Article

Advances in the definition of needs and specifications for a climate service tool aimed at small hydropower plants operation and management†

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Abstract: The operation feasibility of small hydropower plants in mountainous sites is subjected to the run-of-river flow which is also depending on a high variability in precipitation and snow cover. Moreover, the management of this kind of systems has to be performed with some particular operation conditions of the plant (e.g. turbine minimum and maximum discharge) but also some environmental flow requirements. In this context, a technological climate service is conceived in tight connection with end users, perfectly answering the needs of the management of small hydropower systems in a pilot area, and providing forecast of river streamflow together with other operation data. This paper presents an overview of the service but also a set of lessons learnt related to features, requirements and considerations to bear in mind from the point of view of climate services developers. In addition, the outcomes give insight into how this kind of services could change the traditional management (normally based on the past experience), providing a probability range of future river flow based on future weather scenarios according to the range of future weather possibilities. This highlights the utility of the co-generation process to implement climate services for water and energy fields but also that seasonal climate forecast could improve the business as usual of this kind of facilities.

Keywords: small hydropower plant, river flow, seasonal forecast, energy production.

1. Introduction

Hydroelectric power is one of the cheapest, reliable, sustainable, and renewable sources of energy [1]. Hydropower projects may also be considered as an adaptive measure regarding the impacts of climate change on water resources, because regulated basins with large reservoir capacities are more resilient to water resource changes [2]. However, small-scale hydropower plants are in most cases Run-of-River (RoR) systems, hydropower plants located in mountainous areas, with no dam or water storage. This type of facility, despite being one of the most cost-effective (with relatively low operational and maintenance costs) and environmentally benign energy technologies [3], has the disadvantage of having an irregular production and is subjected to the RoR flow which is also depending on a high variability in precipitation and snow cover duration. As RoR plants typically have a small or no storage facility which allows very short term water storage, the hydropower station does not have enough water to remain operational when inflow drops below the minimum technical inflow of the turbines. Another drawback of these systems is that when inflows are high and the storage available is full, water will have to be "spilled", which represents a lost opportunity for generation [4].

Europe is a market leader of small hydropower production technology, with Spain, together with Italy, France, Germany and Sweden being the main producers [5]. However, the potential of RoR plants has not been fully explored and exploited and there is a considerable scope for development and optimization of this technology [5]. The management has to be performed with some particular operation conditions of the plants but also some environmental flow requirements. In this context, it would be useful for decision-makers to have information about the short and medium-term streamflow, in order to know the energy to be produced in the following months for market issues, as well as planning the maintenance tasks or other energy resources when the discharge drops below the minimum operation inflow.

Although some forecast models have been already proposed and applied in the small hydropower production field [6-9], there is still an existing gap to link forecasts with decision support processes. Indeed, although there have been great advances in the climate forecast framework, thus far, RoR system managers (and managers of other water infrastructures such as reservoirs) normally take decisions based on historical inflows. There is currently a number of European projects (e.g. MED-GOLD, CLARA, S2S4E, H2020_Insurance, VISCA, CLIMATE-FIT, SECLI-FIRM, PROSNOW, CLARITY) involved in the development of tailored and usable climate services (CS) that can facilitate the uptake and use of climate information and forecast by the final users. In the framework of the H2020 project CLARA (Climate forecast enabled knowledge services),a CS targeted at end-users and able to support small hydropower systems management, has been developed. A preliminary version of this tool is presented in [10], showing the structure of the tool and utilities but without delving into details such as the data and models used and the co-development process outcomes. That preliminary version used a single forecast. However, as probabilistic forecasts are based on ensembles, in this paper we use a set of forecasts that represent a range of future weather possibilities. Multiple simulations are run, each with a slight disturbance of the initial conditions of the weather models [11]. The new version presented here includes the range of probabilistic forecasts in order to show end-users the range of weather possibilities. The aim of this work is also to show the main outcomes of the co-generation process in order to provide a short guide to help future CS developers to connect climate forecast data with the decision support process. It will provide a very useful knowledge for technicians in charge of control operation centres of small hydropower plants and managers in regional administrations.

The main novelty of the proposed solution is the development of a leading-edge CS building upon the newly developed Copernicus Climate Change Services (C3S) [12], which offers information based on satellite Earth Observation and in situ (non-space) data. Future climate information from C3S, in this case the SEAS5 [13], will provide input seasonal forecast data to the developed CS. Another novelty is that, thanks to the co-generation methodology used, the proposed service bridges the gap between data providers who provide climate-impact data on one side, and managers and policy makers on the other side. Moreover, the service is based on a scalable database allowing its implementation in other systems. This will ensure that the available information is useful for small hydropower management at local and regional scale across Europe, which contributes to the marketability of this type of information. More generally, this paper aims to highlight the value that CS tools can bring to the hydropower energy field but also to bring out relevant outcomes about the skill of the forecast data when applied at the local scale in a pilot area in Southern Spain.

The paper is organized as follows: section 2 introduces the methodology carried out for the service development, including a pilot area description, data and models used, and the CS approach which also illustrates the CS workflow, section 3 presents the main outcomes of the co-design process, the final structure of the web user interface and service outputs examples, and section 4 contains the findings and implications of the main results.

2. Materials and Methods

2.1.The pilot area in Southern Spain

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The CS was tested in southern Spain, in a Mediterranean high mountain area where the snow has a critical influence over the hydrology of the downstream areas. The pilot RoR system consists of three small hydropower plants in sequence located in the Poqueira River basin (Figure 1), with a generating capacity between 10 and 12 megawatts and managed by a leading company in the Spanish energy sector. The basin is located in Sierra Nevada Mountains, National Park and Biosphere Reserve, which explains why it is especially important to carry out an adequate management of the water resources respecting the minimum environmental flow. It is also an Alpine/Mediterranean climate region where the annual precipitation regime in the site is highly variable and ranges between values close to 1000 mm in wet years and 200 mm in dry years [14]. Snow recurrently appears in the mountain range at altitudes above 1000 m a.s.l. and it is mostly persistent above 2500 m a.s.l. from November to May, undergoing several cycles of accumulation-ablation during the snow season [15]. The mean annual fractional snow cover area for the period 2000–2013 was 0.21 $m^2 \cdot m^{-2}$, ranging from 0.9 to 0.16 $m^2 \cdot m^{-2}$ in wet/cold and dry/warm years, respectively, with a mean standard deviation of 0.23 $m^2 \cdot m^{-2}$ [16]. This, results in a very heterogeneous spatial distribution over the years, which makes this pilot area a great candidate to implement the CS proposed.

Under these circumstances, climate is extremely variable and seasonal forecasts usually show a very limited skill and performance. However, the use of a seasonal forecast in this pilot area will allow managers to estimate the production in the next 6 months thanks to the knowledge of the water availability in terms of volume of snow (from the real time hydrological state of the contributing basin to the RoR plants) together with the information of seasonal forecast of river inflow.

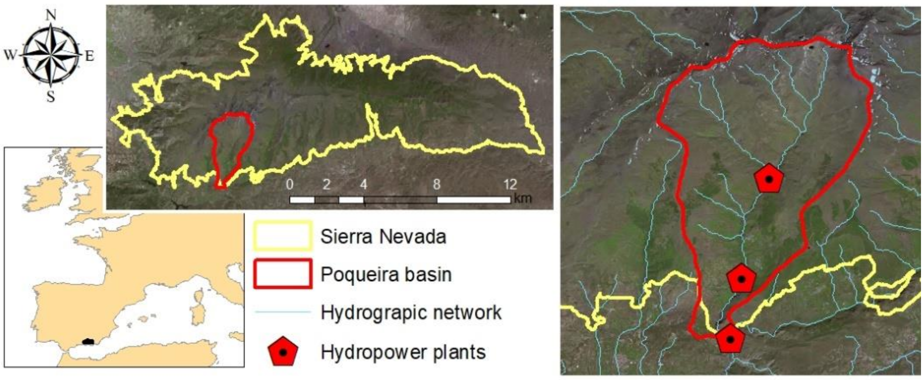

Figure 1. Location of the Poqueira basin in Southern Spain and the three small hydropower plants system in the pilot area.

2.2. Data and models

Several data sources were used in this work: historical information, seasonal forecast data and local data, all of them provided in the collaborative framework of the CLARA project.

On the one side, the service includes dynamic data, that is seasonal forecast data and simulated hydrological data, that can be updated as better knowledge of the physical environment and more measurements become available, resulting in improved data forcing and models:

- Seasonal (seven months) forecast of daily river flow data issued monthly by the Swedish Meteorological and Hydrological Institute (SMHI). SMHI produces these data by forcing the E-HYPE model with the ECMWF SEAS5 seasonal forecast. SEAS5 is based on a global climate model which, since the oceanic circulation is a major source of predictability in the seasonal scale, is based on coupled ocean-atmosphere integrations [17]. E-HYPE is the European setup of the HYPE model, which calculates hydrological variables on a daily time-step at an average sub-basin resolution of 120 km^2 over the entire continent [17-19]. Probabilistic forecasts are produced as an ensemble of scenarios that present the range of future river flow possibilities. In

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the service testing stage, we used the SEAS5 hindcast period 1981-2015 for each calendar month and up to seven months ahead considering an ensemble of 51 members. In this work, the raw seasonal forecast data were presented at monthly scale and downscaled to the intake points of the three RoR systems to match the temporal and spatial scale suitable for this particular application. This was done by using a quantile mapping methodology [20, 21], usually adopted as bias correction method, which leads to a good performance [21, 22].

- Interpolation of the meteorological real-time data and current state of the hydrological variables are extracted from GMS-Snowmed service [23], which makes use of WiMMed [24-26], a physically based and fully distributed hydrological model. This service makes use of past and quasi-real time observations of daily hydro-meteorological data (precipitation, temperature, river flow), from different meteo-hydrological networks in the area (Red Guadalfeo, SAIH Guadalquivir, RIA-JA, Red Hidrosur). The outputs of GMS-Snowmed directly offer distributed information about the antecedent weather and current water availability in the basin upstream the RoR plants at daily and monthly scales.

On the other side, the service makes use of static data related to local specific facility features defined by end-users:

- Past observations of daily streamflow measurements, provided by the managers of the hydropower system and available for the period 1969-2018. These data providea very adequate overview of the historical river inflow to the RoR system.
- Some records related to the specific consumption of the turbines also provided by the managers of the hydropower system. This information is mainly used to compute the production of the hydropower plants.
- Threshold value of the target indicators in the service, according to the minimum and maximum technical inflow of the turbines, provided by the managers of the hydropower system.
- Minimum environmental flow restrictions, as defined in the Hydrological Plan of the Mediterranean River Basin, the water authority in the study site.

2.3. Climate service approach

The new technological pilot tool developed as CS was named SHYMAT (Small Hydropower Management Assessment Tool).It was developed following a co-generation process involving data providers, service purveyors and end-users (Figure 2), all of them engaged on equal footing in an effort for co-designing, co-developing, co-delivering and co-evaluating CS tools [27]. The outcomes and conclusions of this co-development process are presented in Section 3. Figure 2 shows an overview of the structure of the service, including the inputs from different data sources, the data processing workflow and the service outputs.

Firstly, the historical and quasi-real time hydro-meteorological information is collected from the GMS-Snowmed service, and the seasonal forecast of daily river flow is combined with historical and real time local data to make the downscaling generation of river flow in the RoR system uptake point, as an indicator of available water to generate electricity. Then, a set of local specifications, such as indicator thresholds, turbine performance, specific consumption curve and environmental flow rules are defined by end-users as well as the outputs answering their needs.

Once all the seasonal forecast, basin and river data and local facility data are automatically collected, a data model including all the available information and the topology of the pilot RoR system is developed in order to build a scalable database with an administration panel, allowing the implementation of SHYMAT in other sites. Thus, the on-line implementation of SHYMAT included two aspects:

- A web administration panel, where a set of users, hydropower systems, elements of the system (rivers, load chambers, hydropower plants, basins, electrical towers) and available data (related

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to climate, hydrology and energy production) are defined, stored and managed. This panel is only accessible by service developers or customers with an administrator role login.

- A web user interface with capacities for SIG geolocalization, user registration, data processing and acquisition and a graphical monitoring and supervision system, which allows fast and intuitive access to all information. The graphical application allows users switch between a "historical information" mode and a "forecast" mode. The first one shows weather and hydrological past and real time data. The second one includes not only weather and hydrological forecast data, but also some information related to the operability of the plant and the energy production expected for the next seven months (the current and the next six months).

The service was implemented using a View Controller Model (VCM). When an end-user sends a query to the application, the controller (administration panel) asks the model the information from the database, which answers the controller by sending the requested information. Then, the controller sends the information to the view (web user interface). This software architecture was developed integrating HTML and JavaScript. The data models and processing routines were implemented in Python programming language; for that reason, the web framework Django was used for their integration in the database. Thus, the end-users directly access the web user interface, which automatically collects the updated information from the web administration panel that is only accessible by service developers or end-users with administrator role.

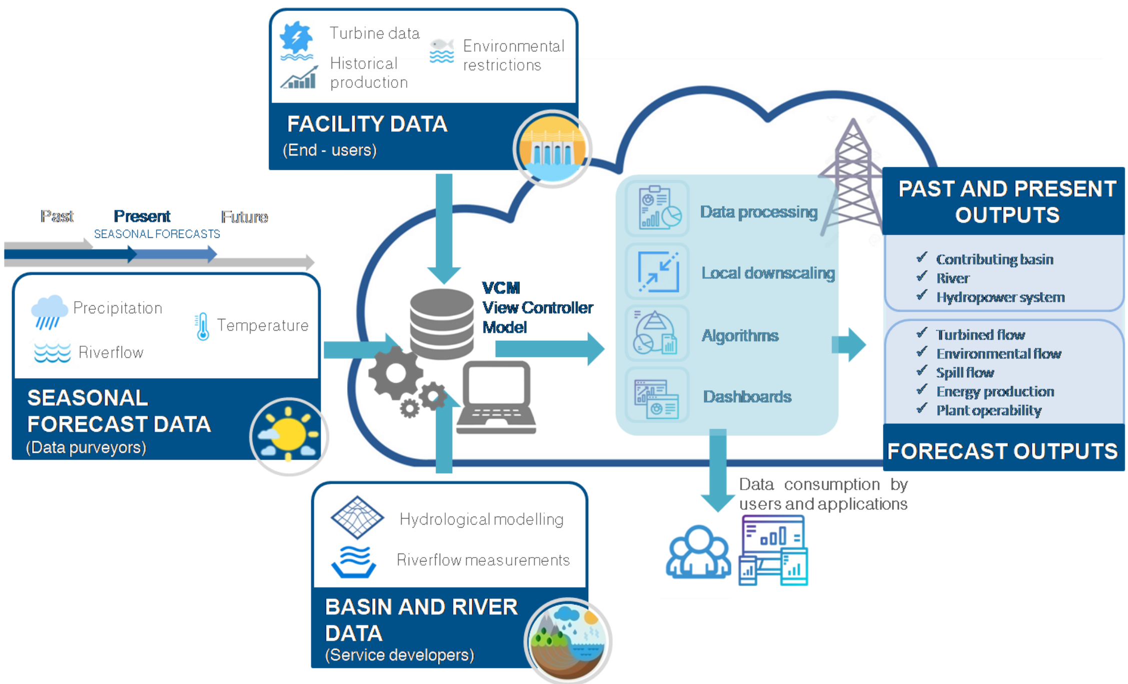

Figure 2. Structure of the CS developed in CLARA project for the operation of RoR plants (SHYMAT), including seasonal forecast, facility data and historical data.

3. Results

3.1. Outcomes of the co-development process

The co-development process was carried out through seven face-to-face meetings during an 11-month period, when service providers and pilot end-users were discussing about the user needs and the specifications and requirements to be implemented in the CS. The main lessons learnt from the meetings were:

- The user needs and the specifications and requirements to be implemented in the CS were set according to the operation in RoR plants. SHYMAT should cover the end-user needs providing

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an answer to these questions: 1) Will my RoR plant be operative during the coming months?; 2) When are conditions for turbinable river flow expected for the coming months?; 3) What is the best date to plan maintenance tasks for the next coming months?; 4) Will the minimum environmental flow restrictions be met for the next months?; 5) What will be the energy production expected for the coming months?; 6) When should I tune up the machines to increase the capacity of my plant to take advantage from the water excess discharges coming from snowmelt?

- Hydropower managers traditionally use historical inflows in order to predict the water availability and the energy production; different past data-based scenarios (last year, driest year, wettest year) are compared to the current situation on a monthly basis, as a simple forecast approach. The difficulty in using forecast information is mainly that data do not provide reliable and concise information to be used in the decision support process.
- The main data required for the CS implementation to be provided by the end-users were identified: specific consumption of the machines, minimum and maximum turbine thresholds, ecological flow to be considered, historical daily production and turbined flow data.
- Regarding the analysis of how the CS could improve the management of the plants, the definition of payoff should be considered in terms of amount of produced energy. However the value of the energy production forecast is also related to market issues and to the schedule of the operation for investment or maintenance tasks.
- The web user interface and graphical outputs were defined. One of the main lessons learnt was that users preferred not too technical graphs and not too much information in the same graph, as well as clear information about forecast skill and comparison between past forecast and observed data. Moreover, users were also interested in the hydrological state of the basin upstream (defined by variables such as the current amount of snow) and short time forecast data, as managers also need to plan for the short time (which will be taken into account in the updated version of the service).
- The CS tool should be easily scalable to other small hydropower plants. It is presented as a cloud web application based on a scalable database allowing the implementation in other systems with similar characteristics to the pilot area. This database will be managed through an administration panel, which includes the users and typical component and data of the hydropower systems (Figure 3). From the information included in this database, a topology panel will be dynamically generated showing the different components and relations (Figure 4).

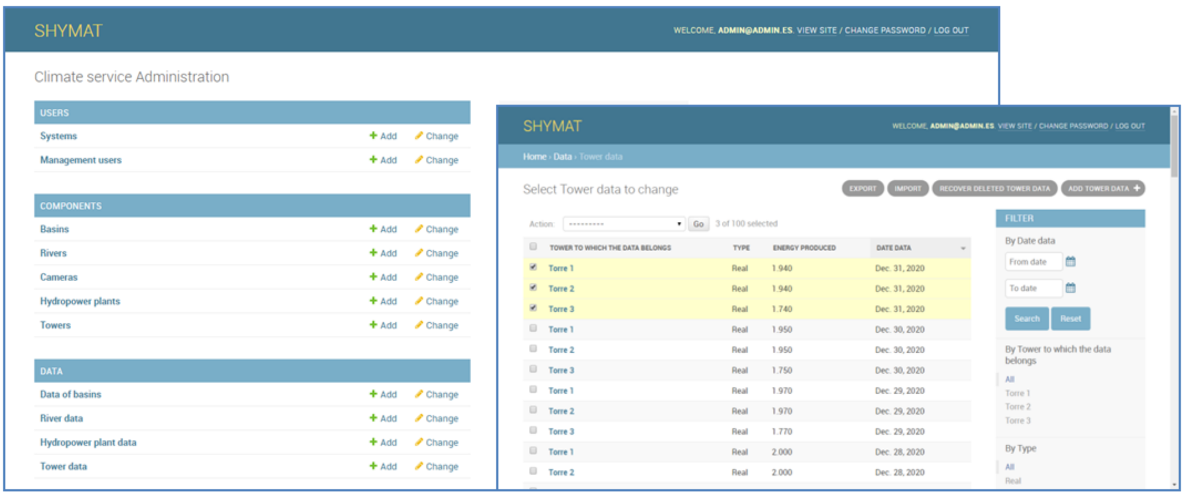

Figure 3. Visualization of the database panel showing the users, components and data of the pilot RoR system (SHYMAT).

Finally, the structure of the web user interface and the graphical outputs for the on-line monitoring system were defined as follows:

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- A login screen for each customer to access its personalized web page service. After a first on-line registration, access is given to certain RoR systems (payed access) or only to public information (open access). Both types of access login need to be previously accepted by the service developers' team.
- A GIS map: A customer can be manager of different RoR systems. For this, once the user is registered, all the systems managed by that user are displayed in a geolocalized map, where the user can choose the system in which he is interested.
- A topology panel module: A panel containing the topological representation of the RoR system shows the different elements, such as rivers, basins, load chambers, hydropower plants and electrical towers. The properties of these elements are defined by data corresponding to the meteorological, hydrological and plant operation variables. The topological scheme also shows the interactions between all the entities that compose the small hydropower system and is dynamically generated from the web administration panel during the setup of the CS.
- A water availability and operation module: Here a set of weather data (rainfall, snow and temperature), hydrological data (river flow) and operation data (number of days with operation and energy production) is computed and stored. This provides users with the information about past, present and future climate and water availability in the basin and in the uptake point of the plant. This module includes both a historical and a forecast information mode. In the historical mode, hydro-meteorological and operational data related to the RoR system are displayed and compared for the different years at daily and monthly scale. The forecast mode covers the outputs related to operation aspects which are only defined for forecast purposes. One of the outputs is the operability of the facility expected, according to the provided forecast, for the next seven months. In addition, seasonal forecasting of the river flow, the energy produced and the environmental flow conditions are displayed for the end users.
- A tool for exporting the raw data to different formats required by the user and sending queries for certain periods. This facilitates the integration of the CS outputs into the individual operational and managerial systems of the end-users.

3.2. Service outputs

The result is a technological tool targeted at end-users which provides forecast of river flow and displays it in a user-friendly web interface, together with other information useful for small hydropower managers. The user interacts with SHYMAT by logging and selecting one small hydropower system of interest in a GIS map (Figure 4). A panel containing the topological representation of the small hydropower system is automatically displayed showing the different elements (Figure 4). Once the user chooses an element of the topology panel, the available information appears in the screen at the requested time scale.

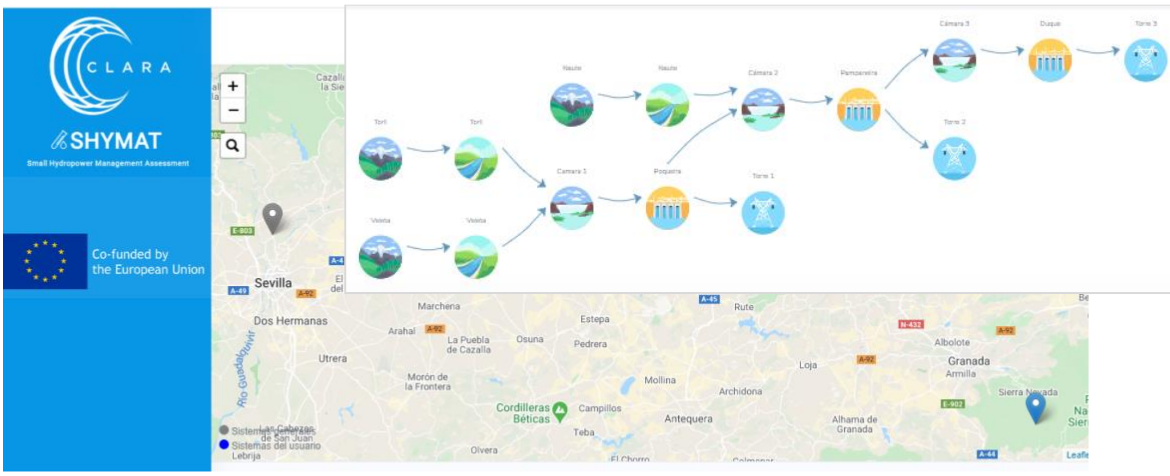

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Figure 4. Example of visualization of the GIS map for hydropower system selection and the topology panel of the hydropower system selected that shows the different elements of the system and the relations among them.

On the one hand, by choosing the historical mode, the user can check real time information from each one of the system elements, such as basin data (snow water volume, temperature, precipitation, water availability), river data (simulated and measured river flow, environmental river flow), hydropower plant data (discharge) or energy tower data (energy production). The CS also offers a comparison between those real time and historical data at both daily and monthly time scales. This option allows the user to have information about the behavior of the river basin under similar, drier or wetter hydrological conditions. Figure 5 presents an example of the historical mode outputs, where a comparison of the river streamflow data but also the energy production along the hydrological year, are presented for two different periods. Both graphs show the high annual variability of the study case.

On the other hand, the main outputs of the forecast mode are:

- *Hydro-meteorological forecast:* The user can check how temperature, precipitation or river flow forecasts compare with past years. Information about both periods, the previous past five months and the next seven months, is shown in the same graph. Moreover this option allows the user to compare the past forecast data with past observed data so that the end-user can check how the skill of the seasonal forecast information is.
- *Operability forecast:* The operability of the small hydropower plant for the next seven months is displayed in a graph. Operability is represented in terms of the number of days of the month in which river flow will be higher than the minimum technical inflow of the turbines, which indicates when water volume in the plant is enough for the system to remain operational.
- *Inflow forecast:* Seasonal forecast of river flow (as an indicator of the water available) is given and split into turbined flow, minimum environmental flow and spilled flow. Minimum environmental flow restrictions, but also the minimum and maximum technical inflows of the turbines, are considered to compute these data.
- *Energy production forecast:* From the forecast of water available to be turbined and the turbines specific consumption curve, the energy production forecast is computed and displayed in a graph. Figure 6 shows how well the energy production forecast data fits the real data. In most of the cases, the forecasted values are close to real values, which was expected because forecast data show a wide range of possibilities.

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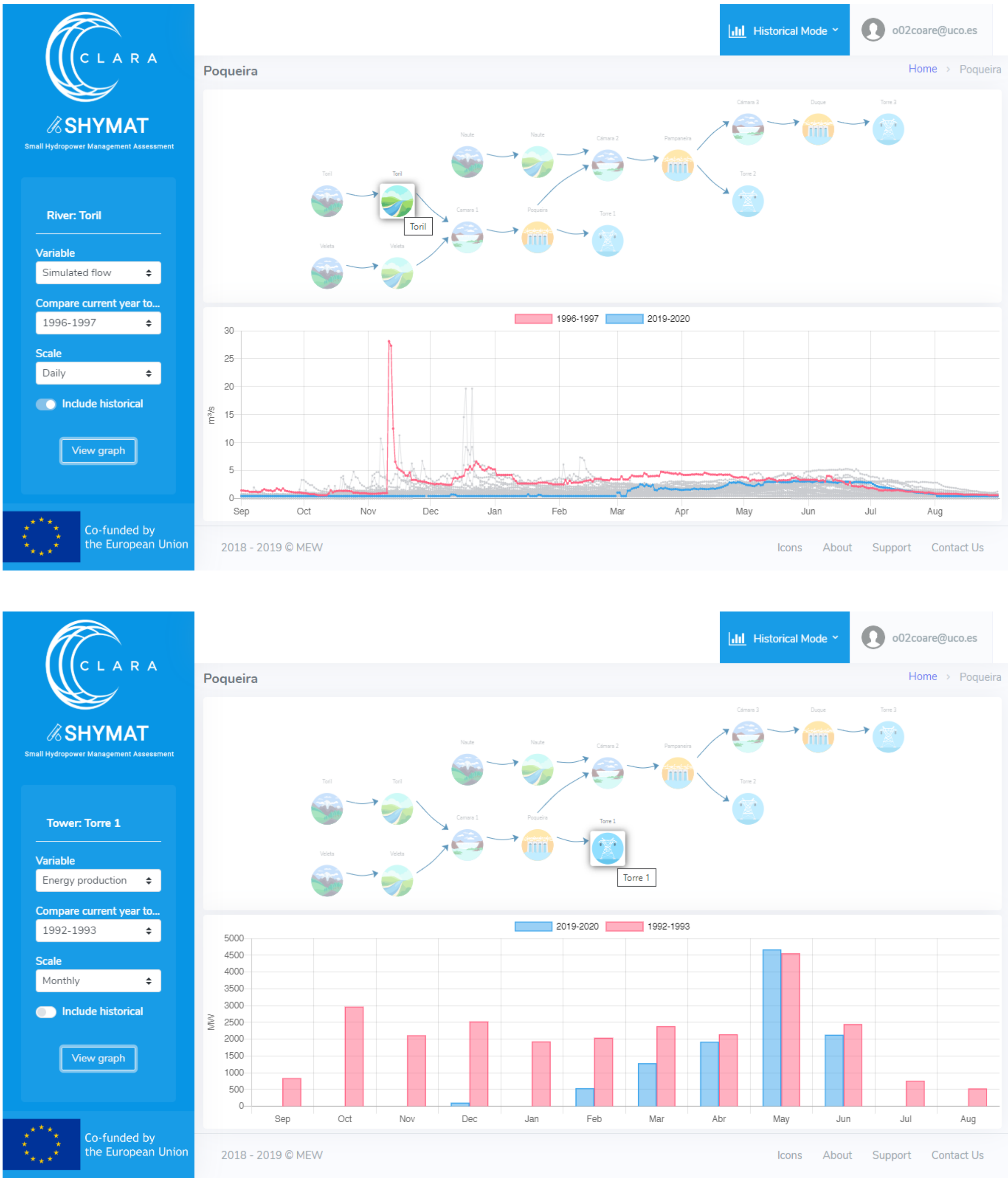

Figure 5. Example of visualization of the historical mode outputs by SHYMAT:river streamflow data from a river element and energy production data from an electrical tower element at daily and monthly time scale, respectively.

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Figure 6. Example of visualization of the forecast mode outputs by SHYMAT: energy production expected for the next months and real energy production from an electrical tower element.

4. Discussion and conclusion

The CS proposed in this work is aimed at the use of climate forecasts to foresee operation feasibility in RoR systems and it has been co-designed in close connection with end users, perfectly matching their needs. The co-generation process allows managers to make operation decisions knowing that they will have at their disposal the most up-to-date hydrological knowledge combining measurements and modelling, together with the most forward-looking seasonal forecast that currently exist at European level. Additionally all features are adapted to their real operating needs. The operation of the RoR plants should not be only based on historical local data, since water availability presents a very high interannual variability, which is even more significant in mountainous Mediterranean areas where snow cover and snow processes have a large influence in the quantity and timing of water availability. Thus, seasonal forecasts constitute an added source of information that may help to narrow down the operational options inferred from just historical data sources. The proposed CS provides simple and intuitive results, while supported by the state-of-the-art knowledge on snow hydrology and weather forecasting.

SHYMAT shows hydropower managers how seasonal climate forecast can provide advanced information about the risk of drought/scarcity scenarios, but also about the water excess discharges coming from snowmelt to quickly tune up the machines in order to increase the capacity of the plant when possible. Thus, users can take advantage of climate forecasts in order to: (1) anticipate whether the hydropower plant could be operative in order to schedule the daily and monthly operation for short term operation (for example maintenance tasks) and medium-long term investments (such as buying new machines); (2) avoid losses of spilled water flow by having the turbines ready to start operation tasks, and (3) predict the energy production of the facility for market issues. In addition, the development of this kind of tools, addressed to hydropower managers to predict the operability of the plant and the expected energy production, should consider not only forecast information, but also past data at the local scale. Both types of information provide the end users with more reliability and trust.

Keeping these general ideas in mind, the major problem to solve is how to generate forecast data with the highest skill and reliability possible. In this work, a quantile mapping approach was adopted as a direct and easy-to-run method to downscale the raw forecast data to the local spatial resolution required by the RoR system; more complex methodologies for stochastic bias correction

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[28] can be applied to further overcome these scale issues. Moreover, future research could be focused on the improvement of forecast information at the local scale by using both local historical data and high-resolution model outputs with better performance when reproducing the local results.

The findings presented in this work have enormous implications in the emerging markets of the climates services, helping future climate service developers to connect climate forecast data with the decision support process in the hydropower sector. In addition, SHYMAT has been designed to be easily applied in other small hydropower plants for planning and management of operation tasks with very low cost, thanks to the scalable software architecture used. This largely adds value to the development of data and ensures that the available information is useful for small hydropower management at the local and regional scales across Europe, which contributes to the marketability of both this type of information from C3S and the CS itself.

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