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STARS4Water

Added value of the next generation tools

Deliverable 4.1

September 2025

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Summary

This report highlights the calibration, validation, and stakeholder-driven development of advanced modelling tools and frameworks to assess future water resource availability across seven river basin hubs: Rhine, Danube, Messara, Duero, East Anglia, Seine, and Drammen. As part of the STARS4Water project, the modelling frameworks and tools are co-developed in collaboration with river basin stakeholders. Designed as a two-level approach, stakeholder champions were selected from a wide range of different groups, such as river basin organizations, public administrations, water managers, and environmental groups. Integrated into a river basin-specific co-creation process, the stakeholders participated in workshops, surveys, and scenario-building sessions. Their input influenced key aspects of the models, from identifying priorities to validating results. STARS4Water has co-developed data-driven models and complementary data services in collaboration with stakeholders. The validation of these tools is documented in deliverables D3.4 and D2.6, respectively.

The stakeholder-driven approach of the STARS4Water project is also inherent to the calibration and validation process of the improved modelling frameworks. Applied calibration and validation methodologies relied on the unlocked and improved datasets gathered within the STARS4Water project. The metadata were published on the STARS4Water Metadata Portal (Stars4Water). Combining new data services at a large scale with local observational data offered new possibilities for calibration and validation.

Advanced techniques such as split-sample testing, multi-objective optimization, and k-fold cross-validation were employed to evaluate model performance. For instance, the GRSD model in the Seine basin was calibrated using daily discharge and evapotranspiration data, achieving high Kling-Gupta Efficiency (KGE) values, which demonstrated its reliability in reproducing observed streamflow. Similarly, the LISFLOOD model in the Drammen basin underwent a stepwise calibration process, achieving KGE values above 0.75 for most stations, despite challenges in high-altitude catchments. In the Duero basin, the MODFLOW model was calibrated using a decade of reliable groundwater pumping data, while the RIBASIM model in the Danube basin was validated against discharge data from multiple sources to ensure its accuracy in simulating water allocation scenarios.

The calibration and validation processes also incorporated scenario modelling to test the models under future climate and socio-economic conditions. For example, the Rhine basin models integrated KNMI’23 climate scenarios to predict water shortages by 2050, while the Seine basin models evaluated reservoir management impacts under low-flow conditions.

The overall goal of improving data-driven models and data services was to create an added value. This added value stems from collaboration at every stage, starting with understanding and identifying the water management needs in the basins. Stakeholders contribute by helping to improve the accuracy of models through feedback on calibration and validation methods. They also play an important role in ensuring that the models are practical and relevant for real-world use.

A key part of this process is building trust in the modelling framework. Confidence in the models is essential for assessing the risks and challenges that climate change and socioeconomic development pose to Europe’s freshwater resources. Addressing stakeholder needs with reliable and practical modelling frameworks, STARS4Water creates a strong foundation for water resource availability management. This combination of trust, collaboration, and practical application is what defines the added value.

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1. Introduction

1.1. STARS4Water project

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

The project aims to:

- Improve understanding of climate change impacts on water availability and related vulnerabilities.
- Develop advanced data services and models to support sustainable freshwater management.

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

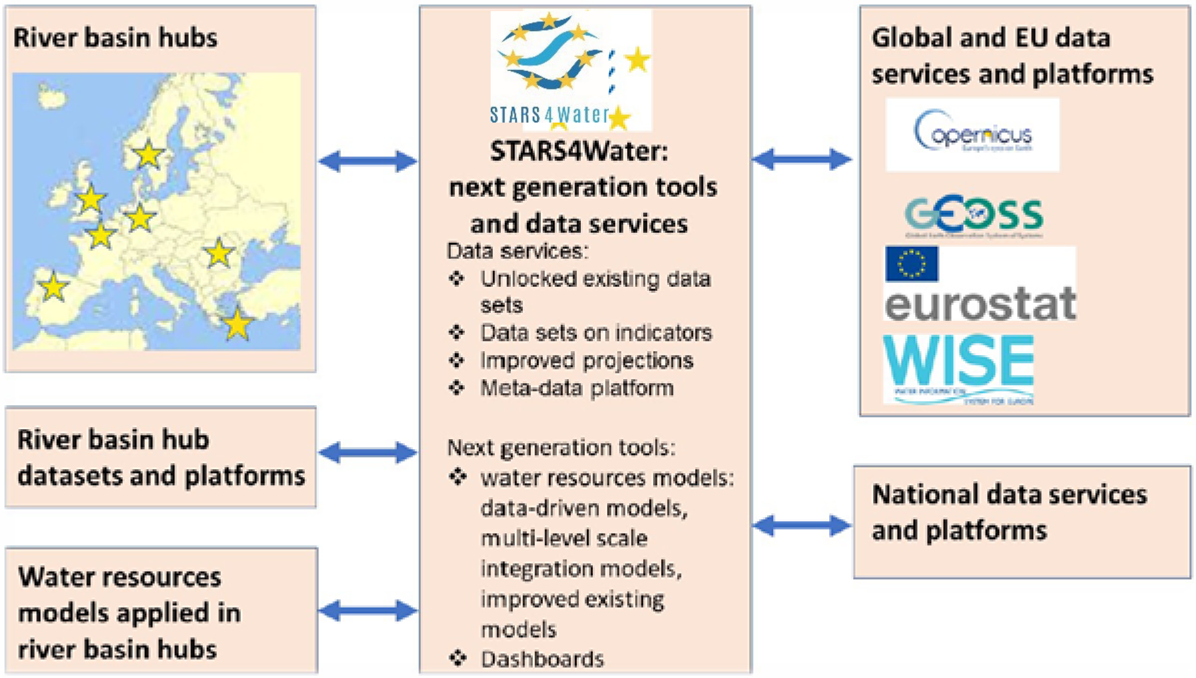

Figure 1.1. Overview of STARS4Water activities within the context of stakeholders and data providers.

1.2. Integrated assessment of future water resources.

One of the objectives of the STARS4Water project is to validate and apply new data services and modelling tools to provide an integrated assessment of Europe's future freshwater resources under a changing climate. This objective is driven by the desire to provide water managers across Europe with better data and models to better understand current and future hydrological processes and flows at river basin scale. The next generation tools are developed in collaboration with stakeholders, ensuring a strong application focus and reflection of the needs of river management. Work Package 4 (WP4) of the project is dedicated to the integrated assessment of future water resources.

The main activities in this work package are:

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

The interrelation of Work Package 4 in the STARS4Water Framework is displayed in Figure 1.2.

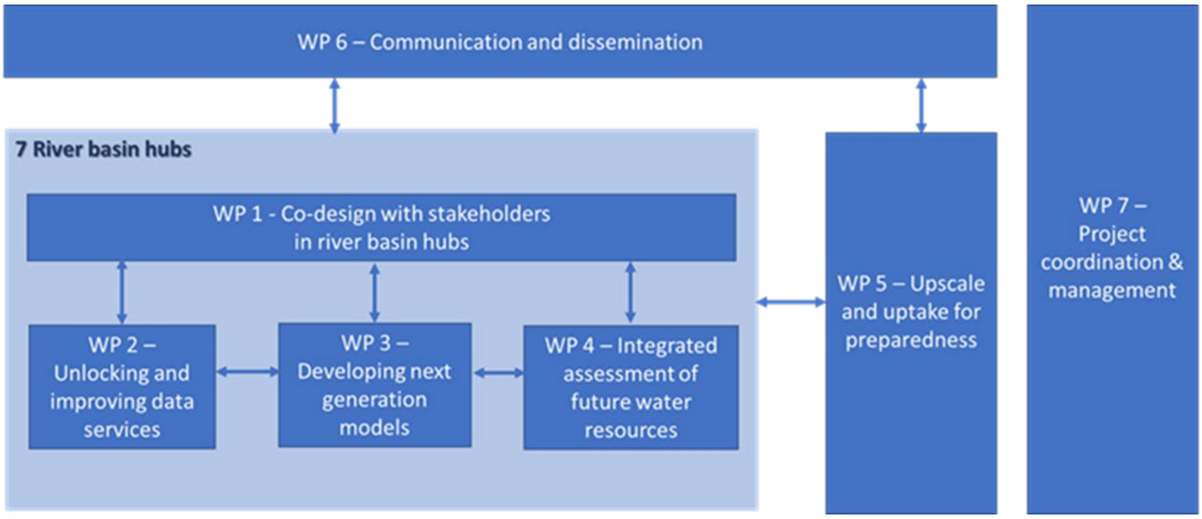

Figure 1.2. Work package structure of the STARS4Water project: the development of the next generation models (WP3) through a co-creation approach (WP1), benefitting from data sources available (WP2) and calibration and validation activities in WP4 to explore future water resources availability in European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

1.3. This report

This report (Deliverable D4.1) presents the following:

a) Brief outline of newly developed or improved modelling frameworks to assess future water resources availability. For a full description of the models and new data tools, please see the reports on tasks 3.2, 3.3 and 3.4.

b) Stakeholder supported process of calibration, validation of the improved modelling frameworks

c) Added values of the developed modelling frameworks in addressing the future water resources challenges identified by the river basin stakeholders.

In addition to advancing the river basin modelling frameworks, STARS4Water has developed data-driven models and complementary data services. These tools are documented in Deliverable D3.4 (data-driven models) and Deliverable D2.6 (data services). In several river basins, the data-driven tools will be employed to assess both current and projected water resource availability, along with their associated impacts. A brief overview of these tools is provided in this report. This report primarily focuses on the enhanced modelling frameworks, which have been co-developed in close collaboration with river basin stakeholders.

2. Drammen

Authors: Kolbjørn Engeland, Trine Jahr Hegdahl, Shaochun Huang

Historically, the main water-related challenge in the Drammen River basin has been large floods, which caused significant damage to buildings, infrastructure and farmland. The Drammen basin plays a key role in Norway's hydropower production and therefore contains many hydropower reservoirs. These reservoirs are also used to mitigate the impact of floods during extreme events. Additionally, reservoir management helps maintain minimum streamflow levels to support ecological favourable conditions. In recent years, droughts have introduced new challenges as water scarcity becomes an increasing concern scarce. Changes in the magnitude, frequency, and seasonality of extreme events, both droughts and floods, are amplifies the pressures on ecology, society and energy production.

2.1. Modelling framework overview

The modelling framework for the Drammen Basin incorporates three hydrological models: LISFLOOD, a gridded HBV model and wflow_sbm. Using these models together is a novel approach that creates a small ensemble, enhancing the robustness and reliability of the results by providing multiple perspectives on hydrological processes. The LISFLOOD model has been customised specifically to represent all 54 reservoirs within the Drammen Basin. This updated version also accounts for changes in land use and water demand, providing a more accurate reflection of current and future conditions in the region. The gridded HBV model has been developed with a spatial resolution of 1 km to calculate water balance and runoff with high precision. This fine resolution allows for detailed insights into the basin's hydrological dynamics. The wflow_sbm model is tailored to the Drammen River Basin and uses global datasets refined with national data, including detailed reservoir information. This integration ensures that the model captures both large-scale patterns and localised characteristics of the basin.

Two distinct modelling chains are used in the Drammen Basin to address different aspects of water management and hydrology (Figure 2.1). The first modelling chain integrates the hydrological models (HBV or LISFLOOD) with energy production tools to improve regional simulations. In this chain, the hydrological models generate inflow data for EOPS (a reservoir management simulator widely used by local stakeholders). EOPS then calculates key reservoir operations such as water levels, power production and outflows. These outputs are then fed back into LISFLOOD to evaluate the impact of river regulations on streamflow. This iterative process is supported by data exchange protocols to ensure seamless integration between the models. By combining data on energy production, land use changes and water demand or extraction, the chain provides a comprehensive understanding of the interactions between hydrology and energy management.

The second modelling chain uses the RIBASIM model, linked to wflow_sbm, to simulate natural hydrological processes and human impacts on the system. This approach is particularly well-suited to the management of multipurpose reservoirs, as it enables the evaluation of various scenarios involving water storage, distribution and usage. Together, these two modelling chains provide a flexible and comprehensive framework for addressing the intricate hydrological and resource challenges of the Drammen Basin.

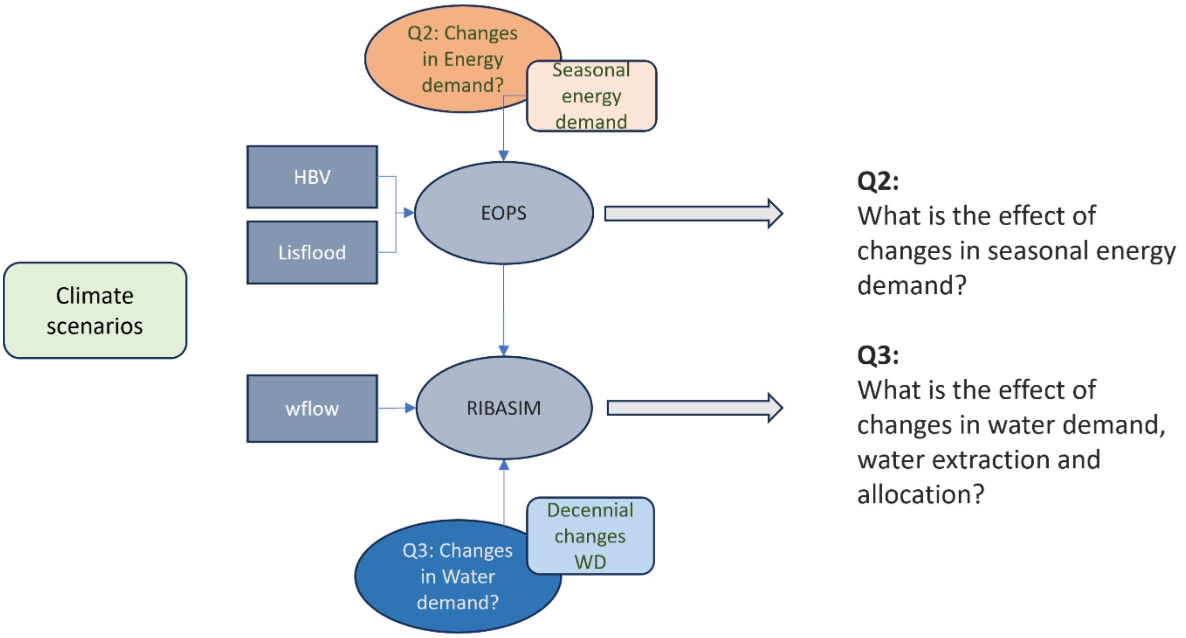

Figure 2.1. The Drammen basin modelling framework highlighting the two modelling chains used to answer the effect of changes in the energy market (Q2) and changes in water demand, water extraction and allocation (Q3), more details on the modelling chain in D3.3.

2.2. Calibration and validation

The three hydrological models (LISFLOOD, HBV and wflow_sbm) were calibrated using local streamflow data from the Drammen gauging station. HBV and LISFLOOD used streamflow from 11 subcatchments not affected by river regulations. Wflow_sbm excluded the two smalllest catchments and used 9 of these for calibration. LISFLOOD and wflow_sbm used additional 6 streamflow datasets downstream reservoirs to tune the reservoir modules. All models were calibrated using data from the period 2001-2020 using Kling-Gupta Efficiency (KGE) as the objective. 1981-2020 was used as validation period. All models used daily temperature and precipitation product, SeNorge2018 (Lussana et al., 2019), on a 1 km spatial resolution.

The LISFLOOD model was calibrated using streamflow data from the Drammen gauging station, with the Kling-Gupta Efficiency (KGE) used to evaluate performance. Calibration was conducted in a stepwise manner. First, seven hydrological parameters were adjusted using streamflow data from 17 locations, starting with headwater catchments and progressively including downstream areas while keeping parameters constant in intermediate zones. For the 6 gauging stations located downstream reservoirs, naturalized flow series were used for calibration. Next, two reservoir parameters were calibrated using measured streamflow data from the six locations downstream of reservoirs. These parameters were held constant in the surrounding sub-catchments. As shown in Figure 2.2 the calibration results indicate that all stations in unregulated sub-catchments achieved KGE values above 0.7 during calibration and validation. The calibration results for locations downstream of reservoirs show lower KGE values than for unregulated catchments. The poor performance is primarily due to the LISFLOOD model's simplified representation of reservoirs.

The calibration of the HBV model process focussed on six parameters related to soil and groundwater processes, which varied depending on soil type, and two parameters related to snowmelt processes, which depended on land cover type. The performance of HBV is slightly lower than for LISFLOOD, with 0.58 as the lowest KGE-value.

Wflow-sbm was in a first step calibrated to 9 sub-catchments with natural flows and thereafter to 6 sub-catchments downstream reservoirs. In the first step the ratio between horizontal and vertical saturated conductivity, KsatHorFrac was tuned (Wannasin et al., 2021). The reservoirs were modelled by using a target filling given as range. The target filling depends on day of the year. Each reservoir should stay within this target range by releasing or storing water. This enables us to simulate the seasonality of reservoir water levels. The target filling for each reservoir were based on the water levels observed during the calibration / validation period (1981-2020). Figure 2.2 shows that the performance for wflow-sbm is poorer than for both HBV and LISFLOOD, however wflow is less calibrated than the other two models.

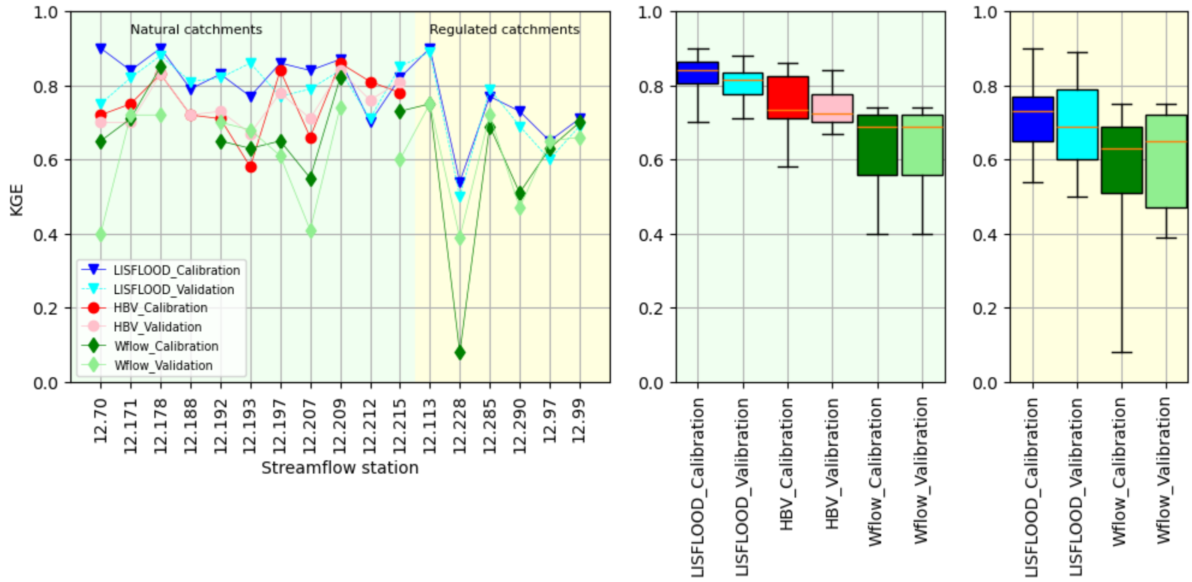

Figure 2.2. Calibration (years 2001-2020) and validation (years 1981-2000) results for streamflow gauging stations in Drammen River basin. The KGE criterion is used for evaluation, and a value close to one indicates a good performance. Left panel: calibration and validation performance for individual streamflow stations, middle panel: box-plots showing the minimum, maximum, quartiles and median KGE values for streamflow stations in unregulated catchments, right panel: similar as for middle panel in regulated catchments.

The models' ability to simulate reservoir water levels was assessed by comparing the average seasonal patterns of simulated and observed reservoir filling for all reservoirs (see Figure 2.3). The results show that EOPS provides a more accurate representation of the reservoir seasonality compared to the reservoir models used in wflow-sbm and LISFLOOD. This underscores the importance of continuing to develop and apply the new modelling framework we have configured for the river basin.

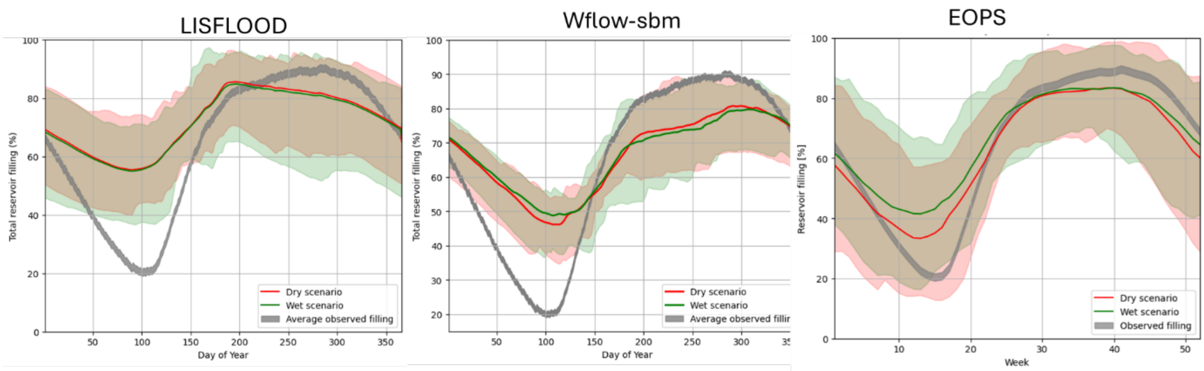

Figure 2.3. Seasonality of reservoir-filling as simulated by LISFLOOD (left) wflow-sbm (middle and EOPS (right). EOPS runs on a weekly time resolution. The model simulations are based on downscaled climate scenarios from two different climate models.

The reservoir simulation of RIBASIM is still under development and will be presented in coming reports.

The calibration and validation processes for both models show that they are able to simulate the hydrological processes in the Drammen basin, despite challenges such as data limitations and the complexity of reservoir operation. The reservoir simulation of RIBASIM is still under development and will be reported in D4.2.

2.3. Stakeholder engagement

The two modelling chains of the Drammen River basin modelling framework were developed in close collaboration with the Energy Department of NVE. The framework was presented during a stakeholder meeting that included representatives from the hydropower sector, public water supply, and regional and national authorities responsible for water resource management, ecological monitoring, and licensing. The framework was endorsed by stakeholders and recognized as a robust and effective approach for addressing current and future water resource challenges in the Drammen basin, particularly with regard to water management and operational strategies during extreme events. Calibration and validation results from the individual models were shared with stakeholders and received positive feedback.

2.4. Added Value

In an earlier version of the modelling framework, the inflow to the reservoir was estimated using data from a selection of indicator catchments located both within and outside the Drammen River Basin. This method relied on generalised, large-scale calibrations. Specifically, the HBV model was calibrated for Norway as a whole, and the LISFLOOD model was calibrated for Europe as a whole. While this approach provided a broad overview, it lacked the precision required to accurately represent local hydrological conditions. In LISFLOOD, reservoir operations were simplified, with outflows determined solely based on water levels. This limited the model's ability to capture the complexities of reservoir management.

The new version of the modelling framework for the Drammen River basin addresses these limitations by introducing several key improvements. Reservoir inflow is now calculated directly from the sub-catchments associated with each reservoir, providing a much more accurate, localised representation of inflow dynamics. This eliminates the need to rely on indicator catchments, which often introduced inaccuracies. The updated modelling framework also incorporates enhanced representations of land use and climate change, enabling a more detailed and realistic evaluation of their influence on energy production and water availability.

A further significant enhancement is the local calibration of the HBV and LISFLOOD models using streamflow data specific to the Drammen River Basin. This ensures that the models are tailored to the region's unique hydrological characteristics, significantly improving their accuracy. Additionally, the LISFLOOD model has been expanded to include more reservoirs, with reservoir outflows now being directly integrated into the river network. This enables the modelling framework to simulate the operation of reservoirs and downstream streamflow much more realistically, capturing the interactions between reservoirs and the river system more effectively.

3. Rhine

Authors: Judith ter Maat, Tatjana Edler, Devi Purnamasari and Esmée Mes

One of the primary concerns in water resource management within the Rhine Basin is the occurrence of low flow conditions. The decline of Alpine glaciers, coupled with the anticipated increase in the frequency and intensity of drought events, is expected to exacerbate these conditions—leading to further declines in water levels and prolonged periods of low flow.
The development of the Rhine basin modelling framework was a collaborative effort, involving extensive stakeholder engagement and active participation from representatives of the three Rhine commissions: the International Commission for the Hydrology of the Rhine Basin (CHR), the International Commission for the Protection of the Rhine (ICPR), and the Central Commission for the Navigation of the Rhine (CCNR). Throughout the process, multiple stakeholder meetings were convened to gather input on key components of the project, including scenario development, local data collection, and model design. These discussions emphasised the importance of harmonising national and local datasets to inform scenario narratives and enhance model accuracy. Bilateral consultations with the ICPR Expert Group on Low Water were particularly valuable as they provided detailed insights into region-specific challenges and data needs. The modelling framework was further strengthened through the integration of local datasets provided by ICPR representatives, ensuring that the tool accurately reflects the unique hydrological characteristics of the Rhine Basin.

3.1. Modelling framework overview

Significant advancements in the Rhine River basin modelling framework have been made by integrating the Rhine RIBASIM water allocation management model with the Rhine wflow_sbm hydrological model and incorporating new water demand modules. The updated model can simulate current and future scenarios. The modelling framework includes the latest RIBASIM version featuring a modern graphical interface, improved database capabilities, and a robust computational framework. Consequently, the new RIBASIM enables a better representation of the Rhine River basin. Enhancements in the representation of the Rhine River include integration of localised data and expert knowledge, refining the model schematisation of 9 sub-basins, detailed representation of the river networks, reservoirs and lakes and different water users and supply.

The Rhine basin modelling framework links the RIBASIM model with the wflow_sbm model, a free, open source, distributed hydrological tool suited for large-scale, high-resolution applications and grounded in physical processes and characteristics. The Rhine wflow model is at 1km spatial resolution and daily temporal resolution. The integration allows the model to consider key hydrological conditions such as rainfall, evaporation, and runoff. The framework includes updated data on water storage, catchment hydrology, land use, water demand and use from regional and local databases, as well as EU and global datasets. A novel approach to estimating irrigation water demands was developed, using an irrigation map based on earth observation data and statistical analyses. Information on detailed irrigation water use is one of the stakeholder needs to improve water management practices in the Rhine basin. Further developments of the approach to estimate detailed irrigation water use is part of an ongoing PhD research project (2022-2026) within the STARS4Water project.

At last, the datasets that represent the new transboundary Rhine River basin scenarios were generated and included in the modelling framework. The modelling framework for the Rhine basin cannot only simulate the current situation, but also future scenarios regarding climate change and socio-economic developments based on specific information of the Rhine basin. The scenarios that are integrated in the modelling frameworks are the climate change scenarios based on the KNMI’23 regional climate scenarios (KNMI, 2023) and the socio-economic scenarios based on narratives co-designed with stakeholders (CHR, 2025). These scenarios analyses support the informed decision-making process on the climate adaptation plan in the Rhine basin that is currently underway.

3.2. Calibration and validation process

The calibration process of the Rhine basin modelling framework used monitoring data to fine-tune the model's representation of the Rhine River's flow dynamics. Performance evaluation of the wflow_sbm model without further calibration showed results ranging from 0.6 to 0.9 (Imhoff, van Verseveld, van Osnabrugge, & Weerts, 2021). Buitink et al (2023) calibrated and validated the wflow_wbm model for the Rhine basin in detail in context of assessing the implications of the KNMI'23 climate scenarios (based on AR6 of IPCC) for the discharge of the Rhine. More details on calibration methods can be found in those studies. The daily discharges generated with the Rhine wflow_sbm are transferred to the Rhine RIBASIM model, simulated at a 10-day timestep. The model was tested by simulating historical hydrological and meteorological conditions, comparing results with monitoring datasets to verify accuracy. The simulated discharge timeseries are put in wider perspective by comparing projected future discharge changes with the results of the HCLIM study (ICPR, 2024). In the HCLIM study discharge timeseries from different hydrological models and based on different climate change scenarios (AR4 and AR5 of IPCC) in the Rhine countries were collected and evaluated to detect the range of future projected discharge changes.

The model's water demand estimates that are generated by the wflow water demand module and that are included in the RIBASIM water allocation simulations were compared with other studies, including the German WADklim study, localised data from Switzerland, France and Germany, and the ongoing PhD research. The model was benchmarked against existing methods to evaluate performance in for example estimating agricultural water demand and irrigation use (Figure 3.1 and 3.2).

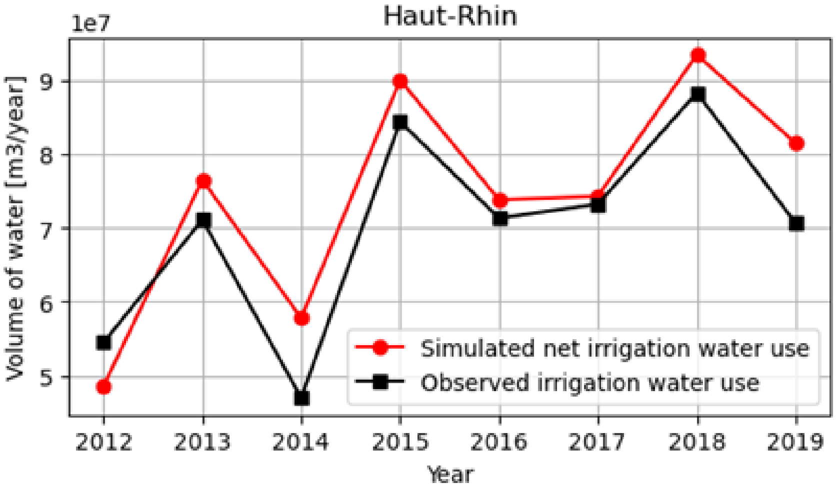

Figure 3.1. Comparison.between.simulated.(using.the.novel.approach.developed.in.STARS0Water).and.
observed.water.irrigation.water.use.for.the.Haut_Rhin.regions.(Purnamasari?in.preparation)¡

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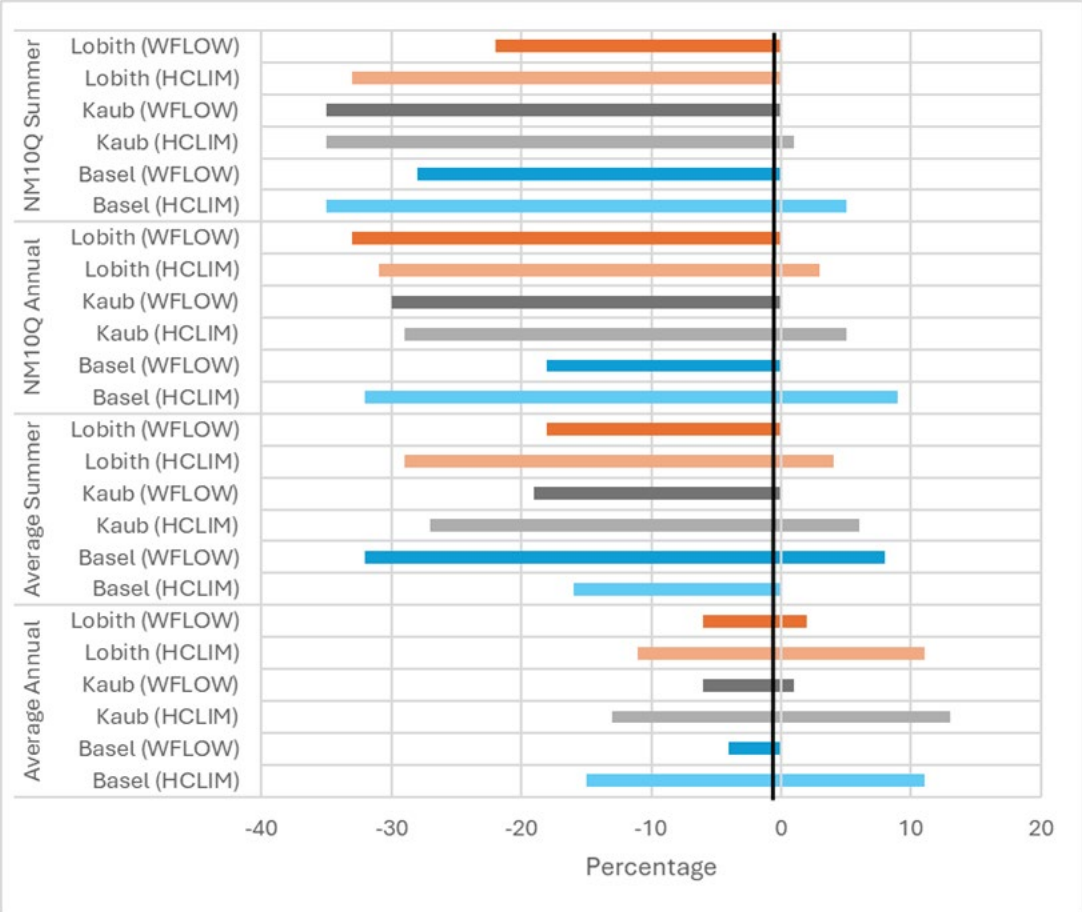

Figure 3.2. Comparison projected future discharge changes per gauge in HCLIM study using ensemble of models and STARS4Water/ CHR SES study using wflow.

Despite these advancements, certain challenges persist. Access to certain local datasets, such as private data on reservoir operations and specific local water abstractions, remained limited or difficult to obtain. Furthermore, harmonising localised datasets from different countries within the Rhine basin was a complex task that could not be fully realised within the project's timeframe. These limitations highlight areas for improvement in the future and emphasise the importance of continued collaboration among stakeholders to improve data availability and integration.

3.3. Stakeholder involvement

Between 2023 and 2025, stakeholders played an active role in shaping the scenario modelling tool, attending a series of meetings and events in the process. Scientific officers and representatives from the CHR, ICPR and CCNR contributed their expertise to ensure the tool aligned with these commissions' strategic goals. Country representatives within the ICPR Expert Group on Low Water provided valuable insights to address challenges associated with low-flow conditions, and CHR members offered technical and strategic guidance to enhance the tool's functionality. A significant milestone in this collaborative process was reached in March 2025, when the ICPR's Rhine Climate Adaptation Conference featured a keynote presentation on the results of the tool. This event brought together institutions and stakeholders to discuss climate adaptation strategies and the potential role of the tool in supporting these efforts.

The review of the CHR Socio-Economic Scenarios report (mid 2025) by country representatives provided additional feedback and input to further improvement of the modelling framework. The CHR biannual meeting in October 2025 will be an important opportunity to reflect and collect feedback on the results of the assessment of future water resources, and to explore new opportunities for further practical application and define next steps. The results on future water resources availability will also be presented in the ICPR Expert Group Low Water Strategy in November and the ICPR Strategy Group in December 2025. These collaborative efforts have ensured that the modelling framework is informed by a diverse range of expertise and is embedded in the work of the CHR and ICPR, making it a robust and effective tool for managing the complex challenges of the Rhine River basin in the face of climate change.

3.4. Added Value

The new modelling framework of the Rhine basin plays a vital role in the CHR's mission to establish a robust scientific foundation for understanding the hydrology of the Rhine catchment area. It enables the analysis and simulation of water systems, providing insight into how they respond to environmental and socio-economic changes.

The Rhine basin modelling framework is a critical tool for supporting the development and implementation of Rhine basin's climate adaptation plan. It delivers reliable, science-based information and insights that enable researchers and policymakers to assess various scenarios and make informed decisions. In response to the specific questions from the ICPR, the tool contributes to the development of strategies for managing water resources and mitigating the effects of climate change.

The modelling framework provides detailed analyses of water balances, river discharges, and the reliability of water supplies. Its core objective is to assess the current availability of water within the Rhine catchment and to project how this may evolve under future climate conditions. It also evaluates present water use, particularly in the agricultural sector, and forecasts potential increases in demand. Moreover, the framework identifies regions within the Rhine Basin that may face water scarcity by 2050, thereby helping to anticipate and address emerging risks.
The STARS4Water project has made significant progress in improving the quality of data available for the Rhine basin. A first transboundary dataset archive has been created, containing data on meteo, water availability and water demand for domestic, industrial and agricultural use The first database on present Rhine reservoirs has also been developed. Important detailed local data such as information on reservoir operations and specific water abstractions (location and rates) remains unavailable or difficult to collect. Efforts to harmonise national data cross-boundary for improved local modelling were not completed within the project's timeframe and requires cross-national and coordinated efforts.

The project successfully integrated regional climate scenarios into the tool, incorporating reference climate data and three KNMI'23 climate change scenarios for 2050. A major achievement was also the co-design of three socio-economic scenarios, including datasets, in collaboration with stakeholders. These socio-economic scenarios are combined with the climate change scenarios. The tool was expanded by linking the Rhine RIBASIM water allocation model with the Rhine wflow hydrological model, as well as by incorporating new water demand modules. This integration ensures that the tool is scientifically accurate and practical for addressing future challenges in the Rhine basin and will support the development of the climate adaptation plan and sustainable water management

4. Danube

Authors: Martin Glas, Tamara Graf, Max Preiml, Mario Klösch, Albert Scrieciu, Andrei Toma

4.1. Modelling framework overview

During the needs assessment of stakeholders of the Danube basin including ICPDR (Hegdahl et al-, 2023) a model approach allowing an evidence-based estimation of water availability was mentioned as a key challenge. A need for such a model approach was identified to establish or improve low flow modelling and to gain information on available water at a certain location in the basin. Such a modelling framework was not in place for the Danube River until now to assess low flow conditions and water abstractions for agriculture, drinking water, industry, cooling water and environmental needs.

The RIBASIM model, developed collaboratively by BOKU, Deltares, and GeoEcoMar, is a tool used to simulate water resource management in the Danube River basin (Figure 4.1). Its development has been guided by local expertise, particularly from BOKU and GeoEcoMar, and focuses on addressing water demands. The model is applied across the whole basin, with a focus of the upper Danube region, such as Germany and Austria, as well as of Romania, which is part of the lower Danube. RIBASIM is closely integrated with a hydrological framework based on the wflow_sbm model, which was originally developed as part of the European research project "DOORS Black Sea" and forms the basis for simulating natural flows in the basin. Within this framework, RIBASIM incorporates demand nodes and links to represent water use and distribution across the Danube basin with a focus on the Danube River during low flow conditions.

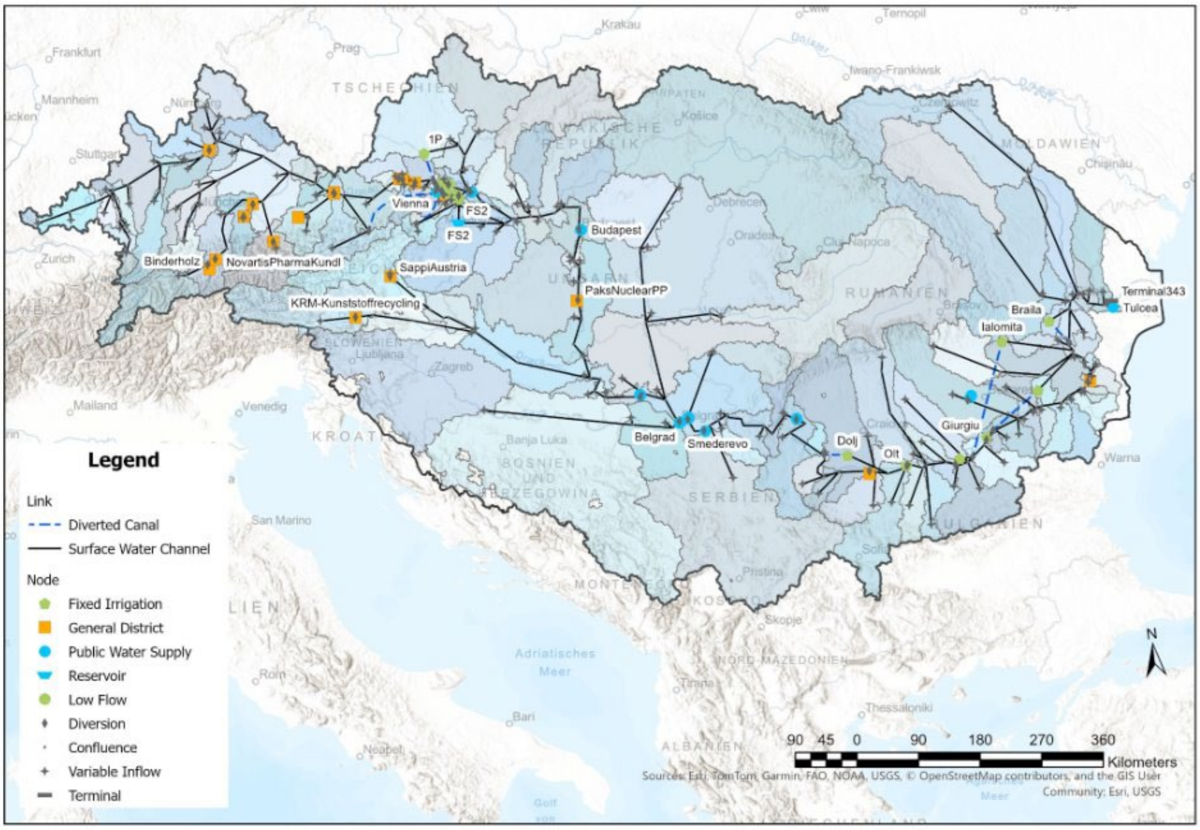

Figure 4.1 Scheme of the RIBASIM model set up for the Danube River basin.

4.2. Calibration and validation process

The calibration and validation of the RIBASIM model present significant challenges due to the complexity of water demand, which is influenced by a wide range of ecological and socio-economic factors, such as population, economic development, hydropower, navigation, land use and agricultural practices. Achieving a comprehensive and accurate representation of water demand and its interactions with the biophysical state is not feasible, consequently, the validation process relies heavily on measured discharge data. This data serves as the most reliable basis for assessing the model's performance.

Validation of RIBASIM is conducted using datasets from sources such as Eurostat, Wanders et al. (2018) and Eureau, which provide detailed information on water usage. Discharge data were derived from GRDC, ehyd, DanubeHIS and Institutul Național de Hidrologie și Gospodărire a Apelor, București (Figure 4.2). The wflow model calibration and validation was applied in the framework of the "DOORS Black Sea" project. In subbasins representing major Danube tributaries, where calibration results for a sub-basin are already available from the DOORS project, water demand was not included to avoid double-counting in RIBASIM. However, in sub-basins where the wflow model has not been calibrated, water demand is incorporated into the RIBASIM model. The combined natural flow and water demand are then validated against observed discharge data, ensuring the model's accuracy and reliability (Figure 4.3). Danube basin stakeholders confirmed the model's reliability under low flow conditions, supporting its application for estimating future water resources availability. Sensitivity analyses were also performed to assess how variations in water demand affect the overall system, providing further insights into the model's robustness. The outcomes of these analyses were logically consistent and aligned with expectations.

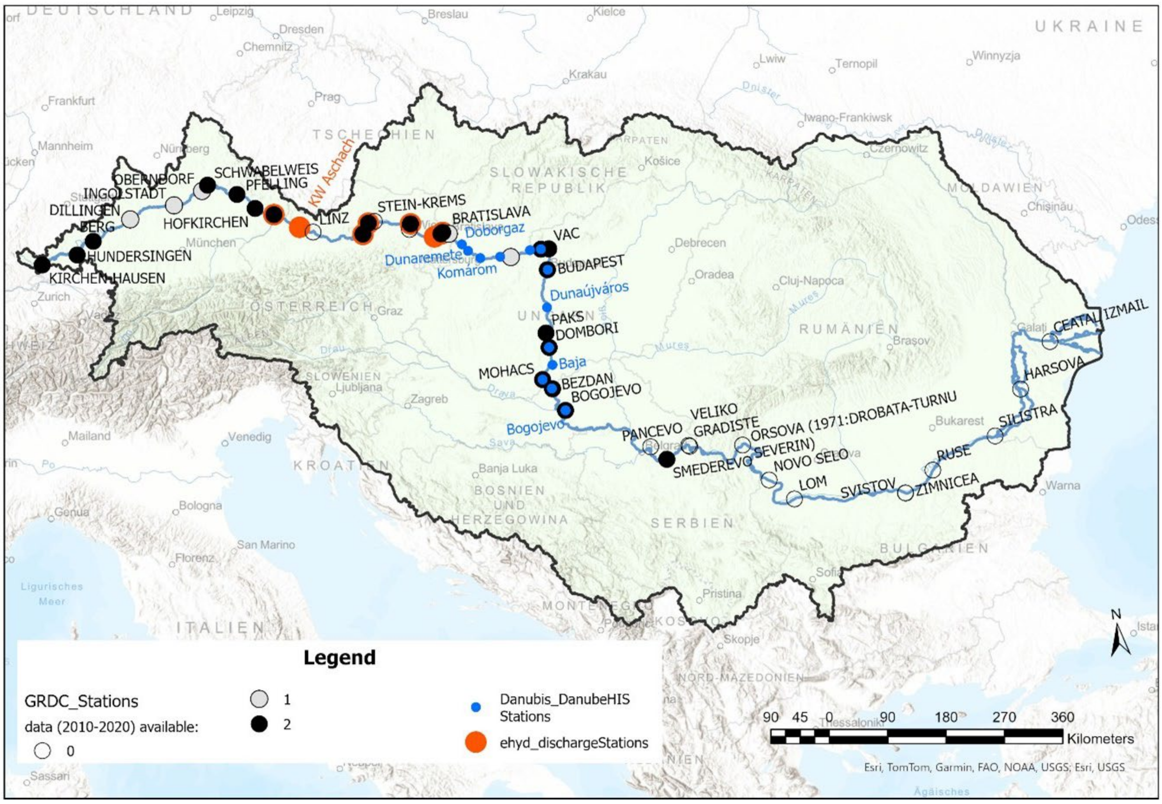

Figure 4.2. Discharge measurement stations used for validation of the RIBASIM model (sources: GRDC, ehyd, DanubeHIS and Institutul Național de Hidrologie și Gospodărire a Apelor, București).

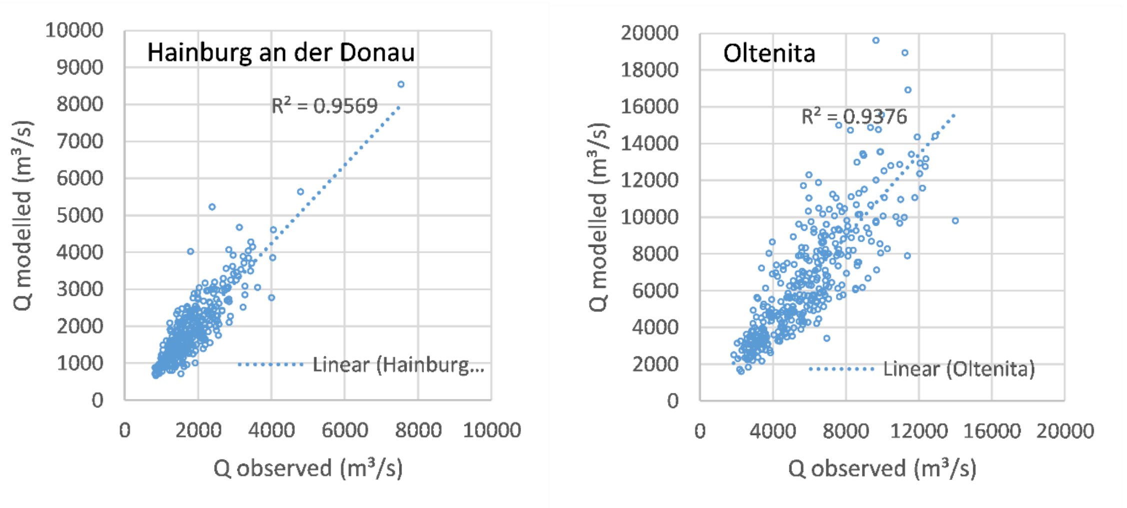

Figure 4.3. Examples from the validation of discharge Q of the RIBASIM model. Left: Upper Danube, Hainburg an der Donau near Vienna, Austria. Right: Lower Danube, Oltenita near Bucharest, Romania (sources: ehyd, Institutul Național de Hidrologie și Gospodărire a Apelor, București).

4.3. Stakeholder engagement

Stakeholder engagement has been a critical component of the RIBASIM model's development and application. The International Commission for the Protection of the Danube River (ICPDR) has played a key role in evaluating and integrating explicit water demands into the model. During a stakeholder meeting in October 2024, the importance of these integrations was acknowledged. Furthermore, the first results of the model were discussed during the ICPDR River Basin Management Expert Group meeting held in Vienna from May 6 to 7, 2025. These exchanges with stakeholders contributed to refine model assumptions and parameters, strengthening the model's relevance for regional water management. The ICPDR stated that the modelling framework developed in STARStars4Water initiative contributes significantly to integrated river basin management in the Danube region. It enhances the capacity to anticipate potential conflicts arising from low water conditions—such as droughts—within the broader context of climate change and socioeconomic developments across the basin.

4.4. Added Value

Driven by the needs of stakeholders, a Danube River basin modelling framework was developed encompassing a specialized water allocation model with a particular emphasis on low-flow conditions. The modelling framework is designed to evaluate how water withdrawals directly from the Danube—excluding its tributaries—affect critical sectors such as hydropower generation, navigation, agriculture, industrial operations, and domestic water supply. By focusing on periods of reduced water flow, the model examines the competing demands for water and their impact in the river's flow patterns. It also planned to explore strategies for sustainable water management under conditions of limited availability.

This is the first water management model for the Danube River basin, co-created with ICPDR, that integrates such a wide range of water demands, providing a comprehensive and realistic representation of the Danube's water resources and availability within the focus area. Within the Austrian modelling area, the model accounts for agricultural water needs in the Marchfeld region, supported by the artificial Marchfeld channel, which is used for both irrigation and groundwater recharge. Irrigation demand in Romania was considered using data from eight districts along the Danube provided by ANIF – Romania's land reclamation agency. Industrial water use is incorporated using data from major facilities in Austria and Bavaria, including cooling water requirements for key sites like nuclear power plants in Pacs (Hungary), Kozloduy (Bulgaria) and Cernavoda (Romania). Environmental flow needs are also considered, particularly for the Upper Lobau floodplain, a protected area within the Donau-Auen National Park. Additionally, domestic water consumption is estimated for major cities such as Vienna, Bratislava and Bucharest, using locally sourced data combined with European data by EEA.

One of the key challenges encountered was the need to simplify the complex, real-world water system to align with the structural requirements of the RIBASIM model. Another significant limitation was the limited availability of data on return flows, which necessitated the use of assumptions and simplifications. For example, it was assumed that cooling processes return 100% of the water used, although this may not accurately reflect actual conditions in all cases.

A further difficulty was the ambiguous definition of "industrial water supply," which was often used inconsistently. In some cases, it overlapped with agricultural or public water use, depending on the city. Furthermore, a lack of detailed information on residual water supply added complexity to the modelling efforts. These challenges highlight the need for more accurate and standardized data.

5. Duero

Authors: Pedro Martínez-Santos, Manuel Rodríguez del Rosario, Víctor Gómez-Escalonilla, Silvia Díaz-Alcaide

5.1. Modelling framework overview

STARS4Water adopted a hybrid modelling framework in the Duero basin, integrating conventional numerical simulation techniques with advanced AI-based models to address the stakeholders' requirements. Numerical models provided a physically consistent representation of groundwater flow and water resources availability, while AI-driven approaches enhanced predictive capability by capturing complex, nonlinear relationships within the system that are difficult to resolve through traditional methods alone in order to predict the spatial distribution of key contaminants -nitrate- across the basin. By combining these two approaches, the study was able to generate robust, data-informed insights that improve the assessment of water resources availability and the risks of groundwater contamination, ensuring that management strategies are both scientifically sound and aligned with stakeholder needs.

The updated version for the Duero basin groundwater model encompasses all major interconnected groundwater bodies in the southern half of the basin. It incorporates improved estimates of groundwater demand, climate change scenarios and pumping rates designed to restore aquifers and groundwater-dependent ecosystems.

MLMapper is a machine learning tool developed to map the spatial distribution of groundwater contamination. This model currently focuses on nitrate, as this was identified by key stakeholders as the most widespread groundwater quality problem in the basin. This data-driven model uses observations from both uncontaminated and contaminated boreholes for training and testing purposes. It is particularly effective at identifying explanatory variables and can be extended to clustering for trend analysis.

5.2. Calibration and validation

For MODFLOW, the calibration period runs from 2013 to 2022. This is the longest uninterrupted timeframe for which reliable groundwater pumping data is available. This interval includes an average-to-wet climatic sequence, providing a robust dataset for model calibration.

The validation period, which covers the years from 1998 to 2010, includes a short but extremely dry period from 2004 to 2005 and a wet period from 2008 to 2010. Groundwater pumping data from this period is less reliable as it is mainly derived from remote sensing.

PEST software is used for calibration and validation, with groundwater levels serving as the primary parameter. The model is calibrated using data from 150 observation wells to ensure comprehensive representation of the basin's groundwater three-dimensional dynamics (Figure 5.1).

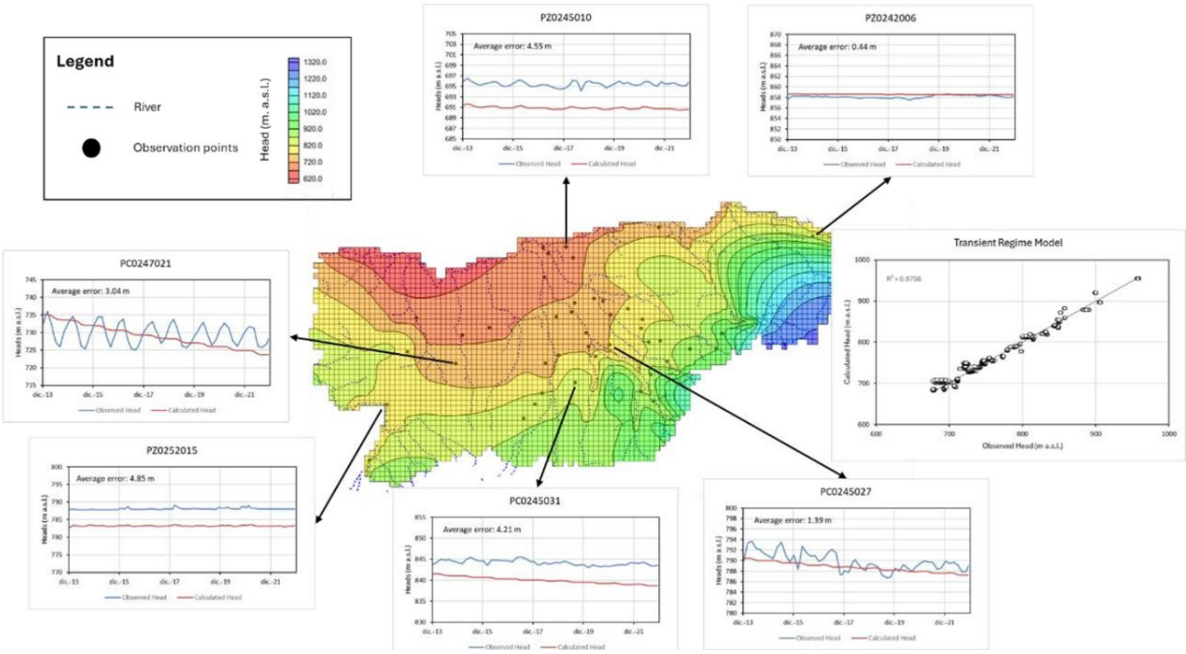

Figure 5.1. Modflow model calibration results.

Concerning MLMapper, the focus is on spatial predictions rather than temporal ones. Because it is typically unfeasible to forecast which of the many available machine learning algorithm will perform best on a given dataset, MLMapper relies on a brute-force approach that applies twenty algorithms from different families to each dataset. The best performers are subsequently kept for analysis, while the others are discarded. To ensure accuracy in mapping nitrate contamination and other groundwater quality parameters, the model requires a robust dataset of borehole observations. We relied on a comprehensive database of nearly 300 monitoring wells distributed across the whole basin (Figure 5.2). The calibration procedure uses k-fold cross-validation, as well as routines such as recursive feature elimination. Calibration and validation processes rely chiefly on metrics such as the area under the curve (AUC) and test scores.

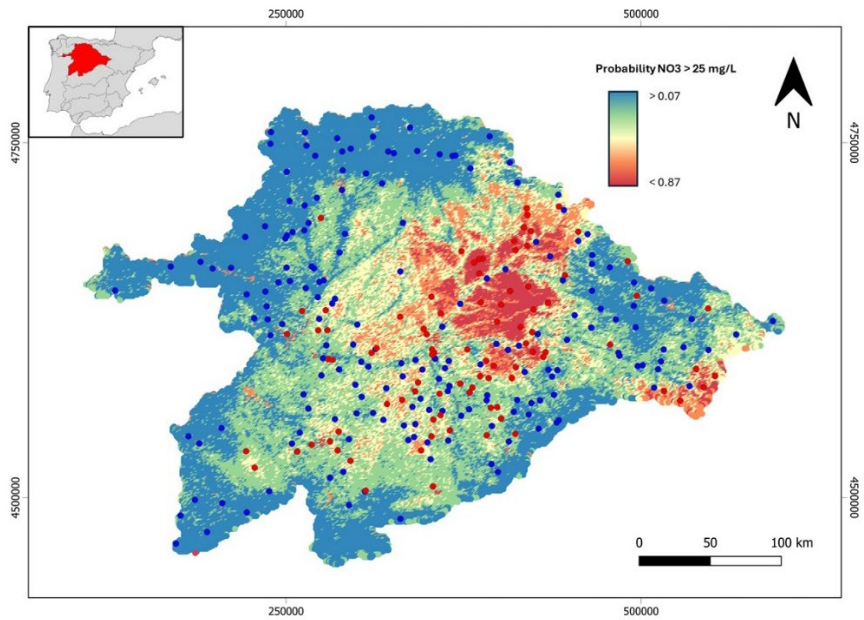

Figure 5.2. Ensemble map to predict the spatial probability of nitrate concentration in groundwater for Duero basin.

Joint application of these two models provides reliable simulations of groundwater levels and contamination patterns, offering valuable insights for sustainable management.

5.3. Stakeholder engagement

The models and scenarios have been shaped and adapted to address the specific needs of Duero stakeholders. Stakeholders offered valuable insights on the modelling framework and data concepts, but their contribution has been particularly valuable in developing scenarios that address both groundwater availability and quality. In particular, the stakeholders contributed to set the main targets for model predictions based on current water management needs and concerns.

Stakeholder feedback was collected in two phases. First, a questionnaire was sent out to approximately 800 people, including public administrations, farmer associations, water supply companies, actors from the private sector, environmental conservation groups, and research institutes. This was done through the mailing list of the Duero Water Authority. The survey consisted of seventeen questions addressing different aspects of water management that included items on the key drivers for future change in the basin. We obtained 103 full replies, which is considered sufficiently diverse and representative for practical purposes.

Survey results were used subsequently to frame the debate during the second STARS4Water stakeholder workshop, held in Arévalo, on March 12th, 2024. The purpose of this meeting was to clarify how stakeholders perceive that each of these issues could unfold in the future, in order to develop scenario narratives for modelling. The meeting was attended by twenty-three stakeholders. Incorporating these to the modelling process ensured that the models remain relevant and aligned with real-world challenges.

5.4. Added value

The updated MODFLOW model for the Duero basin is the largest groundwater available for the basin. It covers multiple groundwater bodies and addresses the areas most affected by water stress. A major added value is the scenario modelling framework, which relies on a series of drivers for change identified by stakeholders. These include as climatic variability, the likely evolution of agricultural and photovoltaic surface under different scenarios, and demographics and domestic water supply, among other variables. These have been translated into model inputs by converting the estimates into either pumping or recharge.

As well as focusing on groundwater availability, the Duero modelling framework addresses groundwater quality, particularly nitrate contamination. Integrating traditional numerical modelling with machine learning tools offers a novel, efficient approach to groundwater management. MLMapper's map-based outputs clearly identify contamination patterns, enabling new areas of interest to be identified where additional monitoring points may be needed. This capability enhances the monitoring network and supports more targeted management strategies.

6. East Anglia

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

During discussions with stakeholders in the East Anglian river basin hub (RBH) there was specific interest in how new data driven modelling approaches could strengthen insights into water resources challenges in the region, especially in the impacts of changes in hydrological regimes of East Anglian rivers on environmental flow (e-flow) conditions, reservoir operations and groundwater contamination.

E-flows are an important concept within UK environmental regulation and policy, as set out in the Water Environment (Water Framework Directive). As such, the need for an e-flows indicator was highlighted to allow for assessments of potential impacts on the riverine eco-system, and how this may change going forward.

Stakeholders also noted a need for more reliable forecasts of reservoir stocks given the occurrence of both flood and drought conditions in the region over recent years, and the reliance of the water sector on both online and offline reservoir supplies. The requirement of a modelling tool to compliment the current modelling suite in the short-term planning of water allocation was therefore seen as another key area to explore.

The East Anglia region is well established in arable farming, and as such the monitoring of water courses and flow paths is key to ensuring the sustainable and environmentally harmonious production of crops. Part of this monitoring includes the assessment of groundwater for contaminants such as nitrate, which is a key component of crop fertilizers. Stakeholders identified a need for a tool to identify the presence of nitrates in chalk aquifers across the region, both helping to explain trends in the presence of nitrate within the systems and also for the potential siting of new monitoring boreholes.

6.1. Data driven modelling tools for East Anglia: overview

Three specialized tools have been developed to address specific challenges in water resources management in the East Anglia RBH. Firstly, the Ecological Risk due to Flow Alteration (ERFA) tool is an environmental flow (e-flow) screening method assessing the risk to river ecosystems as post-impact conditions differ from pre-impact conditions (e.g. climate change, new abstraction scheme); it is fully described in deliverable D3.2 (Rickards and Keller, 2024). Alongside this tool, two data driven models have also been developed. A random forest (RF) machine learning algorithm has been developed and trained to forecast monthly reservoir storage in the Anglian RBH, providing precise data to optimize water allocation and reservoir operations. The Machine Learning Mapper (MLMapper) has also been applied to predict groundwater quality spatially, identifying contamination risks and enabling targeted interventions. This is the same model as used in the Duero basin, developed by UCM.

Ecological Risk due to Flow Alteration (ERFA) tool

The ERFA tool is a screening method designed to evaluate the potential impact of hydrological changes on environmental flows (e-flows) (Laizé *et al.,* 2014). It compares scenarios with specific flow conditions (e.g. forecasted future flow, altered current flow to investigate potential flow management *measures*) with a set of baseline flow conditions to identify risks to ecosystems and water resources.

By analysing either daily or monthly flow time series, the tool helps to pinpoint geographical areas where river ecosystems may be at risk. Within STARS4Water, this tool was further developed to include: (i) implementation of the method at the daily timestep (originally monthly only), (ii) application to visualise multiple sites simultaneously (originally single site only) and (iii) inclusion of indicators to capture flow intermittency. The tool has been tested and further developed at sites in East Anglia. It has also been applied to other basins, such as the Narew basin in Poland and the Rhine, to validate its applicability.

The tool uses daily flow series data, requiring one pre-impact or baseline series and at least one post-impact series, such as observed post-impact data or future scenario data. In one case, for example, baseline data from 1961 to 1990 and future scenario data from 2040 to 2069 were used. Preprocessing steps were undertaken, such as reformatting hydrological time series data into simple flat files (.csv). The tool was applied using data from the Rhine, with baseline flow series from 1991 to 2020 and scenario data from 2019 to 2048. The tool was also used on two East Anglia sites under various abstraction/ flow return options and for all basins as part of the WP2 ecological indicator. It was also used for preliminary runs on the Drammen. Further runs are in preparation for additional sites in East Anglia, and for the Seine basins. Its ability to assess environmental flow risks under various scenarios makes the tool a valuable resource for environmental management.

Machine Learning Model for Reservoir Storage Forecasting

The reservoir machine learning model has been designed to forecast monthly reservoir storage, with the aim of providing a hydrological outlook for lead times of 1-3 months. Such outputs can be included alongside the current suite of hydrological variables including streamflow and groundwater levels and has the potential to improve the management of reservoirs and water resources allocation across sectors within the basin.

Initial analysis of model runs produced promising results, with all reservoirs considered showing added value over using the historical distribution for monthly forecasts. A spot-analysis of forecast performance at the Rutland reservoir for the years 2011 to 2013 shows that the model is more skilful during low storage conditions, as observed in 2011, than high storage conditions, as in 2012, although unexpectedly high rainfall and low temperatures in the 2012 summer season may contribute to the modelled underestimation of storage. More thorough analysis is required, but current indications are that the model is a valuable tool for improving our understanding of, and management of, reservoir storage under varying climatic conditions. More detail on the model and model results are presented in the STARS4Water report D3.4.

MLMapper

The MLMapper is a tool for predictive spatial mapping. In East Anglia it was used to produce predictive maps of nitrate contamination in the chalk aquifers, which is useful to explore trends in groundwater contamination and to help site new monitoring or abstraction boreholes. The model demonstrates good accuracy in the East Anglia region, scoring highly in a range of performance metrics when assessed against the validation data, and aligns well with current understanding of nitrate contamination in the region. Explainable ML techniques have been applied in this work to further investigate the variables which contribute to nitrate contamination in the model, which improves process understanding and helps to interpret and validate the model outputs. MLMapper is a versatile tool for spatial predictions, and there is interest in applying this model in the future to consider different groundwater contaminants in the East Anglian region. More information on the model and model results are available in the STARS4Water report D3.4.

6.2. Stakeholder engagement

The ML model for reservoir storage forecasting was first presented to regulators, researchers, water companies and consultancies at a seasonal forecasting workshop organised by UKCEH in October 2024. Another workshop in June 2025 gave stakeholders a more in-depth understanding of the method. Similarly, the ERFA tool was introduced to stakeholders at an online meeting in July 2024 and was later presented to the STARS4Water stakeholder group in March 2025. The MLMapper was developed in close collaboration with Anglian Water, with many online stakeholder meetings, a site visit to Anglian water, and a seminar at UKCEH. Figure 6.1 shows a site visit to one of the boreholes.

Figure 6.1. Site visit to Anglian Water boreholes, January 2025

Stakeholder engagement and feedback has been integral to the development and validation processed throughout, ensuring that the models align with their needs and expectations and providing the necessary information and data to do so. For instance, during the setup and validation of MLMapper, stakeholders offered insights into its application and potential future endeavours, including modelling per- and polyfluoroalkyl substances (PFAS).

6.3. Added value

The data-driven modelling tools offer significant added value for the management of water resources in the East Anglia basin. Designed for environmental flow risk assessment, the ERFA tool offers a systematic approach to evaluating the potential impact of hydrological changes on ecosystems and water resources. It does this by comparing projected future river flow conditions with baseline flows. This allows it to identify areas where environmental flow requirements may be at risk. This enables stakeholders to prioritise regions for intervention, ensuring that water management strategies are effective and sustainable. Its ability to analyse a wide range of scenarios, including the effects of climate change and reservoir management, makes the tool a valuable resource for integrating hydrological modelling with environmental management.

ML Mapper provides a reliable method for predicting groundwater nitrate levels in Anglian chalk aquifers. Its spatial predictive capabilities are particularly valuable for addressing contamination issues and planning the creation of new boreholes, and its development and application for the East Anglian

RBH with stakeholders from Anglian Water and the Environment Agency ensured its relevance and uptake as part of the suite of tools currently in use within the region.

The ML model for reservoir storage forecasting enhances the current capabilities of the Hydrological Outlook in East Anglia by offering predictions of reservoir storage at 1-3 month lead times. This advancement enables more effective water management in the RBH, particularly during periods of low storage. The purpose and nature of reservoirs in East Anglia vary, including various offline storages. As such work is ongoing to ensure relevance and accuracy of the ML tool, offering a more bespoke assessment of water resources at the catchment scale.

7. Seine

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

The Seine River basin is regulated by four upstream large dams and their reservoirs, which are able to store 810 million m³ of water. They are operated considering multiple objectives: flood control, low flow support, and protection of the environment and biodiversity. Operations are integrated by the EPTB Seine Grands Lacs in river basin management planning, in partnership with the government and the Seine-Normandie water agency.

In the STARS4Water project, stakeholders from the EPTB Seine Grands Lacs expressed a main concern related to the projected increase in the severity of low flow events, as stated in the recent released climate and hydrologic projects from the national Explore2 project. In particular, they are concerned about the impacts of eventually not filling up the reservoirs before the dry summer period and when operations for low flow support starts. There is a need to better understand how reservoir filling/releasing operations might be impacted by climate change in the river basin, and how sustainable current management practices might be over time.

While some multi-disciplinary, mostly physically-based modelling studies of the Seine River basin have already been conducted in the past, they remain largely research tools explored by modelling experts. The goal of the modelling exercise here was to setup a more transferable modelling tool that can be used to explore different climate and management scenarios and their impact on flows downstream, up to the city of Paris. This involved engaging stakeholders in co-designing the way the modelling tool would provide additional knowledge for their operations, putting in place a robust, multi-criteria model calibration/evaluation strategy, where the influence of reservoir operations is directly considered in the modelling of the hydrological cycle, and connecting model output to real-life operations, so that it can be used to inform on regulatory indicators in the context of low flows and hydrological droughts in the river basin.

7.1. Modelling framework overview

The hydrological modelling framework developed for the Seine basin is based on the GRSD modelling tool, a semi-distributed rainfall-runoff modelling tool developed at INRAE (de Lavenne et al., 2019). It incorporates the GR4J lumped modelling tool within each sub-catchment, providing a consistent representation of the river system. The GRSD was adapted to account for the influence of the four upstream water reservoirs managed by the river basin authority EPTB Seines Grands Lacs. They play a critical role in regulating the discharge in the Seine River basin. They are operated to sustain low flows during the dry, summer season (July-October), protect downstream areas against floods, and for the preservation, management and restoration of biodiversity.

The modelling framework integrates reservoir management into the hydrological modelling process. It utilises time series data on reservoir storage evolution, accounting for water withdrawals from the river network and release patterns. Withdrawals for storage are constrained by the availability of water coming from the upstream river basin area and by legal requirements to maintain a minimum flow downstream. This setup enables to capture well the reservoir operations in their specific aim at supporting low flow downstream. The framework allows users to evaluate the effect of various climate and management scenarios on low flow indicators at gauging stations located downstream of the reservoirs.

Figure 7.1 shows the configuration of the modelled river basin system, with indication of the location of the upstream reservoirs in the Seine River basin and of the gauging stations used for the model calibration/validation (left). It also illustrates how the modelling framework was applied, with focus on the set up adopted for a sub-catchment upstream a reservoir (right).

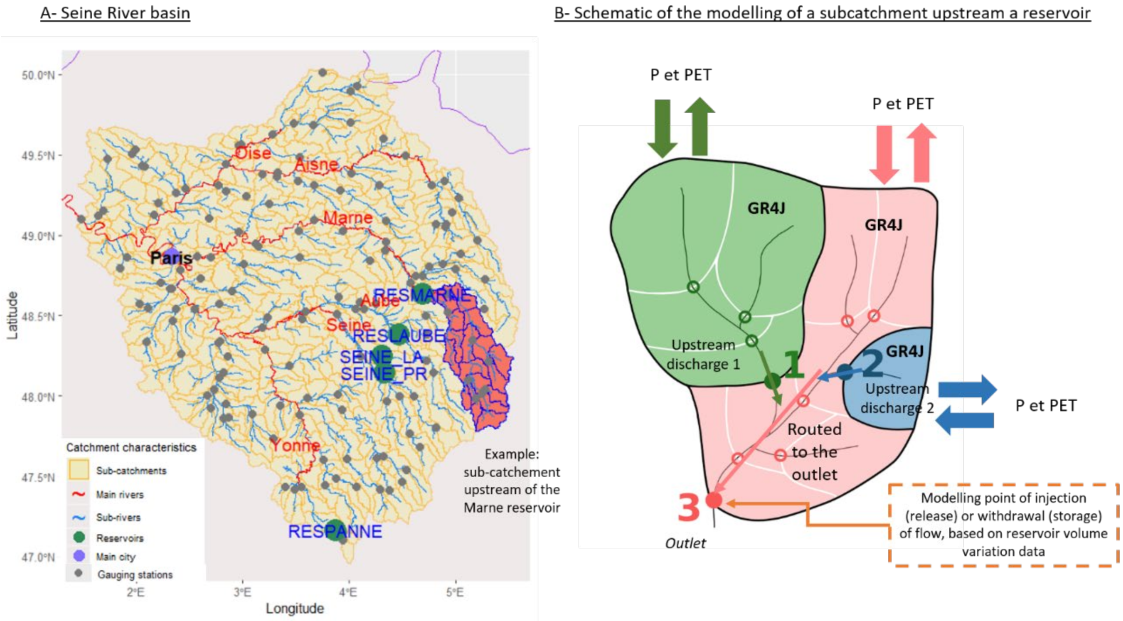

Figure 7.1. The gauging stations in the Seine River basin used for model calibration/validation (A- on the left) and the modelling framework of the GRSD model illustrated for a sub-catchment upstream a reservoir (B- on the right).

7.2. Calibration and validation process

The Seine River basin model was calibrated and validated using a multi-objective optimisation approach within a split-sample testing framework (Hsu et al., 2024, 2025). Model performance was evaluated using the Kling-Gupta Efficiency (KGE) criteria, computed over the daily discharges and evapotranspiration variables. The calibration process involved estimating the four GR4J model parameters, along with a celerity parameter for each sub-catchment to route streamflow to the outlet. For the multi-objective optimisation, the CaRamel package was used (Monteil et al., 2020), and the simulations were carried out using codes in R and Fortran.

Calibration was performed against daily observed discharge data from the French HydroPortail (https://hydro.eaufrance.fr/) and actual evapotranspiration computed using the Budyko equation (Andréassian and Sari, 2019; Le Moine et al., 2007). The Météo-France SAFRAN meteorological reanalysis dataset, commonly used as historical reference for France's climate (Vidal et al. 2010), was used as input to the hydrological model and to the Budyko equation, providing the gridded values for precipitation and potential evapotranspiration that are needed to run the models. The calibration/validation procedure covered the period from 2000 to 2020, for which both meteorological and hydrological data are available at all the stations in the Seine River basin.

A split-sample test was carried out to assess model performance and model robustness in the calibration/validation process. Firstly, the first 10 years were used for calibration and the last 10 years for validation, and then we applied the inverse, using the last 10 years for calibration and the first 10 years for validation. This allows us to have a pooled 20-year period of simulated variables in both the calibration and the validation analyses.

The results are presented in Figure 7.2, where model performance for all stations were pooled together to evaluate the distribution (boxplot) of KGE values when considering the calibration and the validation periods separately. They show very good KGE values for daily discharge (median values greater than 0.87) and therefore satisfying model performance in terms of reproducing observed stream flows in the river basin. They also show a stability of the KGE performance between the calibration and the validation periods, which illustrates also very good robustness of the model.

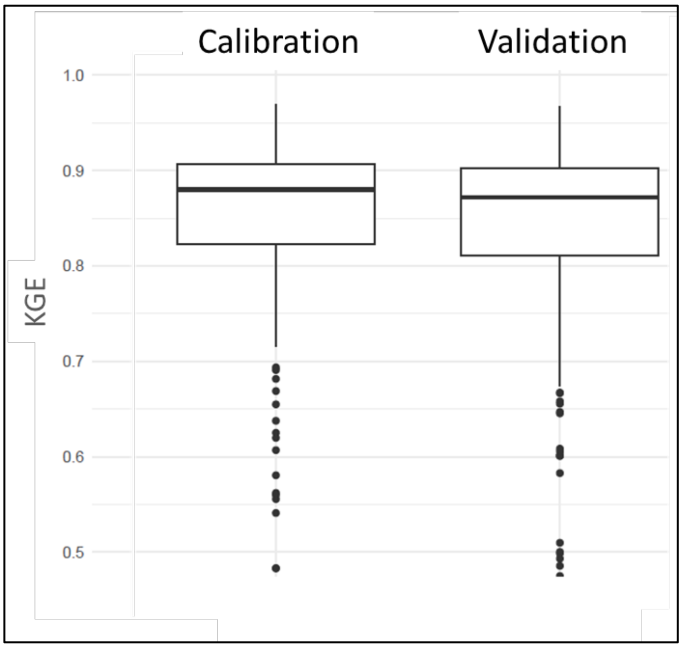

Figure 7.2: Distribution of KGE values computed on daily discharges for calibration and validation at all gauging stations considered in the Seine River basin. Data period: 2000-2020.

7.3. Stakeholder engagement

Stakeholders from the EPTP Seine Grands Lacs were involved in a series of meetings to define needs and requirements in terms of hydrological modelling and datasets (15/02/2023), to discuss the first modelling performance results (25/01/2024 and 2/05/2024) and validate the modelling framework (25/11/2024), and to validate the results obtained on model robustness (11/04/2025). Stakeholders provided extensive feedback, confirming that their operational experience was aligned with the modelling results, such as the expected influence of reservoir management downstream, at the gauging station in Paris. They also found the approach interesting for illustrating how the presence of the reservoirs positively affects river flows downstream during low flow periods, raising awareness of the risks incurred in the river basin. Finally, they provided suggestions on how to define indicators and critical thresholds to the evaluation of water availability and low flow risk under future climate and management scenarios.

7.4. Added value

The meetings with stakeholders resulted in elaborating 'what if' scenarios of their particular concern in terms of the performance of the management operations of the upstream reservoirs under future conditions. One key concern was: '*What if the reservoirs cannot fulfil their management objectives in the future due to more severe low flows and/or socio-economic changes leading to higher water demand downstream?*' The modelling framework was set up to address this question. Focus was put on (i) future climate conditions that could impact the way operations are currently carried out, and (ii) low flow regulatory conditions that could be guaranteed (or not) downstream.
The calibration/validation focus on the robustness of the hydrological model offers more confidence to users on its capacity to extrapolate and simulate streamflow under conditions that might not yet have been observed in the historic data period used for model calibration. The modularity of the modelling framework, with the option to include or not the influence of the reservoirs in the rainfall-runoff model, allows users to include in their analysis simulations in which the effect of having 'no reservoir' can also be considered, even though it remains a hypothetical situation as the dams and diversions are physically implemented in the river basin and their removal is not under consideration in the river basin management plans.

The added value to stakeholders can thus be summarized in the comprehensive, easy-to-use and easy-to-understand modelling framework that was set up under the STARS4Water project, where not only different climate scenarios but also different management options can be simulated and assessed in terms of impacts on water availability downstream the reservoirs and reservoir management operations (Collignan et al., 2025).

8. Messara

Authors: Maggie Kossida, Ioannis Tsoukalas, Fotis Fotopoulos, Marinos Kritsotakis

The growing irrigation demand in the Messara basin, exacerbated by climate change, has led to groundwater overexploitation with cascading impacts on the environment and the economy. The need for a disaggregated water allocation model is imperative in order to be able to accurately assess the fragile balance between water availability and demand and sustainably manage the water resources also in view of more severe drought conditions in the area.

8.1. Modelling framework overview

The Messara Basin employs two advanced models to address the water resource management challenges in this highly agricultural area. The first is the Sacramento Rainfall-Runoff Model (SAC-SMA) using the HydromadR package and calibrated with 13 parameters. This is coupled with Exponential Hydrograph Routing model (3 parameters). The second is the RIBASIM water allocation model. Both models run at monthly timestep and have been developed and adapted to meet the region's specific needs, protecting aquifers from overexploitation, ensuring sustainable water management and compliance with regulatory frameworks and the EU Directives among others the Water Framework Directive and Food Directive. In particular, the RIBASIM model has undergone significant enhancements to address stakeholder priorities. The basic management units are the groundwater districts (nine in total, Figure 8.1), each one linked with the relevant water demand nodes (water users, Figure 8.2). 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.

This integration enables the evaluation of a broad spectrum of scenarios, encompassing infrastructure development, operational strategies, and demand management. Operating at a highly detailed spatial scale, the model 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 planning.

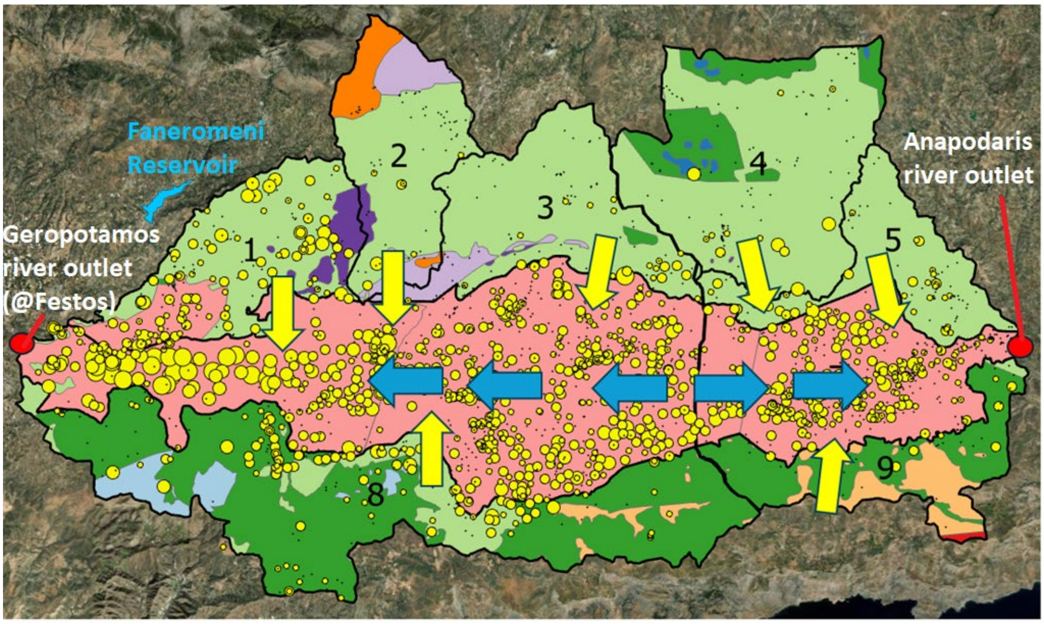

Figure 8.1. The Messara model conceptual scheme, illustrating the 9 groundwater districts and the lateral groundwater flows.

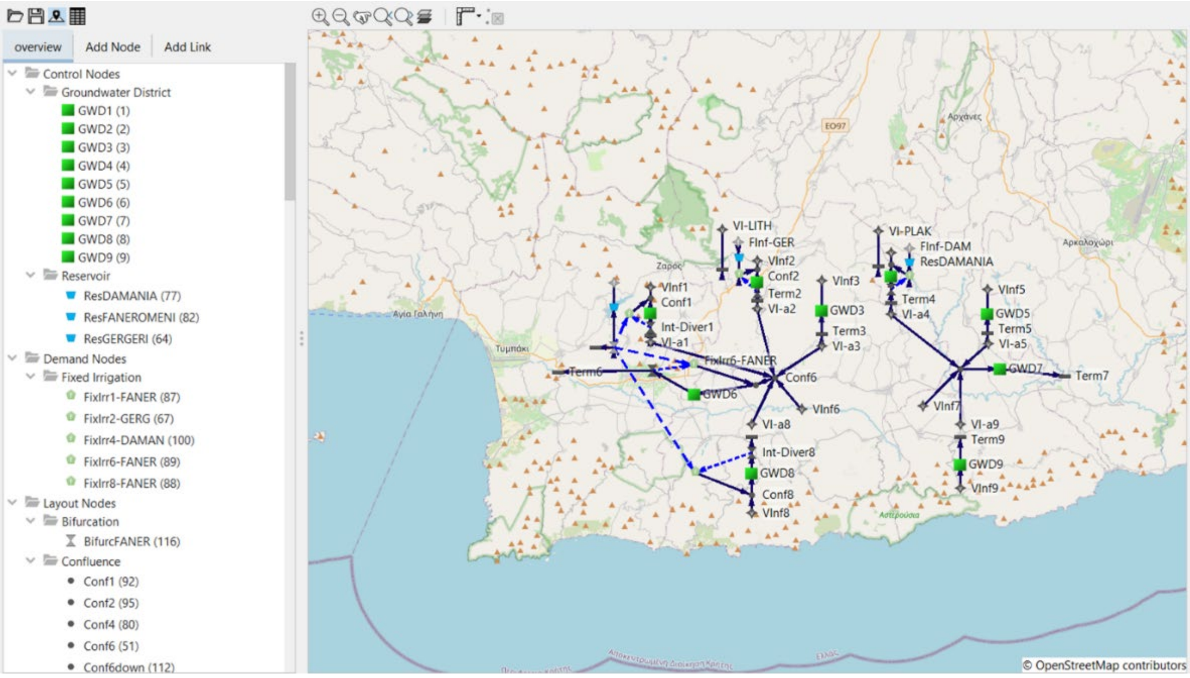

Figure 8.2. Scheme of the RIBASIM model set up for the Messara.

8.2. Calibration and validation

The Sacramento model was calibrated and validated using in-situ streamflow data at the Geropotamos river outlet and at Anapodaris outlet collected over a thirty-year period from 1973 to 2003. However, after careful inspection of the data, and consultation with the stakeholder a significant regime change was identified and verified in the Anapodaris river around 1989. Therefore, the calibration/validation process was eventually constrained within the period 1989-2003. Calibration and validation were performed for two distinct time periods to ensure accuracy and reliability: 1993-2003 and 1989–1996 respectively (Figure 8.3). Records of groundwater licences were also taken into account 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 ($NSE_{calibration} = 0.78$, $NSE_{validation} = 0.65$). Calculations (model runs of the calibrated RR model) have been carried out until 2022 using ERA5 rainfall and temperature datasets as an input (due to data gaps in the in-situ data sets after 2010). Continuous exchanges with the stakeholders took place for additional validation of both the Sacramento and RIBASIM models. They provided expert knowledge related with the observed regime change of Geropotamos river streamflow identified on 1989-90 and onwards. They also validated the intermittent behaviour of Geropotamos river, observed during the last decades and approved the time period used for the calibration as more representative of the current state. With regards to the RIBASIM model, the stakeholders validated the following components:

- The model scheme: the rationale behind the groundwater districts setup was agreed with them and the demand nodes were validated as representative of the current reality in the basin
- The water flow and availability simulation is physically realistic
- The priority rules, constraints, and users' shares are implemented as intended
- The key scenarios (e.g. "severe drought", "new reservoir", "policy reform") can be simulated in the model based on its setup.

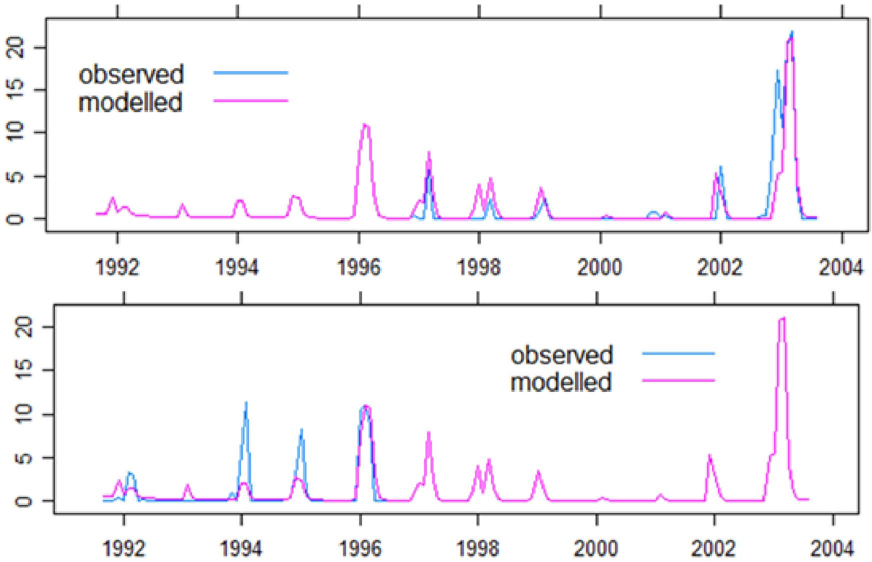

Figure 8.3. Calibration (top) and validation (bottom) of the Messara basin rainfall-runoff model at the Geropotamos river outlet.

8.3. Stakeholder engagement

Experts provided valuable insights into the observed changes to the flow regime of the Geropotamos River, particularly the changes that occurred between 1989 and 1990. These changes were attributed to two main factors: an increased infiltration rate due to the depletion of the water table in the primary aquifer system and the construction of a 0.25 million cubic metre reservoir upstream in the Lithaios sub-catchment. The flow regime was subsequently validated as being more representative of the current state, with performance metrics confirming the changes that occurred in the late 1980s.
In February 2025, a stakeholder meeting was held to review the model's results and pinpoint areas for improvement. During this meeting, the stakeholders validated the model's findings, including abstraction rates, water demand and unmet demand. They also reached a consensus on the quantification metrics to be used for future scenarios. However, stakeholders highlighted the need for certain improvements. Specifically, they requested a sensitivity analysis of the crop coefficient (Kc) for olive trees, as well as refinement of the irrigated areas for these trees, given prevailing uncertainties in irrigation practices. The stakeholders also expressed their support for migrating to RIBASIM version 8 and suggested simulating selected adaptation and mitigation measures. These simulations are planned to take place between August and November 2025.

8.4. Added value

The enhanced RIBASIM model offers several significant benefits that add value to water resource management in the Messara Basin. One of the key advancements is the harmonisation of precipitation and temperature data from ERA5, which has a resolution of 10x10 kilometres. This data was bias-corrected using the statistical properties of historical data from 1980 to 2008 to ensure its accuracy and relevance. Despite the absence of recent in-situ measurements, the model was successfully calibrated for future use, showcasing its robustness and adaptability.

Another notable feature of the model is the disaggregated representation of the system and the development of a node-based water allocation tool. Unlike lumped approaches, the model uses a node-link structure to simulate localized water use, transfers, and shortages, reflecting the true spatial heterogeneity of Messara's agriculture-driven water demands and aquifer dynamics. It also simulates competition between agriculture, domestic use, and ecological needs in a transparent way. This tool is designed to evaluate the potential for issuing new abstraction permits, providing a practical solution for the effective management of water resources, but also improving stakeholder trust. The model captures groundwater abstraction nodes, enabling tracking of groundwater abstraction pressure against aquifer recharge and allowing users to assess overexploitation risk under various irrigation strategies.

A set of policy-relevant parameters can be calculated as output from the model: water allocation per demand node and time step, water deficits (volume of unmet demand, % of demand), water supply reliability (% of time demand met), groundwater net abstraction vs recharge, environmental flow compliance at river or spring nodes, return flows and reuse potential, priority satisfaction indicators (e.g. are urban needs always satisfied before irrigation?). A combination of these parameters can be used to define the safe operating space based on the targets set by the stakeholders. For example, the model can identify areas where the water supply is less than 60 per cent reliable, enabling targeted interventions to address these vulnerabilities.

Furthermore, the model enables the exploration of future scenarios and 'what if' analyses. Using scenario analysis and threshold testing, target achievement can be assessed ex-ante and relevant questions can be transparently addressed among the stakeholders, such as:

- Who will experience shortages in future dry years?
- What abstraction caps are needed to stabilize aquifer levels?
- Where are the highest water stress hotspots?
- Which demand management strategies yield most benefit?
- Can a reallocation scheme improve equity or efficiency?

9. Conclusions

One of the central objectives of the STARS4Water project is to establish river basin-specific modelling frameworks that are suitable to address the challenges of managing future freshwater resources. These frameworks are designed to focus on the issues identified in co-creation with stakeholders. In cases where no modelling framework previously existed, new models were developed. Conversely, where a framework was already in place, we refined and improved it, adapting the concept to meet the specific needs of the river basin. As part of Work Package 4 (WP4) the modelling frameworks and tools were calibrated, validated and tested for the first time.

To evaluate the performance of the modelling frameworks and tools, stakeholder meetings were organized at various levels and in diverse formats. These discussions provided critical feedback on the models' functionality and relevance. A key achievement of the project, and an important step toward addressing future water resource availability, was building stakeholder confidence. This confidence stems from the assurance that the models employed are state-of-the-art and specifically address the specific needs of each river basin hub. However, the models are inherently limited by their dependence on the quality and availability of data. This is why, within STARS4Water, new datasets were unlocked and enhanced (see metadata portal for details) and global and local monitoring data sources were used to validate the models. Despite the progress made, the full potential of the modelling frameworks could not be fully realized in certain cases due to limitations in data availability and quantity. This finding highlights the critical importance of robust and accessible data in effective water resource modelling.

Nevertheless, the integration of newly available datasets, improvements to the modelling frameworks, and alignment with stakeholder needs have led to a high level of acceptance across all river basin hubs. This widespread endorsement ensures that the models are not only technically sound but also responsive to stakeholder priorities, making them well-suited to address the challenges of river basin management. The early and active involvement of stakeholders is regarded as a key advancement, significantly enhancing the models' relevance and utility in supporting decision-making processes related to adaptive, resilient, and sustainable freshwater resource management.

The added value of the modelling frameworks is closely tied to the active engagement of stakeholders throughout the process. The early involvement of stakeholders is recognized as a significant advancement in supporting decision-making for adaptive, resilient, and sustainable freshwater resource management. The design of the modelling framework development process, which incorporates a stakeholder-driven approach, is both a key feature of the project and a source of its added value.

The validated and approved modelling frameworks are now applied to future projections of climate change and socioeconomic impacts on water resource availability.

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