻¹ · day⁻¹]).

The GRSD model discretizes the catchment into sub-catchments that delineate the modelling units. To capture the spatial variability of the meteorological inputs, a maximum size of the modelling unit is set at 250 km². The modelling units are delineated at all gauged points and then at as many ungauged points as needed to ensure that there is no modelling unit larger than the predetermined size. The lumped GR5J model is then applied on each modelling unit, which receive their own meteorological inputs (rainfall and potential evapotranspiration). Finally, the outflow of each modelling unit is routed to its downstream catchment using a linear lag propagation model. This routing functionality implies an additional free parameter (the average flow velocity C in m/s). The model is described in de Lavenne et al., (2019).

G.I.2. Novel digital methods / tools / solutions

In the modelling of the Seine River basin in STARS4Water, the GRSD model was setup and fully calibrated based on data from 155 gauging stations within the river basin. The snow module was not activated since the river basin is not strongly influenced by snow processes and the focus in the project was low flow simulations during summertime.

Furthermore, additional modelling unit points were introduced in the model to add modelling equations that were able to consider the management curves (storage and release volumes) of the four reservoirs located upstream in the river basin. In practice, to account for the four reservoirs and their influence, reservoir operations were translated into water withdrawals from the river (storage) and injection into the river (release) and set as an external module to the model structure. We added

injection points on the routing of the model, where we used the observations of reservoir management to release or withdraw water from the system accordingly, during the historical period (Collignan et al., 2026). Reservoir modelling rules and constraints were extensively discussed with stakeholders, as well as model calibration and validation.

For the calibration of the model, we adopted a multi-variate strategy. Beyond the traditional calibration based solely on discharge data, we introduced an additional constraint on evapotranspiration (ET) data to better represent the catchment's water balance under historic climate and enhance model transferability to simulate flows under future climate conditions (Hsu et al., 2025; Collignan et al., 2026).

G.I.4. Enabling / limiting factors

This novel modelling setup allows us to evaluate the influence of the reservoirs in sustaining low flows up to the gauging station located downstream in Paris. The calibration strategy we have adopted produces more spatially coherent fluxes and a more stable model response in non-stationary conditions. By better framing internal fluxes, this approach enhances the trustworthiness of hydrological projections under future climate scenarios, which is essential for water resources availability assessments and adaptive management (Collignan et al., 2026).

A limiting factor is that, by simplifying the representation and introduction of complex reservoir operations in the model to focus on reservoir and climate impacts on low flows, anticipatory simulations for preventive management of upcoming high flows or floods are not possible with the current model version.

G.I.5. Re-usable tools

The model setup introduced with the STARS4Water project is comprehensive for users' uptake and not computationally time-consuming. Additional modelling steps can be easily integrated in the code, including for water demand scenario simulation, and have already been discussed with stakeholders as a potential topic for the continuation of the work carried out within STARS4Water in the future.

G.I.6. Data collection, platforms and maintenance

Climate and hydrological data are openly available in France from Météo-France and the French national database HydroPortail. Climate projection data are also publicly available from the website of the national project Explore2.

In STARS4Water, we collected reservoir management data, which are also available from stakeholder EPTB SGL. These data were also used by other partners in STARS4Water (JFZ – Avila et al., 2025 and CEH).

GRSD simulated data produced was made available in the STARS4Water community Zenodo.

The GRSD modelling setup for the Seine River basin will be maintained by INRAE and may be enhanced in the future within further collaborations with the stakeholders.

G.I.7. Key deliverable for the above theme

Scientific publications

Collignan, J., de Lavenne, A., Ramos, M.-H.: The added value of considering evapotranspiration fluxes in the calibration of a semi-distributed hydrological model. *International Journal of River Basin Management*, accepted, 2026.

Hsu, S. C., de Lavenne, A., Perrin, C., Andréassian, V.: Extra constraint on actual evaporation in a semi-distributed conceptual model to improve model physical realism. *Hydrological Sciences Journal*, 1–14, [doi: 10.1080/02626667.2025.2468846](https://doi.org/10.1080/02626667.2025.2468846), 2025.

Other references

Avila, L., de Lavenne, A., Ramos, M.H., Kollet, S.: Estimation of Monthly Water Table Depth Anomalies Based on the Integration of GRACE and ERA5-Land with Large-Scale Simulations Using Random Forest and LSTM Networks. *Water Resources Management* (2025), [doi: 10.1007/s11269-025-04097-7](https://doi.org/10.1007/s11269-025-04097-7), 2025.

de Lavenne, A., Andréassian, V., Thirel, G., Ramos, M.-H., Perrin, C., 2019: A regularization approach to improve the sequential calibration of a semi-distributed hydrological model. *Water Resources Research*, 55 (11): 8821-8839. [doi: 10.1029/2018WR024266](https://doi.org/10.1029/2018WR024266), 2019.

G.II. ML reservoir storage forecasting model

Authors: Helen Baron (CEH)

G.II.1. Target water types and water bodies

Reservoirs are a major source of freshwater for anthropogenic use and can be used to meet water demand for irrigation, industrial or domestic use, along with for hydropower, flood control, and maintaining river levels for ecological and navigational purposes. Reservoirs are often operated for multiple purposes which results in challenging management decisions, for example, how much water should be released from a reservoir before the start of the wet season to reduce risk of flooding while ensuring sufficient available water at the end of the dry season. Therefore, it is important to have a reliable forecast for reservoir status to ensure efficient operation of individual reservoirs and the wider water resource system, particularly during critical periods such as extreme drought and floods. This is a current issue for many regions across the globe and will become increasingly vital under changing climate and growing demand for water and hydropower.

To address this, STARS4Water has developed a data-driven tool to forecast reservoir storage at a monthly timestep, for seasonal to sub-seasonal forecasts at a national or basin scale which can help both water users and water managers with operational decision making.

G.II.2. Novel digital methods / tools / solutions

This tool uses existing datasets, including historic monthly reservoir storage data for each reservoir, along with local meteorological data, catchment characteristics from the Caravan dataset^[4] and reservoir characteristics from the GranD database (Lehner et al, 2011). These data are used to train a multi-site ensemble forest model for reservoir predictions and forecasting at a monthly timestep. This tool is an advance on models which exist in the research sphere, as these are single-site models and so do not benefit from the additional information available from a large-sample approach which has been shown to improve accuracy (Baron et al., 2025). It is quick to run, requires no specialist knowledge of reservoir operations, and has minimal data requirements (monthly historic reservoir storage data is the only local data requirement for model training and meteorological inputs the only driving data required for forecasting). This is balanced by the relatively coarse timestep and broad-brush approach, since this model is intended to give a basin or nation-wide overview of future reservoir stocks.

The model demonstrates strong predictive skill across all the reservoirs, with a median Nash-Sutcliffe Efficiency (NSE) of 0.93 for one month ahead predictions (a skill increase of 0.43 over a simple benchmark) and a median NSE of 0.79 for three-month ahead predictions (a skill increase of 0.47 over a simple benchmark). The model was tested in forecast mode for UK reservoirs, using an ensemble meteorological forecast as driving data, and demonstrated good forecast skill with a Continuous Ranked Probability Skill Score of 0.45 and 0.42 for one month ahead and seasonal forecasts respectively. Comparing model performance across different reservoirs, it was observed that the model performed better for reservoirs with less noisy storage patterns, and in climates with a higher frequency of high and low precipitation days.

G.II.3. Geographical coverage / implementation

The data-driven reservoir forecasting tool targets surface water reservoirs across multiple river basin hubs: 14 reservoirs from the UK, 15 from the Duero basin in Spain, and four reservoirs in the upper Seine. These reservoirs are operated for a range of purposes, including supporting water resources (drinking water etc.), irrigation demand, flood control and hydropower production.

G.II.4. Enabling / limiting factors

-

G.II.5. Re-usable tools

This model will be made openly available through GitHub and archived through Zenodo, along with required data and training materials. The model can be adapted to new regions provided there is historical reservoir storage data (which could potentially be derived from satellite data), although model performance may vary for different types of reservoirs or regions. It is recommended that the model is retrained on available data before being applied to a new reservoir. Materials will be provided to guide the user through this process, but it is non-trivial, particularly if the region is not already covered by the Caravan dataset.

G.II.6. Data collection, platforms and maintenance

-

G.II.7. Key deliverable for the above theme

D3.4: Baron, H., Keller, V., Klotz, D., Kenne, A., Avila, L., Purnamasari, D., Martínez-Santos, P., Aguilera, H., Gómez-Escalonilla, V., Rodríguez del Rosario, M., Díaz Alcaide, S., Beckers, J., Hegdahl, T. J. (2025): Data-driver modelling tools for the STARS4Water River Basins. Horizon Europe project STARS4Water.

Baron et al., (Submitted). Subseasonal to Seasonal Prediction and Forecasting of Reservoir Storage Using a Machine Learning Model in the UK, Spain and France. The International Journal of River Basin Management

G.III. Data-Driven Groundwater Monitoring (RF – LSTM) model

Authors: Leandro Avila (Juelich)

G.III.1. Target water types and water bodies

- Groundwater as the primary water resource: alluvial, porous, fissured and karstic aquifer systems within the sedimentary Paris basin, one of Europe's major groundwater reservoirs
- Surface water with strong groundwater contributions to river baseflow across the basin
- Total terrestrial water storage integrating groundwater, soil moisture, surface water and snow components (as measured by GRACE)
- Seine River Basin (~76,000 km²), northern France

G.III.2. Novel digital methods / tools / solutions

STARS4Water developed for Seine river basin a data driven model based on Random Forest and LSTM networks that can estimate monthly total water storage anomalies based on the integration of GRACE and ERA5-Land datasets.

The main features of this data-driven modelling approach are:

- Pixel-scale data-driven framework integrating satellite remote sensing, global reanalysis and large-scale physics-based simulation outputs to estimate monthly water table depth anomalies (wt_{da}) without new computationally expensive model runs
- Two machine learning architectures independently implemented and compared at each pixel: Random Forest (RF) and Long Short-Term Memory (LSTM) networks
- Inputs: GRACE/GRACE-FO total water storage anomalies (CSR-RL06 mascon, 0.25° resolution, monthly); ERA5-Land variables including precipitation, maximum temperature and evaporation (remapped to 0.11° via conservative spatial aggregation)
- Target variable: spatially continuous water table depth derived from TSMP-G2A.
- Performance vs. TSMP reference: average KGE 0.52 (RF) and 0.54 (LSTM); average Pearson correlation 0.61 (RF) and 0.60 (LSTM); average RMSE 0.18 m (RF) and 0.23 m (LSTM)
- Independent validation against 486 in-situ wells: higher correlations (up to 0.89) in upper basin where groundwater dynamics are tightly linked to surface processes; systematically lower performance in lower Seine where coastal processes and karstic chalk formations introduce dynamics not captured by TSMP or the surrogates.

G.III.3. Geographical coverage

- Full Seine River Basin (714 pixels at 0.11° resolution), northern France
- Developed in collaboration with INRAE (UR HYCAR, Université Paris-Saclay), contributing Seine basin expertise, hydrological memory analysis and access to in-situ validation data
- Directly relevant to Water Framework Directive groundwater status reporting and regional drought and water scarcity management planning in France

G.III.4. Enabling conditions / limiting factors

Enabling conditions

- GRACE and ERA5-Land are globally available open-access products, making the methodology directly transferable without new data agreements
- Open ADES groundwater well database provides independent validation across the full basin

- TSMP-G2A provides a spatially continuous, long-term training target not subject to the spatial sparsity limitations of in-situ networks
- Lightweight pixel-scale models executable on standard computers, lowering barriers for operational uptake by water managers and planners

Limiting factors

- Performance degrades in lower Seine basin where coastal processes, sea level influence and karstic chalk–streamflow interactions are not represented in TSMP or the surrogates
- GRACE coarse resolution (0.25°) limits ability to resolve local-scale groundwater heterogeneity; a single GRACE pixel drives wtde estimates for multiple TSMP pixels
- Maximum lookback period of 8 months tested may be insufficient in sub-catchments with documented multi-year precipitation–discharge memory.

G.III.5. Re-usable tools

After STARS4Water, the following assets remain:

- Trained RF and LSTM model weights, pre-processing, re-gridding and data formatting scripts published openly via STARS4Water GitHub (<https://github.com/openeearth/stars4water>)
- Transferable pixel-scale modelling workflow applicable to any river basin globally where GRACE, ERA5-Land and a physics-based model target are available
- Pixel-specific optimal input configurations and trained model parameters available for the Seine basin
- Methodology extendable by incorporating in-situ wtde observations as additional training targets via multi-objective loss functions, improving performance in well-monitored sub-regions
- RF framework recommended as baseline for new basin applications given computational efficiency; LSTM recommended where long-term memory and sequential dynamics are critical
- Results can be extended to include additional hydrometeorological variables (soil moisture, runoff) and static inputs (geology, land use) to improve performance in complex hydrogeological settings
- The main output of this project are uploaded in a local cloud service from FZJ. (<https://datapub.fz-juelich.de/s/its/Stars4Water/>). This cloud service is also reference in Zenodo. (<https://zenodo.org/communities/stars4water/records?q=&l=list&p=1&s=10>)

G.III.6. Data collection, platforms and maintenance

Multiple datasets were used as input to develop this data-driven model, most of the datasets are open-access.

Data collected:

- GRACE/GRACE-FO: CSR-RL06.2 mascon product, 0.25° monthly, January 2003–January 2024; missing months interpolated via cubic spline (available at <https://www2.csr.utexas.edu/grace>)
- ERA5-Land: hourly 2-metre temperature, daily precipitation and evaporation 2002–2022, aggregated to monthly; remapped to 0.11° via conservative spatial aggregation (Copernicus Climate Data Store)
- TSMP-G2A: daily pan-European hydrological and climatological simulations at 0.11° (CORDEX EUR11 framework); water table depth used as target variable
- In-situ groundwater wells: 486 WTD observation wells from the open ADES database (<https://ades.eaufrance.fr>), covering diverse aquifer types and depths across the Seine basin

Platform and tools:

- Data-driven modelling approach developed in Python

G.III.7. Key deliverable for the above theme

Deliverable 3.3: Improving existing models based on multi-scale model integration

Publications:

Estimation of Monthly Water Table Depth Anomalies Based on the Integration of GRACE and ERA5-Land with Large-Scale Simulations Using Random Forest and LSTM Networks:
<https://link.springer.com/article/10.1007/s11269-025-04097-7>

Integrating GRACE and ERA5-Land with simulations to estimate monthly groundwater table depth anomalies based on Random Forest and LSTM networks over the Seine River Basin
<https://agu.confex.com/agu/agu24/meetingapp.cgi/Paper/1610809>