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AquaVar decision support system for water resource management: Lessons learned from the first five years of operation

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ABSTRACT

Decision support systems (DSS) based on physically based numerical models are standard tools used by water services and utilities. However, few DSS based on holistic approaches combining distributed hydrological, hydraulic, and hydrogeological models are operationally exploited. This holistic approach was adopted for the development of the AquaVar DSS, used for water resource management in the French Mediterranean Var watershed. The year 2019 marked the initial use of the DSS in its operational environment. Over the next 5 years, multiple hydrological events allowed to test the performance of the DSS. The results show that the tool is capable of simulating peak flows associated with two extreme rainfall events (storms Alex and Aline). For a moderate flood, the real-time functionality was able to simulate forecast discharges 26 h before the flood peak, with a maximum local error of 30%. Finally, simulations for the drought period 2022–2023 highlighted the essential need for DSS to evolve in line with changing climatic conditions, which give rise to unprecedented hydrological processes. The lessons learned from these first 5 years of AquaVar use under operational conditions are synthesized, addressing various topics such as DSS modularity, evolution, data positioning, technology, and governance.

KEYWORDS

decision support system, distributed physically based models, holistic approach, water resource management

1 | INTRODUCTION

In the environmental management sector, decision support systems (DSS) can be defined as information systems that improve the consistency and quality of decision-making processes while reducing the time in which decisions are made (Haagsma & Johanns, 1994; Poch et al., 2004). This definition is generic, as the concept of DSS, along with its scope of application in environmental management, and particularly in the water management sector, has come a long way since DSS was first conceptualized in the 1970s (Gorry & Scott Morton, 1971). The variety of DSS concepts is due to the evolution of computer science, the growing diversity of application domains, and the transdisciplinarity in the fields (numerical modeling, information and

communication technologies, data science, statistics, management and social sciences, engineering, economy, etc.) that support DSS construction (Ma & Gourbesville, 2022; Goharian & Burian, 2018; Power, 1997).

Aiming to address a broad variety of complex issues, the water resource management sector depends on supporting fields such as hydroinformatics (Cunge & Erlich, 1999; Gourbesville & Ma, 2022; Price & Solomatine, 2009). Hydroinformatics has evolved in the last two decades as a field having a predominant horizontal role, integrating water sciences, data sciences, computer science, and information and communication technologies, targeting an interdisciplinary socio-technical approach (Holz et al., 2013). In the process, the use of numerical models has become a common central practice to help operators make informed

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decisions. Simulation results are often key elements in decision support systems designed to facilitate day-to-day choices, long-term strategy, or emergency planning.

Based on the example of the AquaVar DSS development experience (Du, 2016; Gourbesville, 2023; Ma, 2018; Zavatiero, 2019), which relies on numerical modeling for hydraulic, hydrological, and hydrogeological aspects at a watershed scale, Ma and Gourbesville (2022) have schematized and generalized the DSS development strategy in a five-stage process: (i) the requirements analysis, (ii) the design proposal, (iii) the primary development, (iv) the implementation process, and (v) the future or evolution stage. This formalized development approach aims to bridge the gaps identified in DSS development, such as end-user acceptance through involvement in the development process, DSS flexibility and durability through the construction of multiple modules, and optimization of real-time decisions through an architecture adapted to real-time monitoring and numerical modeling system.

Yet, this multi-stage approach proposed by Ma and Gourbesville (2022) emphasizes that developing a DSS in the water sector is a long-term task, particularly when it comes to tackling complex scientific and operational issues. In addition, one can argue that over time, the initial objectives of the DSS can become a moving target as the multiple technical components, drivers, and factors constituting or acting on decision-making evolve (regulations, data, models, technology, operator needs, etc.). Consequently, the evolution stage is essential to keep the DSS relevant to operators and to ensure management support.

In this context, this article reflects on how operators can, instead of maintaining a DSS that may become obsolete or outdated, improve their DSS throughout the evolution stage and operation. This is considered crucial to ensure that the initial effort and investment in DSS development remain useful for decision-making. We present the perspective of a water utility operator based on the well-documented experience of developing the AquaVar DSS. The focus is on the lessons learned from the first 5 years of using the DSS in operational conditions. The objective is to show how the difficulties and successes encountered can actually test the quality and resilience of the DSS to adapt to a new context (extreme events, data sets, functionalities, technology, governance, etc.).

An introduction to the AquaVar DSS is first presented (Section 2). It summarizes the context of water management in the Var watershed (France), the DSS development strategy, and operational deployment. Then, feedback from 5 years under operational conditions is given (Section 3), highlighting the strength of the DSS and the limitations encountered in modeling aspects during extreme events (two flash floods and one severe drought event). Lastly, the lessons learned are synthesized (Section 4), putting in perspective recommendations on DSS modularity, evolution, positioning toward data, technology, and governance change aspects, before the conclusion (Section 5).

2 | THE AQUAVAR DECISION SUPPORT SYSTEM: FROM CONCEPT TO DEPLOYMENT

2.1 | The challenges of water management in the Var watershed

The Var watershed covers an area of 2800 km² in the French Mediterranean region (Figure 1). Topographic elevations range from sea level to the heights of the Southern Alps (0–3100 m). The watershed climate is Mediterranean, with dry and hot summers and cool and rainy winters (Ma, 2018). Lands are mainly covered by forests and pastures (80% of the basin area). Densely urbanized areas can be found along the last 20 km of the Var River before the estuary. Known as the lower Var valley, this downstream area encompasses the alluvial plain of the Var River.

Water management in the Var basin involves two main challenges. The first is the management of water resources, in terms of both quantity and quality. Water resources in the basin are used to supply drinking water to the population of the Nice city area, the fifth most densely populated in France. In 2021, 65 million cubic meters of water were produced by extracting both surface water from one of the Var's tributaries and groundwater from the alluvial aquifer of the lower Var valley. The alluvial aquifer is also used for energy production, as several geothermal systems have been installed. The other challenge concerns flood risk management. As urbanization increases, so does vulnerability to flooding. With climate change, these water management issues are set to intensify (IPCC, 2023). Following

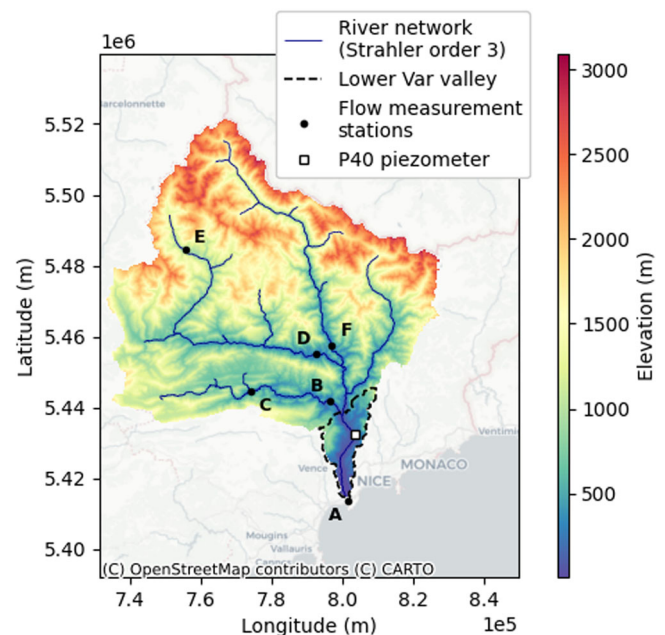


FIGURE 1 Topography (IGN, 2022) and river network of the Var watershed (2800 km²). The lower Var valley subbasin is outlined in dotted lines. The map also shows the locations of the measurement sites mentioned in this article.

the drought of 2007, in particular, a major phase of discussion and reflection between water management stakeholders led to the creation of the AquaVar project. The project, initiated by the water services operator in 2013, consists of the collaborative development of a DSS called AquaVar, which aims to (i) help understand hydrological processes in the Var watershed, (ii) provide forecasts on multiple hydrological variables in order to anticipate drought and flood episodes, and (iii) analyze the impact of different scenarios on the resource (e.g., pumping scenarios, implementation of flood mitigation systems).

2.2 | AquaVar development strategy

AquaVar DSS is the result of collaboration between several institutions including local stakeholders (such as the Nice Côte d'Azur Metropolis, the Alpes-Maritimes Departmental Council, and the French Rhône Méditerranée Water Agency), water services operator (Veolia, replaced in 2014 by Régie Eau d'Azur, which is referred to as the operator throughout this article), and research institutes of Nice Côte d'Azur University (Polytech lab, Mediterranean Institute of Risk, Environment and Sustainable Development, and Geoazur).

Detailed by Ma and Gourbesville (2022), the development strategy was initially based on an analysis of operator and stakeholders' needs. This led to the adoption of a modular modeling strategy. This modular framework, described in the following paragraph, uses the integrated and distributed modeling codes commercialized by the DHI company: MIKE SHE (Danish Hydraulic Institute [DHI], 2023; Graham & Butts, 2005), MIKE 21 (Danish Hydraulic Institute [DHI], 2017), and FEFLOW (Diersch, 2013). The integrated and distributed modeling approach was chosen for its capacity to provide a detailed description, in time and space, of flow processes. In addition to providing a precise spatial and temporal description of variables of operational interest (river flows, surface water heights and velocities, and position of the alluvial water table), this modeling approach is a powerful tool for investigating the hydrological processes involved in the basin. Using commercial codes ensures that the codes are maintained so that the DSS developed is sustainable over time. Moreover, these codes have a graphic interface that makes them more accessible to operators with various profiles, who can also access assistance in using the software.

From 2013 to 2019, the AquaVar DSS was first developed as part of three doctoral theses at the Nice Côte d'Azur University (Du, 2016; Ma, 2018; Zattero, 2019). They built the three modules forming the modeling core of the DSS detailed below.

2.3 | AquaVar modeling core: A modular framework based on integrated and distributed modeling approaches

Three different modules compose the DSS modeling core to meet the operator's needs (Figure 2): First, the hydrological

module aims to investigate the hydrology of the Var on a basin scale. It enables the study of operationally relevant variables, such as river discharge and changes in snow cover. Then, the hydraulic and hydrogeological modules focus on the lower Var valley (Figure 1), as it is a strategic location for both flood risk management and drinking water production. In particular, they are used to simulate flood heights in the Var alluvial plain, and the evolution of water table levels in the alluvial aquifer.

The hydrological module consists of a model of the entire Var watershed using MIKE SHE (Danish Hydraulic Institute [DHI], 2023; Graham & Butts, 2005), which is a flexible modeling tool allowing different approaches of varying complexities and distributions to represent hydrological processes. In the model of the Var basin, developed by Ma (2018) with a 100 m lateral spatial discretization, infiltration in the unsaturated zone is represented by a two-layer water balance method for the root zone and the zone below the root. This method includes evapotranspiration calculations based on the model of Yan and Smith (1994). Saturated zone flows are calculated within an aquifer layer whose thickness is assumed to be that of the regolith (i.e., the layer of unconsolidated solid material overlying the bedrock), by solving the groundwater flow equation in two dimensions. The diffusive wave approximation to the Saint–Venant equations is used to compute two-dimensional overland flows. MIKE SHE uses MIKE 11 (Danish Hydraulic Institute [DHI], 2021; Havnø et al., 1995) to calculate surface flow in the river system, solving the one-dimensional Saint–Venant equations. In addition, the MIKE SHE model includes a temperature-dependent snow model. Meteorological input data (temperature, precipitation, and relative humidity) are obtained by spatial interpolation of data measured on the Météo-France station network (Ma et al., 2024; Tardieu & Leroy, 2003). The potential evapotranspiration is obtained using Turc's formula.

The hydraulic module is a model of the Var river alluvial plain located in the lower Var valley. It was built by Zattero (2019) using MIKE 21 (Danish Hydraulic Institute [DHI], 2017), which solves the Saint–Venant equations in two dimensions. The spatial resolution ranges from 10 to 25 m. River flow, obtained from MIKE SHE model results, is used as the upstream boundary condition, while sea level is used as the downstream boundary condition. The hydraulic module can also be used independently of the MIKE SHE model by applying measured discharges as the upstream boundary condition.

The hydrogeological module is a model of the aquifer system in the lower Var valley (146 km²), built with FEFLOW (Diersch, 2013) by Du (2016). The diffusivity equation is solved in 3D for the saturated zone only, using free-surface boundary conditions (Diersch, 2001). The model was constructed with a spatial lateral resolution ranging from 25 to 100 m. The subsurface depth, ranging from 100 to 600 m, is discretized into six layers. Measured piezometric data are used as the upstream boundary condition, while sea level is used as the downstream boundary condition. The river water level simulated with MIKE 11

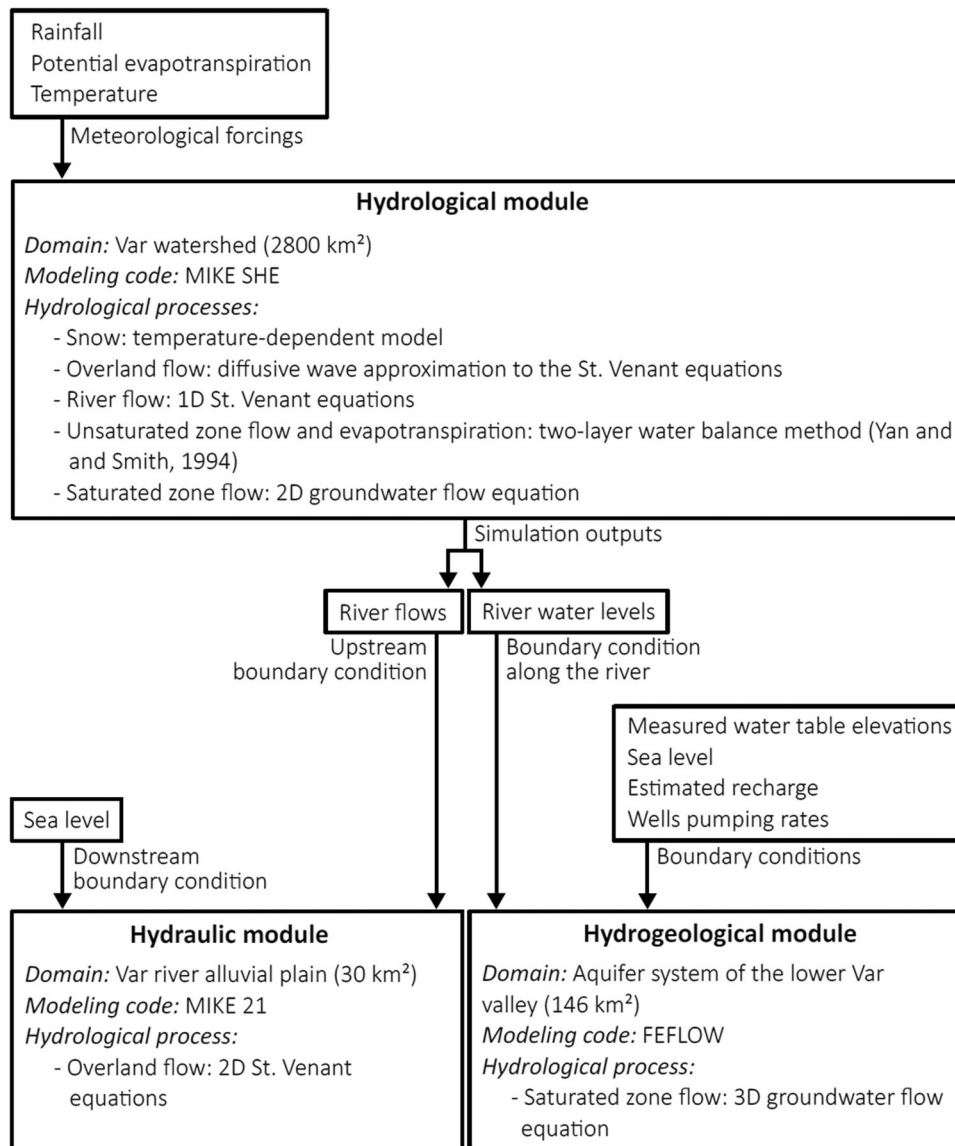


FIGURE 2 Synoptic view of the modular structure of the AquaVar modeling core.

(in the hydrological module) is used as the boundary condition along the river. On the domain, estimated recharge and measured pumping rates are imposed as flow boundary conditions.

2.4 | Operational deployment

Once built, calibrated, and validated against observations (Du, 2016; Ma, 2018; Zavattono, 2019), the modeling core is deployed in two ways.

First, the DSS models are used to carry out various surveys on the basin. In total, almost 20 studies were performed between 2019 and 2023 using AquaVar models. For example, the operator has assessed the impact of geothermal energy production projects on the hydrodynamics and temperature of the alluvial aquifer, using the FEFLOW model of the lower Var valley aquifer system

(Gourbesville & Ghulami, 2022). Other studies have been conducted on the impact of various urbanization projects on the hydrodynamics of the alluvial aquifer, as well as on the impact of new water intakes to secure drinking water production. The MIKE SHE and MIKE 21 models were used to carry out a post-event study on the severe flooding caused by storm Alex on October 2, 2020, and to assess the risk of flooding in several sub-basins in the lower Var valley. Most of these studies using the AquaVar DSS are internal to the operator and rarely published (Picourlat et al., 2024).

In addition to one-off studies, AquaVar's objective is to carry out real-time simulations. Every 2 h, the modeling core is used to automatically run a simulation over a 7-day period including the last 4 days, forced by updated observed hourly meteorological data, and the next 3 days, forced by updated hourly meteorological forecasts. The aim of this real-time functionality is to create a warning

system for operators in the event of flooding or drought. A first version of the functionality mobilizes the hydrological and hydraulic modules for real-time simulations (the hydrogeological module will be implemented in a future version). This first version forces simulations with meteorological data interpolated from four measuring stations, which were the data available to the operator during the real-time function development. Moreover, setting up such a tool requires considerable computing resources: the hydrological module simulations are run using 38 (virtual cores) 2.10 GHz Intel Xeon Gold 6130 processors, while the hydraulic module simulations are run using both 32 (virtual cores) 2.80 GHz Intel Xeon Silver 4309Y processors and an NVIDIA A30-12C GPU. This computing architecture enables the MIKE SHE and MIKE 21 simulations over 7 days (with hourly maximum time step) to run for around 2 h.

The results of real-time simulations and one-off studies can be accessed on the AquaVar web platform. Intended for local stakeholders as well as government representatives, this platform aims to concentrate knowledge of the Var watershed in a single environment. Besides the simulation results, the platform gathers measured data relating to meteorology, river flows, and piezometric heights, as well as regulatory data (e.g., protected environmental zones or protection perimeters for water extraction sites) and property data (e.g., sensitive sites, dykes, and buildings).

Figure 3 traces the chronology of DSS AquaVar's development and operation, with associated Technology Readiness Level (TRL) indices. Developed by NASA, the TRL is a scale for assessing the degree of maturity reached by a technology, ranging from 1 to 9. By the end of the three doctoral projects, the three modules of the DSS modeling core had been developed, calibrated, and validated over periods of several years. The TRL is consequently estimated at 5 (for lab validation). After 2019, the operator gradually took over the development and operation of the DSS. In 2020, the Alex storm event allowed the operator to validate the tool on an extreme rainfall event. AquaVar results have been integrated into the

post-Alex hydrological consensus (Pons et al., 2024), led by the French Center for studies and expertise on risks, the environment, mobility, and development (CEREMA). This event, as well as the numerous studies conducted with the different modules of the AquaVar modeling core, confirmed its validity under operational conditions, and we consider a TRL of 6 at this stage (for validation in an operational environment). Initially carried out in the research institutes, the development of the real-time functionality was taken over by the operator in 2022. This feature was launched along with the web platform in December 2023, bringing our TRL estimate to 7 (for initial operational deployment).

3 | AQUAVAR RESULTS OVER THE 2019–2024 PERIOD

Since 2019 (TRL 5), various hydrological events, such as the Alex storm, have allowed the DSS robustness to be evaluated (Figure 3). Here, we present AquaVar's results on flood simulation and forecasting (Section 3.1) and on the drought event of 2022–2023 (Section 3.2).

3.1 | Flood simulation and forecasting results

3.1.1 | Alex (2020) and Aline (2023) storms

In 2020, storm Alex caused intense rainfall in the Var watershed, from the early morning of October 2 to the middle of the night of October 2–3. Cumulative rainfall locally exceeded 500 mm in 24 h (Chochon et al., 2022; Pons et al., 2024). The peak flow measured at the watershed outlet almost reached 3000 m³/s. Three years later, on October 20, 2023, the Aline storm brought cumulative rainfall locally exceeding 150 mm in 24 h. This resulted in a peak flow of around 600 m³/s at the outlet. The MIKE SHE model, which forms the hydrological module of

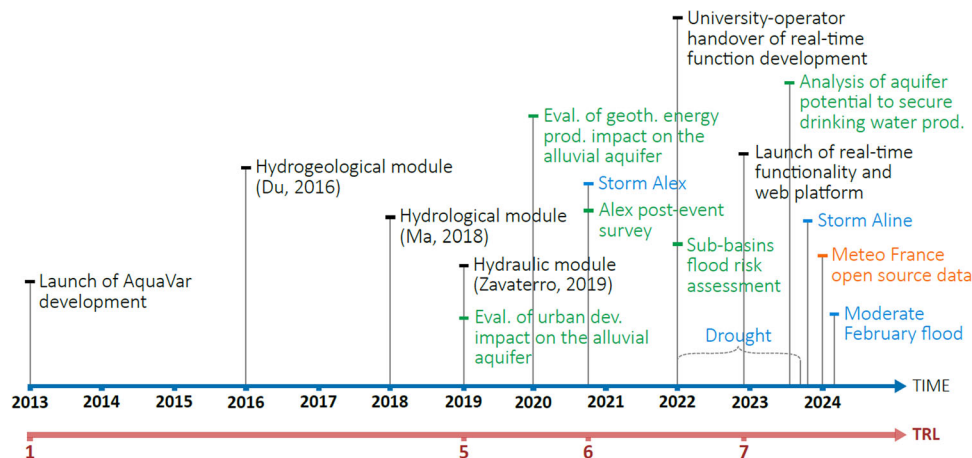


FIGURE 3 AquaVar development and operation timeline: development steps and launch of main features (black); selection of one-off applications (green); hydrological notable events (blue); and change in access to DSS input data (orange). DSS, decision support system.

AquaVar, is used to simulate the response of the watershed to these two rainfall events. To do so, a maximum time step of 1 h is applied, and the input meteorological forcing is obtained by interpolating hourly data measured at 13 stations distributed over the 2800 km² basin. The comparison between measured and simulated flows at the Var watershed outlet is shown in Figure 4. Peak flows are reasonably well estimated for both events, making the model a potentially effective warning tool in case of extreme flooding. However, the simulated peak flow occurs before the observed peak by a few hours, and the recession is much slower than observed. These discrepancies result in KGE (Kling-Gupta Efficiency) coefficients of 0.22 and -1.36 for the Alex and Aline events, respectively (Gupta et al., 2009). They may be explained by the fact that the MIKE SHE model of the Var basin has been calibrated and validated on a daily time step (Ma, 2018). Calibration work needs to be carried out on an hourly time step in order to improve the results and make the model suitable for real-time simulation.

3.1.2 | The moderate flood of February 2024

At the beginning of 2024, Météo-France's data sets became open source (Figure 3), giving the operator real-time access to meteorological data from the 13 measurement stations spread across the basin. Previously, the operator only had access to real-time data from four stations. The impact of the distribution of input meteorological data on the results of the AquaVar hydrological module (MIKE SHE model) is assessed by running two simulations on the February 2024 moderate flood: one forced with data interpolated from the four stations and one forced with data interpolated from the 13 stations. Figure 5 compares the hourly simulated discharges with measured discharges at six locations in the watershed (sites A–F in Figure 1). The peak flow rates simulated with input data from four stations are highly overestimated at all sites. Discharges simulated using input data from 13 stations are around twice as low and, therefore, closer to the measured data. Considering that a larger number of meteorological stations

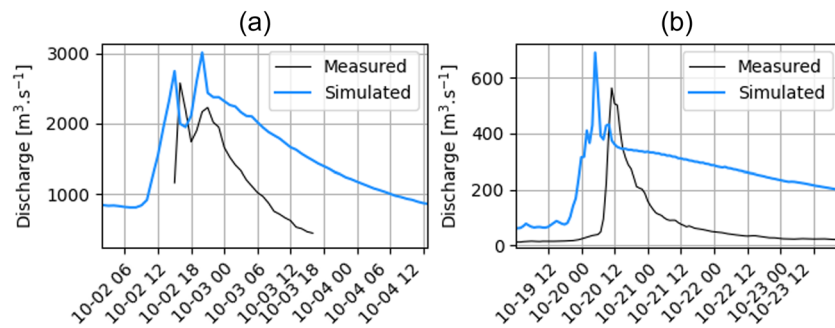


FIGURE 4 Comparison between hourly measured and simulated discharges at the Var watershed outlet (station A in Figure 1) for (a) Alex (October 2020) and (b) Aline (October 2023) storms.

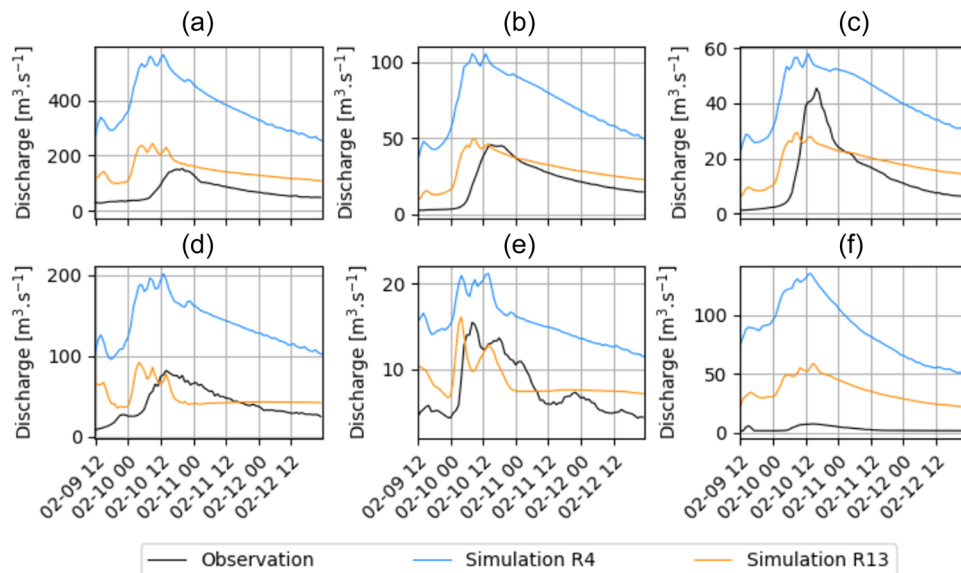


FIGURE 5 (a–f) Hourly discharges simulated for the February 2024 rainfall event at locations A–F respectively (Figure 1), with input meteorological data interpolated from 4 and 13 gauging stations (simulation R4 and R13, respectively). Comparison with measured discharges.

leads to a much more complex precipitation distribution over the basin, which explains the large differences between the simulated runoffs. The 13-station distribution shows large areas with less precipitation than the 4-station distribution (down to minus 16 mm locally). It also shows some areas with more precipitation (up to plus 53 mm locally), but over more limited areas. This result underlines the importance of updating the real-time functionality of the DSS, considering the constraints of meteorological data availability and accessibility. These are likely to evolve over time, depending on the data-sharing policies of Météo-France and the evolution of the measurement network. In addition, as in the case of storms Alex and Aline, a time lag of a few hours is observed between simulated and measured peak flows. We also note poor results at site F, which may be explained by the presence of upstream dams and water intakes that are not represented in the model.

The moderate flood of February 2024 is also used to evaluate the forecasting performance of the AquaVar real-time functionality. Three simulations are performed using the hydrological module (MIKE SHE model) forced with forecast meteorological data at different times preceding the rainfall event: February 8 at 00:00 (forecast 1), February 9 at 12:00 (forecast 2), and February 9 at 18:00 (forecast 3). Forecasts 1, 2, and 3 are, respectively, produced 68, 32, and 26 h before peak flow at the outlet (site A). Figure 6 shows the simulated discharges at sites A–F (locations in Figure 1). They are compared with the discharges simulated from measured meteorological data. The peak flow rates simulated at the different sites with forecast forcing data are greater than those simulated with measured forcing data: 1.1 to

2 times greater for forecast 1, 1.3 to 2 times greater for forecast 2, and 1.1 to 1.3 times greater for forecast 3. This is due to an overestimation of precipitation in the forecast data sets for this event. In other words, at 68 and 32 h before peak discharge at the outlet, the error in DSS flow forecasts reaches 100% locally. The maximum error is reduced to 30% for the forecast made 26 h before the peak. This analysis will be extended over several events.

3.2 | Groundwater resource monitoring during the 2022–2023 drought episode

In 2022 and 2023, Western Europe and the Mediterranean region were affected by an intense and prolonged drought (Toreti et al., 2022, 2023). At the Météo-France measurement station in Nice, the annual precipitations recorded for the 2 years are 466 and 403 mm, respectively, while the annual average over the 1950–2023 period is 788 mm. The average air temperature reaches 17.7°C and 17.6°C in 2022 and 2023, following an upward trend of 0.4°C per decade since the 1970s. This unprecedented drought episode has been simulated at a maximum daily time step using AquaVar's hydrogeological module (FEFLOW model). Figure 7 compares the water table level measured in the alluvial aquifer at the P40 piezometer (location in Figure 1) with two simulated water tables. The water table level obtained with the FEFLOW model calibrated and validated by Du (2016) is shown in blue. The water table level obtained with a transfer rate parameter manually calibrated from January 2022 is shown in red. In FEFLOW, the transfer rate parameter Φ [T^{-1}] is a conductance term

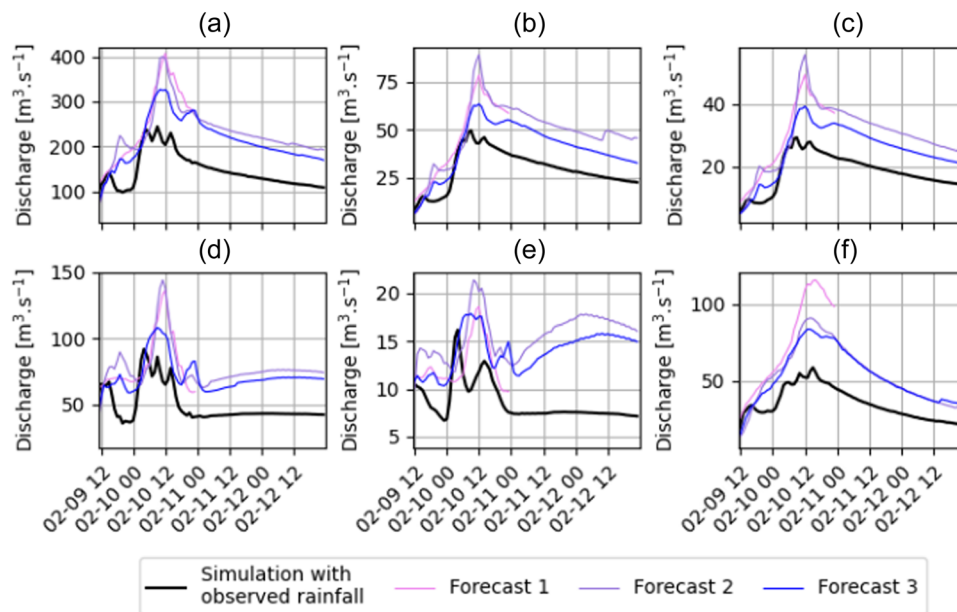


FIGURE 6 Hourly discharges forecasted at various times before the February 2024 rainfall event: 08/02/24 00:00 (forecast 1), 09/02/24 12:00 (forecast 2), and 09/02/24 18:00 (forecast 3). Comparison with discharges simulated from measured rainfall. (a–f) Results obtained at locations A–F respectively (Figure 1).

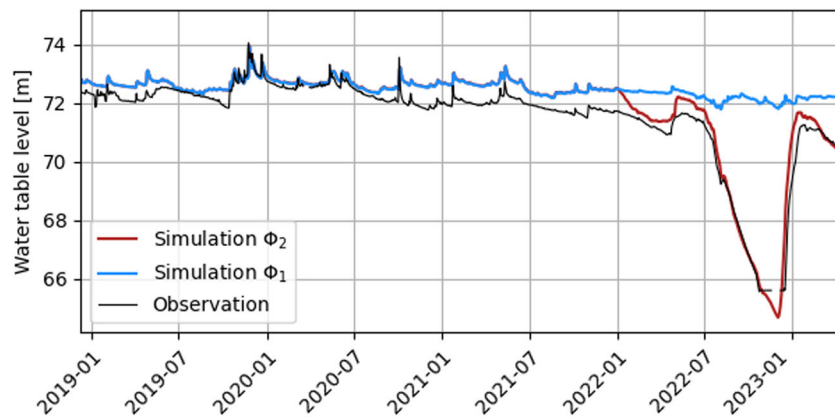


FIGURE 7 Water table elevations simulated from 2019 to 2023 at the P40 site (Figure 1), with a transfer rate parameter derived from the calibration work of Du (2016), and a transfer rate parameter manually modified from January 2022 (respectively, simulations Φ_1 and Φ_2). Comparison with the measured water table elevation.

involved in the calculation of the inflow/outflow from the river Q [L^3T^{-1}]:

$$Q = A\Phi(h_r - h_a),$$

with A being the transfer surface area (i.e., the area of the river bed) [L^2], h_r [L] being the water level in the river, and h_a [L] being the water level in the aquifer. In the model of Du (2016), the transfer rate varies spatially between zero and $5 \times 10^{-4} s^{-1}$. In the simulation shown in red in Figure 7, the transfer rate was lowered to zero locally on the river section near the P40 piezometer. In doing so, we observe that the model is able to reproduce the drop in the water table during the drought of 2022–2023, which is not the case for the model calibrated by Du (2016).

This result shows that AquaVar is unable to simulate the evolution of the water table depth during the drought of 2022–2023. However, this is possible by locally forcing the exchange rate between the river and the aquifer to zero. We conclude that the FEFLOW model, as developed, does not take into account certain physical processes that determine water table levels under extreme drought conditions. These processes could be linked to the water table's connectivity with the river. Further work will be required to better understand the interaction processes between the river and the aquifer, and to represent them in the DSS. This work will be crucial to correctly simulate the hydrodynamics of the alluvial aquifer, particularly during extreme drought events such as that experienced in 2022–2023.

4 | LESSONS LEARNED

Here, we propose to draw some lessons learned from the first 5 years of AquaVar DSS exploitation in operational conditions.

As indicated in Section 2.2, the development of AquaVar is the result of collaboration between several

institutions: local stakeholders, water utility operator, and research institutes. The first set of lessons concerns this governance strategy:

1. As the development of a DSS is a long-term investment and a slow development process, the individual initiative of an institution may be subject to time constraints to be finalized. The collaborative approach, on the other hand, creates a resilient framework for development and operational deployment, enabling the adoption of a more ambitious end product as well as ongoing innovation.
2. Involving the operator and local stakeholders in the development of the DSS by the research institutes ensures that the tool meets their needs and addresses their water resource management issues. However, we note difficulties for the research institutes to anticipate some of the operators' constraints: after taking charge of the development of the real-time functionality (2022, Figure 3), the operator had to adapt it in particular to meet its material and logistical constraints (need to bring together significant computational resources) and legal constraints (obligation to follow public procurement rules). Particular attention needs to be paid to taking account of such constraints right from the start of development to ensure effective transition in the deployment of the feature in the operational environment.
3. Multi-actor governance provides a learning experience across a large team that facilitates replication of the DSS or legacy initiatives such as DSS version extensions. Replication is thus facilitated. In the case of the AquaVar DSS, this has led to the optimized development, in adjacent catchments, of two by-products: AquaCagne and AquaPaillon DSS (Game, 2023; Wang, 2023).
4. When operating a DSS, decision-makers' knowledge regarding the tool's capabilities and limitations is crucial for safe and efficient decision taking. To this end, the long-lasting collaboration between researchers,

operators, and decision-makers throughout the development process ensured an appropriate understanding of the DSS strength and weaknesses by the operator. This reduces the risk of misuse of the DSS. Yet, work remains to be done to ensure an appropriate level of understanding around confidence and uncertainty levels, especially to secure this knowledge over of the command chain profiles (technician up to political level) to face standard human resources' turnover over time.

The second set of lessons concerns the DSS modeling core construction:

1. The modular framework has successfully responded to the needs of the operator and stakeholders for the management of both surface water (with the hydrological and hydraulic modules) and groundwater (with the hydrogeological module). It enabled an integrated approach, while offering the possibility of working independently with each module for specific studies. This proved very useful for carrying out one-off studies (more than 20 in total), which were one of the major thrusts of the tool's deployment. In addition, each module has different spatial and temporal resolutions. This is necessary to be able to simulate processes of operational interest that occur at different temporal and spatial scales. This multi-scale approach can, however, pose a certain challenge when it comes to coupling different modules. Du (2016) and Zavattero (2019) encountered this problem when working on a coupling procedure between hydrogeological and hydraulic modules.
2. Commercial modeling codes have the advantage of being maintained over time, and offer user-friendly graphical interfaces along with a support service. However, the drawback of these proprietary codes is that they are inaccessible, making them impossible to modify. This limitation became apparent when developing the aforementioned coupling procedure between the hydrogeologic and hydraulic modules. After discussion with the company that owns the codes, Du (2016) developed a chaining method between the FEFLOW and MIKE 21 models. Zavattero (2019) tested the method on the Smith and Woolhiser (1971) case study, but did not apply it to the Var basin. Working on the DSS representation of river–aquifer interactions in the lower Var valley is one of the tool's development perspectives. This will require an overhaul of the modular framework, working on coupling modules, or developing a single module involving integrated modeling of surface and subsurface processes in the lower Var valley.

Finally, the last set of lessons learned is the constant need for DSS dealing with complex environmental problems to evolve with its environment, where multiple variables are constantly changing. Giupponi et al. (2024)

discuss the importance of keeping the technologies used up to date. We note that in addition to technologies, other moving variables need to be taken into account when updating the DSS.

1. Changes in sharing policies, damage to equipment, or modifications to the measurement network may affect the availability and accessibility of input data sets over time. Here, simulations carried out on the moderate flood of February 2024 showed the sensitivity of the models to the spatial distribution of meteorological data, underlining the importance of adapting the tool to changes in data accessibility.
2. The DSS must evolve in line with feedback from experience where the DSS has shown limitations in terms of representing the physics of some extreme phenomena. Changing climatic conditions, for instance, give rise to unprecedented hydrological processes. The drought of 2022–2023 has led to historically low groundwater levels in the lower Var alluvial aquifer, with a potential disconnection between the river and the aquifer. Given the modeling assumptions of the hydrogeological module, such a phenomenon could not be simulated by the tool.

5 | CONCLUSION AND STEPS FORWARD

AquaVar DSS was developed in response to the operator's need for a water resource management tool in a territory where water is at the heart of several challenges (flooding, drinking water production for France's 5th most populous metropolis, geothermal energy production). The DSS is one of the few based on an integrated, distributed modeling approach that enables variables of operational interest to be consulted locally. Since 2019, AquaVar's modeling modules have made it possible to carry out various analyses on the territory with great satisfaction for the operator. In 2023, the launch of the real-time functionality and the web platform marked the official deployment of the tool in its first version. At this stage, we estimate the DSS TRL to be 7 out of 9.

From 2019 to 2024, several hydrological events were used to evaluate the performance of the DSS. The results show that the hydrological module is capable of simulating the peak flows associated with two extreme rainfall events (storms Alex and Aline). To take this a step further, additional calibration work will be carried out to simulate flood peak occurrence times and recession dynamics more accurately. Regarding real-time functionality, results for the February 2024 flood showed that forecasting 26 h before the flood peak produced a simulation result with an error of up to 30% locally. This analysis will be extended to other events. Finally, simulations for the 2022–2023 drought have highlighted the need to work on understanding groundwater–river interaction processes and on representing them in the tool.

Lastly, lessons learned from this 2019–2024 period concern governance strategy, the multi-modular framework of the modeling core, use of commercial modeling codes, and finally, the need for the DSS to evolve with its environment. In particular, we stress the need for the tool to remain relevant by evolving in concert with technological developments, changes in the availability and accessibility of input data, and emergence of new climatic conditions.

With this lesson in mind, we recognize that the final form of the AquaVar DSS, which would correspond to a TRL of 9, is a moving target. Several avenues are already being explored to converge toward this target. The first is, as already outlined, the implementation of an improved representation of interactions between rivers and aquifers in the modeling core. The second is the integration of the hydrogeological module into the real-time functionality. Finally, a third area of development concerns the design of an alarm system based on real-time simulation results, to assist operators in the decision-making process for flood or drought management.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICS STATEMENT

None declared.

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