SOS Water deliverable report

D4.1 Review of water indicators and gaps identified

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1. Introduction

The review of indicators and the gaps identified is the outcome of task 4.1 and will be used as a starting point for the definition of innovative indicators aiming at filling the gaps (Task 4.2), the development of a framework to combine them (Task 4.3) and the setting of systems of indicators for the case studies (Task 4.4). D4.1 collects an extensive review on past and ongoing literature and research on the associated topics, characterizing them by the spatial scale, the temporal scale, the variables, or parameters involved and the information sources. Besides this characterization, typical thresholds set in the literature to these indicators will be proposed too.

This deliverable presents a selection of key indicators relevant to the SOS-WATER project. It is important to note that this list is not intended to be exhaustive, as the range of indicators in the field of water resources is vast and diverse. Clearly, this list of selected indicators is incomplete, as there are other similarly essential indicators that address specific aspects of water management, use, and quality. However, for this task, we have provided a minimal set of indicators that any project should consider. These indicators represent a solid starting point that can be customized and expanded upon the case study's particular requirements and objectives. In the context of SOS-WATER, we intend to provide a solid and adaptable foundation for assessing and monitoring water resources.

2. Methodological approach

According to the Cambridge Dictionary (https://dictionary.cambridge.org/), an indicator is "*something that shows what a situation is like*". Indicators can be defined regardless of the science field and the information source, and their purpose is to facilitate the transferring of information and decision-making by providing a clear vision of "*what a situation is like*". In this way, indicators are bound to be capable of summarizing the current status of a system to provide a clear vision of its current and/or expected status.

In the water sector, there is a long tradition in the definition and use of water indicators. At first, statistical moments of relevant variables (e.g., average, standard deviation, coefficient of variation) were used as indicators (Hashimoto et al, 1982). Early definitions of indicators and indices can trace back to the 1960's, with the Palmer Drought Severity Index or Palmer Drought Index (Palmer et al, 1965).

In SOS-Water, the indicators will be assessed depending on the following feature trees:

- Depending on the variable
    - Water resource indicators
        - Quantity indicators
            - Surface resource indicators
                - Climatic
                - Hydrological
                - Water Resource
            - Groundwater resource indicators
                - Recharge
                - Level
                - Discharge
        - Quality indicators
    - Water demand indicators
        - Socio-economic demands
            - Economic losses
            - Water use intensity
        - Environmental demands
            - Environmental flows
            - Species habitat
        - Agricultural demand
- Depending on the source of information
    - Indicators defined from monitoring
        - Remote sensing

    - Sensors/Gauging stations
  - Indicators defined from modelling
    - Climatic models/ Reanalysis
    - Hydrological models
    - Groundwater models
    - Water quality models
    - Water management models
    - Hydro-economic models

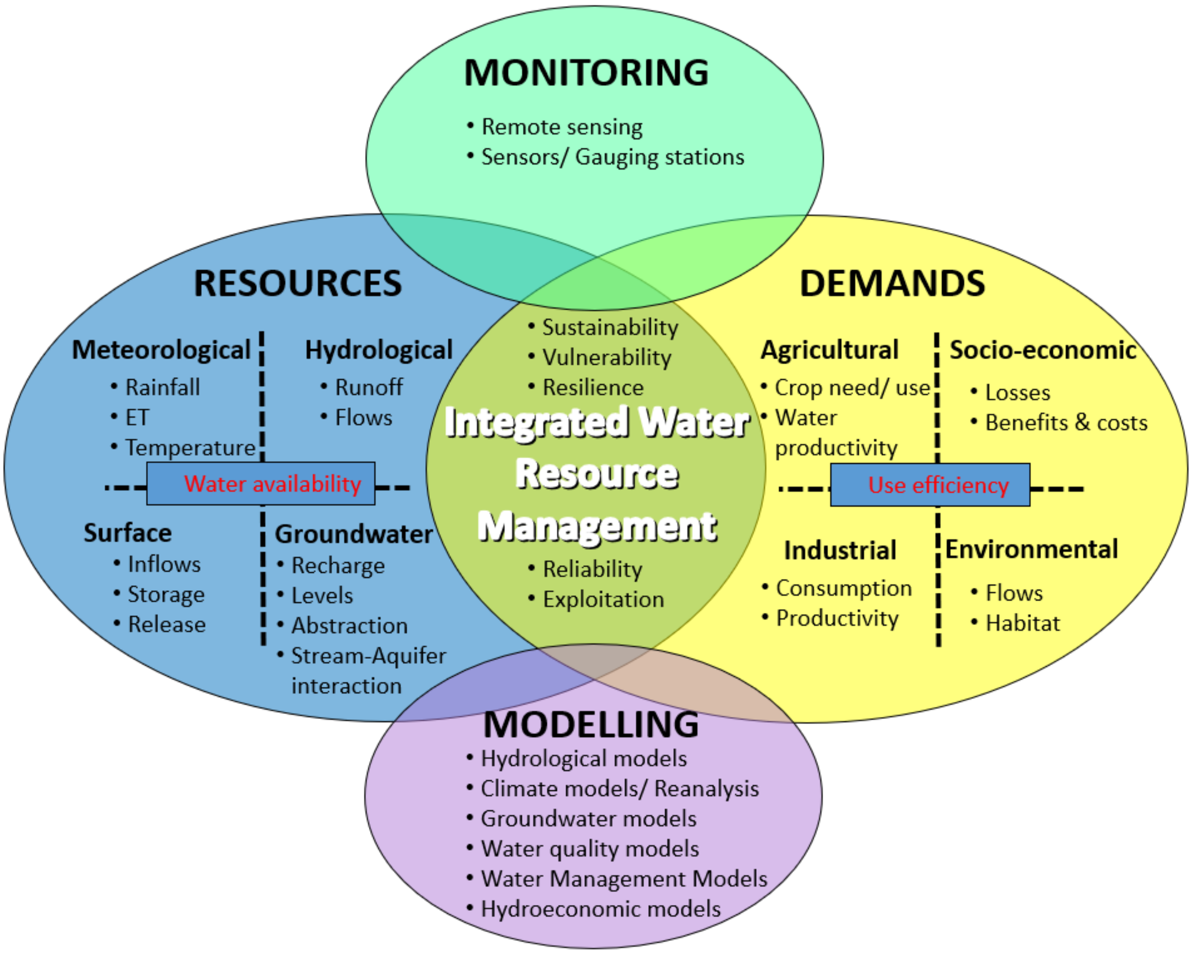

Figure 1: Indicators classification

Moreover, each indicator will be evaluated in terms of the temporal scale(s) and the spatial scale(s) to which it could be applied. Temporal scales, including daily, monthly, seasonal, and annual, enable a comprehensive analysis of short-term fluctuations, seasonal patterns, and long-term trends in water supply and demand. On the other hand, spatial scales, including plot, basin, district, and country levels, are essential for understanding the geographic extent and context of water-related issues. It should be pointed out that some authors establish a distinction between indicators and indices (e.g., Pedro-Monzonis et al., 2015; WMO-GWP, 2016), in which indicators refer to an individual variable while indices refer to a combination of variables and/or indicators, thus implying that indices are meta-indicators. For establishing the Safe Operating Space, however, both could be considered exchangeable and equivalent in terms of assessing the SOS.

The process of reviewing indicators involves collecting and analyzing indicators and indices from four main sources:

- Scientific papers
- Policy reports and guidelines.
- Other outcomes from research projects (e.g., deliverables)
- Legislative documents (e.g., Water Management Plans and water legislation)

This deliverable presents a selection of key indicators relevant to the SOS-WATER project. It is important to note that this list is not intended to be exhaustive, as the range of indicators in the field of water resources is vast and diverse. Clearly, this list of selected indicators is incomplete, as there are other similarly essential indicators that address specific aspects of water management, use, and quality. However, for this task, we have provided a minimal set of indicators that any project should consider. These indicators represent a solid starting point that can be customized and expanded upon the case study's particular requirements and objectives. In the context of SOS-WATER, we intend to provide a solid and adaptable foundation for assessing and monitoring water resources.

3. List of indicators relevant for SOS-WATER

3.1. Water resource indicators

This section describes water resource indicators that can be used to assess resource availability and provide an understanding of water system conditions. In this section, several indicators have been identified, and evaluated and classified into five distinct categories. Each indicator category is tailored to specific variables and water source characteristics, whether pertaining to groundwater or surface water sources. These are the categories of meteorological, hydrological, reservoir and groundwater, surface water, and water stress and use efficiency indicators. This structured classification allows for a better understanding of the complex dynamics that define water resources and then facilitates making informed decisions for sustainable water management.

The evaluation of each indicator considers several key factors, including the fundamental characteristics of the variables involved, whether relating to climatology, hydrology, or the specific features of the water source. In addition, the evaluation considers the origins of these variables and the methods or approaches used to derive linked variables, which may include remote sensing, sensors, or modeling, among other information sources. The dark green color signifies the common source, while the light green color means that the variables can also be derived from that source but it's not the usual practice. Furthermore, the temporal and spatial dimensions at which each indicator can be applied effectively are assessed; this provides crucial insights into its applicability in different contexts. With respect to the colors used in the application scales, both temporal and spatial, the intense color implies that the index can be safely calculated and applied, while the light one means that, although the index could be calculated, its applicability to these scales would not be direct.

3.1.1. Meteorological indicators

3.1.1.1. Standardized Precipitation Index (SPI)

Indicator scope		
Climatic	Hydrology	Water resources

Information source							
Monitoring		Modelling					
Remote sensing	Sensors/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 1: temporal and spatial scales of SPI application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The SPI is one of the most widely used meteorological drought indices. It was selected in 2010 by the World Meteorological Organization (WMO) as a key meteorological drought indicator (*SPI: Standardized Precipitation Index — English*, n.d.). SPI is a statistical indicator comparing the total precipitation aggregated over a certain period (months) and location with the long-term probability distribution for the same aggregation and place. SPI performs a standardization of the aggregated precipitation into a standard normal distribution with average of 0 and standard deviation of 1, being the SPI expressed in the number of standard deviations above or below the average (Guttman, 1998; McKee et al., 1993). This indicator is a quantity indicator, as it measures the amount of precipitation over a given period. Typically, it is applied on monthly timescales but can be aggregated to longer periods (seasonal, annual, multi-year) depending on the type of drought being monitored (hydrological, agricultural, meteorological, etc), to capture different aspects of drought severity and duration. The notation of the SPI includes the time aggregation in months, thus e.g., SPI-6 would imply an aggregation of six months. Although it can be computed by spatially aggregating precipitation records from pixel-level to country-level , its use on the larger scales might imply neglecting the different precipitation patterns found at lower time scales, thereby reducing its validity (Keyantash, 2021; National Center for Atmospheric Research (NCAR), 2022).

- Advantages

  - Easy to calculate and understand.
  - Easy to adapt to particular conditions.
  - Suitable for any information source, including precipitation.
  - Flexibility: The SPI can be calculated for different time scales (e.g., 1 month, 3 months, 6 months, 12 months, etc.), making it adaptable to various drought conditions and impacts.
  - Spatial comparability: The standardized nature of the SPI allows for comparisons across different locations, regardless of variations in precipitation amounts or patterns.
  - Early warnings and risk assessment of drought: By monitoring SPI values over time, the index can provide early warning of potential drought conditions, helping water managers and policymakers make informed decisions regarding water allocation and resource management.
- Drawbacks
  - Distinct data availability requirements: The use of the SPI may provide challenges in areas characterized by a limited dataset spanning fewer than 30 years or a sparsely distributed meteorological network.
  - It assumes a normal distribution of precipitation, which may not be valid in some regions or seasons.
  - Lack of additional variables: The SPI solely relies on precipitation data and does not consider other important factors such as temperature, evapotranspiration, or soil moisture. This limitation can affect its accuracy in some cases, especially in regions where temperature plays a significant role in drought conditions.
  - Long-term average dependency: The SPI assumes stationarity in the long-term average, which may not hold true in regions experiencing climate change or significant shifts in precipitation patterns. Changes in the long-term average can impact the SPI's effectiveness in capturing drought severity.

3.1.1.2. Standardized Precipitation-Evapotranspiration Index (SPEI)

Indicator scope		
Climatic	Hydrology	Water resources
■ (shaded)		

Information source	
Monitoring	Modelling

Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 2: Temporal and spatial scales of SPEI application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

As defined in 2010 by Vicente-Serrano et al. (2010) the SPEI is a multivariable index that aims to overcome one shortcoming of the SPI when used to characterize droughts in a changing climate context, which neglects the influence of temperature. Its conceptualization is similar to that of the SPI, but it replaces precipitation with precipitation minus potential evapotranspiration (PET). This addition makes the SPEI more suitable for characterizing droughts efficiently than the SPI in arid or semiarid climates or under climate change conditions (Vicente-Serrano et al., 2012). However, the inclusion of PET distinctly increases the complexity associated with its computation because it should be usually computed from other variables, which depend on the procedure used to calculate it (for example, Thornwaite, Hargreaves, Penman-Monteith). SPEI can be computed using the same information sources as SPI, with the addition of hydrological models that are able to calculate PET. Likewise, it can be computed as the same spatial scales as the SPI, but its applicability to larger scales is more challenging since its two-variable configuration implies that the changes in precipitation patterns overlap with those observed in temperature (Vicente-Serrano et al., 2012).

- Advantages
    - Suited to climate change contexts and arid or semiarid areas.
    - Easy to adapt to particular conditions.
    - Easy to scale up in space and time.
    - Suitable for any information source including precipitation and potential evapotranspiration (or the variables required to compute it).

- Drawbacks
  - PET should be usually computed from other meteorological variables.
  - Distinct data availability requirements.
  - Need to fit a probability distribution.

3.1.1.3. Heavy Precipitation Days Index (HPDI)

Indicator scope		
Climatic	Hydrology	Water resources

Indicator scope							
Monitoring		Modelling					
Remote sensing	Sensor/ gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 3: Temporal and spatial scales of Heavy precipitation days application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Heavy Precipitation Days (HPD) indicator counts the number of days in a particular period (typically a year) when the precipitation exceeds a certain threshold (commonly 10 mm) within a specific area (Alexander & Arblaster, 2009). The criterion for defining "heavy" varies depending on the study location and objective of the investigation. This indicator provides valuable information regarding the frequency and intensity of heavy rainfall, which can have substantial implications for assessing water resource availability and variability as well as the risk of floods and droughts (X. Zhang et al., 2000). Depending on data availability and resolution, it can be employed at various temporal scales, from daily to annual, and spatial dimensions, ranging from pixels to country aggregation. It is important to highlight that the spatial scale of the analysis is influenced by the availability and quality of precipitation data (Donat et al., 2013). Higher-resolution data from a dense network of weather stations provides more detailed and localized analyses, but coarser-resolution data may require larger spatial units for analysis (Groisman et al., 1999).

This indicator is generated by analyzing historical daily precipitation data for a specific location and period. The data is evaluated to identify and calculate the number of days exceeding the specified heavy precipitation threshold. This count can be expressed as a percentage of the total number of days in a given period. For example, if an area has 50 days with a precipitation over 10 mm a year, the indication value is 50 days or 13.7%. This indicator can be calculated with various thresholds (such as 20 or 50 mm) to capture the different intensity levels of heavy precipitation episodes (Kyselý, 2009).

- Advantages:
    - Easy to calculate and understand.
    - It can capture extreme events that affect water supply.
    - Intensity assessment: This indicator provides information on the intensity of rainfall events, helping to identify periods of intense rainfall that can lead to flash floods, soil erosion, and surface water runoff.
    - Climate change impacts: Monitoring changes in the frequency of heavy precipitation events can offer insights into potential climate change impacts. Increasing trends in heavy precipitation may indicate an increased risk of flooding and the need for appropriate adaptation measures.
    - Water resource planning: This indicator aids in assessing the adequacy of water infrastructure, such as drainage systems and reservoir capacities, by quantifying the frequency of extreme rainfall events that these systems need to accommodate.
- Drawbacks:
    - Limited spatial coverage: This indicator is based on point measurements from weather stations. Therefore, the indicator's spatial coverage is limited to the locations where weather stations are present. Extrapolating the results to larger areas may introduce uncertainties.
    - It does not account for other factors that influence water availability, such as evaporation, runoff, infiltration, and storage.
    - It may not reflect the actual water use or demand by different sectors.
    - Lack of local context: This metric alone does not provide a comprehensive understanding of the local hydrological conditions. Additional factors, such as antecedent soil moisture, catchment characteristics, and storm duration, should be considered to assess the actual impacts of rainfall on water resources.

3.1.2. Hydrological indicators

3.1.3.1. Standardized Runoff Index (SRI)

Indicator scope		
Climatic	Hydrology	Water resources

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 4: Temporal and spatial scales of SRI application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

Also known as the Standardized Streamflow Index (SSI), this index is equivalent to the SPI but is applied to hydrological discharge, surface runoff, and streamflow (Shukla & Wood, 2008). Its applicability range is the same as that of SPI, but it has a broader range of possibilities than SPI in terms of applicability and information sources. Regarding applicability, both hydrological and water resource indicators can be considered, depending on the particular water body to which they are applied (e.g., streamflow through an artificial canal). Regarding information sources, discharges or stream-flows can be calculated from a wide range of possibilities, implying monitoring and modeling. Its primary monitoring sources include sensors, particularly gauging stations, whereas hydrological, IWRM, and hydro-economic models can be used to compute the SRI. Remote sensing instruments can offer information to calculate SRI, but they are restricted to features of surface water bodies. Reanalysis products and climate models are often incorporated as variable hydrological discharge or runoff. However, they do not provide relevant information to compute SRI that could be associated with a water body. Moreover, groundwater models incorporating stream-aquifer interactions can offer data to compute the SRI, although its reliability depends on the relevance of this interaction compared to the total runoff (Nalbantis & Tsakiris, 2009). Similarly, water quality models can be used to compute the SRI if they implement water quantity modeling procedures. Although it can be theoretically computed at any spatial scale, its computation at the pixel level (using fully distributed hydrological models) may not add more information than the calculation at the basin scale, as areas with homogeneous meteorological and hydrological features may offer almost the same SRI values. Spatial aggregations might imply oversimplification of the hydrological behaviors of the included basins.

- Advantages
  - Straightforward calculation
  - Many information sources available
  - Easy to scale up in time.
  - Reflects actual runoff condition.
  - Captures surface water availability.
- Drawbacks
  - Distinct data availability requirements or long-term runs of models
  - Need to fit a probability distribution.
  - May be influenced by water management practices.

3.1.3.2. Low Flow Index (LFI)

Indicator scope							
Climatic		Hydrology			Water resources		
Information source							
Monitoring		**Modelling**					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 5: Temporal and spatial scales of LFI application

		Spatial scale			
		Plot	Sub-basin/Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Low Flow Index (LFI) is a surface water resource indicator that measures the total water deficit of the river discharge when it drops below a threshold and compares it with historical climatological conditions (Cammalleri et al., 2017). This metric is considered an indicator of hydrological droughts used for near real-time monitoring of the start date, spatial evolution, and duration of significant hydrological drought events (Svensson et al., 2005). It is based on simulated daily river discharge outputs produced by the Joint Research Centre (JRC) Hydrological Rainfall-Runoff Model (LISFLOOD) within the Copernicus EMS European Flood Awareness System, which uses precipitation and temperature data as inputs (Cammalleri et al., 2017; Garcia et al., 2017). The LFI values can be interpreted as the number of standard deviations by which the observed water deficit deviated from the long-term mean.
This indicator can be applied at various temporal scales, from daily to monthly, depending on the available data and desired level of analysis. Similarly, it can be utilized at different spatial scales ranging from pixel-level to basin-level assessments. The LFI can also be compared across regions with different hydrological regimes as it standardizes the water deficit distribution for each location and time scale.
It is considered a quantity indicator as it only measures the amount of river discharge and does not account for its quality or usability.

- Advantages:
    - It is based on a physically-based hydrological model that simulates the precipitation-runoff processes.
    - It uses high-resolution precipitation and temperature data as inputs, which capture the spatial variability of meteorological conditions.
    - It can capture different streamflow drought severity and duration aspects using different aggregation periods. This information is crucial for water resource planning, management, and decision-making processes, allowing stakeholders to understand better the vulnerability of a system to water scarcity and to take appropriate measures to mitigate its impacts.
    - It can be compared across regions with different hydrological regimes by standardizing the water deficit distribution.

   - It is sensitive to changes in precipitation patterns and trends over time.
- Drawbacks:
   - It does not account for human interventions such as water abstraction, regulation, or storage, which affect river discharge and water availability.
   - It does not consider streamflow drought's ecological or socio-economic impacts, such as reduced water quality, habitat degradation, or crop failure.
   - It is sensitive to the choice of probability distribution and reference period used to fit the historical river discharge data.
   - The reliability of LFI depends on the robustness of the baseline period in the LISFLOOD simulation, which is limited in length (only 21 years, 1995–2015).

3.1.3. Water stress and use intensity indicators

3.1.4.1. Soil Moisture Anomaly Index (SMAI)

Indicator scope		
Climatic	Hydrology	Water resources

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 6: Temporal and spatial scales of soil moisture anomaly application

		Spatial scale			
		Plot	Sub-basin/Basin	District	Country
Temporal scale	Daily				
	Monthly				

	Seasonal				
	Annual				

The Soil Moisture Anomaly Index (SMAI) was developed at the National Weather Service in the United States by Bergman et al. (1988) to be used in water resource management to assess the deviation of soil moisture content from its long-term average, and to assess global drought conditions. It is considered as an agricultural drought index, since this metric provides information about the degree of wetness or dryness of the soil, which is crucial for understanding water availability for vegetation and the impact of drought on agriculture, crop production, and hydrological processes. The SMAI uses, daily, weekly or monthly data on inputs, such as precipitation, temperature, and evapotranspiration, in a simple water balance equation. It is then calculated by comparing the current soil moisture measurements with long-term historical records or a reference period. It quantifies the deviation of the soil moisture from the average, which is typically expressed as a percentage (Zhang et al., 2015). The information needed to calculate this indicator can be obtained from various sources, including ground-based sensors, satellite observations, and numerical models that simulate soil moisture. Measurements are typically performed at different depths within the soil profile.

The SMAI can be calculated at various time scales, including daily, weekly, monthly, and seasonal, to capture both short-term and long-term variations in soil moisture conditions (Zhang et al., 2015). It can be analyzed at various spatial dimensions depending on the available data resolution and area of interest. Using ground-based sensors, it can be examined at discrete locations or interpolated to estimate soil moisture conditions across larger regions. Satellites for remote sensing can provide spatially continuous data, facilitating regional or global analyses. When determining the appropriate spatial scale for analysis, the spatial extent and resolution of available soil moisture data must be considered. In addition, integrating soil moisture anomalies with other indicators, such as precipitation or evapotranspiration, can provide a deeper understanding of water resource dynamics (Bergman et al., 1988).

- Advantages:
  - Drought monitoring: Soil moisture metric contributes to monitoring and detecting drought conditions because it can provide early warning of water scarcity and help in managing water resources during dry periods.
  - Crop and vegetation health: Soil moisture directly affects plant growth and agricultural productivity. Monitoring soil moisture anomalies assists in evaluating water stress levels and optimizing irrigation practices to ensure crop health and yield.
  - Hydrological processes: Soil moisture is a critical component of the water cycle. Assessing anomalies helps in understanding infiltration rates, runoff potential, and groundwater recharge, aiding in water balance calculations and hydrological modeling.
- Drawbacks:

- Spatial heterogeneity: Soil moisture exhibits significant spatial variability, even within small areas. However, obtaining representative measurements across large regions can be challenging, and spatial interpolation techniques may introduce uncertainties.
- Depth considerations: Soil moisture content varies with depth, and different vegetation types may have varying root zone depths. The choice of measurement depth for calculating anomalies should align with the specific application and the depth of interest for water availability.

3.1.4.2. Multivariate Standardized Drought Index (MSDI)

Indicator scope		
Climatic	Hydrology	Water resources

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 7: Temporal and spatial scales of MSDI application

		Spatial scale			
		Plot	Sub-basin/Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

Hao and AghaKouchak, (2013) developed the Multivariate Standardized Drought Index (MSDI) at the University of California at Irvine, United States to measure the severity and duration of drought episodes based on a combination of precipitation and soil moisture deficits. This index is used to monitor meteorological and agricultural droughts and their impacts on water management and combines data on both soil moisture and precipitation using copula functions to model the dependence between these variables (Erhardt & Czado, 2018). This index is considered as the extended version of the widely employed Standardized Precipitation Index (SPI), with the combination of soil moisture and precipitation data (Hao & AghaKouchak, 2013). The time scale of this index can be calculated on a monthly and seasonal basis. Spatially, the MSDI is calculated at the basin levels, but it can be aggregated at the district scale (Tatli, 2021).

- Advantages:
  - It is able to assess and characterize drought conditions across various temporal scales.
  - It considers multiple variables that affect drought conditions.
  - It is relatively easy to use.
- Drawbacks:
  - It requires accurate and consistent precipitation and soil moisture data, which may not be available or comparable for all locations or areas.
  - The variation in choice of copula function, time scale, and threshold should also be considered, as these factors may differ across different locations and regions.

3.1.4.3. Palmer Drought Severity Index (PDSI)

Indicator scope		
Climatic	Hydrology	Water resources

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 8: Temporal and spatial scales of PDSI application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Palmer Drought Severity Index (PDSI), also known as the Palmer Drought Index (PDI), is one of the earliest and most widely used drought indicators (Vicente-Serrano et al., 2012). PDSI uses temperature and precipitation data to estimate soil moisture supply and demand using a two-layer soil model (Karl et al., 1987; Karl, 1986). This index has some derivatives developed to enhance its capabilities when dealing with specific problems, such as long-term soil dryness (the Palmer Hydrological Drought Index, PHDI), short-term conditions (Palmer Z index), and operational contexts (modified PDSI) (Karl et al., 1987; Karl, 1986). Furthermore, it has been used as inspiration for some other indices from its original formulation. It uses monthly data and has an inherent timescale of approximately 9 months. It can be computed from any information source that provides precipitation and temperature data. Its spatial scale is similar to that of the SPEI because it implies precipitation and temperature, with the additional consideration associated with soil heterogeneity, which might challenge large-scale applications (Alley, 1984).

- Advantages
  - Well-known and straightforward calculation procedure
  - It is frequently used and recognized as a reliable indicator of drought severity, and it can also be used to forecast and plan drought.
  - Easy to scale up in space.
  - Suitable for any information source including precipitation and temperature.
- Drawbacks
  - Distinct data availability requirements.
  - Simplified soil balance might not be adequate in some situations.
  - Not adequate for assessing rapidly evolving droughts.
  - Miss-consideration of frozen precipitation in the calculations.

3.1.4. Surface water indicator

3.1.5.1. Surface Water Supply Index (SWSI)

Indicator scope		
Climatic	Hydrology	Water resources

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 9: Temporal and spatial scales of SWSI application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

As mentioned above, the PDSI has a limitation in that it does not consider frozen precipitation in the calculation; therefore, this Surface Water Supply Index (SWSI) was developed by (Shafer & Dezman, 1982)to cover the PDSI's limitation when considering frozen precipitation in its calculation, including additional information such as snowpack accumulation in mountainous regions (Yihdego et al., 2019). This metric is considered as hydrological index since it is used to assess hydrological drought conditions. As input data, this index requires four essential parameters such as reservoir storage, runoff, streamflow, and snow accumulation. SWSI is similar to Reclamation Drought Index (RDI), but RDI contains a temperature component (Steinemann et al., 2015; Zeynolabedin et al., 2016).

The SWSI is calculated on a monthly basis, but it can also be aggregated to seasonal or annual scales. Spatially, it is calculated at basin level that has sufficient streamflow and reservoir data available (Yihdego et al., 2019)basin level that has sufficient streamflow and reservoir data available (Yihdego et al., 2019).

- Advantages:
  - It provides a reliable understanding and indication of the hydrological state of the basin.
  - Directly related to surface water supply and drought severity.
- Drawbacks:
  - Requires accurate and consistent data on streamflow and reservoir storage, which may not be available or comparable for all basins or regions.
  - Difficulty in comparisons between various cases of study because the calculations for each study area are distinct.

3.1.5. Reservoirs and groundwater indicators

3.2.1.1. Groundwater Level Index (GLI)

Indicator scope		
Climatic	Hydrology	Water resources

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 10: Temporal and spatial scales of GLI application

Spatial scale

		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Groundwater Level Index (GLI) is a valuable indicator in the field of water resources management for evaluating the status and trends of groundwater resources (Halder et al., 2020). This index is a quantitative measurement used to observe and evaluate changes in groundwater levels over time. It aims to provide insights into the dynamics of groundwater resources, including fluctuations, trends, and prospective impacts on water availability and quality. The GLI depicts variations in groundwater levels within a particular region or aquifer. It shows whether groundwater levels are increasing, remaining stable, or decreasing. Users can obtain insights into the overall health and sustainability of groundwater resources by analyzing GLI data. In addition, it can assist in identifying potential problems such as over-extraction, drought impacts, and changes in recharge patterns (Halder et al., 2020). It is a useful tool for water resource managers, hydrogeologists, and policymakers, and it can inform groundwater management decisions, including:

- ✓ Assessing the sustainability of groundwater withdrawals.
- ✓ Detecting and responding to declining groundwater levels.
- ✓ Evaluating the impact of climate variability, droughts, or excessive pumping.
- ✓ Identifying areas where groundwater recharge or management strategies are needed.

Depending on data availability and specific objectives, the temporal scale of GLI applications can vary considerably. It is applicable on a monthly, seasonal, annual, and even longer-term basis. The spatial dimension can vary from basin to regional scale depending on the density of monitoring wells and the size of the aquifer or groundwater system under consideration (Halder et al., 2020).

The Groundwater Level Index (GLI) calculation begins with collecting continuous groundwater level data from observation wells or monitoring wells. The establishment of a baseline period to depict normal or stable groundwater conditions. The data are then normalized, taking into consideration seasonal variations to emphasize long-term trends. Based on the normalized data, GLI values are calculated, with rising groundwater levels yielding positive index values, declining groundwater levels yielding negative index values, and stable conditions yielding values close to zero. Typically, these index values are plotted over time to illustrate variations and trends in groundwater levels, which provides valuable information for water resource management and decision-making (Halder et al., 2020).

- Advantages:
  - Provides a quantitative measure of groundwater status and trends.
  - Helps in identifying areas of concern and guiding sustainable groundwater management practices.
  - Can be integrated into broader hydrological assessments.
- Drawbacks:
  - Requires a network of monitoring wells or observation points, which may not always be available.
  - Interpretation can be complex, as multiple factors may influence groundwater levels.
  - May not capture the full complexity of groundwater quality issues, which may require additional indicators.

3.2.1.2. Aquifer Recharge Rate Index (ARRI)

Indicator scope		
Climatic	Hydrology	Water resources

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 11: Temporal and spatial scales of ARR application

	Spatial scale			
	Plot	Sub-basin/ Basin	District	Country

Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Aquifer Recharge Rate Indicator (ARRI) measures the rate at which an aquifer is replenished with water. It quantifies the quantity of water that enters the aquifer through natural processes such as precipitation and surface water infiltration. This indicator is essential for assessing the availability and sustainability of groundwater resources. It predominantly indicates the rate at which an aquifer is refilled with water. It indicates whether the aquifer's water content increases, decreases, or remains constant over time. A negative recharge rate indicates a net water loss. This data assists in evaluating the overall health and resilience of the aquifer system (Dillon & Arshad, 2016; Levintal et al., 2023).

The rest of the characteristics (advantages and drawbacks) are similar to those of the Groundwater Level Index (GLI).

3.2. Water demand indicators

Water demand refers to the quantity of water required by different sectors for various purposes, including irrigation, urban water use, industrial use, and environmental flow. Water demand is influenced by various factors such as population, economic activity, climate, and water policies. In this section, we present some indicators that can be used to measure and monitor water demand in a multisector context (agriculture, urban, and environmental sectors). These indicators are useful for water resource planning and management, as well as for assessing the potential impact of droughts on water availability and usage.

3.2.1. Socioeconomic water demand indicators

3.2.1.1. Economic losses due to water-related disasters (ELS)

The indicator for economic losses due to water-related disasters captures the direct asset damage and opportunity losses caused by floods, storms, droughts, tsunamis or landslides. The spatial scale of the indicator is highly dependent on the data availability, the method of estimation and the purpose of the analysis. Most studies report economic losses at a country or region scale, often expressed as a portion of gross domestic product (Balbi et al., 2015). Studies at the global scale (WMO, 2023) show that water-related disasters accounted for 74% of related economic losses between 1970 and 2021, amounting to 4.3 trillion dollars. The choice of spatial scale may affect the accuracy and comparability of the estimates, as different scales may imply different assumptions, data sources and aggregation methods. The economic impact of water-related disasters varies by region, income level and sector. For instance, developed economies reported more economic losses than developing ones, but the losses were a smaller fraction of their GDP (WMO, 2023).

This indicator is used to measure the impact and vulnerability of water-related disasters on human lives, livelihoods and assets. Additionally, it is helpful for evaluating the effectiveness of disaster risk reduction and adaptation strategies, identifying hotspots and drivers of water-related risk, allocating resources and priorities for prevention, and raising awareness.

3.2.1.2. Water Use Intensity (WUI)

Water Use Intensity (WUI) is an indicator that measures the efficiency and the intensity of water use by relating the physical uses of water to social and economic aspects. It provides a relative measure of water consumption, linking the ecological dimension of water use with economic activity and the social characteristics of different sectors of the economy (Llop, 2019). The OECD calculates WUI as the total water intake divided by a normalization factor, with the unit of the indicator being m3/normalization factor. WUI can inform sustainable water allocation and explain how well an organization manages its water resources.

The advantages of using WUI as an indicator include its ability to measure water efficiency and pressure and its use in analyzing socioeconomic and environmental issues. However, there may be drawbacks to using WUI as well, such as the need for precise and detailed methods to study water issues, and the potential for local shortages and quality problems despite water being renewable on a global scale.

3.2.2. Agricultural water demand indicators

3.2.2.1. Crop Water Stress Index (CWSI)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 12: Temporal and spatial scales of CWSI application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Crop Water Stress Index (CWSI) was proposed by Jackson et al. (1981) and Idso et al. (1981) to measure the degree of water stress experienced by crops based on canopy temperature and vapor pressure deficit. The CWSI can be used to monitor crop water status and irrigation scheduling, as it estimates the relative transpiration rate of crops from infrared temperature measurements. This metric requires the measurement or estimation of the canopy temperature, air temperature, and vapor pressure deficit. The canopy temperature can be obtained using thermal sensors installed in the field or by remote sensing images. The reference temperature without water stress can be determined using empirical or theoretical methods, and the upper limit temperature with maximum water stress can be assumed to be equal to the air temperature (Bozkurt Çolak et al., 2021; Gu et al., 2021).

The temporal scale of the application of CWSI can be calculated on an instantaneous or daily basis. Spatially, the MSDI is calculated at plot level, but can be aggregated at basin scale.

- Advantages:
  - Directly related to the water stress and irrigation demand of crops.
  - Can account for the effects of environmental factors such as wind speed, radiation, and humidity on the crop water status.
- Drawbacks:

- Requires accurate and consistent measurements of canopy temperature and vapor pressure deficit, as these variables can be influenced by sensor errors, cloud cover, and atmospheric conditions.
- Requires calibration for different crops and case study.

3.2.2.2. Warm Spell Duration Index (WSDI)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 13: Temporal and spatial scales of WSDI application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Warm Spell Duration Index (WSDI) is a valuable indicator for water resource management, particularly water demand (Perkins & Alexander, 2013). It primarily quantifies the frequency and duration of warm conditions or extended periods of heat, which can significantly affect water availability and demand. This indicator's main objective is to provide insight into the frequency and intensity of heat events, enabling stakeholders to comprehend the potential pressure they might impose on water resources (Perkins & Alexander, 2013; Rydén, 2017).

Typically, the WSDI is obtained by analyzing historical temperature data over a specified period to identify instances in which daily temperatures have exceeded a certain threshold for an extended period. This criterion is frequently adapted to the local climate context, as what constitutes a "warm spell" can vary considerably from region to region and depends on the climate. Therefore, the threshold is often defined relative to local or regional climate conditions. A common approach to calculate the WSDI is the count of days in periods with at least six consecutive days with daily maximum temperatures above the 90th percentile of historical temperatures for a particular day of the year (Perkins & Alexander, 2013; Rydén, 2017).

The temporal and spatial levels of the WSDI application depend on the availability of data and the specific aims of the assessment. Temporally, it can be calculated on various scales, such as monthly, seasonal, or annual, depending on the detail's requirements. Spatially, it can be applied at basin, district, or national levels, depending on the extent of the case study (Perkins & Alexander, 2013).

It can be computed using any information source and climate model working at daily or sub-daily time steps. It offers information on how irrigation needs might be modified in a changing climate, as well as urban demand.

- Advantages:
    - It can be used by water resource managers to anticipate and plan for an increase in water demand during warm periods, as higher temperatures frequently result in increased irrigation requirements and evaporation rates. By integrating this index into their decision-making processes, they can better allocate and manage water resources, particularly during periods of elevated demand.
    - It is a straightforward indicator due to its reliance on readily accessible temperature data and its capacity to illustrate trends in the occurrence of warm spells.
- Drawbacks:
    - It is sentitive to the selected temperature threshold and it has limited consideration of other factors such as humidity and wind, which can also affect water demand during warm spells.
    - It does not fully capture the complex interactions between climate, water resources, and socioeconomic factors, which are essential for understanding water resource management.

3.2.2.3. Number of Summer Days (NSD)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 14: Temporal and spatial scales of summer days number application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Number of Summer Days (NSD) indicator is one of the climatic impact-drivers and extreme indices defined by the Intergovernmental Panel on Climate Change (IPCC) to evaluate the changes and impacts of climate variability and change in various sectors and regions (Altın & Barak, 2017). It is considered as the annual count of days when the daily maximum temperature exceeds 25°C. This number is an indicator of heat stress and water demand by different sectors, such as agriculture, urban, and environmental, and is calculated using daily maximum temperature data from weather stations for each year and region (Altın & Barak, 2017).

Regarding the temporal scale of this index's applicability, the number of summer days is an annual indicator, but it can also be calculated for sub-annual periods, such as seasons or months

(Altın & Barak, 2017). It reflects the frequency and intensity of heat waves and droughts during a given period. Spatially, it can be calculated for a basin level, as long as it has sufficient data on the daily maximum temperature (Erlat & Türkeş, 2013).

- Advantages:
  - Simple and intuitive indicator of heat stress and water demand.
  - Can provide useful information for water resource planning and management as well as for evaluating the potential impacts of heat stress on human health, agriculture, ecosystems, and energy.
- Drawbacks:
  - Cannot capture all features and effects of heat stress and water demand because it is dependent on the temperature threshold's selection and applicability.
  - Influenced by data availability, quality, and uncertainty.

3.2.2.4. Number of Tropical Nights (NTN)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 15: Temporal and spatial scales of the tropical nights number application

			Spatial scale			
			Plot	Sub-basin/ Basin	District	Country
Te	m	Daily				

	Monthly				
	Seasonal				
	Annual				

The Number of Tropical Nights (NTN) is similar to the NSD indicator; however, in this case, the NTN represents the annual count of days when the daily minimum temperature does not fall below 20°C. All other characteristics of this indicator (temporal and spatial scales, origins, advantages, and drawbacks) are closely related to those of the NSD.

3.2.2.5. Growing Season Length Index (GSLI)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 16: Temporal and spatial scales of the growing season length application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				

	Annual				

The Growing Season Length Index (GSLI) can have phenological and climatological definitions. Phonologically, it can be defined as the period of the year in which crops grow successfully (Walther & Linderholm, 2006). The length of the growing season depends on various factors such as temperature, precipitation, daylight, and elevation (Menzel et al., 2003; Menzel & Fabian, 1999; Walther & Linderholm, 2006). Climatologically, it is defined in relation to a particular region's climatic conditions and parameters, with temperature thresholds and light availability being the key factors (Walther & Linderholm, 2006). Other factors included soil parameters, precipitation, and water availability. This indicator determines which crops can be grown in an area, as some crops require long growing seasons, whereas others mature rapidly. It is calculated using different methods depending on the data availability and purpose of the analysis. One common method is to use the number of days between the last frost in spring and the first frost in fall, when the air temperature drops below the freezing point of 32 °C. Another method is to use the number of days when the temperature rises sufficiently for a particular crop to sprout and grow (Robeson, 2002; Skaggs & Baker, 1985; Walther & Linderholm, 2006).

This metric is considered a valuable indicator for evaluating climate change and assessing crop water requirements. It can be calculated for any time scale that is relevant to crop growth and development, such as monthly, seasonal, or annual scales (Walther & Linderholm, 2006). Spatially, GSL can be calculated at plot and basin scales.

- Advantages:
  - Simple and intuitive indicator of plant growth and productivity.
  - It provides useful information for water resource planning and management and assesses the potential impacts of droughts on crop yield, food security, and ecosystems.
- Drawbacks:
  - Cannot capture all aspects and impacts of plant growth and productivity.
  - Influenced by data availability, quality, and uncertainty.

3.2.2.6. Consecutive Dry Days Index (CDDI)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 17: Temporal and spatial scales of consecutive dry days index application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Consecutive Dry Days (CDDI) is a water resource management indicator that focuses on the duration of a dry spell, which is a consecutive sequence of days without significant rainfall (Duan et al., 2017). It provides insights into the frequency and length of dry periods, which can impact water availability and demand (Duan et al., 2017; Nastos & Zerefos, 2009). This metric is usually defined by a specific threshold, such as the minimum precipitation amount or the maximum number of rain-free days (Nakaegawa et al., 2014). The threshold used to define a "dry day" can vary depending on the region, climate, and specific objectives of the analysis (Duan et al., 2017). In general, the threshold is fixed at 1 mm.

Daily precipitation records from weather stations are required to obtain consecutive dry-day data. The data is examined to identify and count the number of consecutive days in which the rainfall falls below the specified threshold. A new count of consecutive dry days begins once a rainfall event breaks a dry spell. Ensuring the reliability and accuracy of the data sources used in the analysis is crucial. When weather station data are sparse, remote-sensing-based precipitation products or rainfall estimates from satellite data can provide broader coverage. These remote sensing datasets utilize satellite observations to estimate precipitation, thus enabling the assessment of consecutive dry days at larger spatial scales (Zolina et al., 2013).

The temporal scale for analyzing consecutive dry days can vary depending on the objectives and data availability. It can be assessed at different time scales, such as monthly, seasonal, or annual periods, to capture short- or long-term patterns of dry spells. Spatially, the analysis of this indicator can be conducted at different scales ranging from plot to basin or national levels. The density of available weather stations or spatial coverage of precipitation data sources determines the spatial extent (Duan et al., 2017; Zolina et al., 2013).

- Advantages:
  - Water demand assessment: Consecutive dry days are valuable for estimating water demand patterns, particularly in regions reliant on rainfall for water supply. Longer dry spells can increase the demand for irrigation, municipal water use, and other water-dependent sectors.
  - Drought identification: Monitoring this metric helps in identifying and characterizing drought conditions. Prolonged periods of dry weather can lead to reduced soil moisture, depleted surface water reservoirs, and increased risk of water shortages.
  - Water resource planning: This indicator helps in understanding the frequency and intensity of dry spells, allowing water managers to plan for potential water shortages, manage reservoir storage, and implement drought management strategies.
- Drawbacks:
  - Lack of local context: Consecutive dry days alone do not provide a comprehensive understanding of local hydrological conditions, as it only focuses on precipitation. Factors such as evapotranspiration rates, soil moisture levels, and water availability in surface and groundwater systems should also be considered for a more comprehensive assessment.
  - Spatial variability: The spatial representation of consecutive dry days depends on the availability and density of weather stations or precipitation data sources. This can result in spatial heterogeneity and limited coverage, especially in data-scarce regions.

3.2.2.7. Consecutive Wet Days Index (CWDI)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source

Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 18: Temporal and spatial scales of consecutive wet days index application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Consecutive Wet Days Index (CWDI) is formulated in the same way as the Consecutive Dry Days Index (CDDI); however, in this case, consecutive wet days refer to the number of continuous days with significant rainfall, typically defined by a specific threshold, such as a minimum precipitation amount or a minimum number of rain-affected days. The threshold used to define a "wet day" can vary based on the region, climate, and specific objectives of the analysis. All other characteristics of this indicator (temporal and spatial scales, origins, advantages, and drawbacks) are similar to those of the consecutive dry days.

3.2.2.8. Agricultural Water Poverty Index (AWPI)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source

Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 19: Temporal and spatial scales of Agricultural Water Poverty Index application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Agricultural Water Poverty Index (AWPI), developed by Forouzani and Karami, (2011) is a crucial indicator in assessing and managing agricultural water demand. It aims to assess the water situation in agriculture, particularly in regions where water supply may be limited. The AWPI is a multidimensional index that considers several aspects such as water availability, access, use, capacity, and environment to assess the agricultural water poverty among farmers and regions as well as to provide guidelines for sustainable water management. This index is a constructive tool in sustainable water management and can be used to understand the sustainable trend in the agricultural system (Forouzani & Karami, 2011).

Calculating AWPI is a complex procedure that requires the integration of multiple factors that typically include water availability to assess the quantity and reliability of water sources for irrigation. Socioeconomic factors, such as income levels and employment opportunities, must be considered to evaluate the economic conditions of farmers. Moreover,agricultural factors must be considered in the calculation of AWPI toevaluate farming practices, crop choices, and agricultural productivity. Additionally, AWPI considers environmental sustainability and the impact of agricultural practices on the ecosystem. Depending on their significance in contributing to water poverty, these factors are frequently assigned different weights before being combined into a singular index score. The precise formula and weighting scheme may differ depending on the study or region (Forouzani & Karami, 2011; Shen et al., 2022).

The temporal and spatial scales of AWPI application can vary depending on the data availability and research objectives. It can be calculated at different levels, from the irrigation community or basin level to the national level. Temporally, it can be computed for specific years or over more extended periods to assess trends and changes in agricultural water poverty (Shen et al., 2022; Zoleikhaie Sayyar et al., 2022).

- Advantages:
  - It takes a holistic approach to assessing agricultural water demand that considers numerous dimensions of water poverty.
  - It can help water resource managers and policymakers target interventions and resources to meet the appropriate requirements of farmers and irrigation communities.
  - It can aid in prioritizing investments in water infrastructure and agricultural practices programs.
- Drawbacks:
  - Its calculation procedure is complicated and requires several variables.
  - Some difficulties with data availability and precision, as well as with the uncertainty of assigning weights to the various variables.
  - It should be interpreted in conjunction with qualitative data and local knowledge.

3.2.3. Environmental water demand indicators

3.2.3.1. Indicator of Hydrologic Alteration (IHA)

Indicators of Hydrologic Alteration (IHA) are a suite of variables used to characterize the impact of regulation on flow regimes in environmental flow studies. They are implemented to describe different components of flow regimes and are widely used to evaluate the ecological effect of reservoir operations and other forms of river regulation (Gao et al., 2009).

One of the most commonly used indicators of hydrologic alteration is the Magnitude of Monthly Flow Alteration (MMFA). This metric assesses the change in flow magnitude for each month, comparing regulated or altered flow conditions to normal or baseline conditions. It is calculated as the absolute difference between the regulated and natural monthly flows, expressed as a percentage of the natural monthly flow. MMFA is typically applied at the basin level monthly, making it one of the most common applications (Laizé et al., 2014; Zimmerman et al., 2018).

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source

Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 20: Temporal and spatial scales of MMFA application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

- Advantages
  - MMFA provides a quantitative measure of flow alteration, making it useful for assessing the ecological impacts of regulation on aquatic ecosystems.
  - It is relatively easy to calculate using flow data, which are often available from hydrological records.
  - It is widely recognized and accepted in the field of environmental flow assessment.
- Drawbacks
  - It focuses primarily on magnitude and does not consider the timing, frequency, or duration of flow alterations, potentially missing critical ecological aspects.
  - It may not adequately capture the complexity of flow regimes, especially in highly regulated river systems.
  - MMFA alone may not provide a complete understanding of ecological responses to flow alteration, and it is often used in conjunction with other IHA indicators for a more comprehensive assessment.

3.2.3.2. Mean Species Abundance Index (MSA)

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source							
Monitoring		Modelling					
Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 21: Temporal and spatial scales of Mean Species Abundance Index application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Mean Species Abundance Index (MSAI) is a crucial indicator of environmental water demand used in ecological and conservation studies (Peet, 1974). It is primarily utilized for assessing aquatic ecosystems' health, status, and biodiversity, especially in water resource management and environmental impact assessment (Magurran & Magurran, 1988; Peet, 1974). The MSAI quantifies the average population density or abundance of species within an aquatic ecosystem, indicating whether the ecosystem is productive, stable, or experiencing stress. An ecosystem with a higher MSA value is typically considered to be healthier and more diverse, while a lower value could identify a degraded or polluted environment (Peet, 1974).

Multiple steps are required to determine the MSAI: First, information on the abundance or population density of various species within the ecosystem is collected. This information can be collected through field surveys, sampling, or monitoring efforts. Second, abundance data are typically normalized to account for differences in species' sizes or ranges. This step assures that the index considers rare and common species equally. The MSA is then calculated as the mean of normalized abundance values for every species in the ecosystem. It quantifies the central tendency of species abundance within the system (Buckland et al., 2011).

This index can be applied to evaluate the impact of water management practices, such as dam construction or water withdrawals, on biodiversity. Moreover, it can monitor the effectiveness of conservation efforts and restoration projects. Additionally, the MSAI can be applied to compare the biodiversity of different ecosystems over time or across regions and also to assess environmental water demand (Buckland et al., 2011; Magurran & Magurran, 1988; Peet, 1974).

The temporal and spatial dimensions of MSAI applications can vary considerably. Temporally, it can be calculated for specified time periods, such as annual assessments or as part of long-term monitoring programs. Spatial applications range from small-scale evaluations of local ecosystems to large-scale assessments of river basins or entire watersheds (Peet, 1974).

- Advantages:
    - It assesses the impact of water management decisions on biodiversity.
    - Simple and capable of providing measuresre of ecological health.
- Drawbacks:
    - It needs for accurate data on species abundance, which can be resource-intensive to acquire.
    - It does not capture all aspects of ecosystem health, and its interpretation must consider additional ecological indicators to provide a comprehensive assessment of environmental water demand.

3.2.3.3. *Suitable Habitat Area Index (SHAI)*

DEMAND						
Socio-economic			Environmental		Agricultural	Industrial
Deficit	Benefits	Costs	Env.Flows	Habitat	Agri.demand	Ind.demand

Information source	
Monitoring	Modelling

Remote sensing	Sensor/ Gauging stations	Climate models/ Reanalysis	Hydrological models	Groundwater models	Water quality models	Water management models	Hydro-economic models

Table 22: Temporal and spatial scales of Suitable Habitat Area Index application

		Spatial scale			
		Plot	Sub-basin/ Basin	District	Country
Temporal scale	Daily				
	Monthly				
	Seasonal				
	Annual				

The Suitable Habitat Area Index (SHAI) is a crucial environmental water demand indicator used in ecological and conservation studies to assess the availability of suitable habitats for various species within an ecosystem (Teng et al., 2021). It quantifies the extent and quality of habitat that meets the requirements of specific species or ecological communities, providing valuable insights into habitat quality and biodiversity conservation (Barrio-Anta et al., 2020; Teng et al., 2021). The index is calculated through habitat suitability modeling, spatial analysis, and calculation (Barrio-Anta et al., 2020). It is primarily used in conservation planning and management to identify priority areas for habitat protection, evaluate the impact of land-use changes or development projects on habitat availability, and assess the effectiveness of conservation programs in increasing suitable habitat (Barrio-Anta et al., 2020). Depending on research objectives and data availability, the index can be applied at various temporal and spatial scales, and several studies apply this indicator at the basin and annual scales.

SHAI plays an essential role in water resource management, mainly when the objectives of management include the conservation of aquatic ecosystems and biodiversity. Consequently, suitable habitat areas for numerous species frequently depend on the availability and quality of water resources (Muñoz-Mas et al., 2016; Papadaki et al., 2016). Aquatic species, such as fish, require specific water conditions, such as adequate water flow, temperature, and quality (Papadaki et al., 2016). The index supports identifying areas where these conditions have been met or can be improved through water management practices. Additionally, water resources management decisions, such as dam construction, water withdrawals, or water diversions, can significantly alter aquatic ecosystems and their habitat suitability (Costa et al., 2012). The Suitable Habitat Area Index can be used to evaluate the potential effects of such interventions on habitat availability and the associated biodiversity. Overall, the Suitable Habitat Area Index is important for aligning water resource management with ecological conservation goals, ensuring water resources' sustainable use and protection (Costa et al., 2012; Muñoz-Mas et al., 2016).

- Advantages:
  - It contributes to assessing the potential environmental impact of water-related projects, including dams, reservoirs, and irrigation schemes.
  - It provides a spatially precise evaluation of habitat quality and suitability.
  - It coordinates conservation efforts effectively and helps protect vulnerable species' habitats.
- Drawbacks:
  - It requires accurate habitat suitability models and high-quality spatial data.
  - It does not consider species interactions or the possible effects of climate change on habitat suitability, which should be considered in a complete conservation strategy.

3.2.4. Industrial water demand indicators

3.2.4.1. Industrial Water Footprint (IWF)

The Industrial Water Footprint (IWF) is a comprehensive indicator that assesses the total water consumption of an industrial product or process, both direct and indirect water use (Weerasooriya et al., 2021). It provides a holistic view of the water-related impacts of industrial activities, from the exploitation of primary materials to production and distribution (Willet et al., 2019). Typically, it is measured in cubic meters or gallons per product unit or process. The footprint includes direct water use, such as manufacturing processes, refrigeration systems, sanitation, and employee facilities, and indirect water use throughout the supply chain, including primary materials, intermediate products, and energy sources (Willet et al., 2019). It is used for environmental impact assessment, reporting on sustainability, resource efficiency, supply chain management, regulatory conformance, and product labeling. It aids in identifying high water use areas, reducing water consumption, and minimizing risks, thereby contributing to responsible conservation of water and resource management. The footprint is essential for promoting sustainability and making well-informed decisions along the water resource system (Hoekstra, 2015; Willet et al., 2019).

Depending on the objectives of the study and the availability of data, the temporal and spatial levels of application for the industrial water footprint can vary (Weerasooriya et al., 2021). Concerning the temporal scale, various water footprint assessments for industries are conducted on an annual basis. This assessment level provides a one-year overview of water use and its impacts. Annual assessments are appropriate for monitoring trends, establishing annual sustainability objectives, and reporting on water management performance (Weerasooriya et al., 2021; Willet et al., 2019). With respect to the spatial scale, industries can assess their water footprint at multiple spatial levels, including facility, company, supply chain, regional, and global levels. Assessments at the facility level emphasize specific activities, whereas assessments at the company level combine information from all facilities and operations. Regional and national assessments evaluate the cumulative impact of multiple industries on water resources, whereas assessments at the supply chain level evaluate the entire supply chain. For industries with a significant global presence, global-scale assessments provide insight into worldwide water impacts (Hoekstra, 2015; Weerasooriya et al., 2021).

- Advantages:
    - It provides an extensive assessment of the water-related impacts associated with industrial activities.
    - Industries can identify possibilities to reduce water consumption and increase water use efficiency by analyzing the industrial water footprint.
    - It helps to identify high water use areas.
- Drawbacks:
    - Its calculation can be complex and data-intensive, especially when evaluating supply chains with numerous inputs and stages. This complexity can be an obstacle for small companies and sectors with limited resources.
    - It may not capture all aspects of significant indirect environmental impacts, such as biodiversity loss and ecosystem degradation.
    - It is focused mainly on water quantity and does not provide a detailed assessment of water quality issues or the potential for pollution associated with industrial activities.

3.2.5. Water use performance indicators

3.2.5.1. -Water Use Efficiency (WUE)

This indicator measures the efficiency of water use in achieving desired outcomes (Pereira et al., 2012). It is calculated as the ratio of water used to the desired outcome achieved. It encourages efficient water management practices and reduces water wastage. However, it does not account for environmental or social factors. This metric is usually measured annually or decadal and at a plot, basin or country level (Cao et al., 2018; Pereira et al., 2012; Tzoraki et al., 2015).

3.2.5.2. Non-Revenue Water (NRW) Rate

It quantifies the percentage of water lost or unaccounted for in distribution systems (Farley & Liemberger, 2005), and is calculated as the difference between the volume of water supplied and the volume of water billed to customers. This indicator highlights inefficiencies in water distribution and helps in leak detection and infrastructure improvement. However, it is limited to urban areas with metered systems and may not capture losses in rural areas. It is usually measured annually or monthly and at a city or district level (Farley & Liemberger, 2005; Kingdom et al., 2006).

3.3. Indicators for integrated water resource management at the basin scale

The following indicators are traditionally used by water resource managers and practitioners for monitoring and planning water resources management in a systematic and effective way. They take a more holistic view of the water resource system, considering not only the physical availability of the resources but also the social, economic, and environmental aspects of water use and management.

3.3.1. Reliability

Reliability, in the context of evaluating water resource management, refers to the probability that a system will fail to meet its intended purpose under a given set of conditions. This metric considers the frequency, duration, and intensity of any restrictions that may be placed on water use during periods of drought or other stress. By assessing the reliability of a water resource system, planners and decision-makers can better understand the risks associated with different design and operational strategies (Hashimoto et al., 1982). Consequently, they can make more informed decisions about water resources' sustainable and efficient use.

Several indicators pertaining to reliability within the field of water resource management include the frequency and duration of water shortages, the number of consumers affected by water use restrictions, and the severity of any consequences on water quality or ecosystem health. Other factors that may be considered in the assessment of reliability include the variability of hydrologic conditions, the effectiveness of water conservation strategies, and the system's capacity to adapt to changing demands or unexpected events (Hashimoto et al., 1982).

3.3.2. Vulnerability

According to the definition provided by Hashimoto et al, (1982), vulnerability refers to the potential magnitude of the consequences that may result from a failure or disruption in a system. The vulnerability considers the sensitivity of water users and ecosystems to variations in water supply or quality, as well as the potential economic, social, and environmental impacts resulting from these changes. By evaluating the vulnerability of a water resource system, decision-makers can implement measures and strategies aimed at mitigating the adverse effects resulting from system failures or interruptions.

Some of the indicators used to assess vulnerability include:

-Water Poverty Index (WPI): This indicator combines five components (resources, access, capacity, use, and environment) to measure the degree of water poverty in a region (Sullivan, 2002). It ranges from 0 (absolute water poverty) to 100 (no water poverty) (Lawrence et al., 2002). This indicator can capture multidimensional aspects of water scarcity such as social, economic, institutional, and environmental factors. However, it also faces some challenges, such as data availability and quality, weighting and aggregation methods, and the subjective interpretation of results (Forouzani & Karami, 2011b; Lawrence et al., 2002; Sullivan, 2002).

- Physical and economic water scarcity—The IWMI indicator: This indicator classifies regions into four categories based on the ratio of water withdrawals to renewable water resources and the percentage of population with access to improved water sources (Damkjaer & Taylor, 2017). The categories are little or no water scarcity, physical water scarcity, economic water scarcity, and approaching physical water scarcity (Damkjaer & Taylor, 2017; Liu et al., 2017a). This indicator can provide a more nuanced picture of water scarcity by considering both the physical availability and the economic accessibility of water resources. However, it also has some limitations, such as using a fixed threshold for physical water scarcity (75% of withdrawals to resources), ignoring the environmental flow requirements, and relying on outdated or incomplete data for some regions (Liu et al., 2017a).

3.3.3. Exploitation

- Water Exploitation Index plus (WEI+): This indicator measures the total water consumption as a percentage of the renewable freshwater resources available for a given territory and period (Pedro-Monzonís et al., 2015). It quantifies how much water is abstracted monthly or seasonally, and how much water is returned before or after use in the environment via river basins (e.g., leakages and discharges by economic sectors) (Sondermann & de Oliveira, 2022). The difference between water abstractions and returns is regarded as 'water consumption.' This indicator can provide a more comprehensive and spatially explicit assessment of water scarcity by considering surface and groundwater resources, environmental flow requirements, water quality issues, and climate change impacts (Contreras & Hunink, 2015; Hunink et al., 2019). However, it also requires a high level of data availability and quality as well as consistent methodologies and standards for data collection and analysis (Bisselink et al., 2018; De Roo et al., 2012; Karabulut et al., 2016).

- The ratio water uses to availability: This indicator measures the proportion of the total water use (including domestic, agricultural, and industrial) to the total renewable freshwater resources available in a region (Falkenmark, 1997). It can indicate the level of water stress or scarcity in a region, with values above 20% generally considered a sign of water scarcity and values above 40% indicating severe water scarcity (Falkenmark, 1997; Raskin et al., 1997). This indicator can be applied at different temporal and spatial scales depending on the availability and reliability of data (Alcamo et al., 2000; Liu et al., 2017b). However, it does not account for the variability in water resources over time and space, environmental flow requirements, water quality issues, or socioeconomic factors that affect water demand and access (Falkenmark, 1997).

3.3.4. Resiliency

Hashimoto et al. (1978) define resilience as the capacity of a system to effectively recover from a failure or disturbance and return to its normal operating state. Resilience considers the speed and effectiveness of the system's response to changing conditions, as well as its adaptability in the face of new challenges and the ability to recover from unexpected situations. By evaluating the resilience of a water resource system, planners and decision-makers can gain a more comprehensive understanding of the potential risks related to various design and operational strategies. This knowledge empowers them to implement measures to enhance the system's capacity to adapt to changing conditions and effectively recover from disturbances.

3.3.5. Sustainability

Water sustainability indicators are quantitative or qualitative measures that reflect the status and trends of water resources in a specific area by considering both natural and human factors (Zarei et al., 2021). These can be used to assess the availability and use of water resources in terms of quantity, quality, accessibility, and efficiency. By applying water sustainability indicators, it is possible to identify areas where water resources are scarce or overused, as well as the causes and consequences of such situations (Bozorg-Haddad et al., 2021). Water sustainability indicators can also help evaluate the effectiveness of water management policies and practices, and provide guidance for improving water governance and decision-making (ZamanZad-Ghavidel et al., 2021). Thus, water sustainability indicators can support the achievement of water security and sustainable development goals (Loucks, 1997). As illustrative examples of sustainability indicators, the following can be presented:

4. Indicator gaps identified

Analyzing the identified water indicators' limitations, complementarities, and advantages is essential for identifying gaps and developing a comprehensive system of indicators for efficient water resource management. Specific patterns emerge within the categories of water resource indicator types. The following table summarizes the indicators identified based on the scope of application of each indicator, advantages and disadvantages, ease of calculation, data availability.

Indicator	Scope Covered	Advantages	Drawbacks	Ease of calculation	Comments
Meteorological Indicators					
Standardized Precipitation Index (SPI)	Precipitation variability and drought assessment	Widely used and understood	Data availability varies by region	moderate	SPI is widely accepted, but regional data limitations should be considered.
Standardized Precipitation-Evapotranspiration Index (SPEI)	Combined effects of precipitation and evapo-transpiration	Captures moisture supply and demand	Data on evapotranspiration may be limited	Moderate	SPEI provides a holistic view of moisture conditions. Data on evapotranspiration may require modelling.
Heavy Precipitation Days (HPD)	Frequency and intensity of heavy precipitation events	Useful for flood risk assessment	May not capture long-term trends	Easy	Important for flood risk, but focus on short-term events.

Hydrological Indicators					
Standardized Runoff Index (SRI)	Surface runoff variability and drought assessment	Incorporates streamflow data	Requires streamflow data availability	Moderate	SRI is reliable but depends on streamflow data.
Low Flow Index (LFI)	Low flow conditions in rivers and streams	Indicates ecological health	Data on low flows may be sparse	Moderate	LFI aids in hydrological drought and ecological assessments but relies on data.
Reservoirs and Groundwater Indicators					
Groundwater Level Index (GLI)	Groundwater level fluctuations and trends	Direct measure of aquifer status	Requires continuous monitoring	Moderate	GLI is effective but needs continuous monitoring.
Aquifer Recharge Rate (ARR)	Rate of groundwater replenishment	Essential for sustainability planning	Complex calculation, data-intensive	Complex	ARR informs sustainability but requires complex calculations.
Surface Water Indicators					
Surface Water Supply Index (SWSI)	Surface water availability and drought assessment	Useful for water allocation	Information regarding surface water could display variations.	Moderate	SWSI aids in allocation but may face data inconsistencies.
Water Stress and Use Intensity Indicators					
Multivariate Standardized Drought Index (MSDI)	Comprehensive drought assessment	Captures multiple drought aspects	Data requirements can be demanding	Complex	MSDI is comprehensive but data-intensive.
Palmer Severity Drought Index (PSDI)	Drought severity and impacts assessment	Long history of use	Sensitive to parameter choices	Moderate	PSDI is well-established but parameter choices matter.
Soil Moisture Anomaly (SMAI)	Soil moisture deviations from normal	Early warning for drought and wildfire	Limited by spatial resolution	Easy	SMA is suitable for early warning but has spatial limitations.

Socio-economic Water Demand Indicators					
Economic Losses due to Water-Related Disasters (ELS)	Monetary losses from water-related events	Links water to economic impacts	Data accuracy may vary	Easy	Valuable for economic assessments but data accuracy is crucial.
Water-Related Employment and Economic Sectors	Economic sectors dependent on water	Provides insights into economic linkages	Data can be sector-specific	Moderate	Crucial for understanding sectoral water dependencies.
Water Use Intensity by Economic Activities	Water use efficiency by economic sector	Identifies water-intensive sectors	Data collection may be challenging	Complex	Important for sectoral analysis but data collection can be challenging.
Agricultural Water Demand Indicators					
Crop Water Stress Index (CWSI)	Crop water stress levels	Aids in precision agriculture	Requires satellite or remote sensing data	Complex	Essential for precision agriculture but data-dependent.
Warm Spell Duration Index (WSDI)	Duration of warm spells	Relevant for crop growth and production	Climate-dependent indicator	Easy	Key for crop planning in changing climates.
Number of Summer Days	Frequency of summer-days	Useful for crop planning	Climate-dependent indicator	Easy	Important for crop scheduling but climate dependent.
Number of Tropical Nights	Frequency of warm nights	Crop and disease-related indicator	Climate-dependent indicator	Easy	Relevant for crop health but tied to climate.
Growing Season Length	Length of the growing season	Agricultural planning	Climate-dependent indicator	Easy	Crucial for crop planning, but climate dependent.
Consecutive Dry Days	Duration of dry periods	Drought impact assessment	Climate-dependent indicator	Moderate	Useful for drought impact assessment but

					climate dependent.
Consecutive Wet Days	Duration of wet periods	Crop water managemen t	Climate-dependent indicator	Easy	Useful for irrigation planning but climate dependent.
Agricultural Water Poverty Index (AWPI)	Agricultural water poverty assessment	Captures socio-economic aspects	Data requirements may vary by region	Moderate	Valuable for assessing water poverty but data needs to be region-specific.
Environmental Water Demand Indicators					
Magnitude of Monthly Flow Alteration (MMFA)	Flow alterations in a river system	It provides a clear metric to quantify flow alterations caused by reservoirs and river regulation, helping in environment al impact assessment.	Oversimplify the complex ecological effects of flow alterations and does not consider seasonal variations	Easy	It is a valuable tool for assessing hydrologic alterations, but it should be used in conjunction with other indicators to provide a comprehensive understanding of the ecological impact.
Mean Species Abundance	Biodiversity and ecological health assessment	Measures ecosystem health	Data collection and analysis may be complex	Complex	Valuable for ecological assessments but may require expertise.
Suitable Habitat Area	Habitat quality and availability for species	Identifies areas suitable for species	Data on species distributions may be limited	Moderate	Useful for habitat conservation but relies on species data.
Industrial Water Demand Indicators					
Industrial Water Footprint	Industrial water use efficiency and	Identifies water-efficient practices	Data collection and calculations	Complex	Valuable for assessing industrial water use but data and

	impact assessment		can be complex		calculations can be complex.
Water use performance					
Water Use Efficiency (WUE)	Efficiency of water use across sectors	Identifies efficient water use	Data collection and calculations can be complex	Complex	Important for efficiency assessment but data and calculations can be complex.
Non-Revenue Water (NRW) Rate	Assessment of water losses in distribution systems	Highlights distribution system performance	Data collection and calculations can be complex	Complex	Valuable for distribution system assessment but data and calculations can be complex.
Reliability					
Water Supply Reliability	Assessment the reliability of water supply systems	Vital for water utilities and management	Data on infrastructure may be needed, complex calculation	Complex	Important for water utilities but may require infrastructure data.
Vulnerability					
Water Poverty Index (WPI)	Socio-economic water scarcity assessment	Highlights socio-economic aspects	Data requirements may vary by region	Moderate	Valuable for assessing water poverty but data needs to be region-specific.
Physical and Economic Water Scarcity (IWMI)	Comprehensive water scarcity assessment	Combines physical and economic aspects	Complex calculations, data-intensive	Complex	Provides a comprehensive view but requires complex calculations. Helps to identify areas at economic water scarcity risk.
Exploitation					

Water Exploitation Index Plus (WEI+)	Assessment of water use intensity	Captures water use patterns and can identify inefficient water use.	Requires detailed sectoral data	Complex	Valuable for sectoral analysis but relies on detailed data.
The Ratio Water Uses to Availability	Water use compared to available resources	Provides a simple ratio	May oversimplify complex water systems	Easy	Offers a straightforward comparison but lacks detail.
Resiliency					
Drought Resilience Index (DRI)	Assessment of resilience to drought and water stress	Focuses on drought impacts	Complex calculations, data-intensive, data on system components may be needed	Complex	Provides in-depth drought resilience assessment but requires complex calculations.
Sustainability					
Water Stress Index (WSI)	Water resource sustainability and comprehensive water stress assessment	Captures multiple stress factors and considers multiple dimensions of sustainability	Complex calculations, data-intensive	Complex	Valuable for comprehensive stress assessment but requires complex calculations.
Water Quality Index (WQI)	Water quality assessment and monitoring	Monitors water quality parameters	Data requirements may vary by region, data collection can be complex	Moderate	Important for water quality assessment but may require regional data.

Meteorological indicators, such as the Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI), provide early warning signals for droughts, whereas heavy precipitation days (HPD) offer insight into potential flooding risks. However, these indicators focus mainly on precipitation and may not account for other hydrological aspects of the water system. Hydrological indicators, such as the Standardized Runoff Index (SRI) and Low Flow Index (LFI), provide valuable information on hydrological drought conditions; however, their applicability may be limited by regional differences and difficulties in obtaining accurate runoff data.

On the other hand, reservoirs, and groundwater indicators such as the Groundwater Level Index (GLI) and Aquifer Recharge Rate (ARR) are essential for assessing groundwater availability and sustainability; however, their effectiveness depends on data availability and monitoring infrastructure. Surface water indicators, such as the Surface Water Supply Index (SWSI), help assess surface water availability when reservoir storage is considered. However, they may not encompass differences in water quality and the ecological health of surface water bodies. Water stress and use intensity indicators such as the Multivariate Standardized Drought Index (MSDI), Palmer Severity Drought Index (PSDI), and Soil Moisture Anomaly Index (SMAI) use multivariate approaches for drought assessment and agricultural water stress management but may not incorporate water quality, ecosystem health, or sectoral demands. Socioeconomic indicators, such as Economic Losses due to water-related disasters and Water Use Intensity by economic activities, provide insight into economic impacts and sectoral efficacy regarding water demand indicators. However, these indicators may fail to reflect other aspects of water demand, such as environmental ones. Indicators of agricultural water demand, such as the Crop Water Stress Index (CWSI) and Warm Spell Duration Index (WSDI), play a crucial role in agricultural water management and climate adaptation. However, they focus primarily on agricultural aspects and may exclude critical factors of the complex system soil-plant-atmosphere. Environmental water demand indexes, such as Mean Species Abundance and Suitable Habitat Area, evaluate ecological health and conservation priorities but may not explicitly account for the meteorological and hydrological factors that affect the habitat and the environmental flow. Indicators of industrial water demand are crucial for managing water use efficiency and optimizing industrial resource allocation. However, their primary focus is on industrial processes, and they may cover only some categories of water users. These indicators provide a comprehensive assessment of water resource management within the joint resource-demand scarcity indicators category, considering reliability, vulnerability, exploitation, resilience, sustainability, and performance. Still, they can be complex to calculate, require extensive data, and may not address sector-specific issues. To identify gaps in these indicators, it is essential to consider their limitations and the aspects they do not adequately address. Potential gaps include indicators that comprehensively address water quality issues, consider the environmental impact of water use across sectors, account for the social and economic dimensions of water demand, and provide a more integrated assessment of water resource management. Bridge the space between supply and demand and provide a more holistic view of water system resilience, considering both short-term and long-term challenges. By addressing these gaps and focusing on the complementarity of indicators, a more robust system of indicators can be established to facilitate the holistic and efficient management of water resources within the SOS-WATER project.

5. Concluding remarks

The systematic identification and evaluation of water indicators are essential for achieving comprehensive water resource management. These indicators offer a multidimensional perspective on water systems, including resource availability, demand, quality, and environmental health. The considered indicators include an extensive spectrum of aspects, from meteorological and hydrological conditions to socioeconomic, agricultural, environmental, and industrial water demands. This diversity enables a comprehensive evaluation of water systems.

The link between indicators of water resources and water demands is crucial. Combining these indicators within a comprehensive framework can help decision-makers comprehend the complex connection between supply and demand, allowing for more efficient resource allocation.

Indicators such as SPI, SPEI, and drought resilience indices are valuable early warning signals for potential water-related issues. This proactive approach can increase the resilience of water systems to droughts, floods, and other extreme events.

Indicators for water management enable industrial, agricultural, and urban sectors to optimize water use efficiency. This not only contributes to water conservation but also to economic sustainability.

Indicators of environmental water demand, such as Mean Species Abundance and Suitable Habitat Area, highlight the significance of conserving aquatic ecosystems. They emphasize the need to balance human water needs and ecological requirements.

Effective management of water resources requires addressing the complexity of water systems and assuring the availability of accurate and current data, which requires investment in data collection and management.

The selected indicators have the potential to inform policy-making and regulatory actions. For effective water management, involving stakeholders at all levels, including local communities and industries, is essential.

Identifying and evaluating water indicators is crucial for efficient and sustainable water resource management. When integrated into comprehensive frameworks, these indicators empower decision-makers with the means to make informed decisions, enhance resilience, and ensure the long-term availability of this vital resource. As water remains a global priority, ongoing research, innovation, and collaboration are required to address the challenges of water management in a constantly changing world.

It is important to note that the indicators presented in this deliverable represent the current state-of-the-art indicators within the field. They serve as a foundational set of indicators for the SOS-WATER project, but it is essential to emphasize that they are not the entirety of our indicators. In addition to these established indicators, our project will also incorporate case study-specific indicators identified through an interactive, stakeholder-driven process and through each case study. These additional indicators will be tailored to address each case study's unique challenges and contexts, ensuring a comprehensive and contextually relevant assessment of water resources management within the project.

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