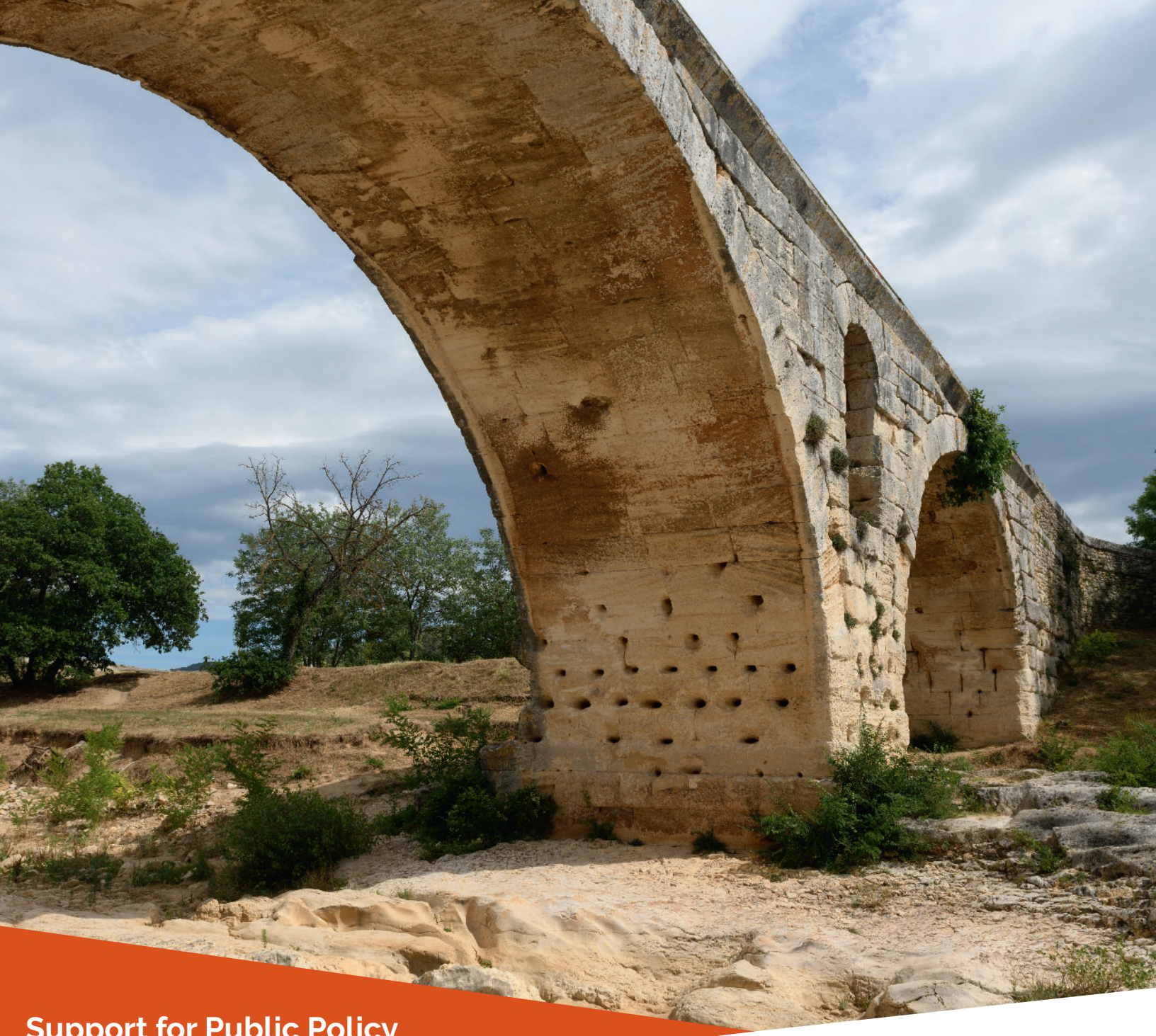


Support for Public Policy

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

INRAE

Explore2: hydrological forecasting for the adaptation of water management

July 2024

Contents of this report

written by Roxane Jupin, Eric Martin, Gisèle Parfait (DAPP, INRAE), Eric Sauquet, scientific manager of Explore2 (INRAE), Claire Magand (OFB) and Maïté Fournier (ACTeon)

Support for Public Policy collection
Publication Director: Marion Bardy
Editorial Director: Gisèle Parfait
Design and production:
Roxane Jupin
Design and layout:
EliLoCom - www.elilocom.fr, Roxane Jupin
Printing: Biprint
July 2024

July 2024

Explore2 projections concur that the impacts of climate change will be increasingly severe as greenhouse gas emissions rise. These impacts will intensify a range of extreme events.

Explore2: hydrological forecasting for the adaptation of water management

Explore2 is an unprecedented project in Europe due to the amount of data it produces. These projections, together with the related technical documentation, developed by a broad scientific community working together in collaboration with two user committees, enable regional studies on water resource availability over the span of the entire 21st century and water management planning.

Conducted from 2021 to 2024, Explore2 set out to describe future climate and water resources across mainland France over the course of the 21st century, along with how to use these resources effectively. The project produced an unprecedented set of projections in terms of model diversity and spatial and temporal resolution unmatched in Europe, thanks to a community of around 40 scientists from various institutions working together on climate change challenges. Some one hundred potential users of Explore2 findings also contributed to the project. Led by INRAE and in cooperation with the International Office for Water (OiEau), this collective effort generated useful and actionable information for water managers at the regional level. Scientists enhanced the readability of uncertainties inherent in the projections by developing four climate narratives illustrating a range of possible futures. In line with IPCC practices, a summary of the main conclusions for mainland France was also produced for a set of variables describing the water cycle, specifying confidence levels and unknowns. The findings of the project, a major asset for French water policy, are available online.

VIEW EXPLORE2 PROJECT FINDINGS

- Hydroclimatic forecasting on the 'DRIAS, Les futurs de l'Eau' portal (in French): https://www.drias-eau.fr/
- The Explore2 MOOC on the OiEau training platform: https://e-learning.oieau.fr/
- Maps showing major project findings on the MEANDRE website (in French): https://meandre.explore2.inrae.fr/
- Technical documents: https://entrepot.recherche.data.gouv.fr/dataverse/explore2
- Recording of the presentation seminar: https://www.seminaire-explore2-lifeeauclimat.oieau.fr/

Updating hydroclimatic forecasting for adaptation policies in France

Development of Explore2 began in 2019 and the project officially launched in July 2021 for a period of three years. The scientific component of the project was led by INRAE, with knowledge transfer and user support handled by the International Office for Water (OiEau). The consortium also includes France's national weather service (Météo France), the BRGM, France's national geological survey, l'École normale supérieure (ENS), the Institut de recherche pour le développement (IRD), the National Centre for Scientific Research (CNRS) –– which includes the l'Institut des géosciences de l'environnement (IGE), the Institut Pierre-Simon-Laplace (IPSL) and Sorbonne Université –– and Électricité de France (EDF). The project was co-financed by these partners, together with the Ministry of the Ecological Transition and Territorial Cohesion (MTECT) and the French Office for Biodiversity (OFB), for a total budget of €2.2 million.

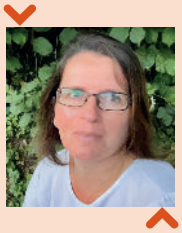
Water and biodiversity authorities at the Ministry coordinated an event to present project findings on 28 June 2024. Consulting firm ACTeon provided project management assistance, including work scheduling, technical and financial oversight, and the publication of a project newsletter for consortium members.

Explore2 updates hydroclimatic projections from surface water and groundwater hydrology research conducted for Explore 2070. Conducted between 2010 and 2012, Explore 2070 was the first project to publish data on projected national water resources in 2046-2065. Explore2 relies on improved hydrological models developed thanks to around a dozen subsequent research projects, together with updated regional climate projections derived from the IPCC Fifth Assessment Report scenarios. Special emphasis is placed on future user needs.

Explore2 project findings respond to a demand for operational data and deliver:

- A broad set of variables related to the water cycle and water management, selected jointly with future users to forecast water resources and uses at the regional level;
- Projections based on 'natural' hydrology, enabling water managers to simulate and test water-use and management scenarios in their regions;
- Educational resources, summary sheets and a MOOC, co-developed with a panel of users, designed to facilitate data uptake, explain modelling tools and raise awareness about related uncertainties;
- Conclusions supported by forecasting outcomes and accompanied by an assessed level of confidence following scientific peer review, taking account of uncertainties, process knowledge and model maturity.

To ensure the correct understanding and effective use of the new projections, OiEau developed and managed a structured support process for water stakeholders, including water agencies, local authorities and consulting firms.



Maud Bérel

'Climate' Project Officer, Ministry of the Ecological Transition and Territorial Cohesion

My role is to promote the inclusion of climate change considerations in water and biodiversity policies and to include water and biodiversity issues in climate policies, for both mitigation and adaptation. The Ministry took part in discussions during the development of Explore2, as the impact of climate change on water resources is a critical issue for water-related public policies. The Ministry therefore co-funds both the scientific components of the project and the support provided to regional stakeholders so they can mobilise the data. We also played a role in the committee set up to oversee the project and helped promote and share project results. Made up of partners and co-funders, this committee issued recommendations and served as a forum for discussion and sharing findings with a wider audience. It also enabled the creation of a user committee for French overseas territories.

A PROJECT ANCHORED IN TWENTY YEARS OF NATIONAL CLIMATE CHANGE ADAPTATION POLICY

National climate change adaptation policy in France was initiated by the environment ministry in the late 1990s in tandem with efforts to mitigate greenhouse gas emissions.

Following the launch in 1999 of the "Management and Impacts of Climate Change" (GICC) research programme, France adopted a national climate change adaptation strategy in 2006. The first National Climate Change Adaptation Plan (PNACC) (2011–2015) emerged from the 2007 Grenelle de l'Environnement Forum.

COP21 provided the impetus to update France's climate change adaptation policy in line with the Paris Agreement. The second PNACC plan ('PNACC2') (2018–2022) aimed to prepare France for a 2°C warming scenario.

These adaptation policies are complementary to the national low-carbon strategy (SNBC)

Milestones in climate change adaptation policies

[1] GICC (Climate change management and impacts) / PNACC (National climate change adaptation plan)
[2] SRADDET (Regional scheme for land planning, sustainable development and regional equality)
[3] PCAET (Regional climate, air and energy plan)

A project similar to Explore2 in France's overseas territories that addresses local challenges

In the overseas territories, knowledge of the impacts of climate change must be deepened in order to launch a project comparable to Explore2. The project's leaders adopted a two-step approach. First, identify existing available data and the tools and knowledge needed by water management stakeholders in these territories. Second, create the conditions necessary to develop a programme of work (instrumentation, modelling, stakeholder consultation). The inventory phase was carried out by INRAE with the support of the project's scientific community. This work continues via technical meetings and the coordination of a dedicated "Climate change in the overseas territories" section on the Gest'eau and DRIAS-Climat websites: https://www.drias-climat.fr/accompagnement/sections/305

and the multiannual energy programme (PPE), both of which are part of broader national strategy on energy, climate and the reduction of greenhouse gases. They are also aligned with public water policies such as the 2022 Varenne forum on water and climate change adaptation, the Assises de l'Eau water forum of 2019 and the 2023 'Plan Eau' water plan.
IPCC climate projections highlight the need to update these public policies. Hydroclimatic projections produced by Explore2 support national climate policy objectives and will contribute to the 'green France' ('France Nation Verte') strategic framework for ecological transition planning.

At the regional level, projections will inform the overhaul, scheduled to begin in 2025, of river basin management plans (SDAGE); the development of 100 regional water management projects (PTGE) by 2027; updates to regional climate, air and energy plans; and the design of flood prevention programmes (PAPI), among others. They will enable water-sector stakeholders to understand how water resources are expected to evolve in their regions, to initiate regional foresight exercises on water uses and the conditions required for the sustainable management of the resource, and to define and implement adaptations plans aligned with the specific challenges of their regions. Explore2 projections

Najib Mahfoudhi
Interministerial Coordinator for the Overseas Territories Water Plan (eau-DOM), Ministry of the Ecological Transition and Territorial Cohesion

I coordinate the Overseas Territories Water Plan ('eau-DOM') aimed at supporting overseas local authorities in the management of water and sanitation services. I rely on an interministerial team and a project team working at regional French State departments for the environment, planning and housing ('DEAL'). As part of the environment ministry's water and biodiversity authority (DEB), I deal transversally with issues relating to biodiversity. As the bodies responsible for these public policies, hydroclimatic projections are of major importance to us. France's overseas territories are confronted both with extreme events and climate change, which is profoundly disrupting the dry-wet seasonal cycle. It was therefore decided, together with OiEau and INRAE, to set up a working group in each overseas territory, composed of stakeholders in water management and climate change, to gain a better understanding of available data, the projects already carried out or under way, and to identify scientific barriers. The medium-term objective is to carry out an Explore2-type exercise in the overseas territories. The project lead for each territory — OiEau, INRAE and the DEB — organise meetings on needs, so that we can establish a trajectory for each territory to launch the process.

will therefore become operational tools for the implementation and formulation of public policies.
An immediate follow-on to the Explore2 project will involve updating findings using a scenario of a 4°C increase in France by the end of the century. This scenario, known as TRACC (reference warming pathway for climate change adaptation), is the reference scenario selected by the government for the forthcoming third National Climate Change Adaptation Plan (PNACC3). All planning documents must therefore be based on this trajectory.

Sonia Siauve

LIFE Eau&Climat water and climate Project Coordinator, International Office for Water (OiEau)

I led the 'support' component of the Explore2 project during its first two years, notably through the creation of two user committees. Positioned at the interface between the scientific community and some fifty categories of users of hydroclimatic projections, I ensured that the concepts were clearly understood and that users' needs were expressed and heard by all stakeholders. I also worked to facilitate users' understanding of, and engagement with, the scientific processes involved. To this end, scientists regularly presented and illustrated complex concepts based on users' expressed needs, including the reference stations used to calibrate the models, results output locations, the selection of variables, and the concept of the modelling chain. Users frequently request points of contact and opportunities to share and exchange scientific knowledge. The development of data-access tools, such as a massive open online course (MOOC) and the DRIAS-eau portal developed as part of the LIFE water and climate project, helps ensure the effective use of highly valuable data by water managers, for example in water management planning. Though not habitual, communication between these two communities is essential to ensure the relevance of decision-making. This is a distinctive feature of the Explore2 project, and I hope to have made a meaningful contribution to this dialogue.

A PROJECT BUILT ON USER FEEDBACK AND USER NEEDS…

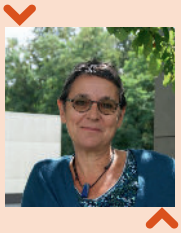
Explore 2070 was the first national study to qualify the impacts of climate change in France. It focused on eight thematic areas: climate, surface water hydrology, groundwater hydrology, aquatic ecosystems, coastal environments, socio-economic and demographic foresight, and the assessment of adaptation strategies.
Launched at the initiative of the environment ministry and led by its water and biodiversity authority (DEB), the study aimed to support public authorities and their operators – including water agencies, river basin committees, bodies responsible for river basin management plans (SAGE), regional environmental, planning and housing authorities (DREAL), departmental directorates for territories (DDT), local authorities, consulting firms, ministries and the French Office for Biodiversity (OFB) – in the development and assessment of adaptation strategies for the management of surface water and groundwater resources.
While the Explore 2070 hydroclimatic projections did contribute to the development of water management strategies, the data was only used by organisations with the technical capacity to process and interpret highly complex datasets.
The user feedback exercise (https://hal.inrae.fr/hal-02930768) carried out by INRAE and funded by the OFB provided the foundations for Explore2. It highlighted the need for an updated national hydrology study to serve as a reference. This study needed to incorporate new time horizons, operational scientific content, and a broader set of indicators. A larger number of modelled locations that better reflect regional needs and decision regions scales were also requested.
Beyond scientific content, the feedback clearly underlined the need to address the accessibility of the study.

…AND ON BROAD ACTION, INFORMATION AND TRAINING OF FUTURE WATER-RELATED USERS AND DECISION-MAKERS

In response to the under-utilisation of Explore 2070 results, due in particular to the complexity involved, Explore2 project leaders integrated a dedicated 'user support' component from the outset, designed to establish a strong interface with users, enabling the co-construction of results and supporting clear understanding. Explore2 was therefore structured around two complementary components: a scientific component and a user-support component.
The user support component partly benefited from the momentum and resources of the LIFE water and climate project, led by OiEau in partnership with Météo-France and INRAE. The project aims to help local stakeholders incorporate the effects of climate change into their management plans and implement locally-suitable adaptation measures. As the timelines and objectives of the two projects overlapped, the LIFE Eau&Climate project funded the DRIAS – Les futurs de l'eau portal, as well as the MEANDRE website, on which are published Explore2 hydroclimatic projections and the interactive maps presenting the main results.

Putting user needs at the heart of scientific research to mobilise results

The 'user support' component of Explore2, led by the International Office for Water (OiEau), is based on regular interaction with two user committees which meet twice a year, along with ad hoc consultations. The first committee, known as "COUT A", is composed of 36 representatives from ministries, the OFB, regional and departmental authorities (DREAL, DDT), consulting firms and local authorities. Members participate in meetings and respond to requests. The second committee, "COUT B", consists of around sixty stakeholders with a broader interest in Explore2 results. They respond to requests but do not attend meetings.
A specific « COUT OM », overseas territories user committee was also established. It brings together representatives from regional environmental, planning and housing authorities (DEAL), OFB, INRAE, the Sustainable Development Observatory, the French environment ministry (MTECT) and its water and biodiversity authority (DEB), as well as the French ministry for overseas territories. This committee takes note of territory-specific needs and challenges with a view to launching a tailored project similar to Explore2 at a later point in time. These committees were actively involved throughout the project.
Consultations aimed to discuss data needs, how data is used, delivery formats and the specific characteristics of France's overseas territories, while also ensuring full understanding and appropriation of hydroclimatic projections by all water management stakeholders over the course of the project and beyond.
The COUT A and B committees clarified ambiguities surrounding certain scientific terms like 'modelled location', 'results output location' and 'assessment location'. The committees also helped refine the scope of Explore2 by identifying the most relevant variables and indicators for water management. The COUT committees were also asked to review streamflow time series used as reference points for hydrological model diagnostics. Certain participants, new to hydrology, discovered the temporal variability of flows and the difficulty of identifying anomalies in data, among other things. This collective endeavour resulted in a scientific publication (https://hal.inrae.fr/hal-04214908). The design of output formats was also discussed, along with prototype result sheets presenting outcomes at modelled locations.
Particular attention was paid to the visual representation of uncertainties and their readability for water managers. Because the future is uncertain, adaptation strategies must incorporate multiple hypotheses and trajectories.
In addition to co-building deliverables and explaining results at the COUT committees, scientists contributed to the design and delivery of a massive open online course (MOOC), coordinated by OiEau, to ensure effective transfer of data and conclusions to water managers.



Natacha Jacquin
Project Coordinator, International Office for Water (OiEau)

Collective intelligence and participatory approaches have been at the heart of my work for many years, so I used this experience in the design of the Explore2 MOOC. This free training course is open to all and designed to facilitate the use of Explore2 results by water managers, consulting firms, non-climate specialists, and others who are responsible for planning water resource use in their regions. The MOOC was therefore developed jointly with the user committee to ensure that training content was tailored to their needs. Its overall structure was co-developed by the project's scientific community and validated by the user committee. Around 20 scientists contribute, providing the keys to understanding the scientific choices made, identifying the information produced at the regional level, and knowing how to use it. The MOOC is composed of 15 modules, sub-divided into three chapters: learn, understand and apply. Users have access to a wide range of videos featuring scientists, an online discussion forum and quizzes.

A MOOC to facilitate understanding and use of results

The Explore2 MOOC (https://e-learning.oieau.fr/) provides the tools required to understand the latest hydroclimatic projections available for mainland France and to use them to develop more climate-resilient water management practices.

The course is composed of three chapters and 15 modules and includes videos, quizzes, an online discussion forum and additional resources.

Chapter 1: Understanding concepts

Chapter 2: Understanding choices

Chapter 3: Applying results at the regional level

Anne Pressurot
Lead for quantitative water management and climate change, Agence de l'eau Rhône-Méditerranée-Corse

My role focuses on strategic work around quantitative water management and climate change. We are using Explore2 modelling outputs in the new adaptation plan for the Rhône-Mediterranean basin to assess regional vulnerability to the impacts of climate change. The results of Explore 2070 had already proved useful for the first French adaptation plan developed for this basin in 2014, and were later used for the Corsica basin adaptation plan in 2018. Explore2's multi-model approach is valuable in showcasing the range of possible projections and the uncertainties associated with them. It also enables a more refined analysis of new hydrological and climate simulations, with sharper regional and climatic resolution. Our role on the user committee allows us to co-design climate-impact simulation tools alongside scientists, to take a step back and explore the different ways these tools can be used, and to help clarify result variability and explain Explore2 products in detail. The diversity of user backgrounds enriches both discussions and proposals.

The science behind Explore2: a multi-scenario, multi-model exercise to represent possible futures

The scientific component of Explore2 is led by INRAE and relies on a scientific consortium that works with users. Together, they develop hydroclimatic projections, select locations used for hydrological modelling, identify variables to be modelled, determine statistical indicators and related uncertainties, produce simulations and evaluate model performance. Other work includes the consolidation of model outputs for diagnostic purposes, the validation of deliverables and the downscaling of global climate projections produced by the IPCC to regional scale and translating them into hydrological variables. This "process" makes it possible to simulate river flows, groundwater recharge and water table levels, and to derive average statistics and extremes such as heavy rainfall, floods, droughts and baseflows. Results are accompanied by a systematic qualification of associated uncertainties and their origins.

CLIMATE PROJECTIONS UNDER THREE GREENHOUSE GAS EMISSION SCENARIOS

Explore2 scientists have developed climate projections to serve as input data for all hydrological models, ensuring that each model uses the same dataset and that their outputs are directly comparable. This climate data is based on regional climate projections from the European EURO-CORDEX database, itself derived from global projections from the CMIP Phase 5 programme (CMIP5). The EURO-CORDEX projections were obtained by combining global and regional models to provide climate descriptions at a spatial resolution of 12 km and a daily time step.

For the Explore2 project, EURO-CORDEX projections were bias-corrected using two methods and interpolated onto an 8 × 8 km grid covering mainland France (Safran grid). Climate parameters – including temperature, humidity, wind, solid and liquid precipitation, solar radiation and evapotranspiration – were provided on a daily basis for the period 1976–2100. Following expert review to ensure consistency with initial findings from the IPCC Sixth Assessment Report, 36 EURO-CORDEX climate projections were selected under three greenhouse gas emission scenarios:

- RCP2.6: Strong mitigation, low emissions,
- RCP4.5: Limited mitigation, moderate emissions
- RCP8.5: No mitigation, high emissions.

SURFACE WATER AND GROUNDWATER PROJECTIONS: IDENTIFYING CLIMATE-DRIVEN CHANGE IN HYDROLOGICAL REGIMES

Explore2 hydrologists used climate projections to model water resources across the entire 21st century. Data generated by the models are variables describing the different compartments of the water cycle, including river

Publications and communication for the Explore2 project

To date, the Explore2 consortium has collectively published around thirty reports and scientific papers. It has invested heavily in publicising the project and its findings, with more than 80 contributions, including seminars, working groups, meetings, training sessions, radio interviews, science festivals, conferences and press conferences.

discharge, piezometric levels, potential groundwater recharge, actual evapotranspiration and soil moisture index. These outputs are used to calculate representative indicators of either average behaviour or extreme conditions, such as average monthly or annual discharge, annual snow or evapotranspiration accumulation, baseflows, flooding, and the maximum number of days below a given discharge rate or soil moisture threshold.

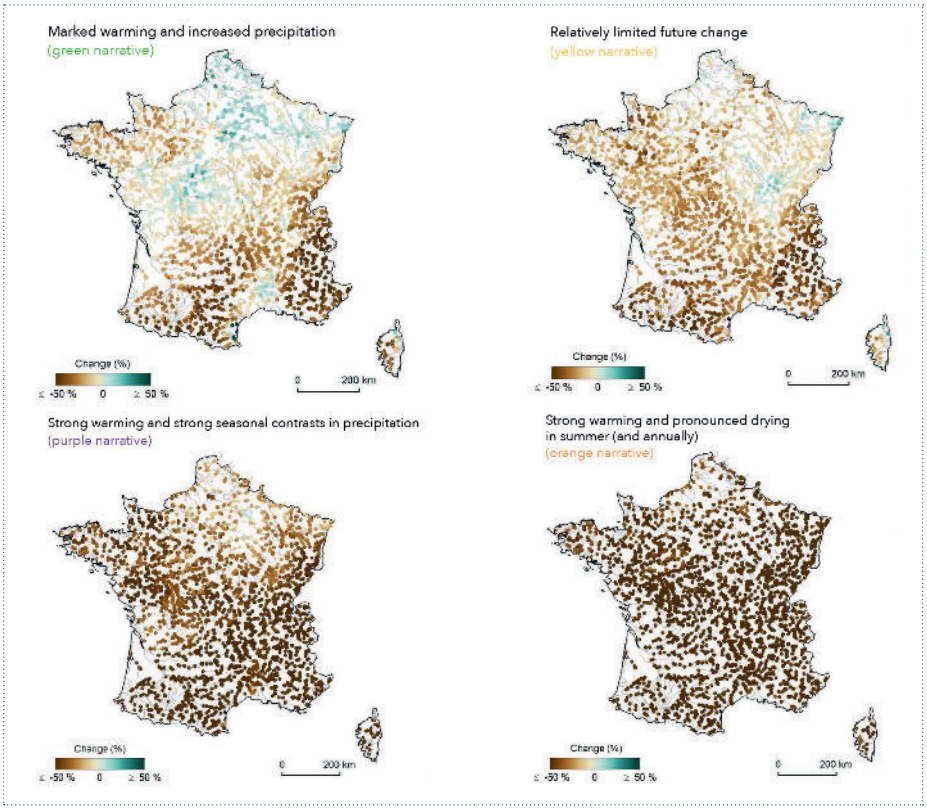
Hydrological projections are produced using a multi-model approach based on nine hydrological models (EROS, CTRIP, GRSD, J2000, MORDOR-SD, MORDOR-TS, ORCHIDEE, SIM2 and SMASH), the RECHARGE model that simulates groundwater recharge, the modelling platform Aqui-FR and the MONA hydroecological model that is specific to the northern Aquitaine context.

Explore2 provides a 'reference hydrology' representing natural conditions, on which foresight studies can be built. Simulated discharges are considered natural. Groundwater levels, however, could not be modelled without accounting for abstractions and were therefore held constant at current levels for the 21st century.

This reference hydrology is compiled from 4,000 river discharge modelling stations (in comparison, 1,522 stations

Selection of hydrometric stations and hydrometric indicators

France has several thousand hydrometric stations, but not all are suitable for detecting changes driven by climate. To reliably identify such changes, an expert-based selection process retained only those stations least influenced by human activities, in order to minimise the risk of detecting changes of non-climatic origin. The selected stations must provide series of measurements spanning at least 40 years to ensure the sufficiently long time span needed to identify long-term trends. They must also deliver high-quality data whose quality has remained stable over time. The longer the time series, the more challenging it is to ensure homogeneity. These constraints explain the difficulty of conducting an exercise such as Explore2 in overseas territories, where hydrological datasets are generally more recent and less stable. Each station provides a continuous record of daily discharge, from which series of indicators are derived to describe the hydrological regime, including the annual maximum daily discharge, used to assess flood risk; the annual average discharge, which reflects the volume of water resources available each year; and the minimum discharge observed annually, which is used to analyse baseflows in rivers.



©INRAE

Changes in annual precipitation totals for the four Explore2 narratives under a high greenhouse gas emissions scenario by 2070 (relative to the 1976–2005 reference period).

Jean-Michel Soubeyrou

Deputy Scientific Director, Climate and Climate Services Department, Météo-France

The department I work for focuses in particular on improving knowledge of past and future climate change in France and on the development of climate services. For Explore2, I coordinate Météo-France's contributions to the project. A major part of our work has focused on correcting biases in the regional climate models used to produce hydrological projections. These biases affect the space and time distribution of temperature and precipitation—variables that are critical for hydrological modelling. To reproduce the climate more faithfully, we therefore apply statistical methods designed to correct these biases. Together with the Explore2 scientific community, we selected two such methods: ADAMONT and CDF-t. The 41 climate simulations retained for Explore2, when combined with these methods, resulted in a total of 82 climate simulations available as input data for the hydrological models. This is a significant improvement from Explore 2070, which relied on only six simulations.

Mireille Brun
Water management project officer, Regional Chamber of Agriculture, Provence–Alpes–Côte d'Azur

In the Provence–Alpes–Côte d'Azur region, agricultural water abstraction is carried out predominantly from rivers and supplies collective irrigation networks. Understanding how river flows are likely to evolve and assessing the volumes that can be abstracted involves public authorities, technical staff from the chambers of agriculture, engineering consulting firms and the scientists running projection models. The Explore2 project is crucial because it is for all these stakeholders. I joined the COUT A user committee when it was first set up, where we were involved in the critical analysis of river data and discharge records. This was a first. We were able to indicate our needs and contribute our field-based knowledge. Enhancements to the DRIAS-eau portal have made the data easier to access and use. Clearer explanations of scenarios and uncertainties also supports projects to modernise infrastructure. We all prefer simple answers to questions about future water availability, but inevitably, certain decisions must accommodate a degree of uncertainty. In the PACA region, there is a portfolio of possible solutions, which include developing agroecology, adapting species and varieties, reducing losses in hydraulic infrastructure and modernising networks.

were used for Explore 2070). Most of these stations are a part of national monitoring networks. These stations generate daily time-step data. Results are also available for small, ungauged drainage basins larger than 64 square kilometres in size. Piezometric levels are provided at 1,200 modelling stations corresponding to piezometers and on spatial grids with resolutions of 1 km for the Aqui-FR model and 2 km for the MONA model. Groundwater recharge is estimated by segmenting groundwater bodies across mainland France.

ESTIMATING AND COMMUNICATING UNCERTAINTY: A PREREQUISITE FOR SOUND DATA USE

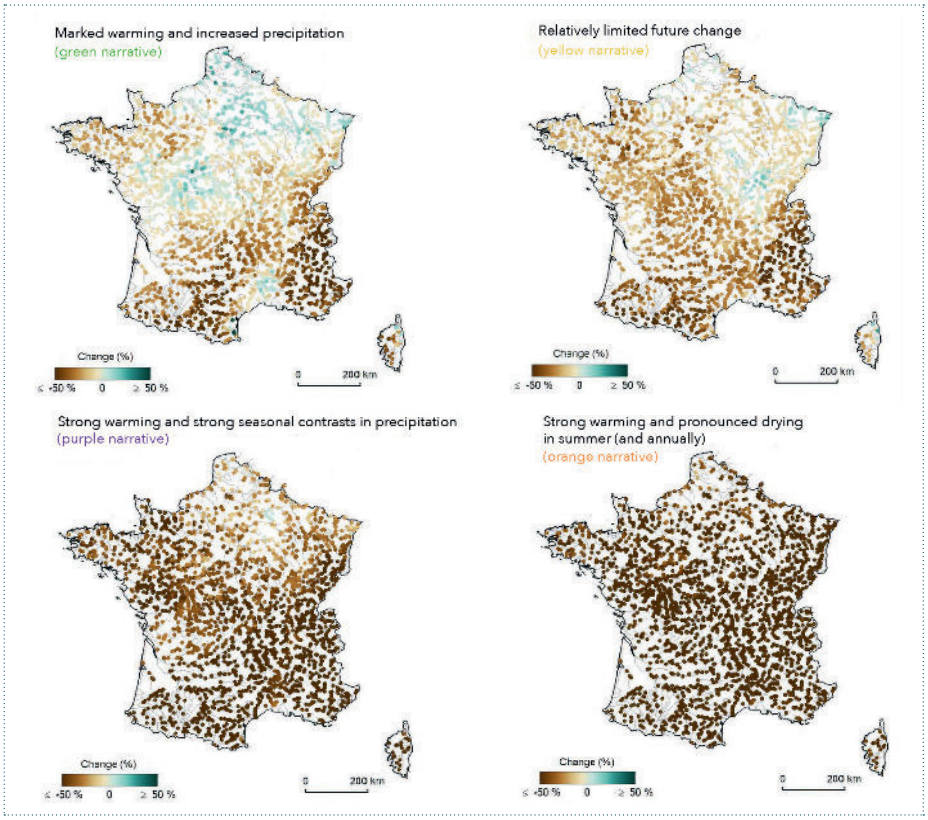
Hydrological projections are the result of a sequence of steps, each involving uncertainty:

- uncertainty related to socio-economic scenarios and greenhouse gas emissions;
- uncertainty associated with climate modelling;
- uncertainty induced by downscaling and bias correction,
- and uncertainty inherent in hydrological modelling.

Residual uncertainty corresponds to the system's internal variability. The succession of models and hypotheses creates a cascade of uncertainties. To quantify these uncertainties, models are usually multiplied at each step.

The use of three greenhouse gas emission scenarios enables analysis based on socio-economic change, while the multi-model approach can estimate uncertainties related to modelling hypotheses and quantify uncertainties related to regional climate, hydrological and hydrogeological modelling.

The multiplication of these simulations generates a significant amount of data, which certain users have trouble using. To illustrate the uncertainty of the project's hydroclimatic projections, they are delivered as 'narratives'.



©INRAE

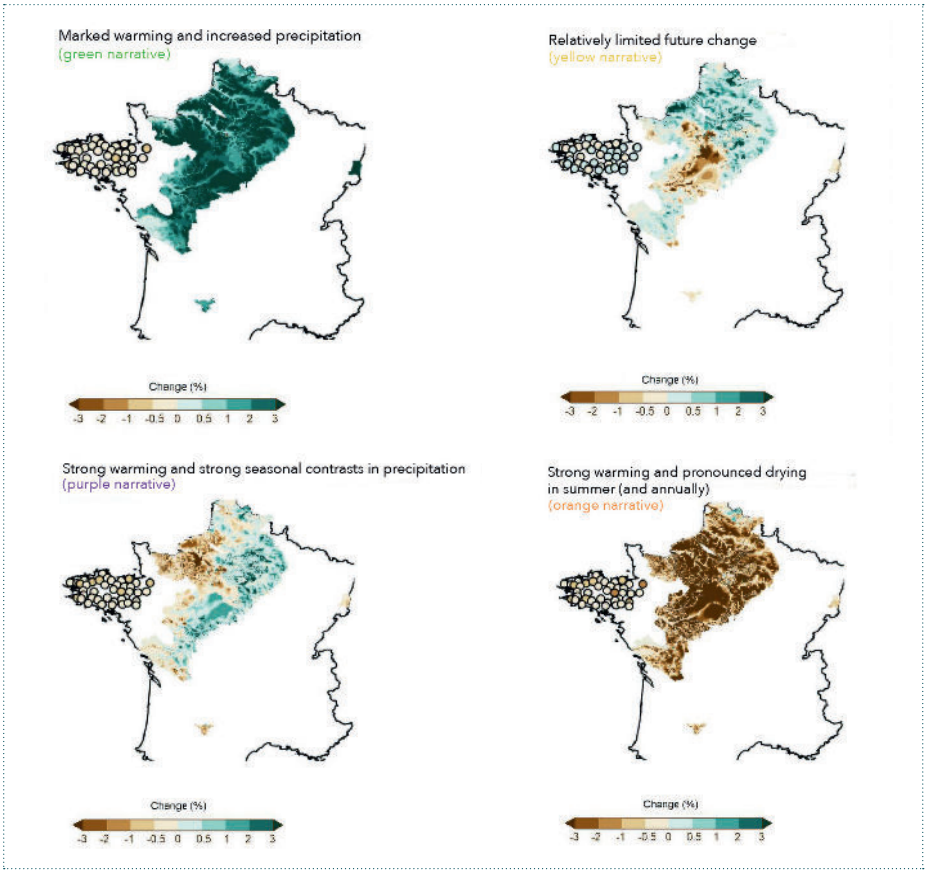
Changes in average summer precipitation levels for the four Explore2 narratives under a high greenhouse gas emissions scenario by 2070 (relative to the 1976–2005 reference period).

HYDROCLIMATIC PROJECTIONS PRESENTED AS NARRATIVES

The narrative approach consists of selecting a limited number of individual projections based on criteria aligned with the specific needs of a study or user. Each narrative corresponds to one projection among the 36 selected and describes a physically coherent sequence of plausible future events. Multiple narratives are required to explore several possible futures, and narrative selection is inherently contextual and subjective. Transparency regarding selection criteria and narrative positioning among the full range of available projections is therefore essential.
Within Explore2, the narratives were selected through a co-development process involving hydrologists and the user committees, in order to illustrate possible futures for climate and water in mainland France, with a special focus on drought risk. Scientists therefore chose four narratives corresponding to contrasting temperature changes under a strong emissions scenario (RCP8.5) and precipitation at the end of the century. Narrative categories were defined relative to Explore2 as a whole:

- Green narrative: marked warming and increased precipitation;
- Yellow narrative: relatively limited future change;
- Purple narrative: strong warming and strong seasonal contrasts in precipitation;
- Orange narrative: strong warming and pronounced drying in summer and annually.

Despite their differences, all four narratives show warming that is consistently more pronounced in summer than in winter, along with an increase in reference evapotranspiration.

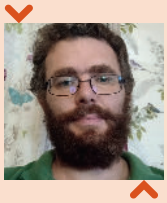


©INRAE

Changes in average annual groundwater depth for the four Explore2 narratives under a high greenhouse gas emissions scenario by 2070 (relative to the 1976–2005 reference period).

Sandra Lanini
Hydroecologial modeller, Bureau de recherches géologiques et minières (BRGM)

I develop different types of models depending on the complexity of the hydrosystems under study. For Explore2, I implement the RECHARGE model, which provides estimates —across France and at the scale of individual water bodies—of the proportion of rainfall that infiltrates and potentially contributes to aquifer recharge. We model groundwater systems using several other hydrogeological models to simulate changes in hydraulic head while also reproducing observed river flows and groundwater levels as accurately as possible at catchment scale.
In order to model the impacts of climate change on groundwater, these models were first applied to the recent past and calibrated in line with observations, and then used to simulate scenarios under varying external conditions.
For Explore2, the models were run several times using different climate projections. Beyond average results, it is worth noting that outcomes varied considerably depending on the climate projections used.



Olivier Canlers
Project Officer, Quantitative water management, DREAL (Hauts-de-France, Artois–Picardie river basin delegation)

In my role as officer in charge of quantitative water management, I work closely with the state water agencies and with river basin management plans to determine how much water can be abstracted during low-flow periods. Our priority is to assess as accurately as possible the impacts of climate change on water resources at local scale. We need daily data, similar to the climate data available via DRIAS. The greater the level of detail, the better. I am very satisfied with the process so far, as cooperation has been highly constructive. Our high expectations for this project make a dedicated forum for dialogue essential.

Yves Tramblay
Research Director in Hydrology, Institut de recherche pour le développement (IRD)

My work focuses on the impacts of climate change on extreme events. It is estimated that 26% of the French population is exposed, with potentially severe socio-economic consequences. My first line of research seeks to better understand how the intensity, frequency and spatial distribution of events are changing; the second focuses on developing simulation tools to improve adaptation to these extreme events. In France, different types of extreme events are observed depending on the region—for example, rapid Mediterranean flash floods, snowmelt-driven ('nival') floods in mountainous areas, or events linked to cyclonic activity on La Réunion island and in the French Caribbean. Hydrological droughts, by contrast, can affect large parts of mainland France simultaneously and are intensifying as temperatures rise. The Explore2 report on hydrological extremes provides scenarios for the probable evolution of intense rainfall, floods and hydrological droughts under the various future greenhouse gas emission scenarios.

FOUR POSSIBLE CLIMATE TRAJECTORIES BY 2100 UNDER HIGH GREENHOUSE GAS EMISSION SCENARIOS

The projected changes described by the four narratives were developed under an assumption of high greenhouse gas emissions and should be interpreted relative to the 1976–2005 reference period:

Green narrative: 'marked warming and increased precipitation'

Warming reaches +5°C across France, with strong seasonal contrasts: 4°C in winter and 6°C in summer. Average precipitation increases by +6%. This upward trend is driven by a marked winter increase—particularly strong across the northern half of the country—which is not offset by the limited drying in summer.
This narrative highlights a strong contrast in summer river discharge, which is maintained in the north of the country but decreases in southern France. Aquifers in northern France benefit from active recharge and show increasing annual average levels, except in Brittany.

Yellow narrative: 'Relatively limited future change'

Warming remains below the +4°C threshold across France, with moderate seasonal contrasts: 3°C in winter and 4°C in summer. Average precipitation increases by +6%. This rise is the result of a notable winter increase over the northern half of the country and is not offset by moderate summer drying that is negligible across a large north-eastern quarter.
This narrative highlights a contrast in summer river discharge, which is maintained in the north-east of the country but decreases in southern France. Aquifers in northern France benefit from active recharge and show increasing annual average levels solely in the northernmost parts of France.

Purple narrative: 'strong warming and pronounced drying in summer'

Warming reaches +4.5°C across France, with strong seasonal contrasts: it is slightly less pronounced in winter (4°C) and stronger in summer (+6°C). Average precipitation decreases by 9%. This decline is driven by pronounced summer drying – particularly across the southern half of the country

Complementary projects to Explore2

Methods and approaches developed for other projects can be used to harness Explore2 hydrological projections within territorial adaptation strategies. This is the case, for example, for:

- methods for using hydrological projections to build water management strategies developed as part of the Life Eau&Climat project, coordinated by OiEau. Twenty-one water management and planning schemes (SAGEs) are concerned;
- the vulnerability diagnostic approach for protected areas, which draws on hydroclimatic projections and data produced under the Life NaturAdap't project;
- nature-based adaptation solutions developed under the Life intégré ARTISAN project to strengthen territories' resilience to climate change.

Eric Sauquet
Research Director in Hydrology, Scientific Lead for Explore2, INRAE

I have been working since the 1990s on characterising how catchments function, and since 2007 on the impacts of climate change on hydrology and water management, through projects supported by the OFB, the water agencies and the environment ministry. These decision-support projects for water management across different river basins sometimes integrate socio-economic trajectories in order to examine the rapport between water supply and demand over time. In 2010, Explore2070 was a pioneering study that addressed the impacts of climate change in France. A few years later, a strong collective demand emerged to update these datasets in light of IPCC findings, which is what motivated me to become involved in Explore2. I received substantial support from the partners in launching and coordinating the project, as well as OFB. Explore2 is not, *strictly speaking,* a research project. Even so, we have debated and revisited certain choices; that is part of the life cycle of any project and shows that addressing climate change remains a research endeavour.

– which is not offset by the moderate winter precipitation increase that is negligible outside the north-eastern quarter.
This narrative, the most critical in terms of water resources, predicts a generalised decrease in summer river discharge and annual average groundwater levels.

Orange narrative: 'Strong warming and strong seasonal contrasts in precipitation'

Warming reaches +5°C across France, with strong seasonal contrasts: 4°C in winter and 6.5°C in summer. Average precipitation decreases by 8%. This trend masks strong seasonal contrasts, with pronounced summer drying – especially in the south – that outweighs the winter precipitation increase, which mainly affects the northern half of the country.

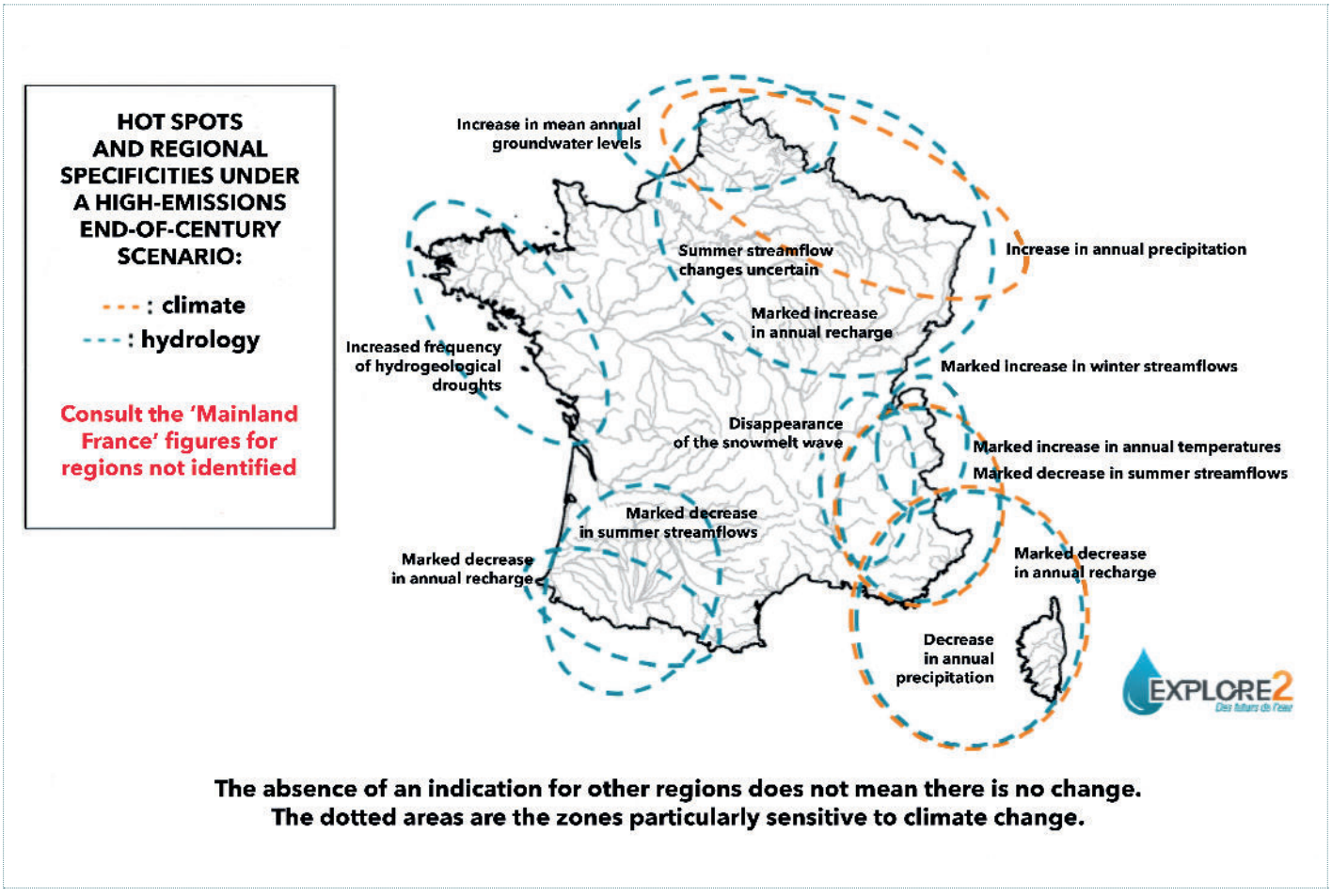
This narrative leads to a generalised decrease in summer river discharge, more pronounced in southern France. Aquifers in Normandy and Brittany show declining annual average levels; elsewhere, annual average levels increase.

KEY OUTPUTS FROM THE EXPLORE2 PROJECT

Based on digital simulations run using hydrological and hydrogeological models, Explore2 scientists have produced a set of projections describing both future climate conditions and the state of water resources over the 21st century across mainland France, under three greenhouse gas emissions scenarios. These national hydroclimatic projections are intended to be used to initiate future-focused, regional-level work on water uses and the conditions required for sustainable water management.

These projections can be summarised in five key points:

- The impacts of climate change will be increasingly severe as greenhouse gas emissions rise.
- Past and future water management practices will necessarily differ in order to adapt to changing hydrological regimes.
- According to Explore2 projections, climate change will lead to an intensification of various extreme events across the modelled domains.
- According to Explore2 projections, the possible evolution of flood flows remains uncertain. However, based on the work summarised in successive IPCC reports, it should be noted that scientists expect an intensification of extreme rainfall



Map of the areas most sensitive to the impacts of climate change under a high-emissions end-of-century scenario.

and an increase in flood intensity in many regions of the world. The climate models used for Explore2 provide only a very imperfect estimate of possible changes in heavy rainfall over mainland France, which partly explains the resulting uncertainty in flood-flow simulations.

- The models used for Explore2 are used in their most complete iteration. Nevertheless, there is room for improvement. Many scientific challenges remain in reducing uncertainty in climate and hydrology, including the incorporation of convective phenomena into climate projections; the effect of rising CO^2 concentrations and their implications for estimating actual evapotranspiration (AET); the identification and inclusion of active groundwater–river exchanges; and the representation of snow cover and glacier dynamics. Challenges also exist in making progress, in particular, on the spatial and temporal resolution of simulations.

Ultimately, the models must also incorporate human activity in scenarios for water management and use, and represent the water cycle as altered by human activities. Research continues into water quality, river temperature regimes, and impacts on ecosystems, with a view to integrating these parameters into the models and rolling them out at national scale. Advances in modelling will enrich a future impact assessment in conjunction with forthcoming IPCC publications.

A PROJECT WITH NEW HORIZONS

Four years of cooperation between the scientific consortium and water managers – the future users of Explore2 results – have made it possible to assess the impacts of climate change on water resources across the entire 21st century, and to generate both high-resolution datasets (on discharge, recharge, groundwater levels) and actionable projections to inform water use at the regional level. The data and expertise developed during the project allows scientists to provide continued support for public policy (notably ecological planning), whether in the field of water, with state water agencies, for example, or more broadly in regional operations, via the MAELIA modelling platform (https://www.maelia-iam.fr/). From a research perspective, a consortium review of the project has helped identify scientific bottlenecks and new research avenues on the impacts of climate change on water resources. These will inform programme agency work on adaptation and mitigation priorities. In addition, the project's scientists would like the consortium to continue in preparation for an Explore3 project based on future climate projections. ■

Claire Magand
Research Project Officer, Office français de la biodiversité (OFB)

After the OFB funded the lessons-learned review of Explore2070, we built the Explore2 project together with the environment ministry. We co-fund the scientific component of the project and host its official website. I provided technical follow-up for Explore2 and acted as an interface between the results and future users of the data at the OFB. The challenges surrounding quantitative water management are reiterated in the government's 'Plan Eau' water plan and in regional projects for water management on which the OFB provides technical input informed by Explore2 results. Explore2 could also be used to check that the nature-based adaptation solutions developed under the LIFE intégré ARTISAN project are correctly calibrated. ARTISAN network coordinators and my colleagues at regional delegations therefore attend user committee meetings, where they were able to submit requests. We are also preparing research projects that will draw on Explore2 data.

Acknowledgements

Thank you to everyone who contributed to the publication of this report.

In particuler, we would like to thank the sponsors and the women and men who share their experience in this report: Maud Berel (MTECT), Mireille Brun (CRA de Provence), Olivier Canlers (DREAL Hauts-de-France), Claire Magand (OFB), Najib Mahfoudhi (MTECT) and Anne Pressurot (AERMC).

All scientific contributors: Ryma Aissat (BRGM), Nadia Amraoui (BRGM), Patrick Arnaud (INRAE), Maud Berel (MTE), Sébastien Bernus (Météo-France), Jérémie Bonneau (INRAE), Flora Branger (INRAE), Yvan Caballero (BRGM), François Colleoni (INRAE), Lila Collet (EDF), Lola Corre (Météo-France), Agathe Drouin (Météo-France), Agnès Ducharne (Sorbonne Université), Guillaume Evin (INRAE), Joël Gailhard (EDF), Florence Habets (ENS), Frédéric Hendrickx (EDF), Louis Heraut (INRAE), Benoît Hingray (IGE), Peng Huang (Sorbonne Université), Tristan Jaouen (INRAE), Alexis Jeantet (Météo-France), Sandra Lanini (BRGM), Matthieu Le Lay (EDF), Claire Magand (OFB), Paula Marson (Météo-France), Samuel Mertz (BRGM), Louise Mimeau (INRAE), Céline Monteil (EDF), Simon Munier (Météo-France), Charles Perrin (INRAE), Alix Reverdy (IGE), Lucia Rinchiuso (Sorbonne Université), Olivier Robelin (INRAE), Yoann Robin (LSCE), Fabienne Rousset (Météo-France), Raphaëlle Samacoïts (Météo-France), Eric Sauquet (INRAE), Jean-Michel Soubeyroux (Météo-France), Laurent Strohmenger (INRAE), Soulivanh Thao (LSCE), Guillaume Thirel (INRAE), Flore Tocquer (Météo-France), Yves Tramblay (IRD), Florent Veillon (INRAE), Jean-Pierre Vergnes (BRGM), Jean-Philippe Vidal (INRAE), Mathieu Vrac (LSCE)

Contributors to the 'user support' component: Audrey Bornancin-Plantier (OiEau), Natacha Jacquin (OiEau), Sonia Siauve (OiEau)

Members of COUT A and B user committees.

Project management assistance: Maïté Fournier (ACTeon)

Direction de l'Appui aux Politiques publiques
Centre siège d'Antony
1, rue Pierre Gilles-de-Gennes
92160 Antony

Rejoignez-nous sur :

https://app.inrae.fr/

Institut national de recherche pour l'agriculture, l'alimentation et l'environnement

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

INRAE