D2.3: Defining indicators for assessing climate risks

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Summary

The project STARS4Water aims at improving the understanding of climate-change impacts on water resources availability and the vulnerabilities for ecosystems, society and economic sectors at river basin scale, providing actionable information to stakeholders. To this end, STARS4Water will develop and deliver new data services and data-driven models for better supporting the decision making on planning on actions for adaptive, resilient and sustainable management of freshwater resources. Data and in particular spatial data play an important role in the project. In addition to generating new datasets, STARS4Water will unlock existing datasets and data services from earth observations initiatives, JRC activities and earlier EU research projects that are currently underexploited by public and private stakeholders in water resources planning.

One of the work packages of the project is dedicated to collecting, managing and providing access to existing and newly developed datasets. This report describes one of the results of this work package: a set of indicators for assessing climate risks and impacts on integrated water resources systems. We propose a three-tiered approach to come to a coherent set, where the indicators in the first two tiers are developed by WP2, and the third-tier indicators will follow from modelling activities within WP3 and WP4.

The first tier is a set of indicators that are directly derived from readily available datasets from e.g. the Copernicus Climate Data Store. We will bring these indicators a step closer to practical support at the river basin scale by projecting them onto the river (sub)catchments and reducing the number of future scenarios to a small set. The implementation of the tier 1 indicators is relatively straightforward, and they can be delivered by mid-2024.

The second tier is aimed at combining the global data sets from tier 1 with auxiliary data from various sources to yield indicators that are more directly related to water resources management. While the calculation methods for these indicators are initially sketched out in this report, the technical feasibility needs to be evaluated in most cases. The tier 2 indicators also depend on the availability of secondary data sources, such as local data. Their implementation will take therefore more time and is foreseen in the second half of 2024 and 2025.

The third and final tier is dedicated to model-based indicators. The evaluation and improvement of models is performed in WP3, but the approach and expected outcome in terms of indicators is briefly described in this report. The modelling activities still need to be discussed with the end users and stakeholders in the respective river basins. To this end, workshops with the RBHs are being planned for the first months of 2024, also involving the project teams that will conduct the modelling. The descriptions of modelling approaches and outcomes in this report should thus be seen as preliminary.

Follow-up activities and planning are described in the final chapter. The implementation of tier 1 will be completed first. Next, the focus will shift to tier 2 indicators and further support of the modelling work and development of tier 3 indicators.

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1. Introduction

1.1 The STARS4Water project

The project STARS4Water (Horizon Europe No 101059372) started in October 2022, with the aims to improve the understanding of climate change impacts on water resources availability and the vulnerabilities for ecosystems, society and economic sectors at river basin scale providing actionable information to stakeholders. The project will develop and deliver new data services and data-driven models for better supporting the decision making on planning on actions for adaptive, resilient and sustainable management of freshwater resources.

The new services and improved models are elaborated in close consultation and collaboration with stakeholders from seven river basin hubs to meet their needs and to promote uptake of data services beyond the lifetime of the project. The River Rasin Hubs (RHB) serve as living labs for co-creation of data services and tools with stakeholder communities and as accelerators for further upscaling of these services and tools to other river basins across Europe.

Geophysical, hydro-meteorological and various other spatial data play an important role in the project. Many datasets are already used by river basin authorities to manage their system. However, the STARS4Water project team believes that global data utilization can be improved. A vast amount of data is produced continuously, and river basin authorities often do not have the capacities to keep track of all new data sources and developments. Some available datasets remain unknown to river basin authorities, are difficult to access or apply at the scale of the river basin.

STARS4Water will unlock existing datasets and data services from earth observation initiatives (Copernicus, GEOSS), JRC activities and earlier EU research projects that are underexploited by public and private stakeholders in water resources planning. The earth observation and other data sources provide potential for improving the accuracy and spatial resolution of models and decision support tools that are currently used in water resources management and climate change adaptation. Moreover, data science techniques like machine learning have resulted in new modelling approaches and ways to combine data and generate new insights. STARS4Water builds upon these new technologies to develop and improve data services and data-driven models, particularly with respect to water use by economic sectors and the impacts on water resources availability for ecosystems and water quality.

The main project objectives are:

1. To provide stakeholders with new generation data services and data-driven models tailored to their information needs and requirements.
2. To improve the accuracy and the spatial-temporal resolution of regional-scale projections of water resources availability and get a more complete picture of the water resources system, including the impacts on ecosystems, society and economic sectors, from 1 km^2 to 10 km^2 grids.
3. To enhance the knowledge base and the scientific underpinning of climate risks and impacts, in various scenarios and time horizons.
4. To improve decision making by stakeholders through the development of ‘dashboards’: co-designed and co-developed information systems.

5. To promote uptake and transferability of the data services and tools by developing guidance documents and capacity building activities.

1.2 WP2: Unlocking and improving data-services

Within the project, there is a special work package (WP2) that is dedicated to collecting, managing and providing access to existing and newly developed datasets. WP2 is named ‘unlocking and improving data-services'. The main activities of WP2 are:

- WP2.1: To make an inventory of existing data sources that are generally used in water resources management and in each of the river basin hubs specifically.
- WP2.2: To develop a metadata portal for global and regional data services for water resources management to facilitate development of new data services and uptake by river basin authorities.
- **WP2.3: To define a set of indicators for assessing climate risks and impacts on integrated water resources system.**
- WP2.4: To develop online data services to support the climate indicators by integrating monitoring and observation of historical and current hydroclimatic data in selected river basins in Europe.
- WP2.5: To develop future scenarios for the climate indicators, in particular for water demand.

This report focuses on the outcome of WP2.3. After completing the first two activities in June and September of 2023, respectively, the team proceeded with the third activity: to compile a set of indicators for assessing climate risks and impacts on integrated water resources systems (WP2.3). This report describes the results of that activity and constitutes the WP2 deliverable related to indicators. Follow-up activities in the remainder of the project (2024 and further) are the implementation of the indicators (WP2.4) and the generation of projections into the future (WP2.5).

1.3 Indicators

According to the Cambridge Dictionary (Cambridge University Press, n.d.), an indicator is “something that shows what a situation is like”. Indicators are commonly used to quantify the current conditions in a system or to describe trends and forecast future conditions. Indicators are used in a wide range of fields, including environmental applications, demography and economics. Some examples are listed below:

- The World Meteorological Organization (WMO) has defined a set of essential climate variables (ECV) that represent physical, chemical and biological variables that contribute to the characterization of Earth’ s climate. Measuring and monitoring these ECVs provides empirical evidence of climate, helping to guide mitigation and adaptation measures, to assess risks and enable attribution of climate events to underlying causes, and to underpin climate services.
- The Copernicus Climate Change Service (C3S) uses a collection of Climate Indicators to show the long-term evolution of several key variables which are used to assess the global and

regional trends of a changing climate. They are updated at least once a year, for the publication of the European State of the Climate.

- The International Monetary Fund (IMF) collects and publishes a set of annual economic indicators to provide insight into the state of the economy of the world and per country. Indicators include exchange rates, fund position, international liquidity, monetary statistics, interest rates, prices, production, labor, international transactions, government accounts, national accounts, and population.

Within the context of this project, an indicator is defined as a quantitative measure of a condition in a river basin that is monitored in terms of trends and variability. The complexity of the hydrologic system and its interactions with the meteorological, ecological and socio-economic environment, spanning multiple spatial and temporal scales, make it difficult for river basin managers and stakeholders to assess changes in the system and the effectiveness of countermeasures. Indicators help to manage this complexity by summarizing the behavior of the system. Indicators have therefore become common practice in policy making for climate change adaptation. Using an adaptive management approach, we can evaluate the current strategy as we go, and decide whether a revision is needed. Indicators can be visualized on dashboards and used in story maps for communication and dissemination, providing insight into possible future development of the system under different scenarios.

Global observational and model datasets are continuous across the globe and allow for a comparison between countries and river basins. However, local effects may not be captured well by global data sets, which is why local models and measurement data are often preferred over global alternatives. Moreover, different river basins face different challenges and therefore need different sets of indicators for specific policy making. The STARS4Water project will therefore develop more specific climate and socio-economic indicators to support water management in each of the seven RBHs. Using the global datasets and general indicators as a starting point, we will derive more local indicators for water management at the river basin scale. The approach is further detailed in this report.

The next Chapter will describe how these steps lead to a proposed set of indicators for STARS4Water. The indicators play an important role in the project and are linked to several other work packages, in particular WP1, 3 and 4. The dashboards and storyboards/narratives that are created in work package 1 will use the indicators as input. The modelling efforts in work package 3 and scenario developments in work package 4 will further detail and enhance the basic indicators from WP2. The design of the indicators has therefore been done in close collaboration with those work packages.

1.4 This report

The next chapter, Chapter 3, describes the three-tiered approach that was applied to come to a set of climate indicators. Chapter 4 describes the first set of indicators, which will be derived from readily available global datasets, mostly from the Copernicus Climate Data Store. Chapter 5 presents the second set of indicators that will be derived in a second stage from combinations of global datasets, auxiliary data and/or modelling efforts. Chapter 7 concludes with a summary of the report and a description of the next steps in work package 2 and relation to the other work packages.

2. Approach

2.1 General approach

In order to come to a set of climate risk indicators at the river basin level that will help to monitor, evaluate and assess developments in water resources availability and impacts of climate change, a user needs assessment was done within task WP1.2. The report that came out of this needs assessment, Deliverable D1.2 (Hegdahl et al, 2023), describes the current practices, the challenges and the user needs in each of the seven river basins. These findings will be used for the design of indicators in this report. Furthermore, since one of the objectives of the STARS4Water project is to leverage global data sets, we will make use of existing global datasets including earth observations as much as possible. An inventory of available datasets was therefore made earlier this year (Beckers, 2023) that acts as an important source of information for the indicator design.

The next two sections will summarize the user needs assessment and the inventory of available datasets. Next, we propose a general approach to derive indicators for water resources management and climate change adaptation. The indicators that are proposed as, as far as we can assess, technically feasible, although there are dependencies on local data availability and details of the calculation methods that still need to be detailed. This will be highlighted in the technical approach sections.

2.2 Needs assessment

The report "Assessment of the needs on data services and modeling tools of stakeholders in selected European river basins", deliverable D1.2 of the STARS4Water project (Hegdahl et al, 2023), provides a valuable overview of the current practices, challenges and the need for additional information in each of the seven RBHs. Below is a summary of the most important topics in each basin. This description is not exhaustive. A comprehensive description of the challenges and user needs for each RBH can be found in Hegdahl et al (2023).

Drammen

The Drammen River in southern Norway has a total length of 308 kilometers. The drainage basin is around 17,000 square kilometers and the average discharge is 300 m^3/s. One of the main challenges for water management of the Drammen River is to prioritize competing demands from a wide range of stakeholders, including energy producers (hydropower), local inhabitants and the environment (keeping environmental flows). Prioritization is especially needed during extreme events. If possible, where should water be withheld to minimize the overall consequences? There is a need for scenarios/storylines that describe expected changes in water availability and water demand in the future.

Hydrological models of the Drammen River have been developed and are being used to support operational water management, there is a need for more detailed and accurate input data (precipitation, temperature, snow storage, land use, soil type and water usage). There is a need for short-range and seasonal forecasts, as well as climate change scenarios. There is also a need for better estimations of low flow and eco/environmental flows for the licensing (e.g., hydropower licenses), and especially for the establishment of thresholds for critical water levels, and the use of simple and scalable measuring techniques.

Danube

The Danube is the second-longest river in Europe. Originating in Germany, the Danube flows southeast for 2,850 km, passing through Austria, Slovakia, Hungary, Croatia, Serbia, Romania, Bulgaria, Moldova, and Ukraine. Its drainage basin amounts to 817 000 km^2 and the average discharge is 6500 m^3/s.

Water management of the Danube requires coordination between many different countries and exchange of information is essential, yet not always a given. Data that is owned by national authorities is not always shared between the countries. There is a need for a common data basis for stakeholders and decision makers in the Danube River Basin, both at the national level and for the River Basin Organizations ICPDR and ISRBC.

Various hydrological, socio-economic and environmental data are needed across the basin for the implementation of the Water Framework Directive and for management of high and low flows, sediment flow, navigation, wetlands and groundwater resources. Information is needed about illegal water abstraction, nutrient pollution from agriculture and pollution from hazardous substances from municipal wastewater and direct industrial discharges.

Douro

The Douro River (or Duero in Spanish) originates in the Spanish province of Soria and flows almost 900 km westward towards Portugal and into the Atlantic Ocean. The basin size is 98,400 km^2 and the average flow is 700 m^3/s.

Challenges for the Douro River are related to the changing water supply and water demand mainly from agriculture. The Douro River Basin Authority (CHD) needs to prepare and adapt, not only to climate change, but also to changing agricultural practices, including the increase of solar irrigation and the introduction of new crop types and associated crop cycles. Specific challenges are the depletion of groundwater reserves and pollution of groundwater from naturally occurring arsenic and other potentially toxic trace elements.

There is a need for further digitalization and improved communication between administration and users (municipalities and communities of groundwater users, or CUAS) in the water sector. Real-time information, like piezometric groundwater level, can be shared through dashboards and provide guidance on measures (e.g. abstraction restrictions) to help protect the groundwater resources. The existing MIRAME-Duero viewer is in need of improvement.

As indicators, the following were proposed: Arsenic concentrations, cost/benefit ratio, maps of ground water storage.

East Anglia

The Anglia River Basin District comprises 14 river catchments and sub-catchments. The total area is 27,746 km^2. Challenge in the East Anglia basin is the limited water availability during droughts and the water quality. Salt intrusion in aquifers is an issue in the coastal regions. Land subsidence due to groundwater abstraction and drying of peat is another problem.

There is a need for information about the uncertainty of hydrological model outcomes, e.g. real-time water usage, and for information about groundwater quality and carbon stores, also in the future. The existing models for water quality and groundwater can be extended/improved.

A visualization tool can help identify best practices from a regulator and user perspective and contribute to public engagement and enable a shift in the perception of the value of water and its use.

Messara

The Messara is an alluvial plain in southern Crete, stretching about 50 km west-to-east and 7 km north-to-south. The Geropotamos River, with its tributaries Lithaois, Plakiotissa and Anapodaris are the main water courses. The total drainage area is 553 km^2. The abstraction of groundwater over the past decades has led to falling groundwater levels and reduced water availability. The uncontrolled overexploitation creates tensions amongst the users.

To address the problems and develop effective solutions, robust climate change scenarios and scenarios for water demand are needed, including the evaluation of uncertainties. This includes climate change trends, e.g. changing precipitation and ET patterns, as well as socio-economic and land use scenarios, including changes in the current cultivated crop mix, in the decision support systems on water allocation and water abstraction caps.

There is a need for an online information and visualization tool (e.g., dashboard) allowing the visualization of key indicators and the dissemination of the relevant information to the stakeholders and the wider public. A distributed water allocation decision support system (DSS), incorporating all water supply sources and water demand needs under different climate and socio-economic change scenarios can support the development of a supply-demand Masterplan for the Local Land Reclamation Organizations (TOEBs) that are responsible for the provision of irrigation water to the farmers.

One important measure to evaluate, highly requested by the stakeholders, is the potential diversion of the Platis River in order to supply additional water to the Faneromeni reservoir, as well as for artificial recharge in the Messara basin.

Seine

The Seine is a 777-kilometre-long river in northern France. The total basin is 79,000 km^2 and the mean discharge is 560 m^3/s. A challenge in the Seine River basin is the uncertainty of climate change projections to support a robust risk analysis for the long term. Furthermore, the surface-groundwater interactions in the models could be improved to better understand the flow of water within the river basin. This should also lead to a better understanding of the downstream responses of the water system to the water releases of the lake-reservoirs during low flow periods. Improving understanding of how much the upstream lake-reservoirs can mitigate the impact of climate change and enhance downstream services to water users, especially during low flow periods.

Extensive data are available, including hydro-meteorologic, piezometric, drought, water quality, reservoir, withdrawals and modelled surface and groundwater data. Hydroclimate projections for the Seine River are available from the nationwide project EXPLORE-2. There is a need for wider spread of these data and of the modelling tools for impact and adaptation studies. The PIREN-Seine program has brought together a multi-disciplinary group of scientists to generate knowledge, data and tools. These tools, however, remain largely in the hands of researchers or some practitioners with modelling expertise.

Rhine

The Rhine originates in the Swiss Alps and flows in a mostly northerly direction through the German Rhineland before turning West and flowing into the Netherlands where it reaches the North Sea. The length of the Rhine is 1230 km and the total drainage area is 9,973 km^2. The average discharge is 2,900 m^3/s.

The balancing act of water resources allocation and river discharge control under present and future scenarios in a transboundary cooperation context has been the main challenge for the International Commission for the Hydrology of the Rhine basin (CHR) since 1975. The uncertainty of on-going changing climate and developments in land and water are a constant concern for water resources management in the Rhine River basin.

CHR has expressed a need for improvement of existing modelling tools and model input data for water allocation, especially under low flow conditions. This includes extended groundwater-, e-flow- and ML-modelling as well as scenarios for socio-economic developments, water demand from agriculture and consequences of low water on shipping. More specifically, ‘what if’ scenarios are to be formulated together with stakeholders about plausible future external developments (like population growth and European markets). The results may be used as input for dashboards and in online story maps to facilitate communication to stakeholders.

Regarding indicators for evaluation and scoring, the ASGII already provides some (e.g. signaling low flow discharge below a certain threshold value at location Lobith or minimum water level at Bodensee). Further indicators need to be determined in consultation with stakeholders.

To summarize, the main takeaways from the WP1.2 report (Hegdahl et al, 2023) are:

- In all river basins, water availability during drought and a sustainable balance between water supply and demand under a changing climate are a concern. Issues with increasing demand and limited water resources refer to surface water, groundwater and water quality.
- Some basins have specific issues and associated data or modelling needs, for example peatlands in East-Anglia and snow storage in the Drammen.
- All basins are in need of future scenarios, averages and uncertainties .
- Most basins are in need of more exchange of information, visualization tools and story maps/dashboards.

2.3 Available datasets

An inventory and review of some 100 commonly known (and some less well-known) global datasets was completed as part of activity WP2.1 in the first half of 2023 (Beckers, 2023). This inventory provides an overview of datasets that can be used in various ways in water resources management. Some of the datasets are typically used as model input, like DEMs, land use and soil data. Other datasets could be considered for climate indicators, such as meteorological data, groundwater observations and soil moisture.

In particular, the water sector indicators on the Copernicus Data Storage (CDS) are worth mentioning. These indicators of hydrological change across Europe from 2011 to 2095 were derived from climate simulations by UKCEH and partners within the C3S project EDgE ("End-to-End Demonstrator for improved decision-making in the water sector in Europe"). The water sector indicators represent the potential change, relative to a reference period of the recent past, in hydrological conditions over the 21st Century based on an ensemble of climate and hydrological models. The indicators cover hydrological variables of river discharge, soil moisture, snow water equivalent and groundwater recharge. There are a number of reasons why this data is not yet used to its full potential in our opinion. Firstly, the data are made available on a 5x5km grid, whereas most river basin managers would prefer to investigate changes for their catchment or sub-catchments of interest at higher resolution. Secondly, the number of (emission) scenarios and (climate and hydrologic) models that can be selected is rather numerous. For a river basin manager, a smaller number of scenarios would be more tractable.

The inventory also includes several datasets that can be used as a motivation for additional climate and socio-economic indicators. For example, potential evaporation and precipitation datasets can be combined to obtain evaporation deficit. Soil moisture and wilting point (a soil property) can possibly be used to predict agricultural water demand. These derived datasets are elaborated in chapter 5.

2.4 Design of indicators approach

The needs assessment done by WP1 calls for several types of indicators. On the one hand, we see a need for general indicators for water supply and demand. In many cases, these can be derived from global datasets, which is in line with one of the objectives of STARS4Water: to unleash the potential of global datasets. On the other hand, we identify a need for more specific indicators that address an issue in one of the basins. Although we strive for indicators that can be used in more than one river basin, the issues and challenges differ across the basins. There are also obvious differences in spatial scales between the river basins. We thus need an approach that is both generic and specific.

To come to a set of climate indicators for STARS4Water, a three-tiered approach is proposed:

1. In the first tier, existing global climate and socio-economic indicators are directly translated into practical indicators at the river basin scale. The global datasets are projected onto the catchment area of the river basin and the number of future scenarios is reduced. This addresses the need for practical information about expected changes in each of the river basins that was expressed by the stakeholders in many of the river basins, while keeping the technical challenges limited. The indicators that will be generated in this tier are described in chapter 4. Because they are directly derived from global datasets, they will, in general, not be as accurate as regional model results. Still, these global indicator projections can give an indication of the relative changes that can be expected in the next decades if no regional model is available. In cases where regional models are available, they can be used as a reference or benchmark.
2. In a second tier, global datasets are combined with local data to yield further 'derived indicators' that are more directly linked to practical water management. For example, we can combine potential evaporation and precipitation to calculate evaporation deficit, which is a common indicator for agricultural drought. Also, the existing soil moisture dataset can be used to indicate agricultural drought in the river basin and -possibly- act as a predictor for water abstraction by farmers for irrigation. Predictions of agricultural water use in future scenarios would be valuable information for water resources management. However, to be

able to generate such derived datasets and indicators, we depend on the availability and accuracy of local data. The indicators that are targeted in this tier are described in chapter 5. They are technically more demanding and require more time to develop and validate. Although the tier 2 indicators will be more specific and meet more user needs, they will still be (partly) based on global datasets.

3. To address more specific user needs, we therefore define a third tier of indicators, for which numerical models and machine learning techniques are employed to precisely capture the catchment hydrology. The indicators that follow from these activities are the most specific to the river basin hubs and will require considerable effort to develop. The model-derived indicators are described only in general terms in this report. Details will be worked out in WP3 and WP4 and further developed in close consultation with the stakeholders for each basin. To this end, workshops with the RBHs are being planned for the first months of 2024, also involving the project teams that will conduct the modelling.

By this three-tiered approach, we aim to meet the objectives of the STARS4Water project of addressing user needs and leveraging the power of global datasets. The three sets of indicators that are developed in three tiers are increasingly more technically demanding and more specific to the river basin, see table 1.

Table 1: Types of indicators that are distinguished in this report.

Indicator set	**Data source**	**Method**	**Effort**	**Specificity**
Tier 1	Fully based on global datasets	Basin projections	Relatively small, done by WP2	Global data, low specificity
Tier 2	Combining global and local data	Arithmetic and regression techniques	Larger effort, done by WP2	Global data made more specific
Tier 3	Combining global and local data	Numerical models and ML	Very large effort, done by WP3 and 4	Highly specific to the river basin

3. Tier 1 indicators

3.1. Indicators based on global datatsets

The first set of indicators is directly derived from global datasets with only limited post-processing. The relatively small effort allows for delivery by April 2024. The tier 1 indicators can thus form a baseline for further developments in the project.

Most global datasets are provided as raster data, making them not directly applicable to river basin management andwill be projected onto (sub)catchments of the seven river basins of the STARS4Water project. For the smallest basins (Messara, Douro) we will only consider the full catchment. For the Rhine and Danube, we can consider up to 10 subcatchments. The shapes of the (sub)catchment areas can be provided by the river basin hubs, or else they can be obtained from the HydroBasins database (Lehner and Grill, 2013).

The implementation of the tier 1 indicators is relatively straightforward. Results are expected by mid-2024 and will be made available to the project team and included in the MetaData Portal. The indicators can then be used for early versions of dashboards and story maps. Their practical use for the river basin hubs will vary per basin. For several river basins, scenarios for e.g. future precipitation and river discharge are already available. In this case, the global datasets-derived indicators would serve as a secondary data source. A disagreement between the local and global indicators could lead to further investigations into the cause of the differences. It is known that global climate models are sometimes not accurate at the local scale.

In other river basins, the tier 1 indicators may be new information. In these cases, the global indicators can serve as a first estimate of future scenarios, possibly giving rise to warning signals and further investigations.

The Copernicus Data Store (CDS) and JRC Data Catalogue offer a wealth of climate data that can be used as a basis for a set of indicators. For STARS4Water, we focus on hydrologic indicators for the time horizon 2030-2050. Of particular interest in this respect are the ‘Water sector indicators of hydrological change across Europe from 2011 to 2095 derived from climate simulations’ (Kumar et al, 2020) and the ‘Hydrology-related climate impact indicators from 1970 to 2100 derived from bias adjusted European climate projections’ (Berg et al, 2021). For the tier 1 indicators, we choose to use the Water Sector Indicators from Kumar et al (2020), which are based on the following variables:

- Air temperature (average per day at approximately 2m above the surface)
- Precipitation (the amount of rain, snow, sleet or hail per unit area)
- Potential evapotranspiration (the amount of evaporation that would occur if sufficient water were available)
- Volumetric soil moisture (the amount of water in the unsaturated zone)
- Snow water equivalent (the volume of water if the snow were to be melted)
- Groundwater recharge (the volume of water percolating through the unsaturated zone to the aquifer)
- River discharge (volumetric discharge through a stream or river channel)

All these indicators are available as relative changes over a 30-year projection window with respect to the reference period 1971-2010. In addition, we add two non-hydrometeorologic datasets to the tier 1 set of indicators, to cover socio-economic developments:

- Population density (the number of inhabitants per unit area)
- Land use classification (fractions of land occupied by a range of classes)

All datasets that are mentioned above are available as rasters (mostly 5x5km, in some cases higher resolution). Raster data can be hard to interpret. It would be helpful to aggregate the data to the catchment or subcatchment level, in order to summarize the expected changes for the river basin of interest. Furthermore, for many datasets, a wide range of scenarios is available, covering emission scenarios, climate models and hydrologic models. For policy making, a smaller number of scenarios is practical.

Therefore, to make the indicators more practical for water resources management at the river basin scale, we will project these data onto the (sub)catchment areas of the seven river basins and select two scenarios, representing an upper and lower end of possible outcomes. The projected datasets will take the form of a lower and upper estimate for a given time horizon per (sub)catchment. The indicator values for 2030, 2040 and 2050 will subsequently be uploaded to the STARS4Water Metadata Portal to be used e.g. in dashboards.

The selected indicators for tier 1 are listed in table 2. Following the Water Sector Indicators from Kumar et al (2020), we choose to provide all tier 1 indicators as relative changes with respect to the reference period 1971-2010.

Table 2: Tier-1 indicators.

Variable	**Proposed data source**	**Indicator(s)**
air temperature	CDS Water sector indicators	mean annual air temperature mean air temperature summer mean air temperature winter
precipitation	CDS Water sector indicators	mean annual precipitation mean summer precipitation mean winter precipitation
PET	CDS Water sector indicators	mean annual PET mean PET summer mean PET winter
soil moisture	CDS Water sector indicators	mean annual soil moisture mean soil moisture summer mean soil moisture winter
SWE	CDS Water sector indicators	mean annual mean SWE winter mean SWE summer
groundwater recharge	CDS Water sector indicators	mean annual recharge mean recharge summer mean recharge winter
river discharge	CDS Water sector indicators	mean annual discharge mean discharge summer mean discharge winter

population	GHS-POP SSP2	total population
land use	Copernicus Global Land Cover Service	fraction of land use classes

3.2. Scenarios

The Water Sector Indicators data on CDS includes two emission scenarios (RCP 2.6 and 8.5), five climate models and up to four hydrologic models. Combining all climate scenarios with socio-economic scenarios leads to dozens of possible outcomes. While this large set of possible outcomes may reflect the actual uncertainty, most policy makers prefer a much smaller set of scenarios for practical reasons. This is recognized by the scientific community who are reducing the number of scenarios. For example, in the Dynamic Adaptation Policy Pathways (DAPP1) analysis for the Rhine River, Haasnoot et al. (2012) considered only four scenarios. These 'Delta-scenarios' cover two representations of future climate (based on Van den Hurk et al., 2007) and two sets of socio-economic developments for the Netherlands. The two climate scenarios represent respectively moderate and large increases in sea water level, temperature and precipitation. The two socio-economic scenarios describe a population growth from the current 16 million to respectively 12 million or 24 million in 2100, and associated changes in economic figures and land use. Recently, the Dutch meteorological institute KNMI presented four climate scenarios for the Netherlands, representing high- and low emissions and a 'wet' and 'dry' variation (van Dorland et al, 2023). These examples of small sets of scenarios are generally received well by policy makers.

For the STARS4Water project, we will adopt the 'business as usual' (BAU) climate scenario and a baseline socio-economic development scenario. In addition, we will consider several 'what-if' scenarios that describe deviations from the BAU scenario as a result of developments in each of the river basins. For example, a logical 'what-if' scenario for the Messara basin would be the diversion of the Platis River to supply additional water to the Faneromeni reservoir.

The BAU climate scenario is based on the Representative Concentration Pathway RCP8.5, which is commonly used for predicting mid-century emissions based on current and stated policies (Schwalm et al, 2020). RCP8.5 is associated with a temperature increase of about 4.3˚ C by 2100 (relative to pre-industrial temperatures). Although RCP3.4 is generally considered a more realistic representation of the emissions in the coming years, the 4.3˚ C temperature increase in RCP8.5 is the more likely outcome if carbon feedbacks come to pass (Hausfather et al, 2020). STARS4Water will not consider other RCP scenarios, because the difference in outcomes for the year 2050 are quite small, because of the delayed response of the earth's climate to changes in carbon emissions.

The socio-economic scenarios are ultimately drawn from the Shared Socio-economic Pathways (SSP) from IIASA (O'Neill et al, 2015). Future projections of population density are available from the Global Human Settlement from JRC (Jones et al, 2020). Only the SSP2, "middle of the road" scenario, will be considered as the baseline scenario, which describes a world with development that occurs at rates consistent with historical patterns, and therefore has moderate levels of investment in human capital, technological change, and economic growth. Demographic outcomes are consistent with *middle of the road* expectations about population growth, urbanization, and spatial patterns of development.

The Copernicus Global Land Service is currently available up to 2019 (Buchhorn et al, 2020). Land use scenarios for the future can be derived from a range of sources, including the LUISA land use modelling tool for Europe (Castillo et al, 2021), the Land Use Harmonization version 2 (LUH2) dataset, which covers the period 2015-2100 at 0.25 degrees resolution (Hurtt et al. 2020), the Land Use maps that were produced by the ISIMIP project (https://data.isimip.org/) and the set of future land use change scenarios for Europe from Rounsevell et al (2006). We will explore ways to apply these methods to the 2019 baseline and generate projections for 2030 and 2050.

The BAU and what-if scenarios will be further elaborated in WP5 and in activity WP2.5, in close collaboration with the stakeholders in each river basin. Several river basin hubs have already developed future scenarios. We will discuss with them how the information from STARS4Water can augment these local data. Workshops with the RBHs are being planned for the first months of 2024 that will further discuss the specific scenarios for each basin.

4. Tier 2: derived indicators

The calculation of the tier 1 indicators is relatively straightforward and can be completed within a few months in the first half of 2024. However, these indicators are rather general and may not be directly applicable to water resources management and policy making. Therefore, in tier 2, we develop a number of indicators that are more directly related to water resources management. The tier 2 indicators are derived by combining existing datasets and auxiliary data, including local measurement data. A proposed list of tier 2 indicators is given below. The technical approach is described in general terms and the feasibility is estimated. It does not involve any numerical modelling or machine learning.

4.1. Precipitation deficit

Precipitation deficit is a common measure for severity of agricultural drought, for example in the Netherlands (see Figure), but it is also used internationally (Narasimhan, 2005). Figure 1 shows an example graph from the Dutch Meteorological Institute KNMI. The precipitation deficit differs from the Standardised Precipitation Index (SPI: accumulated precipitation compared to the long-term average) in that it takes into account evaporation, which can significantly affect the soil water content. Precipitation deficit is therefore considered a better indicator for (agricultural) drought than SPI. Furthermore, it does not rely on a long historical record to be able to calculate the statistics.

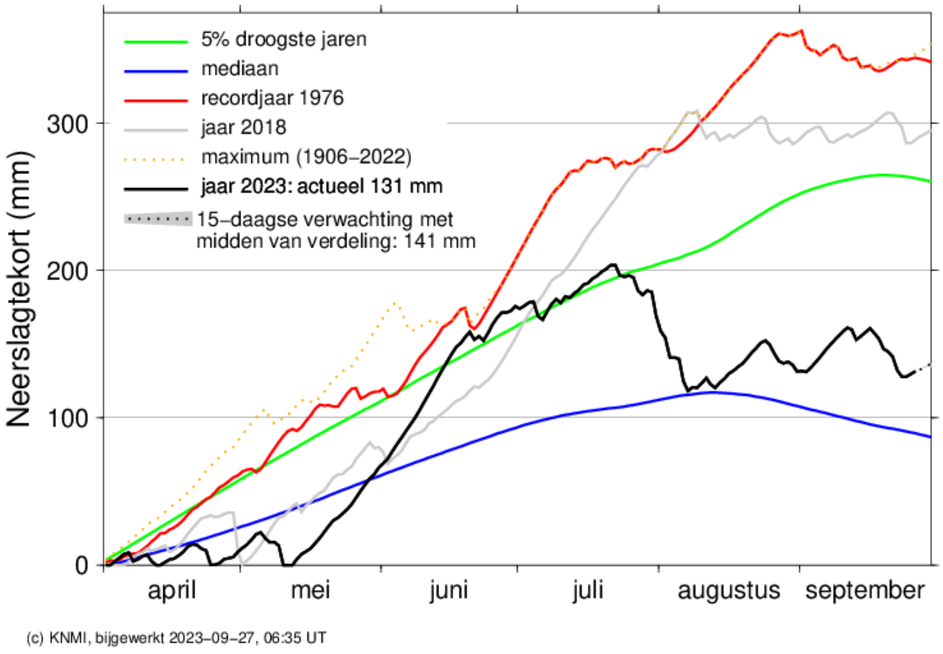

Figure 1: Precipitation deficit as published by the Dutch meteorological institute KNMI.

The precipitation deficit D is defined as the accumulated difference between precipitation P and (potential) evaporation ET.

$$D(t) = \sum_{s=0}^{t} ET(t-s) - P(t-s)$$

Where *t* is the current date and *s* indicates a day in the past. Both P and ET are available from the CDS. However, the CDS only provides the relative change per season. To calculate the accumulated difference, we will need the daily values from the original model runs e.g. from the ERA5 Land data set.

The precipitation deficit is an accumulated index, which takes into account both the intensity and the duration of water scarcity. Thus, low precipitation and high evaporation over a longer period of time will build up a large deficit. The downside of an accumulated indicator is that the accumulation requires a starting date (*s*=0). In the Netherlands, the starting date is April 1, which is the start of the growing season in this part of the world. For other basins, particularly for southern Europe, the starting date of April 1 is not appropriate. An earlier date would be needed to account for a possible drought onset early spring (see Figure 2). As a result of climate change, droughts may occur sooner in the year, which would be missed by a precipitation deficit that is starting on April 1.

The precipitation deficit addresses the need for drought monitoring, which is expressed by several river basins, including the Drammen, East Anglia and Danube. The precipitation deficit in a recent drought year can be used as a reference and compared to the expected occurrence of such values in the future.

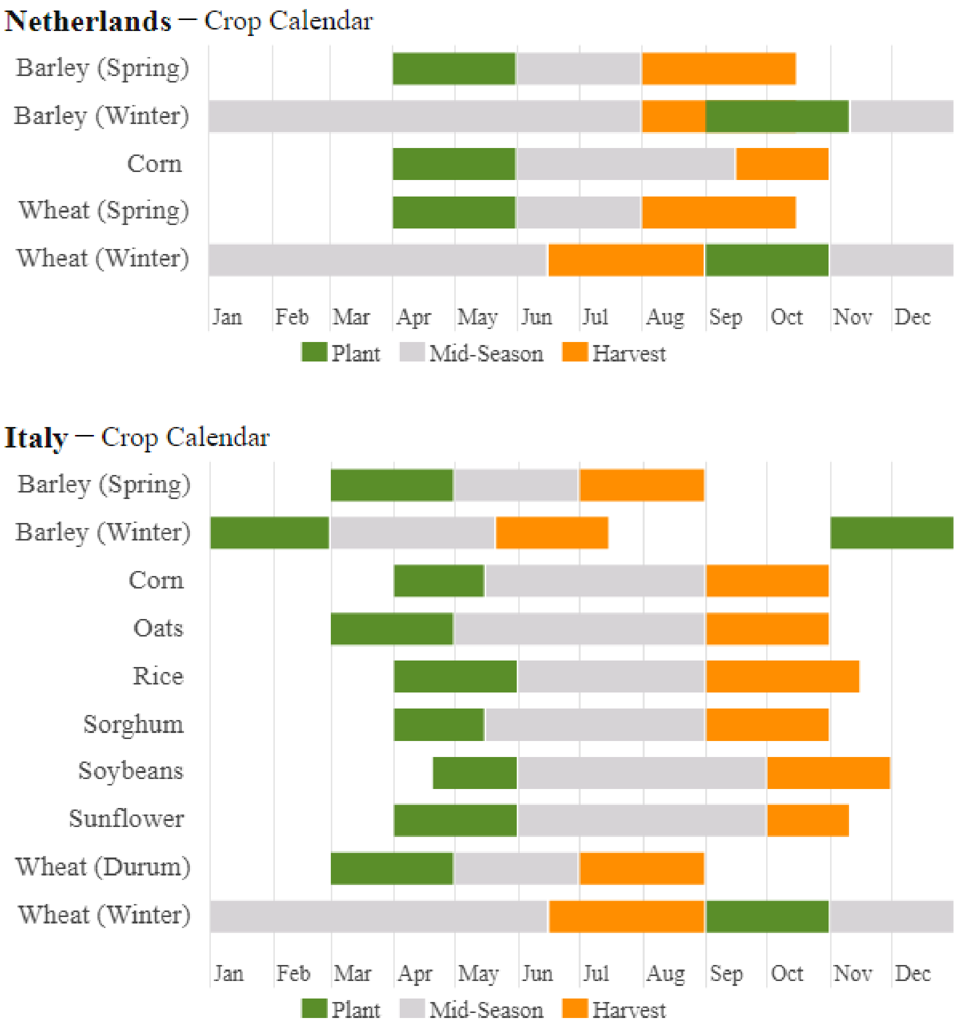

Figure 2: Crop calendars from https://ipad.fas.usda.gov/rssiws/al/crop_calendar/europe.aspx

4.2. Agricultural water demand

Agricultural water demand is available as a global dataset from several public sources. However, these datasets are not directly applicable to water resources management at the river basin scale. For example, AQUASTAT from FAO is available per country. The Human Water Consumption dataset from University of Utrecht is a model-based dataset at 50 km resolution.

For the STARS4Water project, we propose a different approach. We will try to establish a relationship between agricultural water demand and drought conditions. From an earlier study in the Netherlands (not published), we found that there is a strong relationship between soil moisture and irrigation by farmers. The graph below shows the number of irrigation requests by farmers and the weekly average satellite soil moisture in the same area (northeast Groningen). We find that the number of irrigation requests sharply increases when the soil moisture level drops below 0.2 m^3/m^3, which is more or less the wilting point in this area. We will investigate whether a similar relationship can be derived for other areas and try to develop a method for predicting agricultural water demand. This may be a relative water demand (not a quantitative number in mm/day), unless we can obtain information about the irrigated volumes by farmers. As for groundwater storage, we rely on the availability of local data sources, more specifically on irrigation data. The feasibility of this indicator is therefore uncertain.

If an agricultural demand indicator can be developed in this way, its main use will be to support the more quantitative agricultural water demand modelling activities in WP3 (see Chapter 6).

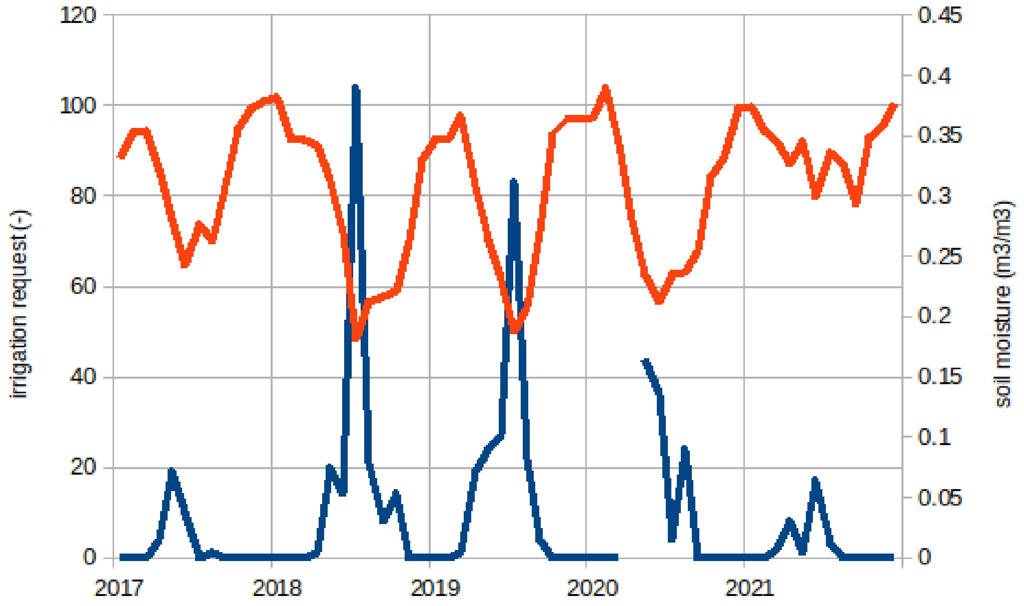

Figure 3: Apparent correlation between soil moisture and irrigation requests

4.3. Water demand per sector

In addition to the agricultural water demand indicator (see previous section), we will investigate the water demand from other sectors, such as energy production, households and tourism. Insights into these sectoral water usages and projections of expected changes can support the development of water resources management strategies in the future. A per-sector water demand indicator will provide insight into the expected change in water demand and help to support policy making in all the river basins.

Sectoral water usage per country is available from public data sources, see e.g. the EEA water use in Europe by economic sector. The EEA provides information about water use from Households, Service industries, Mining and quarrying, Manufacturing and Construction, Electricity, gas, steam and air conditioning supply, and Agriculture, forestry and fishing. Water demand by the tourism industry has been investigated before by the PESETA project (Amelung et al, 2009). The total water use was investigated by Wada et al (2014).

The water usage per sector will be cross correlated to population density and industrial activity per region. The scenarios for demographic development, urbanization and industrialization would then allow to project the water usage per sector and per river basin into the future. The feasibility of this approach is somewhat uncertain.

4.4. Low flow occurrence and duration

Mean river discharge is included as an indicator in tier 1 (see previous section). In tier 2, we will explore the possibility of deriving a more specific low flow indicator. For navigation, a minimum water level is required. The minimum water level can be related to a minimum river discharge and be used as a low flow indicator for navigable water. The occurrence and duration of low flow conditions are important for water resources management. Two indicators that are related to low flow will be investigated:

- Low flow occurrence: the number of times (days) per year that a critical threshold is under-exceeded.
- Low flow duration: the maximum number of consecutive days per year that the flow stays below a critical threshold. The change in average drought duration can be expressed as a percentage increase/decrease relative to present-day conditions.

Both low flow indicators require a threshold. Thresholds for low flow for each stretch of river need to be provided by the river basin hub. For navigation, the threshold is typically a water depth (see e.g. ELWIS for the Rhine), which can be converted into a discharge by using a rating curve. Different low flow thresholds may apply for other types of water use. For example, hydropower companies need to obtain a minimum streamflow where thresholds are defined by concession and licensing agreements. STARS4Water will use discharge thresholds for the low flow indicators, which follow directly from the model calculations, instead of water level thresholds.

For the low flow occurrence, we will derive a frequency distribution of daily flow conditions for each stretch of river. For low flow duration, we will derive distributions of annual maximum low flow duration from the discharge time series. Future scenarios for occurrence and duration of low flow conditions will be derived from climate projections of river discharge and expressed as a percentage increase/decrease relative to present-day conditions.

The calculation of the low flow indicators is based on daily streamflow time series. The feasibility of these indicators thus depends on the availability of these data sets from climate and hydrologic model runs. These time series can either be downloaded from global sources or provided by RBOs (from local model runs).

4.5 High flow occurrence and duration

In analogy to the low flow indicators, we can derive high flow indicators for occurrence and duration. High flow and floods are challenging both in the short term, during events, and in the long-term influencing areal planning, restrictions and flood mitigation expenses. The terms ‘magnitude of 50-year or 100-year flood’ means the magnitude of a flood that has a 2% or 1% percent chance of occurrence in any given year. Within WP2, we will develop two high flow indicators:

- High flow occurrence: the number of times (days) per year that a critical threshold is exceeded.
- High flow duration: the maximum number of consecutive days per year that the flow stays above a critical threshold.

For both indicators, we will investigate the differences between the historical and future periods. An alternative could be to show the change in probability of a flood of a given magnitude e.g. today's 50-year flood to occur in a future climate i.e. addressing the question: "will the probability of floods of a given magnitude increase or decrease in the future?" Climate might also affect the seasonality of floods especially in snow dominated areas. A shift in the mean calendar date of flood occurrence is another indicator that might capture these changes. The feasibility of these indicators depends on the availability of thresholds (to be provided by the RBOs) and daily discharge time series for present-day and future conditions.

4.6. Maximum Snow Water Equivalent

The mean snow water equivalent (SWE) is included in tier 1 as an indicator. For many applications, the maximum SWE in any given year is more relevant than the year-round mean, because the maximum values are needed to estimate the potential for large spring floods and for the hydropower industry to estimate the energy potential of the snow storage at the end of the season. The expected change in annual maximum SWE is important information to prepare for the future.

We will derive a ‘maximum SWE’ indicator, which represents the expected SWE maximum in any given year. It is important to note that this maximum can be reached in a different month in different years. The mean SWE per month (available on CDS) is therefore not sufficient information to derive this indicator. The feasibility of this indicator thus depends in the availability of daily (or monthly) SWE time series for both the present day (e.g. ERA5 Land) and for the future (e.g. Euro CORDEX).

4.7. Conclusion

In conclusion, the tentative list of tier 2 indicators is as follows: Precipitation deficit

- Agricultural water demand
- Industrial and consumer water demand
- Low flow occurrence and duration
- High flow occurrence and duration
- Maximum SWE

The technical feasibility of these indicators needs to be confirmed. As part of activity WP2.4, the methods described above will be detailed, implemented and tested. The feasibility of several of the tier 2 indicators will depend also on the availability of local data, either for deriving relationships between global data and indicators, or for validation. The above list should therefore be seen as preliminary and adjustments are expected over the course of the implementation.

5. Tier 3: model-based indicators

5.1. Introduction

Work package 3 and 4 will develop and employ models to run scenarios of future water resources availability. This will lead to additional information and climate indicators for dashboards and storylines. The tier-3 indicators cannot be specified in full detail yet, firstly because the modelling work in WP3 and 4 is still on-going and secondly because stakeholders will be consulted to select the final set of indicators.

The tier-3 indicators will use combinations of global and local data, and numerical models and machine learning to predict how the hydrologic system will change over the next decades. A great example is given by a recent study by IGME-CSIC and UCM (part of the STARS4Water project team). Future time series of climate variables were generated using the stochastic weather generator LARS-WG, considering 9 Global Climate Models (GCMs) and the future climate scenarios of Representative Concentration Pathway (RCP) 4.5 and 8.5. The results show the impact of climate change on precipitation (P) and temperature (T) climate variables in the Lower Douro subzone (Douro River Basin) for the time interval 2021-2040. The results from this study can be used for further modelling of e.g. reservoir and groundwater storage.

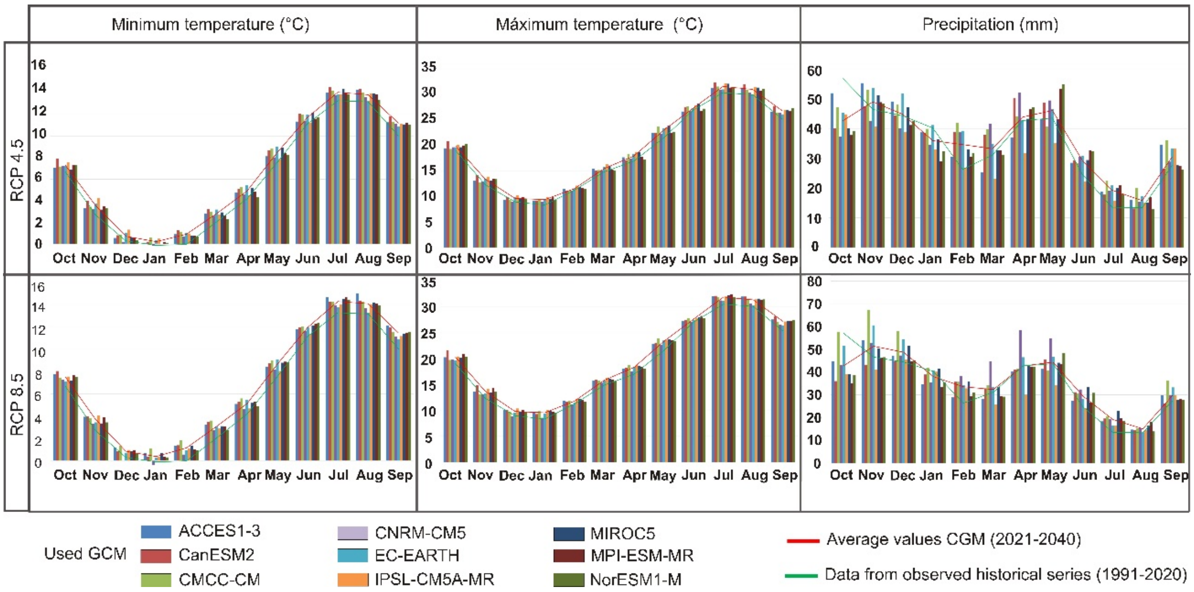

Figure 4: Example of model-derived indicators for the Douro river basin.

At the time of writing this report, the project team is considering the following modelling activities:

- Reservoirs status and storage
- Agricultural water usage
- Industrial water usage
- Ecological flows and thresholds
- Water temperature
- Groundwater/aquifer modelling

These modelling activities will be described in more detail below. We note that this is still preliminary, because the modelling work is still in the planning phase. The modelling plans and potential indicators will be discussed with the stakeholders in the coming months.

5.2. Reservoir status and storage

Reservoir storage is routinely monitored by measuring water levels *in situ*. However, in some cases this may not be possible (e.g. for transboundary rivers) and alternative methods can be considered. The reservoir storage can also be estimated from satellite imagery (through surface area calculation) and predicted by rainfall-runoff or machine learning models. Within STARS4Water, we will explore a combination of the latter two techniques to develop a method for predicting reservoir storage with the specific objective of better understanding how reservoir storages will respond to changing climate conditions and water abstraction.

The reservoir modelling results can be expressed as indicators in several ways. The evaluation of reservoir storage, and hence the management of water resources, could be supported by a standardized indicator which summarizes current reservoir storage in the context of historical values. As data around reservoir storage and releases are often not public, a metric to indicate current status in comparison to previous conditions may be an appropriate alternative to reporting actual values. A number of water body status indicators already exist in the literature. For example, Tiwari et al. (2019) and Gusyev et al. (2016) both use a reservoir status metric based upon the Standardized Precipitation Indices (SPI) (McKee et al. 1993), these being the Reservoir Storage Indicator (RSI) and the Standardized Reservoir Supply Index (SRSI), respectively. Both of these approaches standardize anomalies against a reference period for both monthly and seasonal accumulation periods.

Another approach to quantifying anomalous values in reservoir storage is the percentage difference in storage away from a long-term monthly mean (DMM), as utilized in the UKCEH Hydrological Summary (NRFA, 2022; UK Met Office, 2022). This method identifies a trend in water storage volumes and reports it as the percentage difference from a monthly average. As with the RSI and SRSI methods, a suitable reference period must be established. For SPI-based metrics such as the RSI and SRSI, The World Meteorological Organization (WMO) recommends at least 20-30 years of monthly values, with 50-60 being preferred (World Meteorological Organisation, 2012). However, there is currently no recognized standard length of reference period for assessing trends in water storage status. The current UKCEH hydrological summary uses 25 years, based purely on data availability across all its monitored sites. The following example is taken from Rickards and Baron (2022) and highlights example output from the DMM status methodology at the Wimbleball reservoir, UK. The percentage of reservoir capacity data was used to produce the time series of anomaly data.

Table 3: Anomaly, current and long term monthly average values (%) for the Wimbleball reservoir, October-December 2020 (Rickards and Baron (2022).

Reservoir	**Oct 2020**	**Nov 2020**	**Dec 2020**
Wimbleball, UK	Anomaly = -0.6 Current level = 64.9 Average = 65.5	Anomaly = 3.2 Current level = 76.3 Average = 73	Anomaly = 17.5 Current level = 100 Average = 82.4

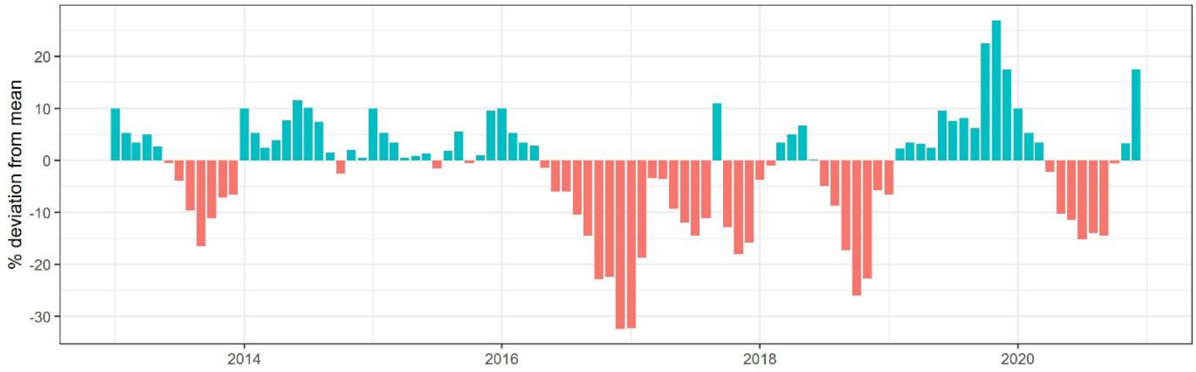

Figure 5: Anomaly metrics for the Wimbleball reservoir, UK, 2013-2020. Reference period = 1989-2020 (Rickards and Baron (2022).

This metric may be useful for water resource practitioners in that it supplies an indicator that compares current storage to the long-term average for a particular month or season and can also be disseminated to basin stakeholders without the need to provide actual water volumes or levels. While not as common as other hydrological metrics, UKCEH are in the process of evaluating and developing indicators for open water bodies to support global water resources management. The proposed approach may be suitable for the River Basin Hubs in STARS4Water where there is a focus on reservoir management and data transparency.

5.3. Agricultural water usage

Currently, irrigated agriculture accounts for 70 percent of all freshwater withdrawals globally, using water from groundwater aquifers, rivers, lakes and reservoirs. While only around 9 % of Europe's total farmland is irrigated, these areas still account for about 50% of total water use in Europe. In spring, this percentage can increase to over 60% (EEA, 2018).

On a large scale, satellite-based earth observation is the sole option for monitoring agricultural water use at field scale level. Growing efforts have been made to assess agricultural water use through earth observation data, using proxies like soil moisture and evapotranspiration (see Jalilvand et al., 2019; Brocca et al., 2018; Van Eekelen et al., 2015; Droogers et al., 2010). Within the STARS4Water project, we will use a hydrological model, wflow_sbm (Schellekens et al, 2019), and earth observation products from thermal sensors which will be used to adjust evapotranspiration estimates of wflow_sbm. The hydrological model used here does not account for irrigation practices. Consequently, the adjusted actual evapotranspiration over the cropland can be attributed to agricultural water use. The rationale is that agricultural water use comprises consumptive water use in the form of actual evapotranspiration. Agricultural water use will be quantified at a 1 km resolution and on a monthly time scale during the main growing season (mm/month). While our methodology remains inherently independent of crop type, there exists the potential to establish correlations between agricultural water use and specific crop types by examining the crop type map.

Indicators that can be derived from the modelling work are the agricultural water demand and water use:

- Agricultural water demand (per 'crop' type) per km^2 land per growing season: agricultural water needed for optimal production of food and fiber minus rainfall during growing season

- Agricultural water use (per ‘crop’ type) per km^2 land per growing season: agricultural water withdrawals from groundwater and surface water.

5.4. Industrial and household water usage

The sectorial water usage and in particular industrial water use will be analyzed in more detail for a number of river basins through RIBASIM modelling. Industry is one of the main water users in Europe, accounting for about 40% of total water abstractions. Mining and manufacturing account for around half of the industrial water use (EEA, 2018). According to EEA (2021) water consumption in the industrial sector is decreasing, while the value of industrial production continues to grow in western, northern and eastern Europe, suggesting a trend towards decoupling of the water resources from industries. The industrial sector is also a major water polluter, as only up to 60% of industrial wastewater receives treatment before being disposed of into the environment. Household water demand (or domestic or consumer demand) accounts for 12% of the annual water use in Europe (EEA, 2018). Data per country can be obtained from national statistics, which can be translated to catchment-level household water demand, using the total population as a scaling factor. In addition, data could be collected from water supply companies who monitor their facilities and production. On average, 144 liters per day per person is supplied to households in Europe, but this varies between countries (see Figure 6).

The CHR conducted a study for the Rhine river basin (Ruijgh, 2019) based on expert judgement and open global datasets. This study has indicated that the water consumption by public water supply and industry is relatively small in comparison to water use for energy production and irrigated agriculture. However, recently more detailed studies in this field (dedicated national research on these topic) became available on country level. STARS4Water will leverage these studies and make them beneficial on the Rhine river basin level, by incorporating their data in the modelling tools of STARS4Water.

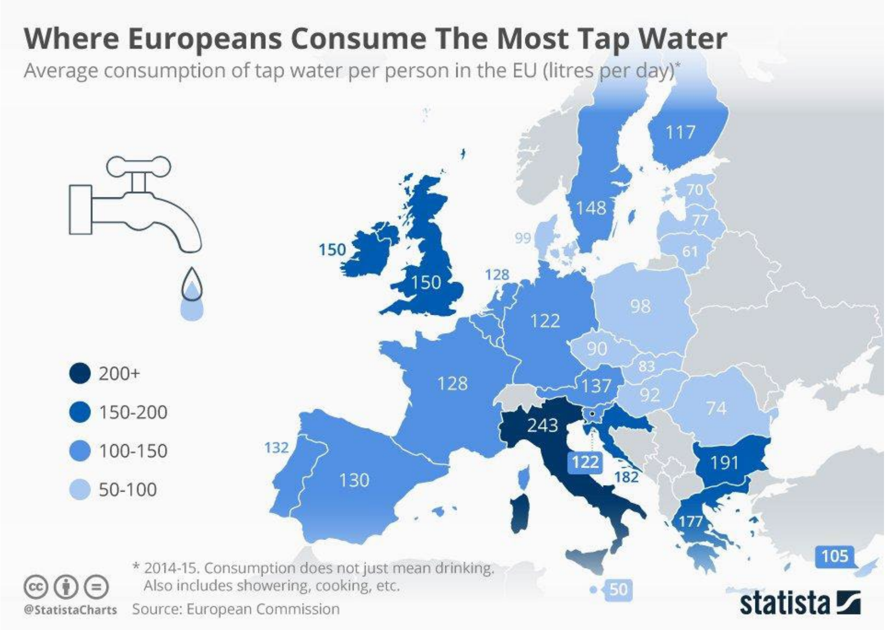

Figure 6: Average consumption of tap water per capita in Europe.

RIBASIM (River Basin Simulation Model) is a generic model package for analyzing the behavior of river basins under various hydrological conditions. The model package links the hydrological water inputs at various locations with the specific water-users in the basin. RIBASIM generates water distribution patterns and enables the user to evaluate the effectiveness of measures in terms of water quantity and water quality. RIBASIM is based on water balances, providing insight into the water sources and water usage and re-use. A wide range of basin performance parameters are generated for evaluation of the simulated situations. RIBASIM requires one year of input data, in 10-day or monthly timesteps per region or subcatchment. The standard output of RIBASIM is the annual water withdrawal per (sub)catchment and per sector, as a total volume and as a percentage of total freshwater availability. Further derived indicators, such unmet demand, water supply reliability and water demand coverage can be calculated from this output (see section on derived indicators below).

A RIBASIM model using global input data has already been implemented for the Rhine. The next step is to use more accurate and refined local input data. We propose to follow a hybrid approach:

- For the Netherlands, we will make use of the data of the National Water Model. We have data for the current situation and for the Delta scenarios (future projections).
- For Germany, we would like to make use of the WADklim project data. This project is about to be concluded and we have requested University of Bochum to share data on industrial water use and public water supply for Germany. The WADklim project has also developed three different scenarios. Data is available on NUTS-3 level up to 2070. For STARS4Water, we will aggregate this to the Subbasin Level.
- The ICBR will support the local data collection, especially for Rhine riparian countries other than the Netherlands and Germany. We will discuss our data needs in the ICBR expert group meeting on the 11th of December.

For the Messara, we propose a similar modelling approach as for the Rhine, albeit with different (significantly lower) demand for drinking water and industrial water. The government of Crete will provide support. For the Danube, we will use output from the CWATM model from IIASA in RIBASIM. We will make use of their data on water demand for consistency.

5.5. Ecological flows

Environmental flows (e-flows), also sometimes referred to as ecological or biological flows, encompass the water requirements to support rivers and their connected ecosystems. Although this concerns both water quantity and quality, e-flows are more often considered in terms of quantity. In the past, they were considered in terms of the minimum river flow necessary to sustain river ecosystems, but more recent studies identified that survival of aquatic organisms requires a wider range of hydrological requirements, e.g. minimum river discharge, timing of floods or freshets, timing and duration of the low flow conditions. It was also recognized that organisms may be only indirectly affected by discharge, while they are directly affected by e.g. flow velocities and water depths or water temperature, etc., which can be related back to hydrology. In many cases, the ecological flow criterion will also depend on the type of organism under consideration. There is a significant increase in complexity as one moves from only inspecting hydrology to disentangling the chain of processes, e.g. climate -> hydrology -> hydraulics -> ecology. Often, data availability is also a constraint.

For STARS4Water, we will explore two approaches:

1. A relatively simple hydrologically-based approach relying on hydrological data only (e.g. bespoke application of ERFA method; see below).
2. A more complex approach that would consider hydrology-hydraulics linkage, and its effect on river physical habitat (e.g. wetted width, depth, velocities) and river connectivity (longitudinal within river channel, lateral with floodplain and other land types), morphology, etc.

In the first approach, we aim to derive ecological risk for the seven river basins of the STARS4Water project by using the Ecological Risk due to Flow Alteration (ERFA) screening method originally described by Laizé et al. (2014). It was developed for Europe as part of the project “water SCenarios for Europe and NEighbouring States (SCENES)” from the European Commission (FP6 contract 036822) and since applied and modified to various ecoregions (Laizé and Thompson, 2019; Thompson et al. 2021). ERFA belongs to the family of e-flow hydrological methods, which are conceptually based on the Range of Variability Approach (RVA) that utilizes Indicators of Hydrological Alteration (IHA) to compare pre- and post-impact river flows, in this case, the baseline regime for the reference period vs future flow scenarios (Richter et al., 1996). The core assumption of these approaches is that under baseline conditions, organisms and/or biological communities are adapted to the current river ecosystem (e.g. all ecological niches created by the interaction of discharge and the river channel and catchment are exploited). If the river ecosystem is adapted to baseline hydrology, then any flow alteration can lead to a risk of ecological impact. All aspects of the flow regime are relevant to ecology: magnitude, duration, timing, frequency and rate of change. The more scenarios depart from baseline conditions, the higher the risk of ecological impacts.

To apply ERFA to a site, one requires a baseline flow time series and one or more scenario flow time series. Daily or monthly time steps can be used. First, a series of flow indicators are derived from baseline and scenario series, which capture all ecologically-relevant aspects of the hydrograph. With monthly flow series, ERFA derives 16 flow indicators. Secondly, the differences between baseline and scenario indicators are calculated. Thirdly, a difference threshold is applied (e.g. default 30% absolute difference): if one flow indicator differs by more than that threshold, then it is counted as significantly different. This is to take into account the natural resilience of river ecosystems, which can cope well with some amount of disruption. Finally, an overall risk category is assigned based on how many indicators are counted as different. A self-explanatory traffic-light color-coded system is used to facilitate engagement with non-specialists. With the monthly ERFA version: blue, no risk (no indicator different); green, low risk (1 to 5 indicators different); amber, medium risk (6 to 10 indicators different); red, high risk (11 to 16 different). See an example in Figure 7.

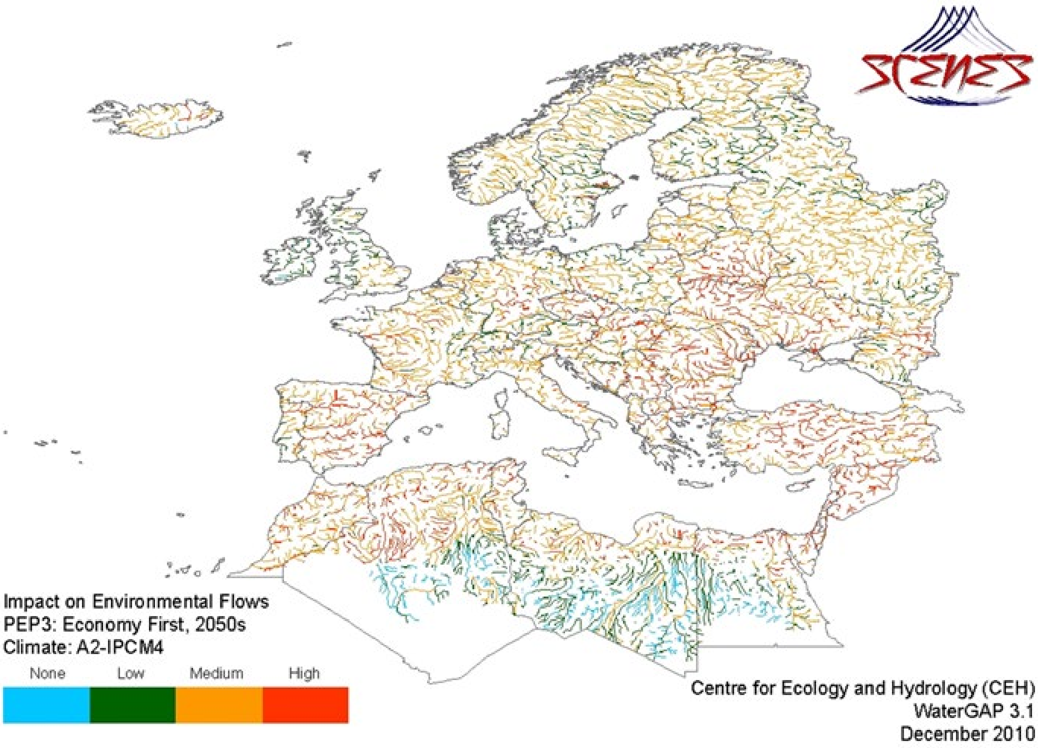

Figure 7: Example of ERFA application to European-scale river network

The second, more advanced approach is based on eco-hydraulic indicators that would most likely take two forms: (i) river (hydraulic) habitat conditions; (ii) connectivity. First, a given flow can cause different hydraulic conditions in different channels (e.g. depending on channel geometry, slope, roughness), to which organisms are very sensitive. Some species or types of organisms need deep rivers, some need shallow water, some prefer faster flowing rivers, other species need slow flows, etc. Through modelling, we could assess how hydraulic conditions may change under future scenarios and derive indicators such as change in total amount of habitat available at a site (loss or gain of available habitat to river organism) or change in velocity distributions (favoring organisms preferring faster or slower waters). Secondly, river connectivity, both longitudinal and lateral, is of vital importance to ecosystems as it controls how far organisms can travel to find resources and settle (e.g. migratory fish). The more a catchment is fragmented, the more the ecosystem is potentially impacted. Indicators could range from static catchment fragmentation indicator taking physical obstacles into account (e.g. percentage of total river length between outlet and first obstacle) to dynamic ones that take into account connectivity loss due to riverbed drying out (e.g percentage of time catchment is hydraulically fragmented).

In summary, indicators for ecological flow can range from a wide variety of properties and variables. The technical feasibility of the modelling approach and the targeted indicators listed above need to be confirmed.

5.6. Water temperature

In Europe, energy production accounts for around 28% of annual water use (EEA 2018). This water is predominantly used for cooling in power plants. The water is heated before it is released back into the river, which can have adverse effects on local species. EU has standards for maximum water temperature in summer and winter.

Measurement of water temperature is relatively easy and is done in most of the larger European rivers. However, modelling of water temperature and future projections are much harder. At the time of writing this report, it is uncertain if water temperature modelling will be done as part of the STARS4Water project.

Indicators for water temperature could be:

- The annual water withdrawal for cooling per (sub)catchment (total volume and as percentage of total water available);
- The number of days per year that the discharge of cooling water from power plants is restricted (because of adverse effects on aquatic life);
- The number of days per year that the water temperature exceeds the EU standards.

5.6. Groundwater status

Groundwater quantity and quality are crucial in Mediterranean basins, where aquifers account for a large part of urban and agricultural supplies. The interconnections between quality and quantity need to be considered comprehensively. Of the seven river basins that are the focus of the STARS4Water project, groundwater issues are the most pressing in the Messara and Douro basins.

For the Douro basin, the project team will focus on extending existing MODFLOW models both in time and space to evaluate water quality and quantity in the main groundwater bodies in the basin. The goal is to incorporate nitrate pollution as a proxy for groundwater quality and assess its potential impact on water supplies under future scenarios. We will work on specific indicators addressing the requirements and needs of stakeholders. These data-driven indicators will reflect the medium-term (e.g., 6-year) trends in groundwater levels, nitrate, and arsenic concentrations. These time periods align with the water cycles developed under the Water Framework Directive.

As part of the data-driven planned developments in WP 3.4, there are models for both groundwater quantity and quality predictions. Concerning nitrate or arsenic pollution, the MLMAPPER model developed by the UCM partner can be used for the spatial prediction of groundwater contaminants. The possibility of incorporating the time dimension into this tool will be explored, allowing for spatiotemporal predictions and using nitrate or arsenic concentration trends as indicators for risk assessment scenarios.

In the case of quantitative groundwater resources estimation, there is a need to improve the estimation of groundwater resources at a finer resolution than that provided by current process-based models, both spatially (e.g., sub-basin scale, GWB scale, etc.) and temporally (e.g., daily, weekly, biweekly, etc.). A deep learning surrogate model able to predict across different spatial resolutions is in the scoping phase. The model is intended to predict groundwater balance components like inflows, recharge, storage, and outflows based on state variables such as streamflow, groundwater level, and discharge, alongside other gridded inputs available within the STARS4Water metadata portal, such as DEM, precipitation, soil composition, soil moisture, evapotranspiration, groundwater recharge, land use, etc. Similar approaches have recently been proposed for the prediction of streamflow (Arsenault et al., 2023) or water balance components

(Droppers et al., 2023). The application to groundwater balance components, however, remains a challenge.

Currently, groundwater balance outputs from current groundwater balance process-based models are available for the Douro. This data can be used to train the deep learning model. In basins where this data is not available, downscaled projections from global pan-European models (e.g., Parflow, LISFLOOD) and datasets (e.g., TSMP) dealt with in WP 3.3 could be used to estimate groundwater balance components and groundwater levels for model training. The results of this work should provide a basis to derive indicators on groundwater storage and recharge, highly valuable for groundwater resources management.

Possible indicators for groundwater are:

- Trends in groundwater levels
- Trends in nitrate and arsenic concentrations
- Water quality maps (nitrate, arsenic)
- Groundwater storage and recharge maps (anomalies)

The technical feasibility of the modelling approach and the targeted indicators listed above need to be confirmed.

5.7. Further derived indicators

In addition to the indicators that directly follow from the model outputs, we can derive further water scarcity indicators that represent the drought situation in various ways. These indicators are often used in drought assessment reports, such as the Water resources across Europe report (EEA, 2021) and the recent European Drought Risk Atlas (Rossi et al, 2023). Below are a few examples:

- Renewable freshwater availability per capita
- Water exploitation index (WEI and variations)
- Demand and supply indicators

These and other derived indicators will be discussed with end users and stakeholders in upcoming workshops. They are often calculated at the national scale. In this project, we focus on the river basin scale.

Freshwater availability per capita

The annual renewal freshwater availability per capita is an indicator proposed by FAO (Baggio et al., 2021) to provide an estimate of the total freshwater available to meet the agricultural, industrial and domestic water demands after the needs of freshwater ecosystems (environmental flow requirements, EFR) are ideally fulfilled. The total annual renewal freshwater availability of a country is calculated as the sum of the internal renewable and external freshwater resources. Internal renewable freshwater resources are defined as the long-term average annual flow of rivers and recharge of groundwater for a given country generated from endogenous precipitation. External renewable freshwater resources refer to the flows of water (transboundary rivers, lakes, aquifers) entering the country. Annual renewal freshwater availability per capita is expressed in m^3 per capita.

According to the Index Mundi's data, Greenland ranked number 1 and Iceland number 2 in renewable internal freshwater resources per capita with 10,660,000 m^3/p and 520,000 m^3/p respectively. A freshwater availability of less than 500 m^3/p is considered as very critical (Baggio et al, 2021).

Renewable freshwater availability per capita is usually calculated at the national level. However, there are also other ways to assess the renewable freshwater availability:

- Renewable freshwater availability per capita within a catchment: the annual flow of the river and groundwater aquifer generated from precipitation within the catchment.
- Renewable freshwater availability per capita within a sub-catchment: the annual flow of the river and groundwater aquifer generated from precipitation within the sub-catchment and in case when the sub-catchment is connected to upstream parts of the catchment the flows of water upstream of the sub-catchment.

Within STARS4Water, we will focus on freshwater availability indicator at the catchment or sub-catchment level, depending on the size of the river basin.

Water exploitation index

The water exploitation index (WEI) is a water scarcity indicator that is calculated as the average demand for freshwater divided by the long-term average of freshwater resources. It is a measure of the water stress that occurs when water demands are not met by water availability. Around 20% of the European territory and 30 % of Europeans are affected by water stress during an average year (EEA, 2021). Water stress is listed as an indicator for SDG6 (indicator 6.4.2). The SDG6 objective is to substantially increase water-use efficiency across all sectors and to ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people affected by water scarcity.

The water exploitation index is defined as the percentage of freshwater withdrawals compared to the total renewable freshwater resources (see previous section). The total freshwater withdrawal is the sum of freshwater extracted from rivers, lakes, reservoirs and aquifers for agriculture, industries, municipalities (including domestic water withdrawal) and industries, including cooling of thermoelectric plants). Freshwater withdrawal includes primary freshwater (water not withdrawn before), secondary water (water previously withdrawn and returned to rivers and groundwater, such as discharges treated wastewater, discharged agricultural drainage water, discharged cooling water) and fossil groundwater. It does not include direct use of non-conventional water sources, i.e., direct use of treated wastewater, direct use of agricultural drainage water or desalinated water. The total freshwater withdrawal is thus equal to the sum of the total water withdrawal (by sector) minus the sum of the direct use of wastewater, direct use of agricultural drainage water and direct use of desalinated water. The level of water stress is usually calculated at the country level, but it can also be evaluated per river basin or subcatchment.

Several variations of WEI have been proposed. For example, recent water stress studies take environmental flow requirements (see also the section on environmental flows) into account in the calculation of the WEI. Environmental flow requirements are the quantities of water required to sustain freshwater and estuarine ecosystems. Methods of assessing environmental flow requirements (EFR) are variable, and in many cases EFR is expressed as a percentage of the available water resources. However, to address EFR properly the method should take into account the variability of flow regime during time and space to support the ecological processes and habitat requirements of key species.

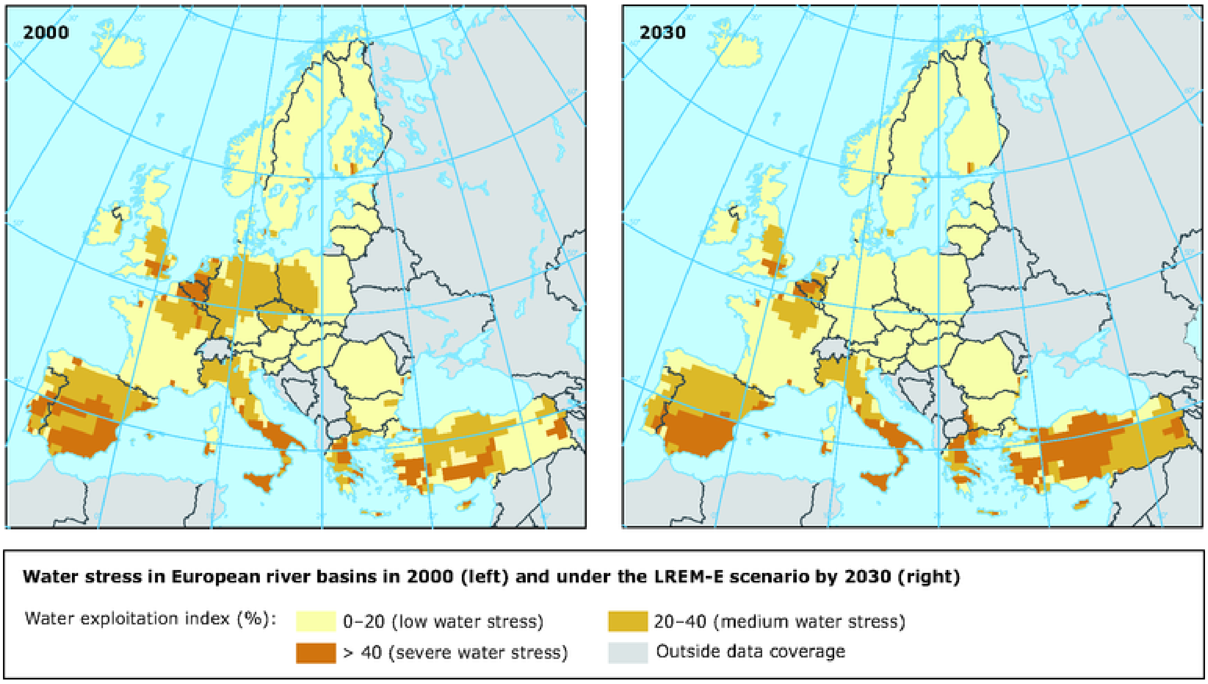

Figure 8: Water stress in European river basins calculated by the WaterGap model. Source: EEA.

The revised indicator of level of water stress within a territory is the total freshwater withdrawal (TFW) in percentage of the total renewable freshwater resources (TRF) after environmental flow requirements (EFR):

$$\text{Water stress} = TFW / (TRF - EFR)$$

The WEI+ is a modified version of WEI that was proposed by the Committee of Experts of the European Commission to account for the possible return flow and management rules. The WEI+ indicator quantifies how much water monthly, seasonally or annually is abstracted and how much water is returned after use to the surface water systems or the aquifers in the basin. The difference between water abstraction and water return is regarded as water consumption or defined as water use (Casadei et al, 2020).

Demand and supply indicators

In addition to WEI, more indicators can be obtained from water balance modelling, for example:

- Unmet water demand / water stress per sector: the difference between demand and supply, at monthly scale and per model water demand node. We could also calculate "unmet demand as % of the total demand per sector/node"
- Water supply reliability per sector and/or per node. The water supply reliability is defined as the percentage of time that a specific water demand is met. For example, if the water demand from a specific sector in a (sub)catchment is not met during a total of 6 months in a 10-year period, the reliability R is calculated as:

  $$R = (\text{time that demand is met}) / (\text{total time}) = (10 * 12 - 6) / (10 * 12) = 95\%$$

  The reliability can be expressed as a percentage or as a classification (from low to high).

- The Water Demand Coverage compares current water storage to the long-term average for a particular month or season. When expressed as a percentage, it can be aninformative indicator to basin stakeholders or the public, without the need to provide actual water volumes or levels. Although not as commonplace as other hydrological metrics, UKCEH are in the process of both evaluating and developing indicators for water bodies to support global water resources management. An approach such as those detailed here may be suitable for the River Basin Hubs in STARS4Water where there is a focus on reservoir management and data transparency.

6. Conclusion and follow-up

In this report, a number of indicators are proposed that can support long-term strategy development and policy making in the water resources domain. The indicators represent conditions in the system that are subject to change over the coming decades due to climate change and/or socio-economic developments.

This report describes three sets of indicators:

- **Tier 1 indicators**
  These indicators can be directly derived from publicly available sources. We will make them more practically applicable to water managers in each river basin by projecting them onto the (sub)catchments of the basin and by reducing the number of possible outcomes to a smaller number. The list of indicators has been fixed and the technical implementation is considered feasible. We expect to deliver the tier 1 indicators by April 2024. The results can be used in dashboards and will set the stage for more advanced modelling and calculation.
- **Tier 2 indicators**
  We describe a number of indicators that aim to be more relevant to the basin managers by building from the tier-1 indicators and combing them with local data. Several examples and calculation methods are described. It is the intention of WP2 to produce these indicators within activity WP2.4 by April 2025, including future scenarios. However, the feasibility of these indicators depends on the availability of local data and still needs to be demonstrated.
- **Tier 3 indicators**
  This report describes a third tier of indicators that are derived from the outputs of numerical models and machine learning. Models and ML simulate the behavior of the hydrological system in a river basin under current and future conditions. The output in terms of e.g. river flows, reservoir storage or water supply and demand can be used to derive further indicators, some of which are described in the previous chapter. At the moment, these indicators should be seen as suggestions. They will be discussed with the river basin representatives in the coming months.

In summary, the set of tier-1 indicators and calculation methods is fully determined. The second tier is described but needs confirmation in terms of feasibility. The third tier is still tentative and will be developed in the months ahead. Technical approaches will be adjusted where needed. The current report is considered a starting point for the discussions with RBOs to come to a final set of indicators for STARS4Water.

Activities in 2024: indicators

Following this description of indicators, work package 2 will focus on the calculation and delivery of the tier-1 indicators, including projections for 2030 and 2050, in the first half of 2024. The first set of indicators consists of projections of readily available global or European scale datasets to the sub-catchments of interest. The results will be uploaded to the STARS4Water Metdata Portal for dissemination and review by the river basins. The tier-1 indicators will form a reference for further developments, more specifically the model- and ML-based indicators.

The report and tier-1 indicators will then be shared with the contact persons for the RBOs and we will organize workshops for further discussion. The aim is to determine which indicators and which *what-if* scenarios are most relevant to each basin. We will also interrogate the larger river basins for the preferred level of subcatchment disaggregation. The feedback from the river basins will be used to further specify the list of tier-2 and tier-3 indicators that are feasible to develop within the scope of the project.

For the tier-2 indicators that are developed within WP2, we need to combine global data with auxiliary datasets, including local data. The collection of local data, combination of different datasets, projections for 2030 and 2050 and validation of the outcomes will take more time. The second set of indicators is scheduled for the end of 2024, with a possible extension into 2025. The report on all indicators from WP2 and future scenarios (D2.6) will be submitted by March 2025.

Activities in 2024: metadata portal

In parallel, the development and content of the metadata platform will continue throughout 2024 and beyond. New datasets will be added to the portal, including local datasets (a first inventory is being made in WP1.3), additional global datasets that were missed in the inventory that was done in WP2.1 and datasets generated by the project. The latter datasets will predominantly be climate and socio-economic indicators and future projections to support water resources management in the river basin hubs.

The functionality of the metadata-portal will also be adjusted following suggestions and feedback from the stakeholders that are currently exploring the first version of the platform. This may concern search and find functionality, or display features of the front end of the platform.

Activities in 2024: scenarios

In parallel to the development of indicators, the work on future scenarios will be performed. For each indicator, a practical number of scenarios will be developed as part of activity WP2.5. This activity is already on-going (in the form of co-design of the indicators) and will intensify in 2024, when the list of indicators is available. This will lead to a report (D2.5) in which projections on future water resources availability are described and the associated datasets are delivered to the metadata portal.

Activities in 2025

In 2025, the work on derived indicators (tier 2) will be continued, leading to a conclusive report in March 2025. The development of the metadata portal will also continue, as more datasets are generated by WP3. These datasets are added to the portal for dissemination, ease of access and archiving.

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