

A co-generation success story: Improving drinking water management through hydro-climate services

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HIGHLIGHTS

- SMHI Aqua is a co-generated service that improved short- and long-term decisions of Swedish users for drinking water supply.
- A co-generation framework was followed consisting of co-design, co-development, co-delivery and co-evaluation phases.
- Users can evolve their decision-making process from monitoring-based to forecast-based considering also extreme scenarios.
- SMHI Aqua provides real-time measurements, localized hydro-meteorological indicators and short- and long-range forecasts.
- Dialogues and knowledge transfer between service purveyors, data providers and users enabled the SMHI Aqua uptake.

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ABSTRACT

Hydro-climate services have been emerging to address the needs in the drinking water supply sector. Here, we demonstrate how co-generation can lead to the uptake of a service for supporting decision-making and ensuring a sustainable use of water resources. Insights are based on the storyline of the SMHI Aqua service co-generation. A framework consisting of four pillars (co-design, co-development, co-delivery and co-evaluation) was implemented based on the active involvement and close collaboration of service purveyors, data providers and users. The service consists of three main components: data assimilation, forecast production and a decision support system. Two hydrological models were locally customized to simulate freshwater availability in surface and groundwater reservoirs, generating further short- and long-range forecasts updated twice a day. Real-time hydro-meteorological measurements are used to update the model and initialize the forecasts, while different water extraction strategies allow simulating freshwater availability scenarios for the upcoming months. The hydro-meteorological measured and modelled data are accessible in a web-based platform and presented in a user-intuitive and informative way. We conclude that knowledge co-evolution is crucial for ensuring a hydro-climate service uptake. For water managers to take informed decisions, the hydro-meteorological information (including propagated uncertainty) generated by the service needs to be efficiently communicated. We finally note that the benefits resulting from the adoption of the hydro-climate service go beyond water-related users reaching to the general public by guaranteeing access to freshwater and by improving awareness and preparedness to extreme conditions.

Practical Implications

The management of water resources for complying with the needs of the water-related sectors (i.e., energy, agriculture or tourism) is challenged by the changes in seasonal weather and consequently

hydrological variability. The occurrence of extreme dry and wet hydro-meteorological conditions is expected to increase in both severity and frequency appealing to scientists to provide accurate and informative tools and to users to adopt innovative approaches in their operations. Hydro-meteorological data and forecasts are being vastly provided through openly accessible databases and services, but several limitations are still hindering their applicability for decision-making and operating activities. While these

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freely available services currently cover a national, continental or global domain, water management operates at the urban, regional or catchment scale requiring post-processing and integration of local data and observations to produce robust and reliable results at a fine spatial resolution. Similarly, daily (or even sub-daily) information is preferred for supporting decisions. Sharp (indicating how spread out the members of an ensemble forecast are and hence conveying the uncertainty in the forecasts) and reliable (indicating how closely the forecast probabilities of an event correspond to the actual chance of observing the event) forecasts are important for users to base their decisions, although a better understanding on forecast uncertainty is needed for planning and investment operations. Hence, the sole data provision is often not sufficient and needs to be complemented with capacity building on how to handle, read and use information for water management.

The co-generation approach for hydro-climate services aims at bridging the gap between scientific innovation and user uptake by providing a methodological framework where all the actors involved interact in each of the phases of the service production chain, from idealization to implementation. The co-generation framework consists of four steps named co-design, co-development, co-delivery and co-evaluation. While in the first step the main focus is put on framing the problem, the second step identifies the interdisciplinary approach to be applied and solutions to be implemented. Through co-delivery results are communicated in an accessible way for ensuring service uptake, and finally usability and effectiveness of the co-generated service are assessed in the co-evaluation step. Service purveyors, data providers and users are called upon to closely collaborate and exchange their expertise in each of the co-generation phases resulting in the co-evolution of technical, scientific and operational knowledge. The facilitated communication between all the involved actors helps detecting trades-off between user needs and technical limitations of the service. Documentation and reporting are carried out for each stage of the co-generation for addressing user involvement and for monitoring to which extent users' input and feedback influence the evolution of the service and knowledge.

SMHI Aqua is a co-generated hydro-climate service addressed to the drinking water supply sector which aims at supporting decision-making for a sustainable use of water resources. This service is the result of a collaborative effort between the hydro-meteorological institute of Sweden (SMHI) and several drinking water producers and suppliers in Sweden. Users' participation throughout the generation process helped shaping the features of the hydro-climate service, e.g., the hydro-climatic indicators, the forecast systems, the outlook of the web-based decision support service and the presentation of the results. Outcome of the co-generation is a hydro-climate service that provides information on the current and future water availability by simulating water levels and inflow to surface and groundwater reservoirs and producing forecasts under different water extraction scenarios. Real-time hydro-meteorological observations, daily hydro-meteorological results from locally calibrated models, short-range (up to 10 days) and seasonal forecasts (up to 7 months) of relevant indicators are provided by SMHI Aqua. The service includes a web-based decision support system, where the area of interest is displayed in a map, while station measurements and modelled results are presented in diagrams and tables. The visualization of the forecasts is facilitated by the display of both an ensemble range and historical values allowing a visual understanding of forecast uncertainty and the comparison to historical normal conditions.

The users that adopted the hydro-climate service reported that its use led to an improved decision-making process. Particularly, decisions are made in a more efficient and innovative way by using meteorological forecasts up to 3 days ahead and seasonal hydrological forecasts up to 6 months ahead. Feedback from the co-evaluation reveals that users in the drinking water supply sector recognized the benefits of using hydrological modelling to improving their understanding of the local hydrological

conditions and to predict high and low flows. Users actively participated in tailoring the service by providing future water extraction scenarios to better manage their water resources. Drinking water producers and suppliers benefit from the service by improving planning and investments, and hence reducing economic losses. The co-generated service conveys usable and understandable hydro-meteorological information accessible to other water-related organizations, policy makers and to the general public, which can improve awareness and preparedness for extreme hydrological conditions, such as floods and droughts. Although the service was co-generated with drinking water producers and suppliers in Sweden, it is designed for an ease exploitation beyond the geographic boundaries of this case study.

Introduction

Access to water remains a critical factor when assessing the socio-economic development, ecosystem thriving and food security, and this makes water management highly susceptible to variability in seasonal precipitation and temperature patterns (van Gevelt, 2020). Seasonal climatic variability influences human activities and drives the development of mitigation and adaptation techniques that ensure optimal exploitation of the available resources, as well as it boosts the memory of human society for facing adverse conditions (David Tabara et al., 2019; White et al., 2021). Future climate scenarios indicate changes in the seasonal variability, while the impact on water resources is considered imminent (Krysanova et al., 2017; Pechlivanidis et al., 2017; Samaniego et al., 2017). Within the climate-sensitive sectors, water management strongly reflects the need to adapt to climate variations for ensuring urban water supply and compliance with water regulations.

The development of decision support systems (DSSs) in the water management sector, which is characterized by a complex system of interconnections with different actors and subjects involved in decision-making, remains a challenging task (Mysiak et al., 2005), whilst such systems are important for driving actions at different prediction ranges (Viel et al., 2016; Christel et al., 2018). Hydro-climate services (HCS) set an added value by complementing mitigation and adaptation actions (Street et al., 2015; Trenberth et al., 2016; Hossain et al., 2019) and urging in providing all target user groups (from policy-makers to the general public) with high-quality, relevant, accessible and integrated hydro-climate information for successfully helping making science-informed decisions (Alexander and Dessai, 2019; Hewitt et al., 2020; Daniels et al., 2020). The provided climate knowledge can be used to reduce climate-related losses and enhance benefits, i.e., protect lives, livelihoods and property (Vaughan and Dessai, 2014; Hewitt et al., 2017; Cortekar et al., 2020).

Decision-making based on seasonal forecast information has shown to provide multiple assets, i.e., supporting the reservoir operation, optimization and/or strategic planning (Hurkmans et al., 2023), improving the preparedness to extreme events (floods and droughts) and enabling the adoption of mitigation measures (Pappenberger et al., 2015) that result in economic benefits (Bruno Soares and Dessai, 2016; Giuliani et al., 2020). However, seasonal forecasts still need to be reliable and sharp to ensure a service uptake (Crochemore et al., 2021). Moreover, efforts need to be put on the provision of seasonal forecast information at the scale that users operate, also including the inherent uncertainty in physical meteorological processes which increases with lead time leading further to a forecast skill decrease (White et al., 2017; Vogel et al., 2021; Pechlivanidis et al., 2020). Limitations linked to usability gaps have reportedly led to a failed or only partial service uptake by the users (Fuglsang & Hansen, 2022; Celliers et al., 2021; Jacobs & Street, 2020; Raaphorst et al., 2020; Vincent et al., 2020; Goddard, 2016).

The HCS design and development entails an evident informational challenge due to the probabilistic nature of forecasts, worsened by the

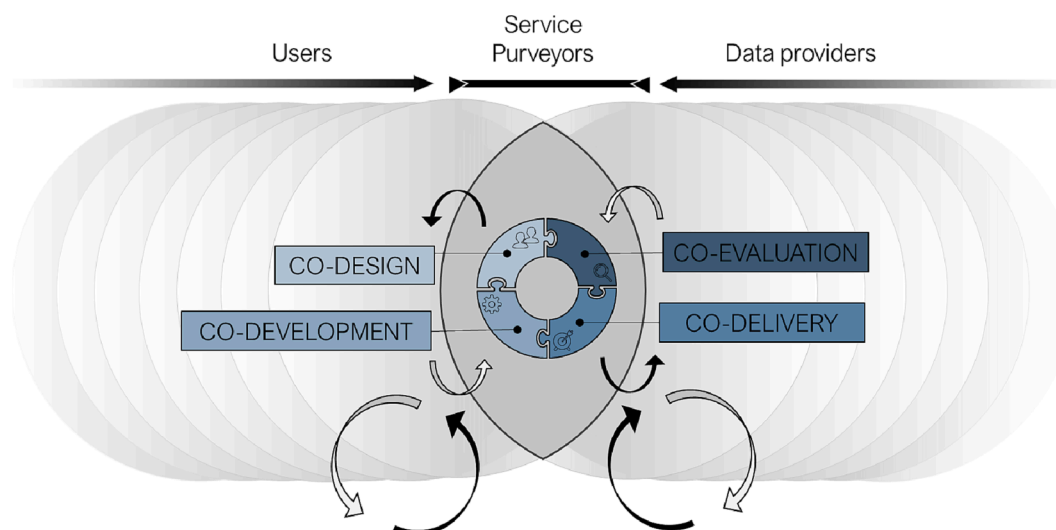


Fig. 1. Conceptual framework of co-generation process. Users and data providers (illustrated as moving spheres) are brought together by service purveyors. Knowledge fluxes are represented by curved arrows. White arrows symbolize the contribution of knowledge from the actors' own experience (small arrows) and the co-evolution of knowledge which is passed on beyond the purpose of the current co-generation (big arrows). Acquired knowledge by the co-generation process and by consideration of external feedbacks and needs is depicted by black arrows, in small and big size respectively. Co-generation occurs when all actors are brought together to exchange their knowledge and collaborate.

lack of communication between scientists and users, which hinders trust towards the use of long-range forecasts for supporting decisions (Dasgupta et al., 2023; Lavers et al., 2020). Consequently, DSSs only have a limited added-value if users rarely make use of them and/or are not keen or able to sustain the service maintenance (Buontempo et al., 2018). To this end, innovative design and data visualization solutions can help tackling the information challenges, which inherits the propagated uncertainty from the climate models (Padilla et al., 2018). Improvements on the effectiveness and applicability of these support services, integrated with user cooperation and capacity building are needed for a more successful service uptake (Pimentel et al., 2022; Contreras et al., 2020; Vincent et al., 2018; Giupponi and Sgobbi, 2013). In this context, service purveyors play a central role in ensuring that the climate information is well interpreted and communicated in relevant ways for supporting practical decision-making.

Service purveyors, data providers and users are expected to closely engage and collaborate in all stages of a HCS lifecycle to foster a mutual appreciation of the knowledge gaps and requirements, as well as the technical and technological opportunities (EC, 2015; Visscher et al., 2020). Participatory collaboration between purveyors and users in designing user-centric services is pivotal for facing climate adaptation challenges (Photiadou et al., 2021; Larosa and Mysiak, 2019; van den Hurk et al., 2016), with applications highlighting the efficiency on supporting water management for reservoir operations (Contreras et al., 2020) and on evaluating climate stressors on environmental systems (Ziogas et al., 2021).

Additional elements must be considered to design a HCS capable for successfully addressing users' needs and ensuring service uptake. Data production and archiving, technical infrastructure capacity, as well as model upgrades require expert knowledge and a solid monetary base for keeping the costs for service sustainability and maintenance. Uptake of HCSs should be supported by a vital market, where offer and demand are appropriately addressed. Business models for HCSs are useful tools with an online-based infrastructure subjected to subscription often resulting in a fortunate solution for reaching the target user (Larosa and Mysiak, 2020; Tart et al., 2020).

Here, we showcase how the co-generation of HCSs can lead to the co-evolution of knowledge, which further improves decision-making and ensures service uptake. Two scientific questions are addressed in this study: (i) *how does the HCS co-generation approach enable user engagement*

and service uptake? and (ii) *can HCSs improve short- and long-range decision-making addressing water management problems at the local scale?* To do so, we present the co-generated SMHI Aqua HCS, tailored towards the drinking water supply user needs and applied as a pilot case on a region in south-eastern Sweden. The co-generation framework follows the fundamental steps of co-design, co-development, co-delivery and co-evaluation. Moreover, we highlight the co-evolution of the service under the four steps of the adopted co-generation framework, which have successfully resulted in the service uptake. The paper is organized as follows. In “*The service co-generation framework*” section, the co-generation framework for climate services is presented. “*Material and methods*” section displays the material and methods from the case study. The co-evolution of the SMHI Aqua HCS according to the co-generation framework is described in “*Co-evolution of the SMHI Aqua – a water supply decision support system*” section. Finally, “*Discussion*” and “*Conclusions*” sections state the discussion and conclusions, respectively.

The service co-generation framework

The co-generation framework brings a conceptual shift from output-oriented to a user-oriented approach in developing and designing products and services enabling communication and mutual participation from data providers, service purveyors and users, henceforth called actors (Vincent et al., 2018; WISER, 2020; Hiron et al., 2021). With the aim of applying a HCS generation approach that ensures inclusion, collaboration and flexibility and at the same time putting all actors on an equal level, the process of co-generation adopted in this study consists of four complementary phases: co-design, co-development, co-delivery and co-evaluation (Sanders and Stappers, 2008; Mauser et al., 2013; Brandsen et al., 2018).

Service purveyors play in this context the role of knowledge brokers who bring together users and data providers and facilitate their communication and cooperation in the HCS co-generation. Both users and data providers contribute to the co-generation with their own competences, assimilated by past and current experience and participation to previous or simultaneous co-generation processes. The co-generation enables even knowledge co-evolution as outcomes in the form of information, tools and lessons learnt are further shared outside the framework of the HCS co-generation, reaching out to downstream users, stakeholders, policy makers, research communities and the

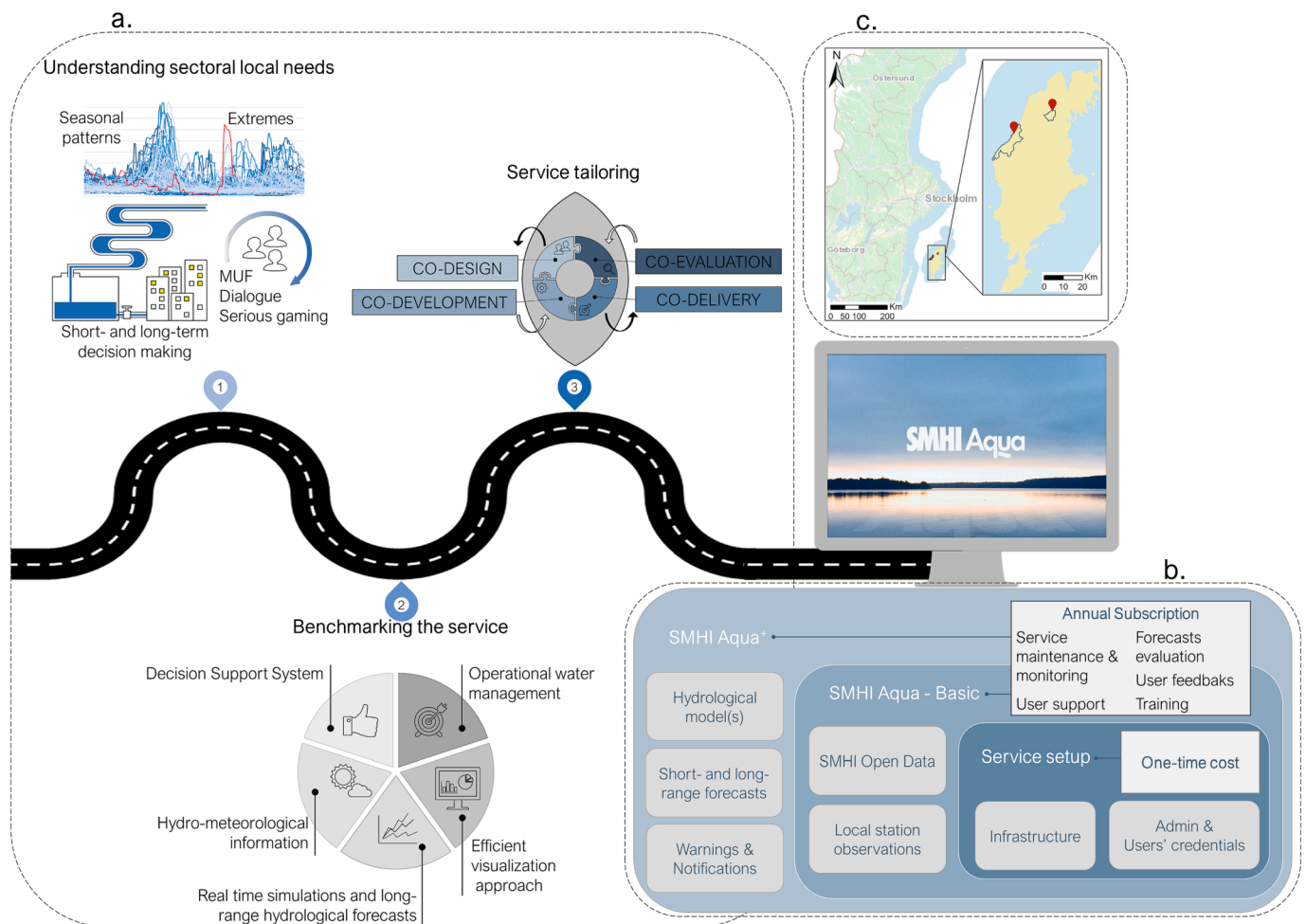


Fig. 2. A. conceptualization of the smhi aqua storyline following the steps of understanding sectoral local needs, benchmarking, and service tailoring. b. the business model adopted for marketing the smhi aqua service. c. overview of gotland island in south-east sweden and marked location of the catchments for groundwater reservoir and surface lake.

general public, allowing for these outcomes to be taken up and shared in further co-generation processes (Fig. 1).

Co-design

This is the first step in co-generation including mutual interactions between scientists, service purveyors, users and stakeholders with the aim of framing the problem and of identifying needs and limitations for solving it. During the co-design phase all involved parties work in an integrated way to best establish a common understanding of the service goals as well as to identify the steps necessary for approaching the topic and agree on the distribution of role and responsibilities for the whole co-generation process.

Co-development

Here a central focus is given to the scientific integration. Once the user needs and service challenges are identified in co-designing, all the involved parties integrate their knowledge to identify the proper interdisciplinary approaches and interfaces to be applied. At this stage, communication between the actors is specifically important for identifying the trade-offs between scientific development, service usability and users' needs and for maintaining quality and credibility throughout the process.

Co-delivery

Following the co-development, the service is delivered to the users and stakeholders. Also, knowledge acquired until this stage is communicated and the obtained results are translated into comprehensible information that is accessible and usable from stakeholders. Co-delivery ensures that the co-generated service can be applied in operation and has the potential to support decision-making.

Co-evaluation

This final stage refers to the selection, development and application of criteria that are used for measuring the quality of the co-generated service and its outputs. The designed approach, methodology, tools and results are analyzed in this phase. The HCS is aimed to be decision-driven and process-based, and hence user-driven metrics, such as usefulness, reliability, benefits and costs, are evaluated to assess the effectiveness and the potential uptake of the service.

Material and methods

Pilot case study

The co-generation framework was followed to setup a tailored HCS for the Gotland Island located in south-eastern Sweden. Gotland has a population of 60,000 people which is supplied with drinking water from

the main lakes as well as by ground water reservoirs. Summer tourism, with a 50% on average increase in the population, exacerbates the stress on freshwater demand. From 2016, a trend of warmer temperatures and reduced precipitation rates during summer led to low surface and groundwater levels, which made it challenging for local authorities to comply with water regulations and to ensure freshwater availability. Here, we focus on the seasonal variations of water resources on a surface lake and a small groundwater reservoir, which are the two freshwater storages providing water to Visby, the main town of the island (see Fig. 2c).

The business-as-usual for the local authorities is to take daily decisions on freshwater management by comparing short-range forecasts (only for 1–3 days ahead) of accumulated precipitation provided by the Swedish Meteorological and Hydrological Institute (SMHI) with historical average values. Information of soil filling rate provided at the national scale by the Geological Survey of Sweden (SGU) also support assessment of groundwater availability. Due to the increase in frequency and severity of extreme hydro-meteorological conditions leading to unprecedented water scarcity, these tools proved to be inefficient in describing the upcoming hydrological situation at the local scale, and hence in supporting short-term (and consequently long-term) decision-making.

Hydrological model setup

Aiming at simulating freshwater availability in terms of inflows and water levels, two hydrological models were setup in the context of this HCS implementation. The HBV hydrological model (Bergström, 1976) was setup for a catchment area of 20.6 km² and calibrated using hydrological observations for the period 1980–2017. HBV has a simple model structure and conceptualizes the hydrological processes in a catchment, which is divided in sub-basins classified by heights and vegetation zones (forest, open landscape, glacier and lakes). Measurements of water flow and water levels are used to calculate water inflow to the lake, while information of water management plan allows predicting changes in the surface water levels.

Moreover, a simple water balance model was developed to simulate the amount of water accumulating as groundwater recharge in the soil. The discharge-volume relation is described by a rating curve whose parameters – among which the cross-section area of the sub-basin – are locally calibrated. Hence, calculated natural inflow and outflow, together with artificial water extraction are used to simulate the amount of water in the groundwater reservoir. The water runoff in the sub-basin is simulated by the S-HYPE hydrological model (Lindström et al., 2010). S-HYPE allows simulating water flow and nutrient concentrations at the catchment level, with average area of 7 km². In addition, the groundwater model takes as inputs measurements of water withdrawal and groundwater levels. These inputs allow to calculate the water balance in the aquifer, where soil porosity is also simulated in a conceptual way for describing the water level corresponding to the modelled volume of water in the groundwater reservoir.

Both hydrological models are forced with daily precipitation and temperature data from the PTHBV database (Johansson, 2000). This database contains gridded data based on a weighted interpolation of measured values from all available stations in Sweden for any given day with a 4 km resolution, and data are available from 1961 onwards. The interpolation method used for generating PTHBV considers factors such as elevation and wind frequency and direction to make interpolated values for precipitation and temperature more reliable.

Hydro-meteorological forecasting

A HCS is implemented to provide forecast information and guide decision-making at both short- (up to 10 days ahead) and long- (seasonal; up to 7 months ahead) ranges. SMHI's 10-day deterministic meteorological forecasts are used, which combine forecasts from

different weather models, while their averaging is weighted differently throughout the forecast range. The last forecasted value in the 10-day range initiates the seasonal forecasting, which is based on historical meteorological conditions. This approach combines short-term forecasts with the Ensemble Streamflow Prediction (ESP; Wood and Lettenmaier, 2006) method assuming that during each forecast, the ensemble of historical data can provide a good approximation of the future. Moreover, the initialization of the hydrological model with updated catchment conditions makes the ESP methodology advantageous over other methods based directly on historical streamflow (streamflow climatology), since initial hydrological conditions are considered a source of hydrological forecast skill (Crochemore, et al., 2020; Musuuza et al., 2023).

Here the combination of 10-day forecasts and ESP is plausible due to the availability of long historical records from the PTHBV dataset. To date, the use of past historical records results in a forecast ensemble set of 62 members. Moreover, to better communicate forecast uncertainty to the users, statistics (i.e., minimum, 25th percentile, median, 75th percentile and maximum) are calculated based on the ensemble.

Aiming at assessing how water usage is likely to affect freshwater availability in the following months, forecasts of surface and groundwater levels as well as inflows are based on scenarios of different water extraction strategies provided by the users for reflecting their actual operation. However, if these water withdrawal plans are missing the last reported outflow is used as a reference for the entire forecast period, and the forecasts are run as if the same extraction/discharge would be valid for all the future months.

Co-evolution of the SMHI Aqua – A water supply decision support system

The SMHI Aqua storyline

Understanding the sectoral local needs

SMHI Aqua (<https://aqua.smhi.se>) is a HCS that was co-generated within the framework of the H2020 CLARA project (September 2017 – December 2020) as an assessment tool for drinking water supply. This HCS aims at supporting the freshwater management sector by providing tailored hydro-meteorological information related to questions: (1) *How does water usage affect availability of freshwater?* (2) *How to implement a sustainable freshwater abstraction plan?* And (3) *How to take the right decisions for the short- and long-term future?* Target users were identified as public authorities (i.e., municipalities, administrative county boards, regions) and sector-specific private companies (i.e., drinking water production, paper mill, mining) whose operations are interdependent with water availability. A continuous dialogue with drinking water producers and water managers both in Sweden and Europe was established as part of the CLARA Multi-User Forum (MUF) (Polo and Jurado, 2018), allowing the identification of the main sectoral challenges, which to a large extent are due to the incomplete (and uncertain) understanding of the hydro-meteorological situation both in space and time (Fig. 2a).

Specifically, SMHI Aqua was the result of the collaboration with Region Gotland in Sweden, the public institution responsible to supply safe drinking water to urban areas of Gotland Island. The water management sector in Gotland is strongly affected by weather seasonal variability, which makes it vulnerable to changes in precipitation and temperature patterns, especially in summer, when the island experiences a relative tourism population increase. Illustrative cases are summer 2016 and 2018, when extremely high temperature combined with precipitation highly below normal conditions led to droughts and water scarcity in Gotland. These events highlighted the need for Region Gotland to access innovative tools to deal with extreme hydro-meteorological conditions. This included a locally calibrated hydrological model for simulating water reservoirs dynamics and hydrological long-range forecasts spanning up to several months ahead to support

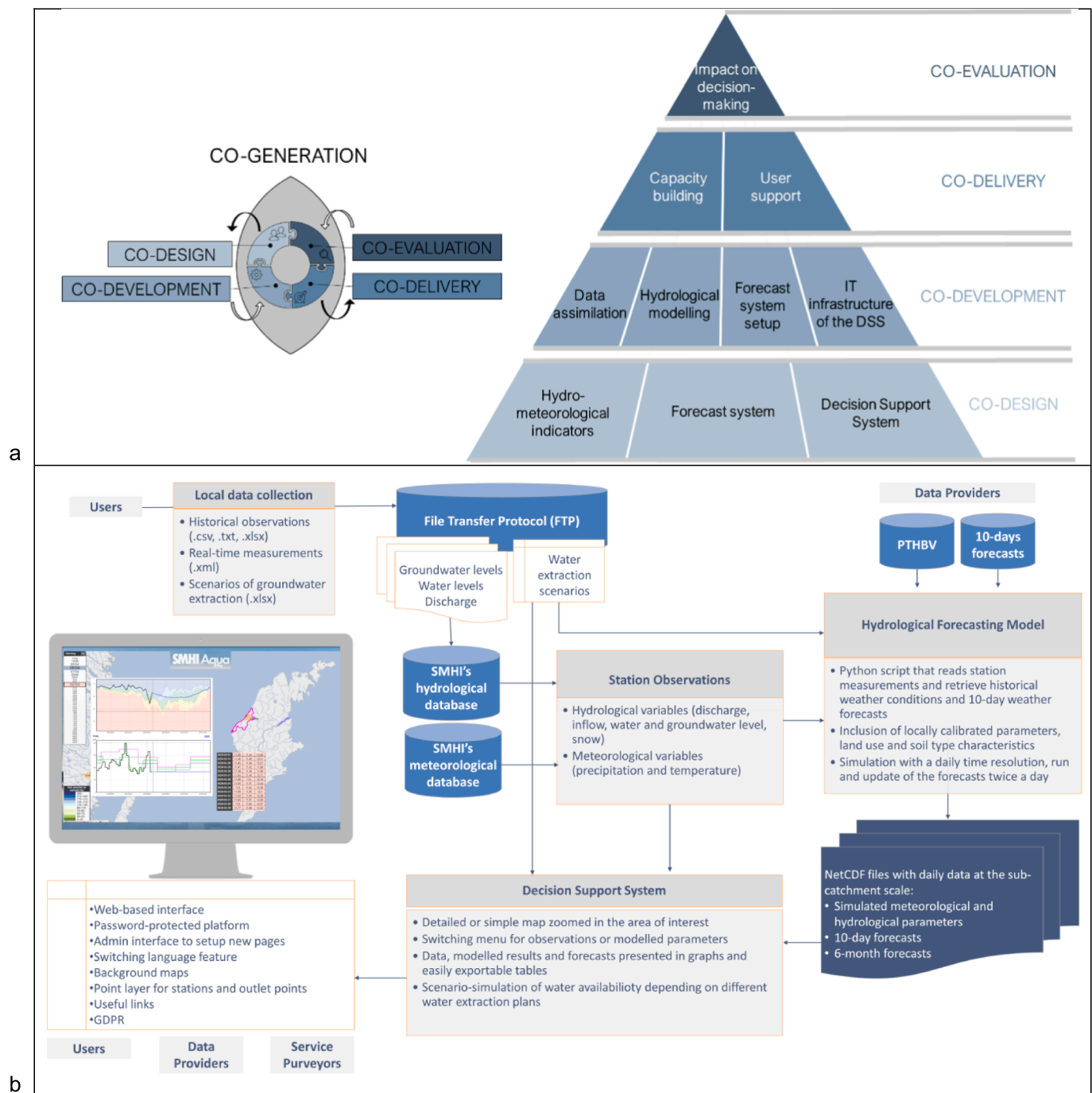


Fig. 3. A. the process of co-generation for smhi aqua. the pillars of co-generation are represented as layers on the pyramid. each layer includes the main outcomes, which influenced shaping the hcs. b. tool-building framework of smhi aqua.

decisions in water usage throughout the year and ensure freshwater availability in the dry seasons.

Benchmarking the service

Drinking water producers and water managers base their decisions on information from real-time observations as well as empirical experience of the local system (i.e., river and/or lake). The local users are not always accustomed on using hydrological models as tools for decision support, while decisions for drinking water supply are often based on short-range meteorological forecasts (temperature and precipitation for 1–3 days ahead). SMHI provides hydrological forecasts up to 10 days ahead, while SGU provides information for soil filling rate simulated at

the national scale. Although such information improves decision-making on freshwater management, there had been no support regarding long-term (seasonal) planning.

State-of-the-art DSSs are driven by customized hydrological models to predict the freshwater reservoir dynamics at the local scale and estimate the water availability for the near future. Such tools not only can improve the understanding on the current and future water situation in space and time, but also support the decision-making process for optimal short- (water abstraction plan, urban water supply) and long-term (drinking water production plan, risk management, and impacts due to extremes, i.e., droughts and floods) water resource planning (Fig. 2a). Consequently, tools that provide accurate and reliable long-term

information can be considered as an added value to the current service in Gotland.

Service tailoring

The SMHI Aqua HCS builds upon the four co-generation phases (co-design, co-development, co-delivery and co-evaluation) for meeting the user requirements and succeeding in providing a usable and valuable service in planning operations. To this end, a continuous interaction between service purveyors, data providers and users was implemented in all phases of the co-generation (see Figs. 1 and 2a). The strong engagement of all actors has driven the HCS uptake through the established trust from the users and the efficient communication of HCS potential and limitations. Result of this approach is a HCS that provides access to data and information generated from different sources and at different time horizons; historical and real-time hydro-meteorological observations (precipitation, temperature, surface and groundwater levels, groundwater withdrawal and water discharge, sea water level), modelled hydrological (daily surface and groundwater levels, water inflow to reservoirs and snow) and meteorological (daily temperature and precipitation) indicators, and hydro-meteorological forecasts at short- (10 days ahead, for temperature, precipitation, snow, surface and groundwater levels and inflow) and long-term (7 months ahead for surface and groundwater levels, as well as water inflow) time ranges. Moreover, data and information are visualized through a user-friendly web-based interface allowing to also convey the scientifically sound background successfully in the data generation process.

Marketing the service

The business model implemented for SMHI Aqua initially included a first investment (funded by the CLARA project) for building the service infrastructure and the layout of the web-based tool. Subsequently, each user of the SMHI Aqua HCS pays for the provided service. The price associated to the HCS consists of two parts: a one-time payment for setting up the service, and an annual subscription. The subscription cost is unique for each user and depends on the data and information provided by the HCS (Fig. 2b). Two subscription types are available: the SMHI Aqua – Basic and the SMHI Aqua +. The former only includes the visualization of data from the local station observations and also open data that are acquired from SMHI. This subscription is hence based on historical and monitored information. SMHI Aqua + includes additional information based on the available hydrological model(s), e.g., daily modelled data and short- and long-range forecasts that are run twice a day. These forecasts can also be used to generate warnings and notifications in the case of extreme events, i.e., floods. The annual subscription covers costs related to the maintenance and monitoring of the service, whilst it also includes support to the users. Finally, subscribed users can receive training sessions to develop their capacity on HCSs, while the data providers conduct a yearly forecast evaluation to assess forecast performance. Information about subscribers to SMHI Aqua and users' responses concerning service evaluation are provided in section 4.5.

Co-generating SMHI Aqua – Insights from co-designing

Following the co-generation framework, both in-person and digital meetings between the actors were carried out since the early stages of the CLARA project. Benefits of this approach were multifold. Firstly, it enabled SMHI purveyors to better understand the state-of-the-art and the current decision-making approach at Region Gotland. Secondly, it allowed a clear definition of the main information needed for guiding users' decisions. This resulted in the identification of surface and groundwater levels together with water inflow to reservoirs as the most relevant hydrological indicators to support water management decisions for Region Gotland (Fig. 3a). Finally, it enabled service purveyors to present technical limitations, which led to constructive discussions for the identification of possible technical solutions. Furthermore, a

conceptualization of the tool-building framework for the HCS (Fig. 3b) was designed.

Facilitated by the CLARA MUF, scientifically focused workshops were organized for improving the understanding and knowledge on seasonal hydro-meteorological forecasting and how probabilistic forecasts play a role in making decisions under uncertainty. A key milestone of this effort was the implementation of the *Call For Water* serious game tailored to the SMHI Aqua case study and used as a training material in the CLARA MUF (Crochemore et al., 2021) to investigate the levels of seasonal forecast characteristics (specifically sharpness and reliability) needed to make informed decisions.

Outcomes from the MUF showed skepticism towards the use of dynamic GCM-based seasonal forecasts. Although this was not investigated further, it is expected that this method was not preferred due to the relatively coarse spatial resolution and lack of frequent initializations of the GCM-based seasonal meteorological forecasts for local applications (Johnson et al., 2019). Consequently, the ESP-based forecast system was selected for the pilot case study in Gotland that uses an ensemble of historical data, and hence the forecast skill is more subject to the quality of the local meteorological observations (Girons Lopez et al., 2021).

In addition, Region Gotland expressed the need for accessing the produced information through a user-friendly web-based tool. Web-designers and expert communicators were thus involved for co-designing the fundamental features of the DSS. Focus was put on effective, from a user-perspective, visualization approaches for successfully conveying the service information. This not only involved the selection of colours to highlight forecasted conditions based on historical records (above / near / below normal), but also how 10-day and seasonal forecasts are depicted.

Co-generating SMHI Aqua – Insights from co-development

Interactions between the actors in the co-design phase resulted in the identification of the main components of SMHI Aqua (Fig. 3b). These included: (1) historical and real-time data collection, (2) model simulation and hydrological forecasts production, and (3) a web-based DSS. The core of the co-development consisted of the implementation of the HCS by assembling expertise-specific working teams focusing on the above three main components. Region Gotland was involved in different phases of the co-development to integrate their knowledge and express their needs for identifying optimal trade-offs between service usability and scientific developments and limitations. The co-generation phase set therefore the basis for the identification of data availability, the production chain for the interplay between the different service components, as well as the visualization practices to be followed in the implementation of the web-based service.

Historical and real-time data collection

Region Gotland provided historical measurements of surface and groundwater levels, water discharge and groundwater withdrawal. To receive real-time data from the measuring stations and store them automatically, a digital data collection system was setup through a File Transfer Protocol (FTP). Training sessions were carried out for building capacity at Region Gotland about setting up automatic data deliveries from hydrological measuring stations, information file formatting and the use of FTPs. In addition, template files were designed for the users to provide information on alternative water management scenarios as daily time series of groundwater withdrawal (Appendix A).

Model simulation and forecasts

Real-time updated hydrological and meteorological observations from SMHI's national network and from Region Gotland are used to feed the hydrological models to simulate the water balance in the water body and initialize the hydrological forecasts at different time ranges. The hydrological models are run twice a day, whilst the latest available observations are used to update the forecast initial state. With the same

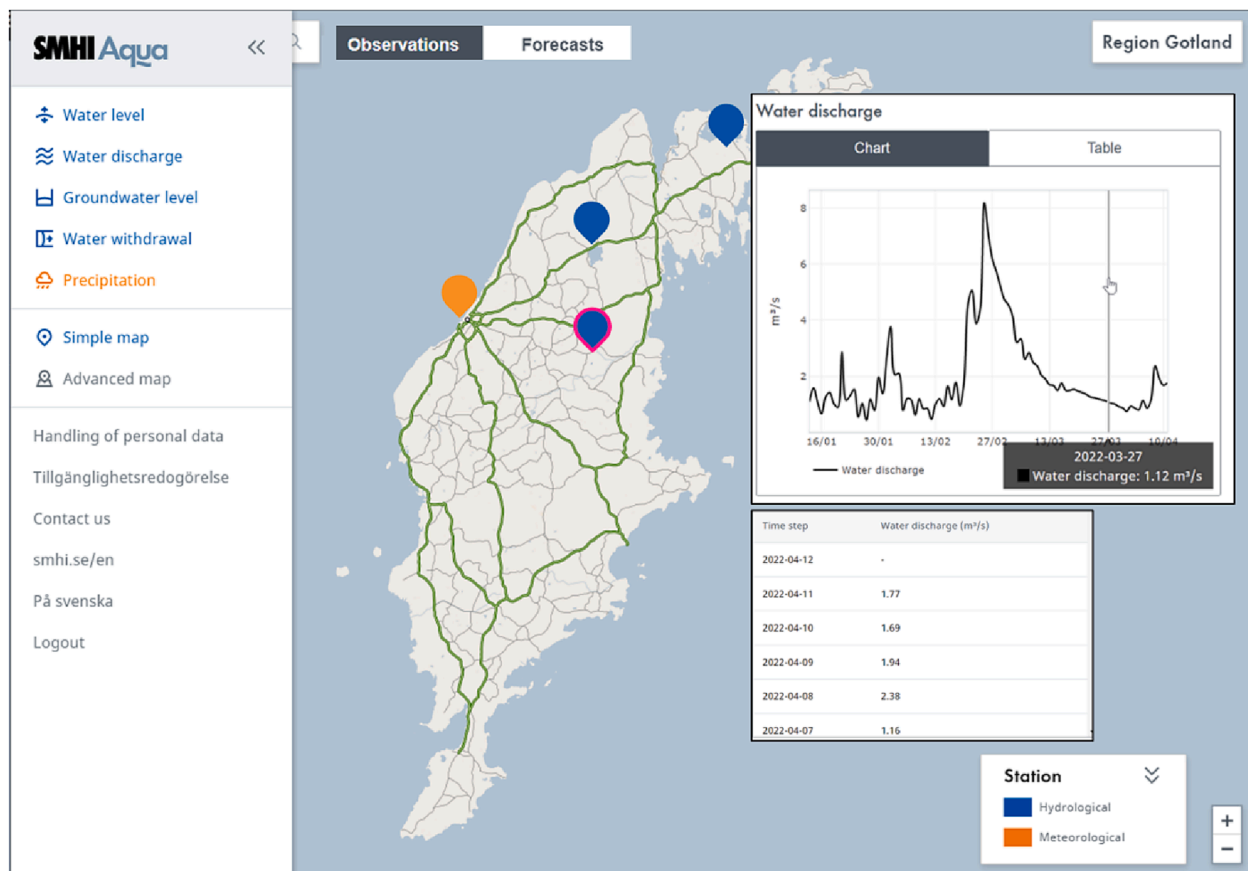


Fig. 4. The SMHI Aqua web-based tool showing the “Observations” product, selected on the top ribbon. Hydrological and meteorological stations are in blue and orange, respectively. Pointers in the map indicate the location of the stations, and when clicked upon (magenta boarder), a graph displays 30 days historical values.

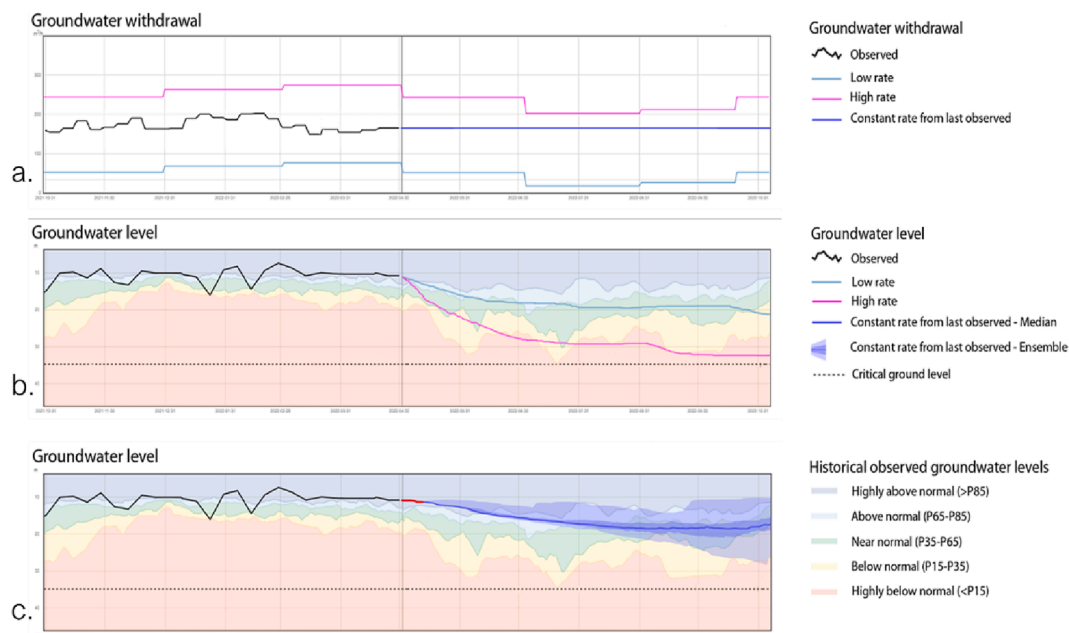


Fig. 5. Visualization of historical and short- and long-range forecasts of groundwater levels: (a) historical and hypothetical groundwater extraction scenarios. The observed groundwater withdrawal (black line) remains constant in the future (blue line) based on today's last observation (vertical line). The pink and light blue lines represent a scenario of “high” and “low” groundwater withdrawal rate, respectively. (b) historical and future groundwater levels using the median of the long-range forecasts of groundwater levels depending on the extraction scenario. In the background historical observed groundwater levels are grouped depending on the deviation from normal conditions (5 groups). (c) the forecasted groundwater levels with a constant daily withdrawal equal to the latest observed. The short-range (10-day) forecast is highlighted in red, and the latest forecast value initializes the seasonal forecasts. A different colour intensity allows distinguishing different statistics (i.e., minimum, 25th, 50th and 75th percentiles and maximum).

Table 1
Co-delivery and co-evaluation approaches chosen for different users of the SMHI Aqua HCS.

Institute / Company	Scope	Nr of users engaged in the co-generation	Nr of total users of the HCS	Co-delivery approach and number of occurrences (in brackets)	Co-evaluation method
Region Gotland	Drinking water production Urban freshwater supply	4	>10	(3) Online demonstration to main users (1) Workshop with all users (1) Handover manual with specifics of the service	Online meetings Face-to-face meetings CLARA Survey
Nodra AB	Drinking water production Urban freshwater supply	4	5 to 10	(2) Workshop with main users (1) Online demonstration to all users (1) Handover manual with specifics of the service	Online meetings Emails
Husum Pulp AB	Pulp mill	2	>10	(1) Online demonstration to main users (1) Handover manual with specifics of the service	Online meetings Emails Questionnaire
Karlskrona Municipality	Urban freshwater supply	2	5 to 10	(1) Online demonstration to main users (1) Handover manual with specifics of the service	Online meetings Emails

frequency, the hydrological modelling system reads the content of the FTP and automatically simulates the hydrological indicators by considering the impact of the different groundwater extraction scenarios provided by the users. The forecast system is setup to update the model runs twice a day every day and produce 10-day and 7-month ahead forecasts, which are further saved in standardized files for the web-based platform (Fig. 3b).

Web-based visualisation tool

Following the request of Region Gotland of an intuitive and informative presentation of measured data together with the results from the hydrological models (historical data and forecasts) through a web-based platform, a team of web-developers and communicators worked together to design the features that best met the user needs to support decisions. The SMHI Aqua service was developed to show the location of the measuring hydro-meteorological stations as points on the map (Fig. 4). This is the view in the “Observation” mode, while the “Forecast” mode presents the location of sub-basin outlet points, where model results are generated. A menu allows navigating between hydrological and meteorological variables and from a less to a more detailed background map. By clicking a point on the map, diagrams of daily measured or modelled values for all the variables in the selected station or sub-basin pop up. For station observations, the graph shows data from the past 30 days. For points where only short-range forecasts are available, historical values of 30 days and forecasts for the 10 days ahead are presented. Where seasonal forecasts are produced, the graph presents a historical time series of 6 months and forecasts up to 7 months in the future. All the data visualized in the graphs can also be accessed as tables and exported for further analyses.

It is worth mentioning that particular focus was put on the underlying visualization practices. The probabilistic component of seasonal hydrological forecasts makes the communication to the users challenging. The visualization of forecasts (e.g., groundwater levels or inflows) is kept by default simple, yet the forecast complexity could be further increased; for example, here we used the ensemble median as a default presentation, while the user can choose to visualize the whole forecast ensemble. Colour mapping in the ensemble forecast enables a simple identification of relevant statistics such as minimum, maximum, 25th and 75th percentiles. The understanding of the forecasted ranges for operational scopes is also facilitated by the provision of historical observations in colour fields divided according to the deviation from the normal conditions (i.e., high above, above, near, below, and high below). Critical levels, presented in the graph as dashed lines (Fig. 5), were provided by the users as they are necessary for decision-making.

Finally, the SMHI Aqua web-based service can be accessed with specific-user credentials (i.e., a unique username and password) or have an “open” setup accessible to any user. Information on how personal data is handled, web accessibility criteria and useful links for contacting

the service purveyors are also included in the main menu of the web-service. The HCS SMHI Aqua is language-independent and for the purpose of a specific case study, it is possible to switch between languages (here English or Swedish). The web-based service was tested following the Web Accessibility Directive (European Commission, 2016) proving that the co-generated HCS is in-line with the Directive criteria and meets specific technical accessibility standards that allow everyone, including people with disabilities, to perceive, understand, navigate and interact with the service.

Co-generating SMHI Aqua – Insights from co-delivery

Following Region Gotland’s active participation in both the co-design and co-development phases, additional training sessions were organized in the co-delivery phase for service purveying (Appendix B). These sessions are crucial for the co-evolution of knowledge and therefore were grouped depending on the involvement level of the user and the nature of the meeting. At first, online meetings were carried out with group members at Region Gotland, who had been involved since the beginning of the project and, due to interest, would have immediately started working with the HCS. In these meetings, all the components of the service were supervised and reviewed with the users for ensuring that the final product was in line with the defined needs and requirements set in the co-design and co-development phases. Subsequently, in-person meetings between service purveyors and the Water and Waste Department at Region Gotland aimed on building capacity to the larger group about the developed HCS and included an introduction on: (1) the chosen hydrological models, (2) the simulated hydro-meteorological indicators, and (3) the hydrological forecasts setup. The conveyed knowledge of the science and technology behind the HCS enabled familiarization with the basic hydrological modelling concepts and indicators, which until then had not been used in operation. Finally, the SMHI Aqua web-tool was presented live, including a hands-on session, allowing testing the functionalities of the service, and learning also how to interpret the information provided for operational purposes. A user guide including the description of the general functionalities of SMHI Aqua and the specific tailored features for Region Gotland was additionally handed out for future revision in operational applications.

In total, three more users who were not involved in the CLARA project got access to the HCS by signing an annual subscription to SMHI Aqua, which includes service tailoring according to the operational needs of each different user in their specific local systems. A similar methodology of co-delivery was followed also for these users, firstly by engaging the main users, who had been involved in the whole co-generation process, and then with all the potential users of the service. Meetings and workshops were carried out in presence and/or online, always including possibility for the users to ask questions and discuss the potential service evolution (Table 1).

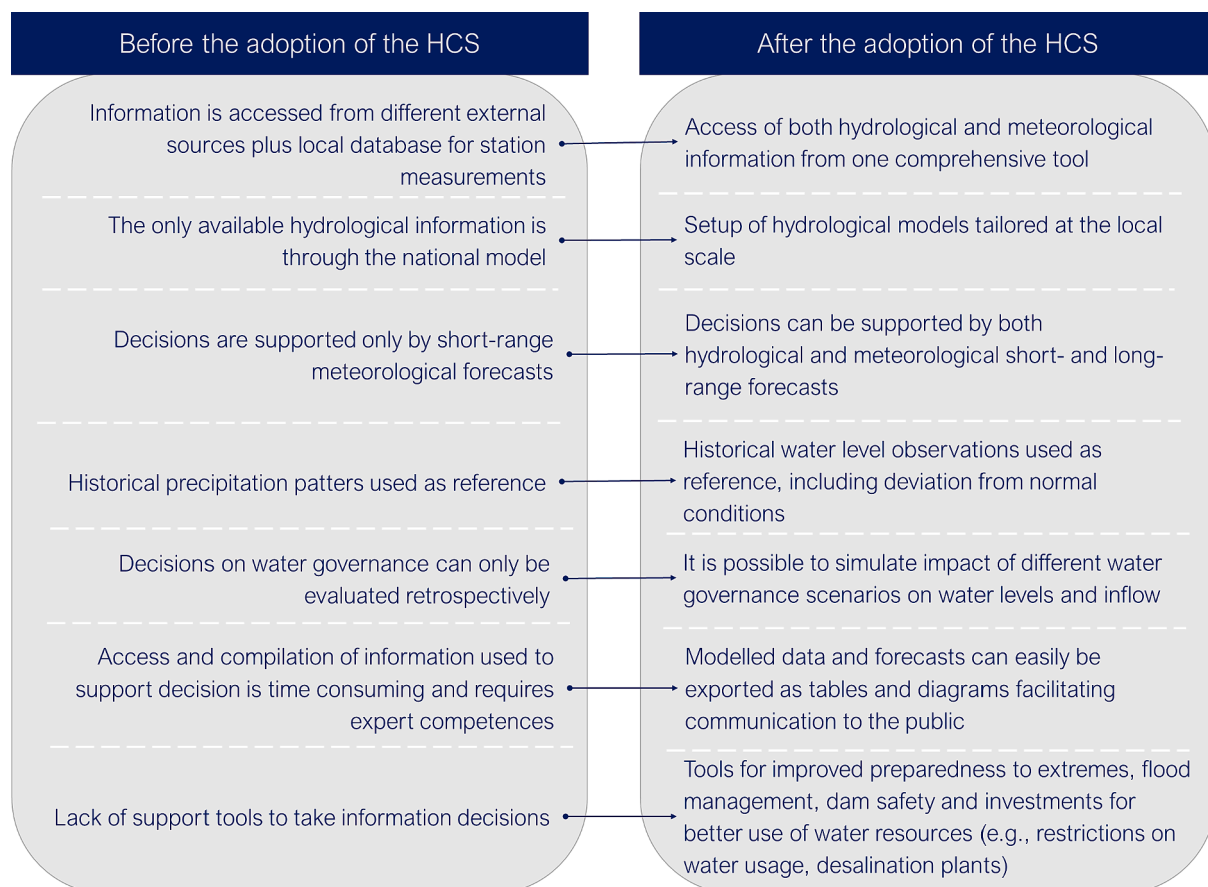


Fig. 6. Decision-making process for freshwater resources before and after the adoption of SMHI Aqua according to the service users.

It is important to note that for a trustworthy HCS, ensuring service reliability is a fundamental element of the co-delivery phase. Through an annual subscription to the service, users have been guaranteed with support, maintenance and monitoring of the modelling steps (during the office hours) by the service purveyors, providing full technical support in case of any temporary service disruption.

Co-generating SMHI Aqua – Insights from co-evaluation

The SMHI Aqua HCS was launched in operation in spring 2019, not only for Region Gotland but even for other users in Sweden (Table 1). Nodra AB that is the municipal water company in Norrköping, Karlskrona Municipality and the pulp mill Husum Pulp AB got access to historical and real-time modelled data, and short- and long-term forecasts of water levels and water inflow in their respective local water systems for drinking water production, freshwater supply, and paper production purposes, respectively.

In the co-evaluation phase, we did not target the assessment of hydrological model performance and/or forecasting skill, which traditionally involves a scientific assessment from a service purveyor perspective. Instead, the co-evaluation aimed on centralizing the user and assessing the service's added value through user feedbacks, which were collected during in-person/online meetings and surveys (Table 1). The whole process of involvement and collaboration between actors led to the establishment of a HCS roadmap useful for users and service purveyors to objectively evaluate the provided service and its deviation from the initial setup. Moreover, the consistent user engagement throughout the co-generation process enabled boosting knowledge over the different aspects of each service components facilitating future service development and exploitation.

A questionnaire aiming at gathering user feedback both on the co-

development experience and on the delivered HCS (Crochemore et al., 2020a; Appendix C) was forwarded to the users. The survey investigates over four main themes: (1) co-development, (2) quality of the service, (3) awareness, and (4) decision-making. Concerning co-development (theme 1), answers from the survey show that the involvement in the co-generation boosted users' motivation to participate in each phase of the service evolution. Users reported that this approach enabled them to influence the service development resulting in a good communication of the needs and a thorough understanding of the different components of the HCS. The final SMHI Aqua service resulted to be in line with the objectives defined in the design phase and users felt that the service outputs evolved substantially throughout co-generation. When they were asked about the quality of the service (theme 2), users identified the provision of information about the current and forecasted hydrological situation as the main added value of the co-developed climate service, while the chance of influencing visualization and more conceptual parts was considered crucial for further communication and supporting decisions. User feedback about increased awareness (theme 3) shows that thanks to a clear communication about the service's advantages and limitations, users recognized the added value of the provided seasonal hydrological forecasts for taking decisions regarding freshwater management, while understanding forecast uncertainties. In addition, the visualization of future water availability scenarios improved awareness of how different water extraction behaviors can impact freshwater reservoirs. Provision of historical normal conditions alongside modelled results and forecasts facilitated understanding and communication of the current and future hydrological trends to other institutions as well as to the general public. The survey revealed that decision-making should not be solely based on the HCS forecasting information (theme 4), and a qualitative assessment was conducted by comparing the forecasted water levels for summer 2019 to the actual

observations to evaluate the service during this very dry season. Produced forecasts were hence used as control-tool and the comparison resulted in a positive agreement with the observed values, which helps building trust in the service, although only a longer use of the HCS can assure the suitability to base decisions on and thus truly impact users' decision-making. Suggested improvements of the SMHI Aqua service include: firstly an easier file formatting for collecting hydrological station observations; updating the system with the newly setup real-time measuring stations of surface and groundwater levels (not yet in place at the time of the CLARA project); and finally the inclusion of metadata and description of the forecasts statistics in the web-based platform.

Users from the drinking water operations in Nodra AB highlighted the importance to visualize historical conditions (above/near/below normal) and further superimpose the forecast spreading to better understand probabilities of reaching extremes. This justifies the usefulness of the co-generated HCS for improving preparedness to adverse hydro-meteorological extreme conditions (Winnfors Wannberg, 2019). Husum Pulp AB, which uses SMHI Aqua as support service for the regulation of the river Husån in Northern Sweden, reported that the access to real-time observations in regulated lakes and river systems provide valuable information for dam safety. In addition, the 3-day ahead forecasts of high flows provide an early warning system, which is communicated to Husum Pulp via SMS, allowing emergency measures to be taken in good time for flood management. The users defined the SMHI Aqua service as "user-friendly, as even people with little computer skills can easily master the decision support system".

Discussion

Benefits of the service for drinking water supply

Here, we highlight the successful user-uptaken, yet scientifically developed, climate service SMHI Aqua. The HCS is the result of four iterative phases following the scientific framework for co-generation where users, data providers and service purveyors interact to identify needs and limitations and find the best solutions. Documentation and evaluation of the co-generation (Crochemore et al., 2020a) highlighted the active involvement of the users who acknowledged their influence in shaping the HCS (e.g., identification of the hydro-meteorological indicators, choice of the forecast system setup, as well as layout and features of the DSS). Knowledge evolution through co-generation builds awareness of the added value given by seasonal hydrological forecasts for decision-making while understanding the associated uncertainties.

Overall, the co-generated HCS has shown potential in bridging the gap between scientific innovation and operational management by providing valuable information for supporting decisions for water management. Planning for groundwater extraction based on provided forecast information resulted into the restrictions for water use in Gotland Island in summer from 2019 to 2021 (Region Gotland, 2021) and investment in desalination plants for sea water (Region Gotland, 2019). By adopting the co-generated HCS, the users' decision-making process shifts from the use of regional or national-scale modelled data and 1–3 days ahead meteorological forecast information (commonly scattered among different sources) to the access of locally refined hydro-meteorological information in one comprehensive tool, which includes short- and long-range forecasts and deviations from normal water level conditions (Fig. 6). Integration of the SMHI Aqua results into benefits for drinking water producers and suppliers by improving water resource management and reducing economic losses, for the public by guaranteeing access to freshwater, and for society in general by improving awareness for water security and preparedness to extremes, such as droughts and floods.

Recognizing co-generation challenges and service limitations

Aligning to the scientifically promoted user-centric approach for HCS

(Wibeck et al., 2022; Daniels et al., 2020; Bremer et al., 2019), SMHI Aqua was co-generated with drinking water producers in Sweden. By training the users on the science behind the service, the co-generation leads to the co-evolution of knowledge which is transferred to other water-related users, stakeholders and the public for further ensuring the usability of the HCS. Particularly, the provision of historical and real-time observations, as well as 10-day and seasonal hydrological forecasts produced by locally calibrated hydrological models, not only brings awareness of the hydro-meteorological status, but also guides the short- and long-term decision-making. The close collaboration between service purveyors and users facilitated communication, which allows the detection of optimal trade-offs between user needs and technical and/or scientific limitations. While co-generation proves to be a promising approach for developing hydro-climate services, its successful implementation entails several limitations (Fleming et al., 2023; Tudose et al., 2023; Bojovic et al., 2021). Here the co-generation had to overcome challenges related to building trust between users and data providers, ensuring a consistent user participation throughout the process. We also note that effort needs to be put on capacity building and ensuring that the service purveyors act as knowledge brokers. Additionally, we highlight that the long-term sustainability of the HCS goes beyond the co-generation timeline, requiring a continuous dialogue and evaluation. Although considerable effort was put on SMHI Aqua, the user engagement remains a continuous necessity and hence dialogues are expected to set the future evolution of the service.

Advanced services and DSSs require components for monitoring the various essential hydro-climate variables, modelling of the (poorly gauged) water systems, and forecasting at different time scales. Considering the recent sectoral needs and challenges from a warmer future, long-term informed decisions are needed based on seasonal forecasts. Uncertainties inherited from multiple sources of the modelling chain still challenge the use of the long-term hydro-meteorological forecasts to support decisions (Bruno Soares et al., 2018a,b; Pechlivanidis et al., 2014) as seasonal forecasts need to be reliable and sharp to ensure a service uptake (Crochemore et al., 2021). The quality of seasonal hydrological forecasts relies on a modelling chain that most commonly includes seasonal meteorological forcing, initialization of hydrological model states and a hydrologic model setup (Mazrooei et al., 2015). Moreover, innovative communication and visualization practices are crucial to convey scientific content efficiently and to translate it into information that can be used in management operation. The process of co-generation not only brings together data providers and service purveyors, but also engages users for the realization of a reliable, robust and usable hydro-climate service.

SMHI Aqua beyond state-of-the-art

At the present stage, SMHI Aqua provides predictions at two time horizons using SMHI's 10-day deterministic forecast system and probabilistic seasonal (7 months ahead) forecasts based on the ESP framework. Based on historical records (from 1961 to today) the framework is unable to capture extreme meteorological events beyond the available climatological range. This limitation could be addressed by using GCM-based seasonal forecasts to predict the future climate (Monhart et al., 2019), although predictability limitation due to the aleatory uncertainty of this system and post-processing requirements (i.e., downscaling and bias adjustment) for application in hydrological impact studies (Macian-Sorribes et al., 2020) makes users skeptical towards the uptake of dynamic forecast systems.

The quality of the long-term hydrological forecasts can further be improved by seamlessly combining in time the forecasts from different systems addressing the short-range (up to 10 days), sub-seasonal (up to 45 days) and seasonal (up to 7 months) time scales. In a seamless approach, the added value in predictability comes from both the forecasts provision from the best system for the time horizon of interest and the frequent initializations of the system itself (Dasgupta et al., 2023; Lavers et al., 2020). In addition, probabilistic forecasts have shown

potential on both capturing future events but also on representing the expected uncertainty (Pappenberger et al., 2013). Here, deterministic forecasts are used for the short-range, which although they are based on SMHI's state-of-the-art system, they could be improved through the complementarity of a probabilistic system (Pechlivanidis et al., 2014).

The ESP-based seasonal forecasts are based on historical observations that represent both (extreme) dry and wet years. Consequently, the extreme ESP member(s) could be used for guiding hypothetical decisions under a low probability high extreme scenario. In this context, SMHI Aqua could evolve as a scenario tool to inform users about hypothetical future extreme conditions by providing water managers with the access to each single member of the forecast ensemble (i.e., forecasts produced by single years of the historical period). This information would enable identifying how the upcoming hydrological situation would have developed in the framework of an observed meteorologically wet (dry) year of the past and enable a simple comparison of the different selected choices.

Availability of good quality station measurements at high temporal resolution (i.e., daily, sub-daily, hourly, sub-hourly) also plays a role for improving both the calibration of the hydrological model at the local scale and the initialization of model states prior to forecasting. When in place, data provided from the users are stored in SMHI's archives and fetched for updating the model states. SMHI can also provide technical support for setting up hydrological stations and ensure that the measuring instruments comply with current regulations and quality standards. Maintenance and management of the measuring equipment is guaranteed by control visits to the stations, which are performed twice a year by expert field hydrologists. This additional component of the service would ensure a stronger user engagement resulting in more detailed information of the local situation and an improvement in the results provided by the HCS.

Service exploitation

Several policies at the European level (e.g., EC, 2000; EC, 2011; EC, 2013) favour the implementation of HCS by promoting sustainable use of water. The aim of such policies is to reduce the stress on the limited available water resources and to make Europe more climate resilient. The objectives outlined in the international framework often co-exist with local quality standards and specific management strategies leading to promoted development for dealing with weather extremes and negative impacts of a changing climate. This legislative context draws opportunities for the implementation and exploitation of HCS addressed to water managers. In addition, supply of good quality drinking water is one of the global water policy objectives (United Nations Sustainable Development Goals 6.1 and 6.2) playing a pivotal role on water usage across Europe and worldwide.

Although a HCS requires adaptation to the needs of each user for ensuring its uptake, some main components of SMHI Aqua were designed by expertise-specific teams aiming at making the HCS easily exploitable beyond the case study. Firstly, the HCS is kept flexible due to the hydrological model independency, which would promote its implementation also in different geographical regions. The two different hydrological models tested within the pilot case can be easily setup or customized in different geographical regions. HBV is a conceptual parsimonious model with few parameters to be calibrated, while one can make use of the E-HYPE (Hundecha et al., 2016) and WW-HYPE (Arheimer et al., 2020; Pimentel et al., 2023) model setups whether the region of interest is inside or outside Europe, respectively. The service uptake is also facilitated by giving the possibility to setup the web-based platform in a preferred language, since access to information in the local language is essential for operational purposes in water management.

Conclusions

Here we demonstrate the usability of co-generated HCSs to address water management problems at the local scale and showcase how the co-generation can lead to the co-evolution of knowledge by bridging the gap between research, services and decision-making. We highlight how the co-generation process enables user engagement and service uptake, and present the methodological framework used for co-generating the SMHI Aqua HCS to guide water managers dealing with drinking water supply. The co-generation framework consists of the active involvement and close collaboration of service purveyors, data providers and users during the co-design, co-development, co-delivery and co-evaluation phases. Overall, SMHI Aqua supports decisions for optimal water resource management by providing historical and real-time hydro-meteorological observations, modelled hydro-meteorological information, short- (10-day) and long-term (seasonal) forecasts of water availability in the main freshwater reservoirs (water levels and inflow). The HCS includes a user-friendly web-based platform where information is updated twice a day, allowing a facilitated access to hydro-meteorological data and presenting the results in an intuitive and informative way for the users. The main conclusions from the HCS co-generation process are summarized as follows:

- To ensure a HCS uptake, it is crucial to involve service purveyors, data providers and users in a continuous dialogue and knowledge co-evolution process that is based on the four co-generation phases. User needs are identified and addressed through the co-generated HCS; however, we conclude that it is also important to communicate the limitations (i.e., forecast reliability and uncertainty) of the service.
- The service provides observations, modelled results and forecasts of freshwater availability that improve the user awareness on the current hydro-meteorological situation as well as future dry/wet periods. The service facilitates good communication of the generated information also to other water-related users and the public, which consequently results into increased preparedness to extreme conditions, ensured municipal water supply and reduced risks for infrastructure damages.
- Users have a focal role in the generation of the service, which should be tailored to their needs. The web-based DSS and the selected visualization practices are key components of the service, and therefore the service purveyors need to ensure in the co-development phase that observations, modelled results and forecasts are understood and adequately presented.
- SMHI Aqua was co-generated based on existing hydrological model setups, which are considered as state-of-the-art for the Swedish domain. However, the service can be locally customized at geographical domains outside Sweden using SMHI's operational hydrological forecasting services. This customization approach is a step forward in the service exploitation to the wider European and global markets.

CRedit authorship contribution statement

Carolina Cantone: Conceptualization, Methodology, Writing – original draft, Formal analysis, Visualization. **Helen Ivars Grape:** Writing – review & editing, Visualization. **Shadi El Habash:** Writing – review & editing, Supervision. **Ilias G. Pechlivanidis:** Conceptualization, Writing – review & editing, Supervision, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The SMHI Aqua tool is available at a web portal (<https://aqua.smhi.se>), which includes the access to a demo version with hydro-meteorological station measurements for a small region in Sweden

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for the design of the service infrastructure, its functionalities and implementation. Finally, we want to thank the A-team at SMHI ensuring that the hydro-climate service is fully operational in real-time, and also Christiana Photiadou (European Environment Agency) and Louise Crochemore (Grenoble Institute of Technology) for sharing their suggestions during the service co-generation.

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Appendix A. Template file for alternative water management scenarios

Aiming at simulating groundwater levels several months ahead due to the impact of different scenarios of water management, template files were designed for the users to provide information on alternative groundwater withdrawal.

These Excel-formatted files consist of as many sheets as the locations where scenarios on water availability are calculated, while the sheet name is uniquely identified to be read by the model and retrieve data for the simulations. In each sheet, a number of columns is provided for each water extraction scenario that is intended to be tested, where each column header uniquely identifies the water extraction scenario (Fig. A1a). These columns contain a daily time series of groundwater withdrawal for the whole calendar year (1 January – 31 December). Moreover, users can add information of groundwater levels that are critical for management operations or corresponds to limits defined by water regulations that are also presented in the web-based tool for reference (Fig. A1b). The template file also includes a set of locked cells that cannot be edited by the user where simple tests are run for ensuring the validity of the time series (Fig. A1c). Finally, a graph with the different groundwater extraction strategies is automatically generated for a quick visualization of the defined scenario (Fig. A1d). This file could be uploaded by the users in the FTP at any time. Instructions on how to use the template is included in the Excel file.

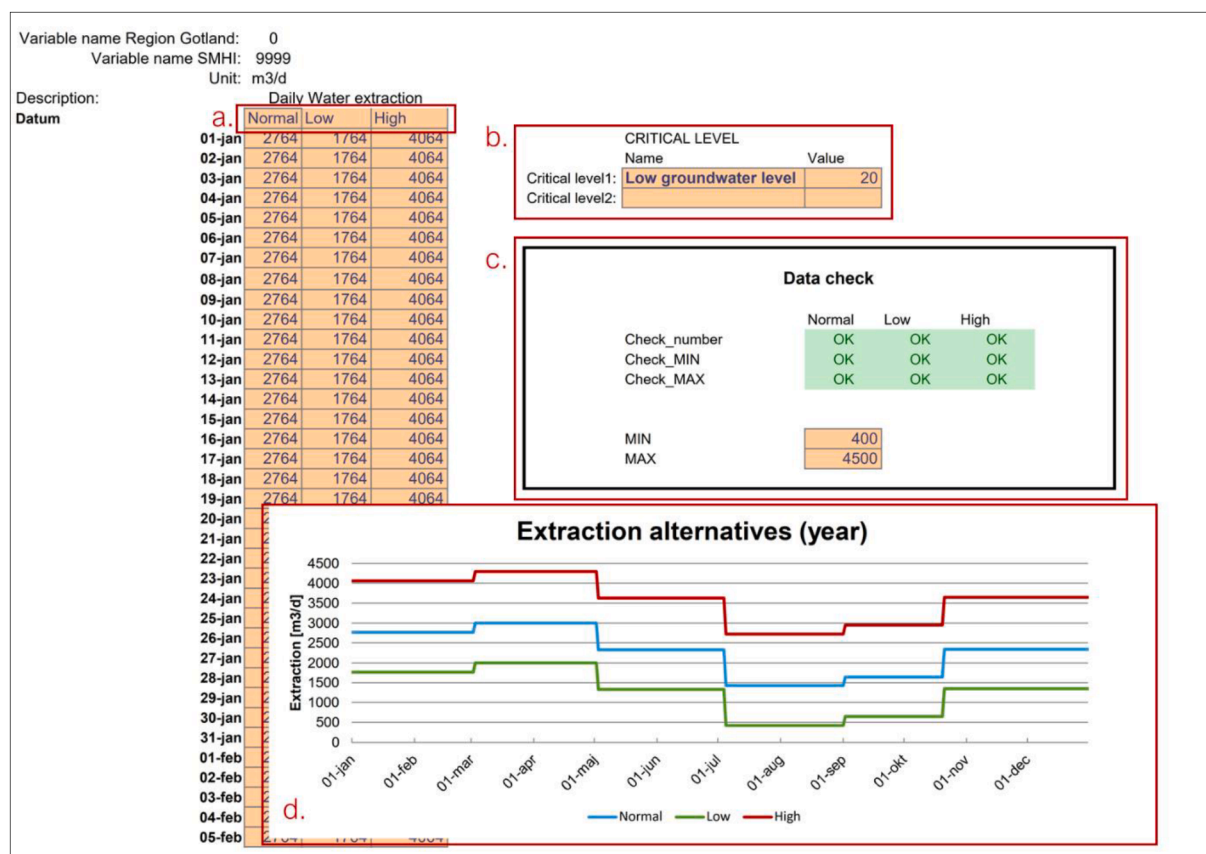


Fig. A1. Excel-formatted template file handed out to the users to provide information on alternative water management scenarios throughout the year.

Appendix B. Interaction with the users

The photos were taken in accordance with the rules of the General Data Protection Regulation (GDPR). Permission was requested from the participants prior to taking the photos, while the photos are available at the CLARA project website (<https://www.clara-project.eu/>) and CLARA deliverables.

Multi-User Forum (Venice, 03–04/10/2019)



Photo A1. Group picture with all the participants to the MUF. (Photo: CMCC).



Photo A2. Breakout session during the MUF. (Photo: CMCC).

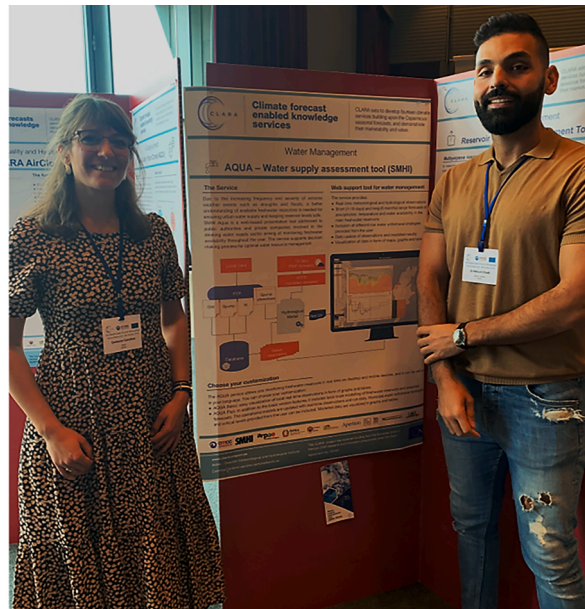


Photo A3. SMHI Aqua poster displayed by Carolina Cantone (left) and Shadi El Habash (right). (Photo: Shadi El Habash).

Workshop for the water and Waste Department of Region Gotland (Visby, 06/02/2020)



Photo A4. Carolina Cantone holding the workshop for the co-delivery of the SMHI Aqua service to the Water and Waste Department at Region Gotland. (Photo: Shadi El Habash).

Customer days with focus on drinking water (Norrköping, 12/03/2020)



Photo A5. Carolina Cantone (left) and Helen Ivars Grape (right) holding the second Customers Day workshop with focus on drinking water. (Photo: SMHI).



Photo A6. Group activity focused on risk assessment of climate stressors on water availability and its impact on drinking water production and provision. (Photo: SMHI).

Appendix 3. Survey for co-evaluation handed out to users within the CLARA project

Co-development

- Were you involved in the co-development process? If yes, what is your experience regarding your involvement in the co-development process?
- What was your desired degree of involvement? How could you contribute to improve the service (e.g. more on-field data collection)? Would you have wanted to participate more in the service development?
- Did you feel that you could influence the development of the service?
- Would you do a co-development project with us again? What part of the co-development phase would you like to change if you could?
- Do you feel that the objective of the service has changed during the process? If so, how?

Quality of the service

- Is there an added value for you with this service? If yes, how? If no, why?
- How do you evaluate the quality of the service (could be with respect to economic benefits, decision impact, data quality and improvement)?
- Which level of model skill is acceptable for you to start using the service?
- Do you think the service is worth the price? / Would you pay for this service?
- Who do you think will find the service relevant?
- In case we go to further versions, what would you change/add to improve the quality?

Awareness

- Do you understand better the value of climate information or seasonal forecasting?
- Has the capacity of your business improved by participating in the project/service? If so, how?

Decision-making

- Is the quality of the provided service in its current state suitable to make decisions? If so, has the provided service impacted the decision-making?

References

- Alexander, M., Dessai, S., 2019. What can climate services learn from the broader services literature? *Clim. Change* 157, 133–149. <https://doi.org/10.1007/s10584-019-02388-8>.
- Arheimer, B., Pimentel, R., Isberg, K., Crochemore, L., Andersson, J.C.M., Hasan, A., Pineda, L., 2020. Global catchment modelling using World-Wide HYPE (WWH), open data, and stepwise parameter estimation. *Hydrol. Earth Syst. Sci.* 24, 535–559. <https://doi.org/10.5194/hess-24-535-2020>.
- Bergström, S., 1976. Development and application of a conceptual runoff model for Scandinavian catchments. *SMHI RHO 7*, Norrköping.
- Bojovic, D., St. Clair, A.L., Christel, I., Terrado, M., Stanzel, P., Gonzalez, P., Palin, E.J., 2021. Engagement, involvement and empowerment: Three realms of a coproduction framework for climate services. *Glob. Environ. Chang.* 68, 102271.
- Brandtsen, T., Steen, T., Verschuere, B., 2018. Co-production and co-creation: engaging citizens in public services. Routledge, New York. <https://doi.org/10.4324/9781315204956>.
- Bremer, S., Wardekker, A., Dessai, S., Sobolowski, S., Slaattelid, R., van der Sluijs, J., 2019. Toward a multi-faceted conception of co-production of climate services. *Clim. Serv.* 13, 42–50. <https://doi.org/10.1016/j.cliser.2019.01.003>.
- Bruno Soares, M., Alexander, M., Dessai, S., 2018a. Sectoral use of climate information in Europe: a synoptic overview. *Clim. Serv.* 9, 5–20.
- Bruno Soares, M., Daly, M., Dessai, S., 2018b. Assessing the value of seasonal climate forecasts for decision-making. *Wiley Interdiscip. Rev. Clim. Change* 9, e523.
- Bruno Soares, M., Dessai, S., 2016. Barriers and enablers to the use of seasonal climate forecasts amongst organisations in Europe. *Climatic Change* 137 (1), 89–103. <https://doi.org/10.1007/s10584-016-1671-8>.
- Buontempo, C., Hanlon, H.M., Bruno Soares, M., Christel, I., Soubeyrou, J.M., Viel, C., Calmanti, S., Bosi, L., Falloon, P., Palin, E.J., Vanvyve, E., Torralba, V., Gonzalez-Reviriego, N., Doblas-Reyes, F., Pope, E.C.D., Newton, P., Liggins, F., 2018. What have we learnt from EUPORIAS climate service prototypes? *Clim. Serv.* 9, 21–32. <https://doi.org/10.1016/j.cliser.2017.06.003>.
- Celliers, L., Costa, M.M., Williams, D.S., Rosendo, S., 2021. The “last mile” for climate data supporting local adaptation. *Global Sustainability* 1–8. <https://doi.org/10.1017/sus.2021.12>.
- Christel, I., Hemment, D., Bojovic, D., Cucchiatti, F., Calvo, L., Stefaner, M., Buontempo, C., 2018. Introducing design in the development of effective climate service. *Clim. Serv.* 9, 111–121.
- Contreras, E., Herrero, J., Crochemore, L., Pechlivanidis, I., Photiadou, C.S., Aguilar, C., Polo, M.J., 2020. Advances in the definition of needs and specifications for a climate service tool aimed at small hydropower plants’ operation and management. *Energies* 13, 1827. <https://doi.org/10.3390/en13071827>.
- Cortekar, J., Themessl, M., Lamich, K., 2020. Systematic analysis of EU-based climate service providers. *Clim. Serv.* 17, 100125.
- Crochemore, L., Cantone, C., Pechlivanidis, I.G., Photiadou, C.S., 2021. How does seasonal forecast performance influence decision-making? Insights from a Serious Game. *Bull. Am. Meteorol. Soc.* 102 (9), E1682–E1699. <https://doi.org/10.1175/BAMS-D-20-0169.1>.
- Crochemore, L., et al. 2020. CLARA project deliverable D3.5 - Final service development report and working prototype. Available online at: <https://www.clara-project.eu/de/liverables/>.
- Daniels, E., Bharwani, S., Swartling, Å.G., Vulturius, G., Brandon, K., 2020. Refocusing the climate services lens: introducing a framework for co-designing “transdisciplinary knowledge integration processes” to build climate resilience. *Clim. Serv.* 19 (2020), 100181 <https://doi.org/10.1016/j.cliser.2020.100181>.
- Dasgupta, A., Arnal, L., Emerton, R., Harrigan, S., Matthews, G., Muhammad, A., O'Regan, K., Pérez-Ciria, T., Valdez, E., van Osnabrugge, B., Werner, M., Buontempo, C., Cloke, H., Pappenberger, F., Pechlivanidis, I.G., Prudhomme, C., Ramos, M.-H., Salamon, P., 2023. Connecting hydrological modelling and forecasting from global to local scales: perspectives from an international joint virtual workshop. *J. Flood Risk Manage.* e12880 <https://doi.org/10.1111/jfr3.12880>.
- David Tàbara, J., Jäger, J., Mangalagiu, D., Grasso, M., 2019. Defining transformative climate science to address high-end climate change. *Reg. Environ. Change* 19 (3), 807–818.
- European Commission, 2016. Directive 2016/2102 of the European Parliament and of the Council of 26 October 2016 on the Accessibility of the Websites and Mobile Applications of Public Sector Bodies. Official Journal 2 December 2016 L 327, pp. 1–15.
- European Commission, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. Official Journal 22 December 2000 L 327/1. Brussels: European Commission.
- European Commission, 2011. Roadmap to a Resource Efficient Europe (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions No. COM(2011) 571). Brussels: European Commission.
- European Commission, 2013. An EU strategy on adaptation to climate change. COM (2013) 216 final. Brussels: European Commission.
- E. Commission A European Research and Innovation Roadmap for Climate Services 2015 10.277/70215.
- Fleming, A., Bohensky, E., Dutra, L.X.C., Lin, B.B., Melbourne-Thomas, J., Moore, T., Stone-Jovicich, S., Tozer, C., Clarke, J.M., Donegan, L., Hopkins, M., Merson, S., Remenyi, T., Swirepik, A., Vertigan, C., 2023. Perceptions of co-design, co-development and co-delivery (Co-3D) as part of the co-production process – Insights for climate services. *Clim. Serv.* 30, 100364 <https://doi.org/10.1016/j.cliser.2023.100364>.
- Fuglsang, L., Hansen, A.V., 2022. Framing improvements of public innovation in a living lab context: Processual learning, restrained space and democratic engagement. *Res. Policy* 51 (1), 104390. <https://doi.org/10.1016/j.respol.2021.104390>.
- Girons Lopez, M., Crochemore, L., Pechlivanidis, I.G., 2021. Benchmarking an operational hydrological model for providing seasonal forecasts in Sweden. *Hydrol. Earth Syst. Sci.* 25, 1189–1209. <https://doi.org/10.5194/hess-25-1189-2021>.
- Giuliani, M., Crochemore, L., Pechlivanidis, I.G., Castelletti, A., 2020. From skill to value: isolating the influence of end-user behaviour on seasonal forecast assessment. *Hydrol. Earth Syst. Sci.* 24, 5891–5902. <https://doi.org/10.5194/hess-24-5891-2020>.
- Giupponi, C., Sgobbi, A., 2013. Decision support systems for water resources management in developing countries: learning from experiences in Africa. *Water* 5 (2), 798–818. <https://doi.org/10.3390/w5020798>.
- Goddard, L., 2016. From science to service. *Science* 353, 1366–1367. <https://doi.org/10.1126/science.aag3087>.
- Hewitt, C.D., Allis, E., Mason, S.J., Muth, M., Pulwarty, R., Shumake-Guillemot, J., Bucher, A., Brunet, M., Fischer, A.M., Hama, A.M., Kolli, R.K., Lucio, F., Ndiaye, O., Tapia, B., 2020. Making society climate resilient: international progress under the global framework for climate services. *Bull. Am. Meteorol. Soc.* 101 (2), E237–E252. <https://doi.org/10.1175/BAMS-D-18-0211.1>.
- Hewitt, C., Buontempo, C., Newton, P., Doblas-Reyes, F., Jochumsen, K., Quadfasel, D., 2017. Climate observations, climate modeling, and Climate Services. *Bull. Am. Meteorol. Soc.* 98 (7), 1503–1506. <https://doi.org/10.1175/BAMS-D-17-0012.1>.
- Hirons, L., Thompson, E., Dione, C., Indasi, V.E., Kilavi, M., Nkiaka, E., Talib, J., Visman, E., Adefisan, E.A., de Andrade, F., Ashong, J., Batureine Mwesigwa, J., Boul, V.L., Diédhiou, T., Konte, O., Gudoshava, M., Kiptum, C., Konadu Amoah, R., Lamptey, B., Lawal, K.A., Muita, R., Nzekwu, R., Nying'uro, P., Ochieng, W., Olaniyan, E., Opoku, E.K., Endris, H.S., Segele, Z., Igri, P.M., Mwangi, E., Woolnough, E., 2021. Using co-production to improve the appropriate use of sub-seasonal forecasts in Africa. *Clim. Serv.* 23, 00246. <https://doi.org/10.1016/j.cliser.2021.100246>.
- Hossain, M., Leminen, S., Westerlund, M., 2019. A systematic review of living lab literature. *Journal of Cleaner Production* 213, 976–988. <https://doi.org/10.1016/j.jclepro.2018.12.257>.

- Hundeche, Y., Arheimer, B., Donnelly, C., Pechlivanidis, I.G., 2016. A regional parameter estimation scheme for a pan-European multi-basin model. *J. Hydrol. Region. Stud.* 6, 90–111. <https://doi.org/10.1016/j.ejrh.2016.04.002>.
- Hurkmans, R., van den Hurk, B., Schmeits, M., Wetterhall, F., Pechlivanidis, I.G., 2023. Comparing seasonal streamflow forecast systems for management of a freshwater reservoir in the Netherlands. *J. Hydrometeorol.* <https://doi.org/10.1175/JHM-D-22-0107.1>.
- Jacobs, K.L., Street, R.B., 2020. The next generation of climate services. *Clim. Serv.* 20, 100199 <https://doi.org/10.1016/j.cliser.2020.100199>.
- Johansson, B., 2000. Areal precipitation and temperature in the Swedish mountains. an evaluation from a hydrological perspective. *Nordic Hydrol.* 31, 207–228.
- Johnson, S.J., Stockdale, T.N., Ferranti, L., Balmaseda, M.A., Molteni, F., Magnusson, L., Tietsche, S., Decremet, D., Weisheimer, A., Balsamo, G., Keeley, S.P.E., Mogensen, K., Zuo, H., Monge-Sanz, B.M., 2019. SEAS5: the new ECMWF seasonal forecast system. *Geoscientific Model Dev.* 12 (3), 1087–1117.
- Krysanova, V., Vetter, T., Eisner, S., Huang, S., Pechlivanidis, I.G., Strauch, M., Aich, V., Arheimer, B., Chamorro, A., Gelfan, A., van Griensven, A., Kumar, R., Kundu, D., Lobanova, A., Mishra, V., Plötner, S., Reinhardt, J., Seidou, O., Wang, X., Hattermann, F.F., 2017. Intercomparison of regional-scale hydrological models in the present and future climate for 12 large river basins worldwide – A synthesis. *Environ. Res. Lett.* 12, 105002 <https://doi.org/10.1088/1748-9326/aa8359>.
- Larosa, F., & Mysiak, J., 2020. Business models for climate services: An analysis. *Climate Services*, Volume 17, 100111, ISSN 2405-8807. <https://doi.org/10.1016/j.cliser.2019.100111>.
- Larosa, F., Mysiak, J., 2019. Mapping the landscape of climate services. *Environ. Res. Lett.* 14 (9), 093006.
- Lavers, D., Ramos, M.-H., Magnusson, L., Pechlivanidis, I.G., Klein, B., Prudhomme, C., Arnal, L., Crochemore, L., van den Hurk, B., Weerts, A., Harrigan, S., Cloke, H., Richardson, D., Pappenberger, F., 2020. A vision for hydrological prediction. *Atmosphere* 11 (3), 237. <https://doi.org/10.3390/atmos11030237>.
- Lindström, G., Pers, C., Rosberg, J., Strömqvist, J., Arheimer, B., 2010. Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. *Hydrol. Res.* 41 (3–4), 295–319.
- Macian-Sorribes, H., Pechlivanidis, I., Crochemore, L., Pulido-Velazquez, M., 2020. Fuzzy Postprocessing to Advance the Quality of Continental Seasonal Hydrological Forecasts for River Basin Management. *J. Hydrometeorol.* 21, 2375–2389. <https://doi.org/10.1175/JHM-D-19-0266.1>.
- Mausser, W., Klepper, G., Rice, M., Schmalzbauer, B.S., Hackmann, H., Leemans, R., Moore, H., 2013. Transdisciplinary global change research: the co-creation of knowledge for sustainability. *Curr. Opin. Environ. Sustain.* 5 (3–4), 420–431. <https://doi.org/10.1016/j.cosust.2013.07.001>.
- Mazrooei, A., Sinha, T., Sankarasubramanian, A., Kumar, S., Peters-Lidard, C.D., 2015. Decomposition of sources of errors in seasonal streamflow forecasting over the U.S. Sunbelt. *J. Geophys. Res. Atmos.* 120, 11809–11825. <https://doi.org/10.1002/2015JD023687>.
- Monhart, S., Zappa, M., Spirig, C., Schär, C., Bogner, K., 2019. Subseasonal hydrometeorological ensemble predictions in small- and medium-sized mountainous catchments: benefits of the NWP approach. *Hydrol. Earth Syst. Sci.* 23, 493–513. <https://doi.org/10.5194/hess-23-493-2019>.
- Musuza, J.L., Crochemore, L., Pechlivanidis, I.G., 2023. Evaluation of earth observations and in situ data assimilation for seasonal hydrological forecasting. *Water Resour. Res.* 59 e2022WR033655. <https://doi.org/10.1029/2022WR033655>.
- Mysiak, J., Giupponi, C., Rosato, P., 2005. Towards the development of a decision support system for water resource management. *Environ. Modell. Softw.* 20 (2), 203–214. <https://doi.org/10.1016/j.envsoft.2003.12.019>.
- Padilla, L.M., Creem-Regehr, S.H., Hegarty, M., et al., 2018. Decision making with visualizations: a cognitive framework across disciplines. *Cogn. Res.* 3, 29. <https://doi.org/10.1186/s41235-018-0120-9>.
- Pappenberger, F., Stephens, E., Thielen, J., Salamon, P., Demeritt, D., van Andel, S.J., et al., 2013. Visualizing probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication. *Hydrol. Process.* 27 (1), 132–146. <https://doi.org/10.1002/hyp.9253>.
- Pappenberger, F., Ramos, M.H., Cloke, H.L., Wetterhall, F., Alfieri, L., Bogner, K., Mueller, A., Salamon, P., 2015. How do I know if my forecasts are better? Using benchmarks in hydrological ensemble prediction. *J. Hydrol.* 522, 697–713. <https://doi.org/10.1016/j.jhydrol.2015.01.024>.
- Pechlivanidis, I.G., Arheimer, B., Donnelly, C., Hundeche, Y., Huang, S., Aich, V., Samaniego, L., Eisner, S., Shi, P., 2017. Analysis of hydrological extremes at different hydro-climatic regimes under present and future conditions. *Clim. Change* 141 (3), 467–481. <https://doi.org/10.1007/s10584-016-1723>.
- Pechlivanidis, I.G., Crochemore, L., Rosberg, J., Bosshard, T., 2020. What are the key drivers controlling the forecasts of seasonal streamflow volumes? *Water Resour. Res.* <https://doi.org/10.1029/2019WR026987>.
- Pechlivanidis, I.G., Bosshard, T., Spångmyr, H., Lindström, G., Gustafsson, D., & Arheimer, B., 2014. Uncertainty in the Swedish operational hydrological forecasting systems. In M. Beer, S. K. Au, & J. M. Hall (Eds.), *Vulnerability, Uncertainty, and Risk: Quantification, Mitigation and Management* (pp. 253–262).
- Photiadou, C., Arheimer, B., Bosshard, T., Capell, R., Elenius, M., Gallo, I., Gyllensvärd, F., Klehmet, K., Little, L., Ribeiro, I., Santos, L., Sjökvist, E., 2021. Designing a climate service for planning climate actions in vulnerable countries. *Atmosphere* 12, 121. <https://doi.org/10.3390/atmos12010121>.
- Pimentel, R., Arheimer, B., Crochemore, L., Andersson, J.C., Pechlivanidis, I.G., Gustafsson, D., 2023. Which potential evapotranspiration formula to use in hydrological modelling world-wide? *Water Resour. Res.* 59 e2022WR033447. <https://doi.org/10.1029/2022WR033447>.
- Pimentel, R., Photiadou, C., Little, L., Huber, A., Lemoine, A., Leidinger, D., Lira-Loarca, A., Lückenköter, J., Pasten-Zapata, E., 2022. Improving the usability of climate services for the water sector: the AQUACLEW experience. *Clim. Serv.* 28, 100329 <https://doi.org/10.1016/j.cliser.2022.100329>.
- Polo and Jurado, 2018. CLARA project deliverable 2.1 – Forum activity report I. Available online at: <https://www.clara-project.eu/deliverables/>.
- Raaphorst, K., Koers, G., Ellen, G.J., Oen, A., Kalsnes, B., Well, L.V., BruggeDer, R.V., 2020. Mind the gap: towards a typology of climate service usability gaps. *Sustainability* 12, 1512. <https://doi.org/10.3390/su12041512>.
- Region Gotland, 2019. Desalinated seawater - Can you really drink seawater? (in Swedish). Available at: <https://www.gotland.se/avsaltatavsvatten>.
- Samaniego, L., Kumar, R., Breuer, L., Chamorro, A., Flörke, M., Pechlivanidis, I.G., Schäfer, D., Shah, H., Vetter, T., Wortmann, M., Zeng, X., 2017. Propagation of forcing and model uncertainty into hydrological drought characteristics in a multi-model century-long experiment in continental river basins. *Clim. Change* 141, 435–449. <https://doi.org/10.1007/s10584-016-1778-y>.
- Sanders, E.-B.-N., Stappers, P.J., 2008. Co-creation and the new landscapes of design. *CoDesign* 4 (1), 5–18. <https://doi.org/10.1080/15710880701875068>.
- Street, R., Parry, M., Scott, J., Jacob, D., Runge, T., & European Commission. Directorate-General for Research and Innovation, 2015: A European research and innovation roadmap for climate services. Publications Office. <https://data.europa.eu/doi/10.2777/702151>.
- Tart, S., Groth, M., Seipold, P., 2020. Market demand for climate services: an assessment of users' needs. *Clim. Serv.* 17, 100109.
- Trenberth, K., Marquis, M., Zebiak, S., 2016. The vital need for a climate information system. *Nat. Clim. Change* 6, 1057–1059. <https://doi.org/10.1038/nclimate3170>.
- Tudose, N.C., Marin, M., Cheval, S., Mitter, H., Broekman, A., Sanchez-Plaza, A., Ungurean, C., Davidescu, S., 2023. Challenges and opportunities of knowledge co-creation for the water – energy – land nexus. *Clim. Serv.* 30, 100340.
- van den Hurk, B., Bouwer, L.M., Buontempo, C., Döschner, R., Erce, E., Hananel, C., Hunink, J.E., Kjellström, E., Klein, B., Manez, M., Pappenberger, F., Pouget, L., Ramos, M.-H., Ward, P.J., Weerts, A.H., Wijngaard, J.B., 2016. Improving predictions and management of hydrological extremes through climate services: www.imprex.eu. *Clim. Serv.* 1, 6–11. <https://doi.org/10.1016/j.cliser.2016.01.001>.
- Van Gevelt, T., 2020. The water–energy–food nexus: bridging the science–policy divide. *Curr. Opin. Environ. Sci. Health* 13, 6–10. <https://doi.org/10.1016/j.coesh.2019.09.008>.
- Vaughan, C., Dessai, S., 2014. Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdiscip. Rev. Clim. Change* 5, 587–603. <https://doi.org/10.1002/wcc.290>.
- Viel, C., Beaulant, A.-L., Soubeyroux, J.-M., Ceron, J.-P., 2016. How seasonal forecast could help a decision maker: an example of climate service for water resource management. *Adv. Sci. Res.* 13, 51–55. <https://doi.org/10.5194/asr-13-51-2016>.
- Vincent, K., Daly, M., Scannell, C., Leathes, B., 2018. What can climate services learn from theory and practice of co-production? *Clim. Serv.* 12, 48–58. <https://doi.org/10.1016/j.cliser.2018.11.001>.
- Vincent, K., Conway, D., Dougill, A.J., Pardoe, J., Archer, E., Bhavé, A.G., Tembo-Nhlema, D., 2020. Rebalancing climate services to inform climate-resilient planning – A conceptual framework and illustrations from sub-Saharan Africa. *Clim. Risk Manage.* 29 <https://doi.org/10.1016/j.crm.2020.100242>.
- Visscher, K., Stegmaier, P., Damm, A., Hamaker-Taylor, R., Harjanne, A., Giordano, R., 2020. Matching supply and demand: a typology of climate services. *Clim. Serv.* 17, 100136.
- Region Gotland, 2021. Irrigation ban (in Swedish). Available at: <https://www.gotland.se/bevattningsforbud>.
- Vogel, E., Lerat, J., Pipunic, R., Frost, A., Donnelly, C., Griffiths, M., Hudson, D., Loh, S., 2021. Seasonal ensemble forecasts for soil moisture, evapotranspiration and runoff across Australia. *J. Hydrol.* 601 (126), 620. <https://doi.org/10.1016/j.jhydrol.2021.126620>.
- White, C.J., Carlsen, H., Robertson, A.W., Klein, R.J.T., Lazo, J.K., Kumar, A., Vitart, F., Coughlan de Perez, E., Ray, A.J., Murray, V., Bharwani, S., MacLeod, D., James, R., Fleming, L., Morse, A.P., Eggen, B., Graham, R., Kjellström, E., Becker, E., Pegion, K. V., Holbrook, N.J., McEvoy, D., Depledge, M., Perkins-Kirkpatrick, S., Brown, T.J., Street, R., Jones, L., Remenyi, T.A., Hodgson-Johnston, I., Buontempo, C., Lamb, R., Meinke, H., Arheimer, B., Zebiak, S.E., 2017. Potential applications of subseasonal-to-seasonal (S2S) predictions. *Meteorol. Appl.* 24 (3), 315–325.
- White, C.J., Domeisen, D.I.V., Acharya, N., Adefisan, E.A., Anderson, M.L., Aura, S., Balogun, A.A., Bertram, D., Bluhm, S., Brayshaw, D.J., Browell, J., Büeler, D., Charlton-Perez, A., Chourio, X., Christel, I., Coelho, C.A.S., DeFlorio, M.J., Delle Monache, L., Di Giuseppe, F., García-Solórzano, A.M., Gibson, P.B., Goddard, L., González Romero, C., Graham, R.J., Graham, R.M., Grams, C.M., Halford, A., Huang, W.T.K., Jensen, K., Kilavi, M., Lalw, K.A., Lee, R.W., MacLeod, D., Manrique-Suñén, A., Martins, E.S.P.R., Maxwell, C.J., Merryfield, W.J., Muñoz, Á.G., Olaniyan, E., Otieno, G., Oyedepo, J.A., Palma, L., Pechlivanidis, I.G., Pons, D., Ralph, F.M., Reis, D.S., Remenyi, T.A., Risbey, J.S., Robertson, D.J.C., Robertson, A. W., Smith, S., Soret, A., Sun, T., Todd, M.C., Tozer, C.R., Vasconcelos, F.C., Vigo, I., Waliser, D.E., Wetterhall, F., Wilson, R.G., 2021. n.d. 2021 Advances in the application and utility of subseasonal-to-seasonal predictions. *Bulletin of American Meteorological Society*. <https://doi.org/10.1175/BAMS-D-20-0224.1>.
- Wibeck, V., Eliasson, K., Neset, T.S., 2022. Co-creation research for transformative times: facilitating foresight capacity in view of global sustainability challenges. *Environ. Sci. Policy* 128, 290–298. <https://doi.org/10.1016/j.envsci.2021.11.023>.
- Winnfors Wannberg, E., 2019. Water supply is secured with modelling tools (in Swedish). *Cirkulation*, 7, 12–16. Available at: <https://www.cirkulation.se/artiklar-och-notiser/vattentillgang-saekras-med-modellverktyg/>.

- Wiser Manual for Co-production in African Weather and Climate Services, 2nd Edition, Weather and Climate Information Services for Africa (WISER) and Future Climate for Africa (FCFA) [https://futureclimateafrica.org/coproduction-manual/downloads/WISER-FCFA\[1\]coproduction-manual.pdf](https://futureclimateafrica.org/coproduction-manual/downloads/WISER-FCFA[1]coproduction-manual.pdf) 2020 Available online at: Last accessed 2023-03-11.
- Wood, A.W., Lettenmaier, D.P., 2006. A test bed for new seasonal hydrologic forecasting approaches in the Western United States. *Bull. Am. Meteorol. Soc.* 87 (12), 1699–1712. <https://doi.org/10.1175/BAMS-87-12-1699>.
- Ziogas, A.I., Pechlivanidis, I.G., Romas, E.D., Tzimas, A.M., 2021. Climate service derived indicators to assess the impact of climate change on local river assimilative capacity. *Clim. Change* 23, 100250. <https://doi.org/10.1016/j.cliser.2021.100250>.