An innovative scenario-based modeling tool for the management of resilient water resources

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ABSTRACT

As freshwater availability for domestic and agro-industrial uses is highly sensitive to climate change, there is an urgent need for the management of this critical resource to be resilient, i.e., to cope with and rapidly recover from climate risks. To achieve this resilient goal, decision-makers need to have a comprehensive understanding of (i) the current and future local water resources, (ii) the ways these resources are and will be impacted by climate change, and (iii) the effects their management decisions can have. In this paper, we present an innovative scenario-based modeling tool that help decision-makers make the most appropriate decision towards managing water resources: the Resilience Performance Assessment (RPA). This GIS-based decision support tool illustrates the current and future effects of climate change on local water resources and simulates the outcomes of different water resources management strategies. The RPA helps guide decision-makers towards the implementation of context-specific adaptation strategies.

Keywords

Climate change, Resilience performance assessment, Water resources management, Scenario-based analysis, Predictive modelling

INTRODUCTION

Freshwater resource is one of the levers for achieving the United Nations Sustainable Development Goals, affecting a wide range of societal sectors, such as agriculture, industry, energy, health, and tourism, among others. Further, preventing disasters induced by water deficit or excess is one of the major challenges that countries are facing or will face in the ongoing context of climate change. In the 6th Report by the Intergovernmental Panel on Climate Change (IPCC) in 2021, experts predict that global temperature warming would exceed 1.5-2°C during this century with a non-homogeneous variation in precipitation at a global scale (Masson-Delmotte *et al*., 2021). As per the IPCC, as the global temperature increases by one degree, an estimated 7% of the world's population is expected to experience a reduction of at least 20% in renewable water resources. Hence, climate change inevitably has direct and indirect impacts on the quantity and quality of freshwater resource. In a context where the availability and quality of water resources could be strongly negatively impacted, resilient management of water is a necessary step towards mitigating the various risks related to this natural resource (Noi & Nitivattananon, 2015). Conflicts over the use and management of freshwater is an additional risk as water demands from stakeholders will become increasingly competitive due to the shortage of available resources to supply socio-economic development and ecosystem functions (Xue *et al*., 2017).

In this context, it is crucial to build and implement appropriate, long-term, and efficient adaptive strategies which could contribute to alleviate these potential conflicts as well as informing trade-offs between competing needs and uses of freshwater resources. Adaptation measures for resilient water resources management can take various forms depending on the context (Greve *et al*., 2018). For instance, decisions can lean towards investing in structures for maximizing the re-use of treated wastewater and harvesting rainwater. Other decisions can entail the transfer of resources with the aim of supplying water to the depleted watersheds from those with surplus. To adopt the more suitable and context-specific solutions to enhance the resilience of water resource, it is crucial to, first, identify the watersheds that are the most vulnerable to water stress or potential flooding. This step can help water management stakeholders prioritize the most suitable watersheds where adaptation solutions can be implemented. It is necessary, then, to define and implement appropriate and context-specific adaptation strategies for each vulnerable watershed. Defining the potential adaptation strategies requires the evaluation of different criteria through a cost-benefit analysis to ensure that the proposed solutions are technically feasible. This cost-benefit analysis can contribute to effectively reduce climatic risks on water resources, generate co-benefits of different types, and avoid mal-adaptation.

There is, thus, a need for tools that can support water managers and risk management stakeholders in their decision-making processes so that they can manage their assets and respond to their regions' need while anticipating current and future climate risks. The creation of models allows to identify the most resilient adaptation measures for a selected region, while accounting for local contexts and budgetary constraints. Many stakeholders directly and indirectly related to the management of water resources express this need (personal communication held with public authorities, water resources users, infrastructure managers as part of our activities in developing and implementing our scenario-based modeling tool). To respond to this need, we developed a scenario-based modeling tool called the Resilience Performance Assessment (RPA). This tool combines several empirical data and models, such as (i) the region's socioeconomic, demographic, ecological, and biophysical characteristics, (ii) outputs of predictive climatic models, and (iii) outputs of prospective analysis of the evolution of socio-economic variables. These data are built from multiples publicly available sources; using a very precise downscaling and modelling methodology developed by our team. The built data are triangulated and checked with stakeholders' perceptions and expert knowledge on future pressure, threats, and water needs.

Easy-to-use and intuitive, our tool can be used by stakeholders to better understand their resources and the socio-ecological context in which they make decisions. Offering a visual support on freshwater management, the tool can also help decision-makers to communicate about water management efforts and their expected outcomes. As such, the outputs generated by this tool can be used to raise awareness on the issue of water resource management. The RPA is thus a powerful tool that supports a concerted process towards the resilient use and management of water resources. In fine, the RPA allows water managers to make the most ecologically, socioeconomically, and financially appropriate trade-offs between competing needs.

In this paper, we present the first component of the RPA: a scenario-based modelling tool which has been applied to a French Department and offers the users a comprehensive view of climate change impacts in the studied areas through the visualization of different climate scenarios. The second component, an analytical dashboard, is still under development and will be the object of a future article. We first offer the context in which our tool is developed, providing insights on the similarities and differences between other water management-related tools. We then describe the methodology that underpins the development of the scenario-based modelling tool. This methodology uses a systemic reasoning approach that can be applied to any area to assess its level of resilience to climate change impacts. Using a real-world case study, but with fictive data for keeping information confidential as requested by our client, we illustrate the applicability of our tool by highlighting the many benefits it can have in terms of supporting decision-making processes in the context of climate change. Presenting the scenario-based modelling tool in the context of its first application to Corrèze Department, we show how our tool can provide insights to better model future water resources availability scenarios; a necessary step towards appropriate resilient management decision-making.

WATER MANAGEMENT-RELATED TOOLS

Although a wide range of water management modelling tools is available today (among which SWAT, WEAP, MODFLOW) (Izady *et al*., 2022), the existing tools are often limited to monothematic approaches (Liang *et al*., 2018). For example, the existing tools either focus on hydrological modeling and do not account for water demand

and allocation, or they consider water demand and management strategies impacts while hydrological parameters are not treated. To run integrated management simulations investigating both hydrological responses to climate change and water management strategies impacts on water availability, one has to combine at least two tools. These models are thus often combined to simulate water demand under climate change conditions. Our tool, however, includes hydrological modeling, water demand, and management strategies impacts within one model for integrated management. Further, these tools use Global and or Regional Climate Models (GCM or RCM) which offer low resolution outputs (e.g., from 300 km to 30km) and do not display context-specific hydro-climatic parameters at the local level. This is problematic because water resources management in the context of climate change is a complex endeavor requiring multidisciplinary approaches that account for the existing socioecological and political systems in which the solution is applied. These efforts often fail to achieve sufficient spatiotemporal resolution for a meaningful identification of vulnerable watersheds and water uses, especially when mapping water scarcity risk, and sophisticated methods are often necessary to adapt global data to local contexts (Solecki & Oliveri, 2004; Themeßl *et al*., 2011). Our tool, however, offers more precise outputs at a resolution of 8 km which leads to more precise results than GCM and RCM.

Further existing modelling efforts combine the IPCC greenhouse gas emission scenarios, the available GCM and RCM, as well as experts' and scientists' hypotheses (Zhou *et al*., 2010; Beauvais *et al*., 2019; Kouassi, 2019; Caquet *et al*., 2021). However, these approaches account very little for the future evolution of hydroclimatic variables under climate change, nor how new anthropogenic pressures can arise from this evolution (Gilbert, 2009; Metzger and D'Ercole, 2009). In contrast, our scenario-based modelling tool project future scenarios of changes in water reserves over various time horizons that account for the local characteristics of the studied regions. These existing modelling efforts are also rarely implemented in digital tools (Finaud-Guyot, 2021).

Table 1. Existing water resources and management modeling tools and their main characteristics

	Application level	Hydrological modelling	Water demand, supply and/or allocation	Climate change impacts	Impacts of management strategies	Features	Limitations	Sources
Soil and Water Assessment Tool (SWAT)	Various spatial and temporal scales	Included		Included at a global scale (Global Climate Model)		Prediction of watersheds' hydrology, sediment, and nutrient transport Needs to be set-up, calibrated, and validated with real data before being used	Inability to capture baseflows of catchments	Hussen *et al*., 2018 Touseef *et al*., 2021 Abbas *et al*., 2022
Water Evaluation and Planning software (WEAP)	Various spatial and temporal scales		Included	Included at a global scale (Global Climate Model)	Included	Prediction of future surface-water abstraction scenarios in a complex river basin under conditions of climate change Simulations are defined by time frame, spatial boundaries, system components		Hussen *et al*., 2018 Touseef *et al*., 2021 Abbas *et al*., 2022
Modular Groundwater Flow Model (MODFLOW)	Various spatial scales	Included		Included at a global scale (Global Climate Model)		Hydrogeological model for the simulation of groundwater recharge, evapotranspiration, pumping, discharge to sub-surface drains		Ostad-Ali-Askari *et al*., 2019 Chunn *et al*., 2019 Abbas *et al*., 2022
Mike Hydro Basin	Large scale and multi-year simulations	Included		Included at a global scale (Global Climate Model)	Included	This model assess aquifers recharge, evaluates climate change impacts, analyses performance of water management infrastructures		Santos *et al*., 2015 Malamataris *et al*., 2020
Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS)	Various spatial scales	Included		Included at a global scale (Global Climate Model)	Included	Combination of a range of 7 methods for simulating precipitation, runoff, and streamflow in fairly simple to very complex infiltration and evapotranspiration environments	Needs complex parameterization	Deb *et al*., 2018 Nyaupane *et al*., 2018

THE RESILLIENCE PERFORMANCE ASSESSMENT METHODOLOGY

The methodology presented here is a holistic and integrated approach developed by RESALLIENCE by SIXENSE. RESALLIENCE is a consulting, engineering, and applied research company attached to the Vinci Group, a world leader in construction, infrastructure, and resource management. The RPA methodology allows to quantify present water resources, estimate present and future excess and water stress in any given watershed or subbasins, and simulate water resources and uses scenarios. By applying the RPA, a decision-maker or watershed manager can better understand (i) the current and future local water resources, (ii) the ways these resources are and will be impacted by climate change, and (iii) the effects their management decisions can have. As such, the RPA is a decision-support tool that guides decision-makers towards the most efficient climate change adaptation solutions in enhancing the resilience of a region.

The RPA is a multiple-steps approach and consists of two operational tools (Figure 1). The first tool is a Geographical Information System (GIS) platform which offers the users a comprehensive view of climate change impacts in the studied areas through the visualization of different climate scenarios. The second operational tool of the RPA is an analytical dashboard. This dashboard is a decision-making tool that helps users to prioritize adaptation and mitigation solutions by applying a multicriteria cost-benefits analysis. This analysis identifies the solutions that will improve the resilience of a region, reduce (or avoid) greenhouse gas emissions, and enhance biodiversity protection, within the investment needs and constraints (i.e., capital expenditures and operating expenses or CAPEX/OPEX). The RPA thus combines a financial analysis with the structural, physical, social, and environmental resilience of a region. Doing so, the RPA quantitively estimates the potential saving costs of the proposed adaptation and mitigation solutions, as well as the cost of inaction. As of now, only the first tool (the scenario-based modelling tool) has been applied on a real-world case study, which is presented in this article. The second tool is under development and requires fine-tuning. A presentation of the complete RPA will be the object of a future article.

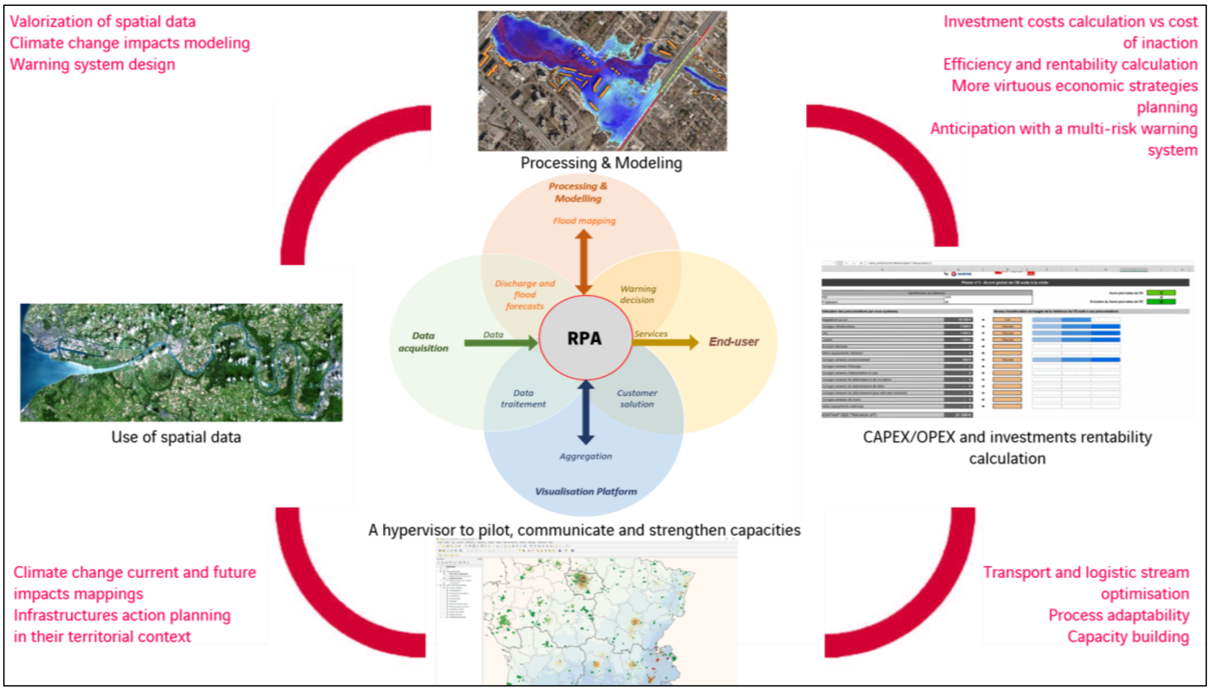

Figure 1 - The RPA methodological approach

Description of the scenario-based modeling tool

The use of a GIS offers an easy visualization of water resources throughout the region of interests along with computational possibilities to both process climate and water resources data. The web-based platform combines present and future climate model outputs with water resources consumptions to examine the variations of water uses sensitivity to potential climatic risks, identify vulnerable water uses, and map vulnerable watersheds. This GIS platform accounts for the spatiotemporal variability of hydroclimatic variables on which water resources depend. Such variables include temperature, rainfall, surface runoff, evapotranspiration, and percolation to aquifer. The location, distribution, intensity, frequency, and other characteristics of these variables are integrated within the platform and represented at two different scales: the sub-basin, the watershed and the departmental scales. The sub-basin scale allows more detailed simulations.

The data behind our modelling tools are built from global spatial data, climatic model, and a variety of reputable sources on water resources and consumption, such as national and international inventories (e.g., BD TOPAGE, Hydro Portail). Other data are built using satellite images (i.e., Landsat and Copernicus). Data used in the models includes landscape variables (e.g., topography, land use and land cover, soil characteristics), hydroclimatic variables (e.g., runoff, evapotranspiration, seepage), and socioeconomic variables (e.g., farm sizes, types of crops, livestock head count, population, number and type of industries), along with the associated water needs for each of categories of land uses and land cover.

All collected and built climate related data are further transformed using a downscaling and correction method developed by our team combining dynamic and statistical downscaling to adapt the outputs to the local topographical features and land-use characteristics of the region of interest. This method is adapted from Willems (2011) to specifically fit water resources management needs (Figure 2). Our downscaling method is especially relevant in contexts where local data may be scarce. Unavailability of local spatial data are thus not an obstacle to the implementation and use of our tool, which makes it replicable throughout the world. They are supplemented with first- and second-hand data collected while visiting the regions of interest and discussing with a range of stakeholders directly and indirectly engaged in the local water resource management. As such, expert knowledge helps contextualize the collected data, which ensures that our models are finely tuned with the local context. This scenario-based modelling tool can be tailored to any types of water consumption in any given regions across the world even regions where local data may be scarce. As such, this tool can be adapted to any local political, environmental, and socio-economic context.

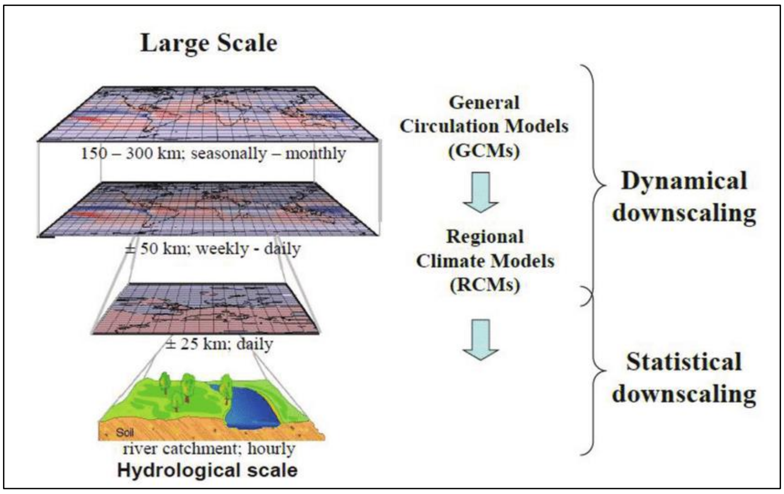

Figure 2 - Downscaling principle to adapt climatic models' outputs to the local context (Adapted from Willems, 2011 in Siwila et al., 2013)

User-friendly, our tool allows users to modify various parameters such as the water consumption, or IPCC scenarios to estimate various water resources balance and visualize the changes induced by these modifications. Indeed, users can anticipate climate risk based on projected climate change threats at different time horizons (up to 2100). This approach simulates the evolution of freshwater reserves under the long-term exposure to different possible hydroclimatic variables projections. Multiple scenarios are considered including a baseline one as well as future evolutions with changing variables based on various global greenhouse gas emission projections provided by IPCC, ranging from the most optimistic scenario (RCP 1.9) to the most pessimistic one (RCP 8.5).

The change in the value of socio-economic parameters is provided in both percent and absolute modes. The parameters can also be considered simultaneously or individually for any scenario period. The modifications can be made at multiple spatial scales (i.e., the whole region of interest, the watersheds, or sub-basins scale), as well as temporal scales (i.e., monthly, and annually). This specific feature allows the users to distribute the water deficit between many different uses and/or watersheds, thus drawing attention to the most critical months and areas with high risk of flooding (i.e., where and when water resources are abundant) and high risk of drought (i.e., where and when water resources are scarce). The tool uses a flexible algorithm that outlines the spatial distribution of the volume of freshwater inputs, the volume required by all types of consumption, and the total available volume. The algorithm was built by our team using a water balance approach (i.e., subtraction of all water demand of the municipalities within a watershed and natural withdrawals (runoff, drainage, etc.) from all the water intakes in the watersheds (precipitation and waterflows from other catchments). In box 1, we described the steps necessary to use our tool. As a web-based software, it does not need to be installed on laptops, could be used anywhere with an internet access, and does not require any technical knowledge or skills.

The configuration of any scenario simulation is set through the following steps:

- Log in on the tool and start the simulation
- Create a new scenario and name it
- Create the baseline situation with the initial features of the uses
- Calculation of baseline exposure of watersheds as well as current and potential future uses
- Choose the desired IPCC scenario and the period
- Define hypotheses regarding the evolution of the water uses in each watershed/sub-basin taken individually or across all the territory under study
- Edit the features of the initial scenario

Box 1 - Our scenario-based modelling tool: a user-friendly interface

APPLICATION OF THE SCENARIO-BASED MODELLING TOOL

To illustrate the interest of our tool, we use a real-world case study on which we applied the scenario-based modelling tool in 2020 for the Department of Corrèze in France. However, for confidentiality aspects, we present here fictive data. This allows us to illustrate the ways our tool works without revealing any sensitive information.

Study area

Located in the Nouvelle-Aquitaine region (France), Corrèze Department has a total area of 5,857 sq.km and a population of around 240,000 people. Agriculture, particularly cattle farming and dairy production, is an important activity in this Department. Other important activities include hydroelectric power generation, tourism, with attractions such as the historic town of Collonges-la-Rouge and the Gouffre de Padirac cave, and manufacturing, particularly of machinery and electrical equipment.

The Department is especially prone to flooding during periods of heavy rain. Corrèze Department has experienced significant flooding events in the past, such as the floods in 2010, 2016, and 2021. The most affected areas tend to be those near rivers or low-lying areas (Figure 3). To mitigate the risk of flooding, the Department has implemented various measures, such as the construction of flood barriers and the establishment of flood warning systems. In addition, the Department has implemented measures to improve water management and conservation, including the preservation of its numerous wetlands in order to regulate water flow and the promotion of water-saving practices. In this Department, climate change will alter the timing and intensity of rainfall, potentially leading to more frequent and severe floods or droughts. This will have serious implications for agriculture, as well as for rivers and waterways. Additionally, hotter and drier conditions could increase the risk of water stress and wildfires in Corrèze. It is in this context that RESALLIENCE was contracted by the Department to apply its scenario-based modelling tool and offer a support-decision tool for local decision-makers towards resilient management of water resources.

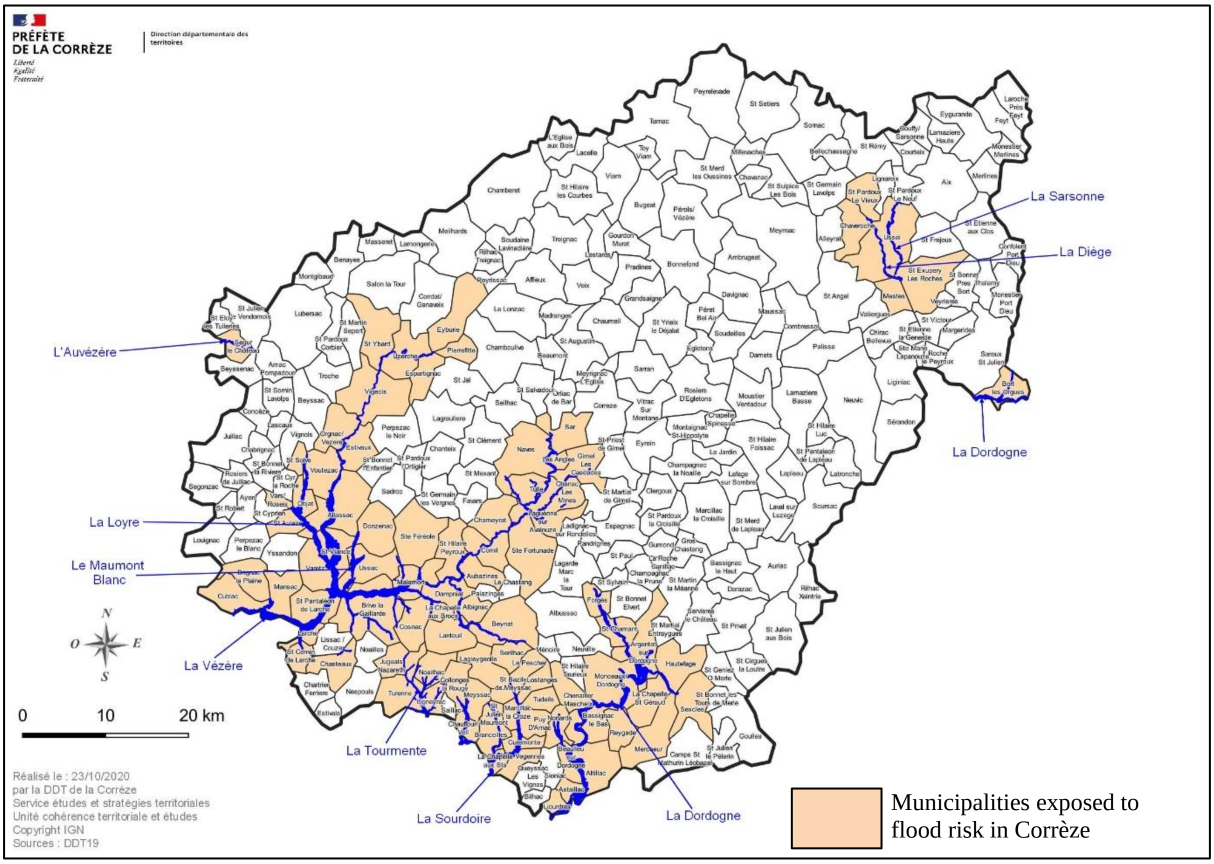

Figure 3 – Municipalities that are the most prone to flooding in Corrèze (Sources: correze.gouv.fr)

Results of the initial testing of the developed scenario-based modeling tool

For this paper, the baseline scenario was defined using fictive data. For example, we made the assumption that most industrial sites are located within watersheds on a North-South axis crossing the central regions of this county. Using this baseline scenario shown in Figure 4, we illustrate the different decisions users could make when using our tool, and the subsequent outputs. In Figure 4, the dark orange regions are watersheds presenting a negative balance for the available volume of water. Assuming a future slight increase of water needs in all industrial sectors of the county, and everything being equal, the annual total available volume of water corresponds to around 870 M m^3 and 954 M m^3 while the yearly industrial water demand is of 59 M m^3 and 65,5 M m^3, for current initial conditions and RCP8.5 in year 2070 respectively. The variability of these numbers across the region of interest confirms the importance of running simulations for estimating climate change effects at a fine scale, consistent with the potential evolution of climatic conditions, rather than at a large scale.

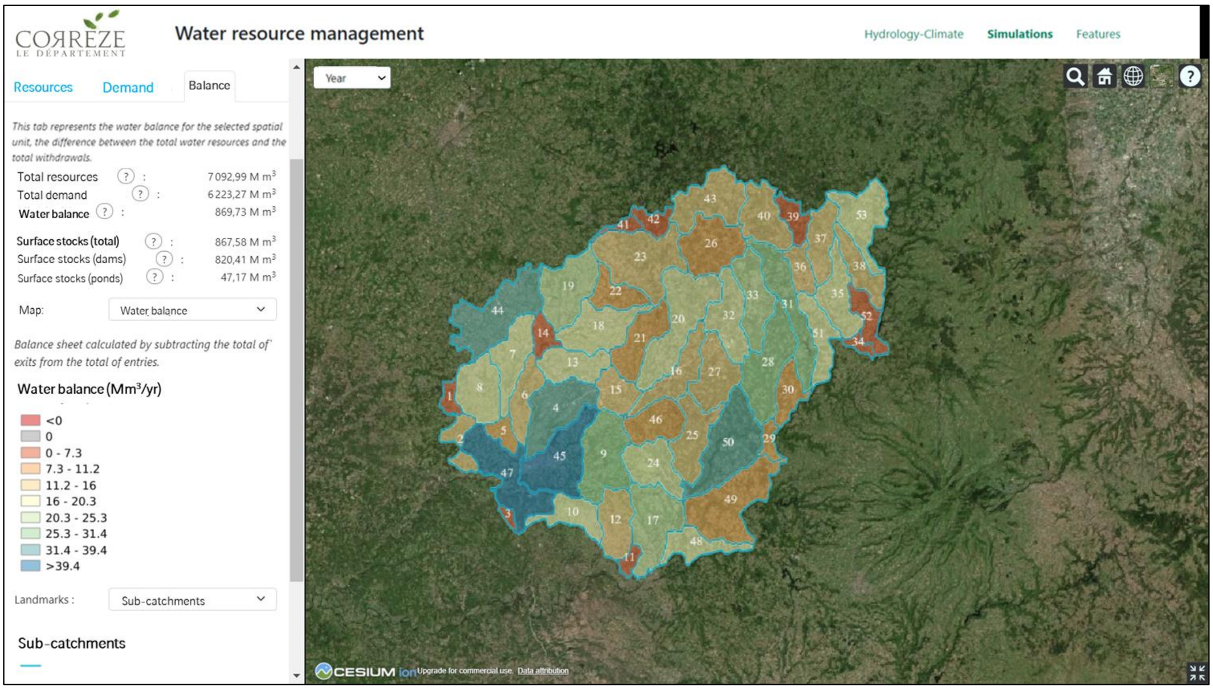

Figure 4 - Baseline scenario with the initial conditions

In comparison to Figure 4, Figure 5 shows how the total available volume of water in sub-basin n° 50 will increase in the future, due to a higher net natural flow of water. Figure 6 presents the outputs of the scenario consisting in a 50% decrease in water needs from the industrial sector by closing some industrial plants. Doing so, the annual total available volume of water shifted from approximatively 954 M m^3 to 986 M m^3 and the new industrial needs decreased to 34 M m^3.

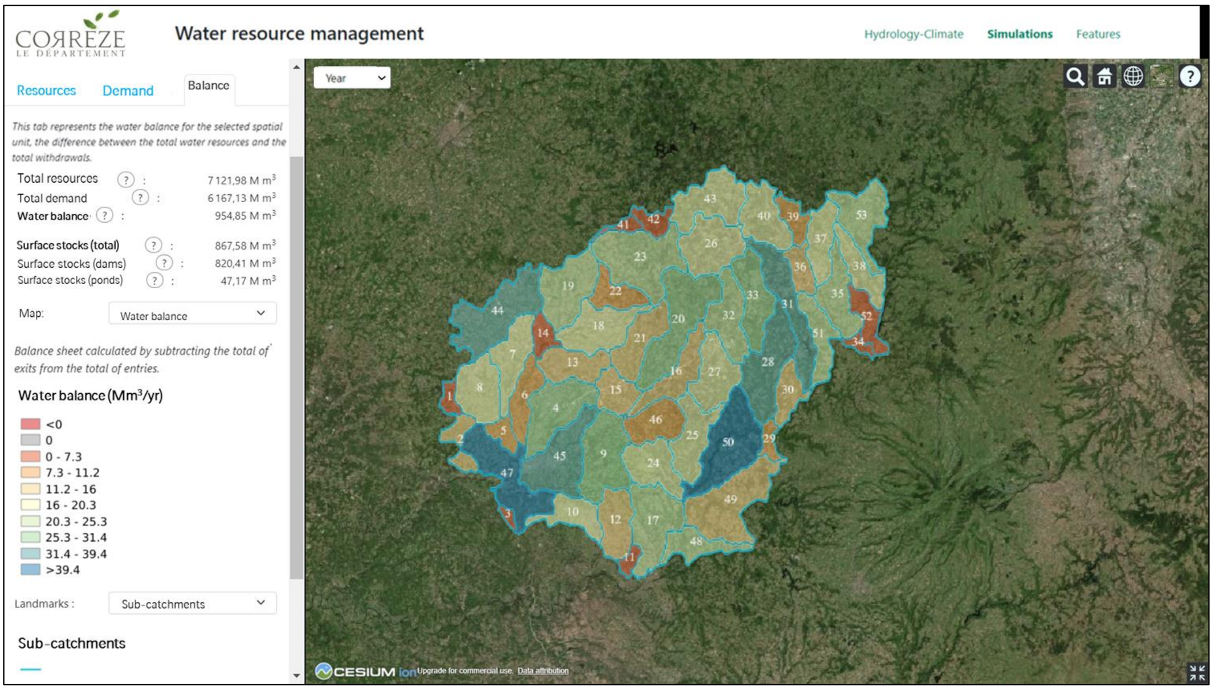

Figure 5 - Baseline scenario evolution in year 2070 under RCP8.5 everything else being equals

Figure 7 illustrates a scenario where, instead of reducing industrial water demand, one decides to cut down half of existing forested areas. In this scenario, the total available volume of water rises to 1,688 M m^3, and the number of sub-basins which may potentially be under water stress decrease in year 2070, compared to the baseline scenario (Figure 4). Figure 8 illustrates a scenario which consists in converting forested areas into several land-use categories with different policy objectives, such as a conversion into agricultural land with a cultivation of fodder for cattle over the whole deforested areas. In this case, the total available volume becomes 907 M m^3, with some sub-basins located in the North-West part of the region losing part of their available volume compared to all other scenarios (Figures 4 to 7).

The results of predictive modelling of climate change effects show that, in all climate scenarios cases, watersheds will experience a wetting trend with a shift in seasonality: an increase in favourable hydroclimatic variables such as precipitation during winter and a decrease in summer. Figures 9 and 10 show the projected equilibrium status of sub-basins in the fodder cultivation (in replacement of cut down forest) scenario in July 2070 and November 2070, respectively. This implies that water from precipitation and other natural inputs considered should be stored in November and then distributed among the different uses and/or sub-basins during the months with the lowest available volume.

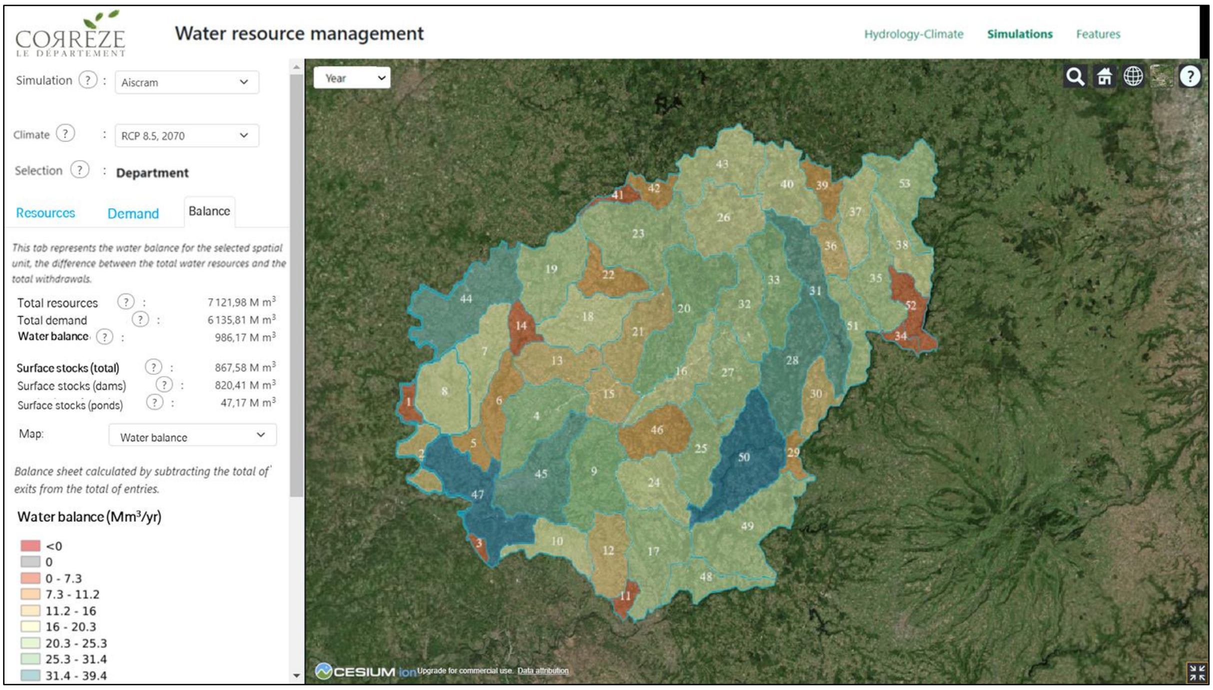

Figure 6 - Results of the implementation of industrial water demand reduction in year 2070 under RCP8.5

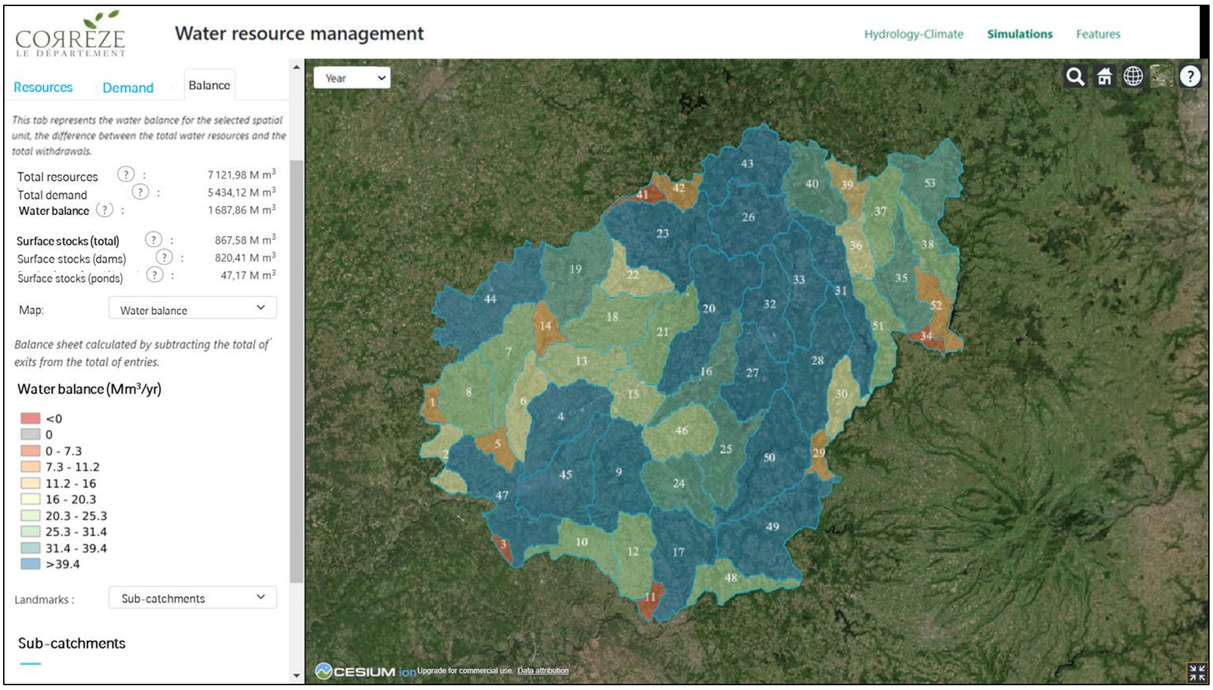

Figure 7 - Results of the deforestation scenario in year 2070 under RCP8.5

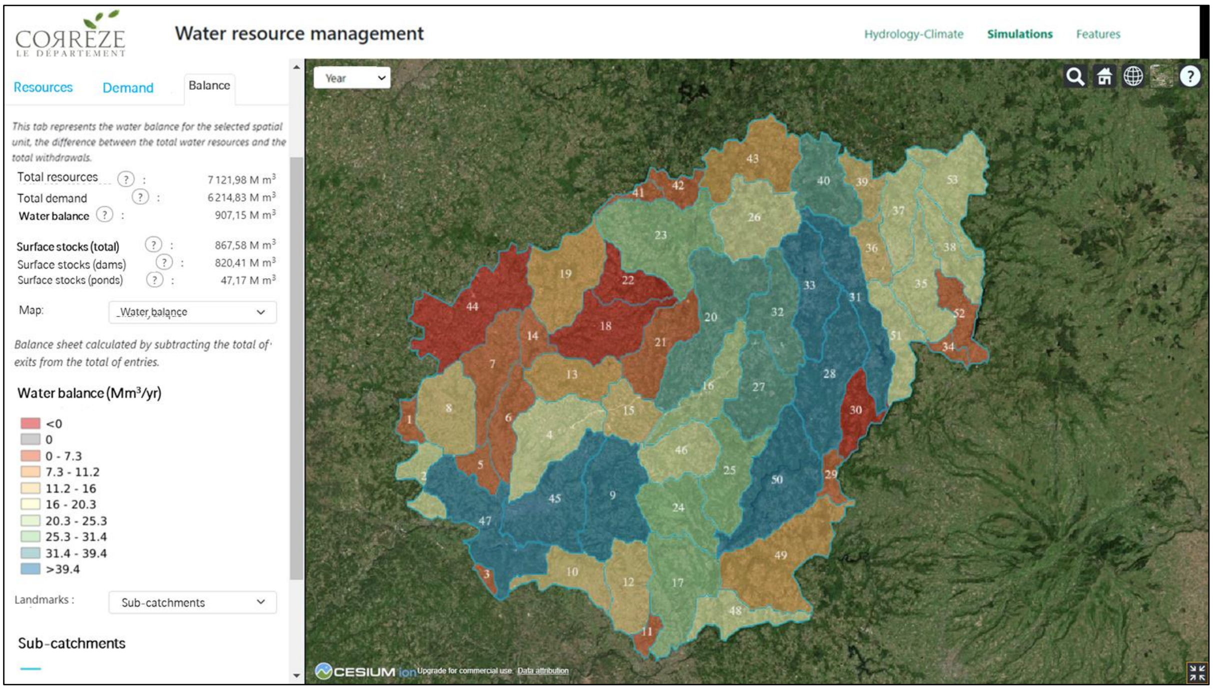

Figure 8 - Results of the fodder cultivation as a substitute of the cut down forest scenario in year 2070 under RCP8.5

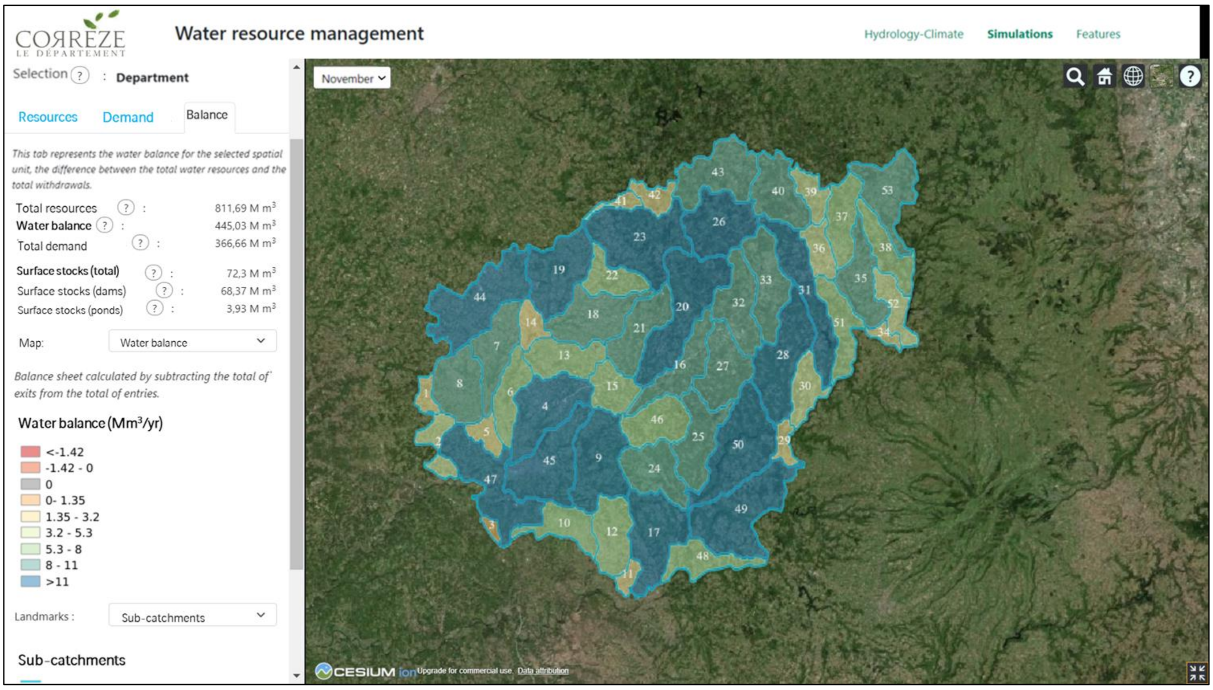

Figure 9 - Results of the fodder cultivation as a substitute of the cut down forest scenario in July 2070 under RCP8.5

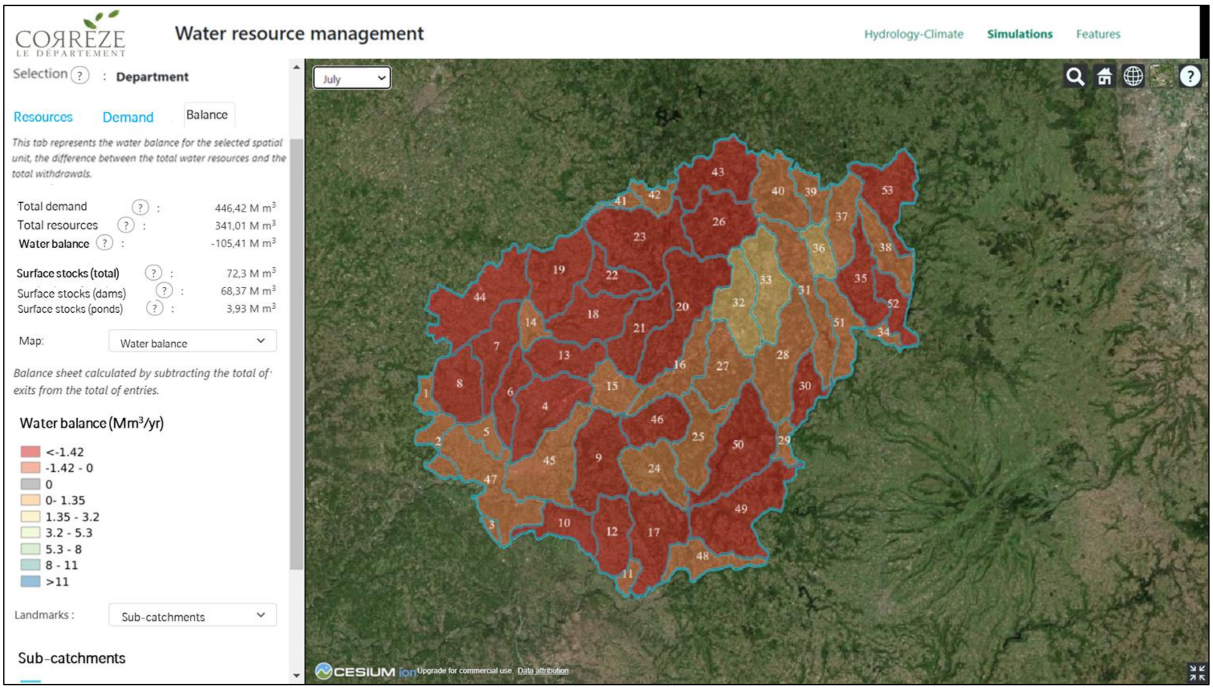

Figure 10 - Results of the fodder cultivation as a substitute of the cut down forest scenario in November 2070 under RCP8.5

CONCLUSION

Demand for freshwater is growing while climate change threatens the quantity and the quality of freshwater resources. In this context, significant pressure is placed on managers to make appropriate decisions that contribute to the resilience of water resources.

This paper describes the scenario-based modeling tool developed by RESALLIENCE by SIXENSE with the goal to facilitate resilient management of water resources through a concerted process between various stakeholders engaged in water resources systems. Decision-makers can use our tool to make informed management decisions as the tool offers a thorough comprehension of three critical aspects: (i) the existing and anticipated regional water resources, (ii) the potential effects of climate change on these resources, and (iii) the potential impacts of their management choices. As such, our scenario-based modeling tool offers insights on expected future climate trends and, therefore, is an important component of a well-informed, data-oriented decision-making process towards the resilient management of water resources systems. The tool provides visual aid for freshwater management and assists decision-makers in communicating water management efforts and their anticipated results. Consequently, the generated outputs of the tool can serve as a means to increase awareness about water resource management. As such, our tool facilitates a collaborative process towards the resilient use and management of water resources, and empowers water managers to make ecologically, socioeconomically, and financially sound trade-offs between competing needs.

The case study illustrates how this tool can be used for projected simulation of water resources management scenarios relying on historical hydrological data in association with current and future strategic plans and trends of water consumption, among others. The description of the outputs illustrates how our tool can help identify watersheds with water resources deficit; a first step towards improving resilience of water resources under climatic changing conditions. As such, this scenario-based modeling tool can provide decision-makers with valuable indications about the impact of climate change on the water uses and availability. Such cost-effective tool requires, however, some simplifications. Water resources systems have complex dynamics, that cannot be fully modelled with the current knowledge and state of the art.

The tool presented in this paper is one of the operational components of the Resilience Performance Assessment methodology; an innovative decision-support tool that enables stakeholders to account for climate change mitigation and adaptation while striking a balance between competing needs at any stage of the life cycle of planning efforts. The RPA models the impacts of climate risks on current and future water resources uses and consumption in any given region, while comparing the effectiveness of various adaptation solutions that can be mobilized to improve resilience to climate change. Although the RPA methodology is still at a prototype stage, its early implementation in the Department of Corrèze shows great potential. Further works will focus on the development and implementation of the second tool that is part of the RPA, i.e., the analytical dashboard. The latter will be linked to the scenario-based modelling tool presented here and consists of a decision-making tool that helps users to prioritize adaptation and mitigation solutions by applying a multicriteria cost-benefits analysis.

Overall, the modelling approach presented in this study provides a basis for further studies worldwide about water resources management alternatives and their potential to mitigate climate change risks. Its usefulness in the context of climate change is already recognized as our tool was validated and supported by local administrative authorities. Further, the replicability of this tool is underway in other French territories and abroad. Applying our tool to other areas will be necessary to refine the tool functionalities and for continued validation of our approach. Such refine will consist in exploring how groundwater resources can be integrated within the existing tool, along with the continued development of the second component of the RPA (the analytical dashboard).

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