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30 years of research for flood prevention

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In this dossier

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Flood prevention policy is based on knowledge of the phenomena, the hazard and the risk, put at the service of action.

30 years of research for flood prevention

Flooding is the leading natural risk in France in terms of impact and extent. It affects one in four French people, i.e. more than 17 million people. Six scientific teams from INRAE, experts in water-related risks, contribute to the implementation of flood prevention policies. They work on tools and methods for predicting and preventing this risk.

The catastrophic record of floods in Europe in recent decades, particularly the major floods of summer 2002, spring 2013 and summer 2021, places flood risk at the forefront of natural disasters. Exposure to these floods jeopardises the safety of populations, the protection of agricultural land and natural environments and, more broadly, the economy of the territories. Over the last 30 years, the average annual cost of damage has been in the order of 650 to 800 million euros.

French public policy on flood prevention is based on decades of experience and successive improvements. One of the strengths of this public policy is that it can rely on a long-standing and stable political will, which has also benefited the collaboration between INRAE and the public authorities. For more than 30 years, INRAE scientists have accompanied the development and improvement of current flood forecasting and prevention tools. They conduct research on the risks associated with river and torrential overflow and runoff. This research concerns the anticipation of floods and hazard forecasting as well as risk prevention and flood protection. These activities are currently carried out mainly by the AQUA division and six research units spread throughout France. They form the foundation of a collaboration with the General Directorate for Risk Prevention (DGPR) of the Ministry of Ecological Transition and Territorial Cohesion.

7 PRINCIPLES OF NATURAL RISK PREVENTION POLICY

1. Know the phenomena, the hazard and the risk
2. Monitor, anticipate and warn
3. Provide preventive information and educate the population
4. Take risks into account in planning and urban development
5. Reduce vulnerability
6. Preparing for and managing crises
7. Post-crisis management and feedback

INRAE'S SUPPORT FOR FLOOD PREVENTION POLICIESS

Research projects

- To disseminate hazard anticipation and monitoring maps
- To choose the right tools for forecasting extreme rainfall and flooding
- To create a database of remarkable floods
- To develop flash flood forecasting systems
- To improve forecasting through artificial intelligence

Tools, models and methods

- To transform rainfall into run-off
- To transform water depth into discharge
- To evaluate the uncertainties of forecasts
- For an economic approach to risk

Scientific and technical support

The general framework of French public policy on the prevention of water-related natural risks

THE PRINCIPLES OF NATURAL RISK PREVENTION

An effective flood prevention strategy could be summed up in the phrase: "Don't be in the wrong place at the wrong time". This implies locating places where it is safe to be at critical moments. These two main dimensions of prevention are reflected in the seven principles that support the national policy of natural risk prevention:

- Knowledge of phenomena, hazards and risks,
- Monitoring, forecasting and warning,
- Preventive information and education of the population,
- Taking into account the risk in development and urban planning,
- Work to reduce vulnerability,
- Preparing for crisis management,
- Post-crisis management and feedback.

France strengthened in 2014 and under European impetus its flood risk management policy with the National Flood Risk Management Strategy (SNGRI). This strategy has three main objectives: 1) Increase the safety of exposed populations, 2) Stabilise in the short term, and reduce in the medium term, the cost of flood-related damage, 3) Shorten the time it takes for affected areas to return to normal. This national strategy is implemented through the flood prevention action programmes (PAPI), launched in 2003 and supported by the local and regional authorities.

RISK IN URBAN PLANNING AND DEVELOPMENT: THE NATURAL RISK PREVENTION PLAN

Controlling urban development is an important lever for flood prevention. For fixed installations and buildings, it is a question of choosing the right location to limit damage in the event of flooding. Thus, the right strategy will consist in not building "in the wrong places". This is what is at stake in the regulation of land use.

In order to avoid the worsening of risks in the future, the national strategy is based on taking into account flood risks in the development of exposed territories with the flood risk prevention plans (FRPPs). These are prescribed and approved by the State and drawn up in consultation with the municipalities and the population. The FRPP maps the areas exposed to flood risks and regulates the use of land, the way in which buildings are built, the use and management of risk areas, depending on the level of risk.

The elaboration of these prevention plans and the regulatory zoning of the risk they propose requires sufficient knowledge of the flooding area. This knowledge is built on the one hand from known historical floods, and on the other hand by using modelling tools made available to public authorities by researchers, who are constantly developing and improving them.

MONITORING, PREDICTION AND WARNING: SCIENCE AT THE HEART OF THE REORGANISATION OF FLOOD FORECASTING

Dramatic floods at the end of the 20th century led to an overhaul of the flood monitoring and warning system which, set up in 1854, left too little time to act and protect the population. The new model is based on close collaboration between science and public actors represented by the French (National) Service for Flood Prediction (SCHAPI).

In 2002, following a report by the National Assembly on flood control, the Ministry in charge of ecology launched a reform to transform the flood warning system into a flood forecasting system. This system must make it possible to anticipate the arrival of floods in the short term and to forecast the corresponding hazard, with sufficient time and precision to effectively activate the warning and emergency chains. Today, the system is supported by 17 flood forecasting services (SPC), resulting from this reorganisation.

The Schapi, with which INRAE would establish a close partnership, is created in 2003 and attached to the Ministry in charge of ecology. Its mission is to manage flood vigilance on a national scale and to accompany the SPCs in

A European framework for flood risk managements

Since 2007, flood risk management policies have been governed by the European directive 2007/60/EC, known as the "Floods Directive", which aims to limit the impact of floods on human health, economic activity, the environment and cultural heritage. This directive was transposed into French law in the law on the national commitment to the environment, known as the "loi LEne", in 2010, and in the decree of 2 March 2011 on the assessment and management of flood risks (decree N°2011-227)..

INRAE's expertise in hydrometry at the international level

Several hydrometric experts are active in international organisations: World Meteorological Organisation since 2008, international working groups, international hydrometric courses run by INRAE since 2013.

Between 2010 and 2020, seven international expertise projects lasting one to three years were also carried out throughout the world on all seven pillars of flood prevention: mapping of hydraulic regimes, design of a dam against debris flows, recommendations for the design, management and monitoring of wetland constructions, or assessment of risks related to heavy rainfall during a state of emergency. Several of these expert assessments used models and methods developed by INRAE.

INRAE-DGPR collaboration to support knowledge, assessment and management of flood risks

INRAE and the DGPR have maintained a partnership since the 1990s in the field of knowledge and prevention of natural and hydraulic risks. The latest agreement signed with the DGPR in May 2022, in application of the framework agreement with the Ministry in charge of ecology, provides for a study and research programme carried out with its Natural and Hydraulic Risks Department (SRNH) in 5 fields of action:

1. Scientific and technical support in risk prevention,
2. Flood forecasting,
3. Safety of hydraulic structures,
4. Flood prevention,
5. Natural land risks.

For the year 2022, 77 research and expertise actions have been undertaken with the DGPR. They call on:

- 3 research divisions: AQUA, ECODIV and ACT
- 6 units: ETNA, G-EAU, HYCAR, LESSEM, RECOVER and RIVERLY
- About 30 FTE, including 10 FTE involving 50 to 60 permanent engineers and researchers

terms of management, advice and training.

It also ensures the scientific and technical coordination of flood forecasting in conjunction with the State's scientific and technical bodies. Since 2006, Schapi, a service of the DGPR, the SPCs, the hydrometric units and the hydrological watch units in overseas France have been in charge of continuous flood watch on the regulatory network of rivers monitored by the State, i.e. 23,100 kilometres in mainland France via the VIGICRUES Flash network. They also contribute to the deployment of monitoring outside the regulatory network. These actions are carried out under the coordination of Schapi, which also produces the national flood watch map available on the VIGICRUES application.

AN INRAE-DGPR PARTNERSHIP FOR THE KNOWLEDGE AND MANAGEMENT OF FLOOD RISK

The 2002 reform on flood forecasting is an opportunity to strengthen and formalise the collaboration between INRAE and the General Directorate for Risk Prevention (DGPR). The latter wishes to reinforce the hydrological skills of the flood forecasting services and provide them with forecasting tools adapted to the needs. Several scientific organisations, INRAE, Météo-France, BRGM, the universities of Toulouse, Montpellier and Grenoble as well as Thalès, are going to combine their efforts over a five-year period to evaluate the quality of various prediction models. This initiative will create a scientific community around the subject of flood forecasting. Today, the INRAE teams are recognised for their skills in modelling and hydrometry. Their actions in support of the DGPR are integrated into broader annual action programmes on "knowledge and prevention of natural and hydraulic risks", which work in particular towards better knowledge and better management of flood risks.

This partnership was moreover confirmed in 2020 by the renewal of the framework agreement between the Ministry of Ecological Transition and Territorial Cohesion and INRAE. This agreement includes a section on knowledge, evaluation and management of risks, including flood risks and the safety of hydraulic structures, as well as a section on territories and cities, targeting, among others, the competency of "aquatic environment management and flood prevention" (GEMAPI) entrusted to the inter-municipalities.

Knowing and

Under the impetus of the Floods Directive, France has mobilised significant resources to support its flood prevention strategy..

Bruno Janet
Scientific and technical advisor to Schapi, DGPR, Ministry in charge of ecology

Schapi steers the VIGICRUES network and coordinates flood forecasting on a national scale, in particular by managing the VIGICRUES website. To improve its efficiency and prepare for the future, Schapi collaborates with scientific organisations. Within this framework, I manage the DGPR-INRAE agreement on three aspects: improvement of forecasting tools and calculation of uncertainties, improvement of discharge estimation techniques, and understanding flash floods in ungauged river basins. I also follow specific needs such as the adaptation of tools for overseas territories, expert assessments, or the follow-up of research projects such as the PICS project on flash flood anticipation. The scientists provide us with ideas that we compare with operational questions in an approach of co-construction of the partnership. We have thus made forecasting more reliable thanks to hydrological models and developed a flash flood warning service, VIGICRUES Flash. In 2023, a symposium organised with the Hydrotechnical Society of France will review 20 years of science-based flood forecasting. But many challenges remain to be met in order to improve forecasts: using overall weather forecasts, mobilising artificial intelligence, opening up vigilance to the whole of the territory, or even communicating better on uncertainties.

modelling risk in river basins

SIMULATING RIVER FLOW: AN ISSUE THAT INRAE'S HYDROLOGISTS HAVE ADDRESSED VERY EARLY ON

A flood corresponds to an increase in a river's flow exceeding several times its average flow. Being able to estimate the river flow is therefore essential to the mission of forecasting and preventing floods carried out by the State services. Since the 1980s, INRAE scientists have been developing complementary flow calculation models. Three models are based on rainfall: GRP, GRD and AIGA. Work is also being done to better account for the water depth-discharge relationship in rivers and associated uncertainties, for example with the BaRatin model. Each year, INRAE provides training at the Ministry's Institute for Environmental Training (IFORE) on the concepts used in the construction of these models, such as statistical hydrology, uncertainties and gauging.

Maria-Héléna Ramos

Research Director in Hydrology, HYCAR unit, INRAE

My work focuses on river flow forecasting and flood warning. Engineer in Brazil, I obtained my PhD in Grenoble and did a post-doctoral fellowship in Italy, at the European Commission's Joint Research Centre, where I worked with the European Flood Awareness System. These skills led me to conduct two major expert assessments on flood forecasting, one in Peru following the 2017 floods via the European Commission and the United Nations, and the other initiated in 2021 with the World Meteorological Organization on the forecasting of flash floods in West Africa. These expert assessments have enabled me to understand the local issues and propose concrete solutions following exchanges with the stakeholders concerned. My research is also enriched by new avenues of reflection. I now enjoy training young scientists and leading the hydrological community, in particular through the international HEPEX network on ensemble forecasting and the European Geosciences Union, which has about 18 000 members from all over the world.

PREDICTING FLOWS IN GAUGED RIVER BASINS USING SIMPLE AND ROBUST MODELS

In the 1980's, HYCAR hydrologists developed the global hydrological model called "GR", for "génie rural" or "rural engineering", and a family of models operating at different time steps.
These models allow to transform the rainfall on the river basin into river flow. They are built on the basis of large data sets and a detailed knowledge of the hydrological behaviour of river basins equipped with gauging stations.
In 2003, scientists joined forces with the Seine moyenne-Yonne-Loing flood forecasting service to develop a variation of the GR model, the GRP real-time forecasting model, for "Génie-Rural-Prévision" or "rural engineering forecasting". Designed to work in a simple way, it depends on only three parameters to be optimized and uses rainfall, potential evapotranspiration, temperature and flow data.
The simplicity of the parameters and settings makes it very robust and one of the reference models for flow forecasting. Following an extensive training policy provided by INRAE and the dissemination dynamics operated by Schapi, it is now used in most flood forecasting services, and runs in real time on several hundred forecasting points. The GRP model was then adapted to floods in the mountains with the addition of the CemaNeige module. It can simulate the evolution of the snow cover on a river basin and estimate the melt. It thus improves discharge modelling at the outlet of snow-influenced river basins.

A collaborative approach at the heart of the development of the GRP model

The GRP model was developed in the context of research, but was quickly transferred to operational tools adapted to field operators. The evolution of these tools, whether in terms of content with associated research, or of form in terms of functionalities or ergonomics, has always involved the end users. Several partners were solicited, in particular Météo-France and the VIGICRUES network, as well as users of the tools, be they in the national forecasting network, private operators or engineering offices. Their feedback has greatly contributed to the development of the tools and associated methods. This collaborative approach is based on a working group that meets annually. It helps to highlight issues that are often complex and sometimes require specific research. For example, a spatialized version of one of the models involved in GRP, as well as methods for quantifying uncertainties, have emerged from this group..

Estimating uncertainties, essential information for risk management

Flood forecasting involves many sources of uncertainty, such as rainfall, weather, flow and parameter settings. Methods have therefore been developed to quantify these uncertainties and to assist in decision-making. INRAE has been involved in leading the international HEPEX group to develop probabilistic forecasting methods, in particular with the emergence of ensemble approaches to account for the uncertainties associated with forecasting. At the request of Schapi, INRAE also designed the OTAMIN software to automatically and systematically associate confidence intervals to hydrological and hydraulic forecasts obtained with different models. The software thus makes it possible to associate a confidence interval with the forecasts, useful for decision-making. This tool is particularly interesting in small river basins where the greater the anticipation, the greater the uncertainty of the forecast.

Three questions to

Lionel Berthet

Deputy Director for Hazard Knowledge and Risk Prevention, Natural and Hydraulic Risks Department, General Directorate for Risk Prevention, Ministry of Ecological Transition and Territorial Cohesion

What is the relationship between risk prevention at the DGPR and scientists?

Within the DGPR, the sub-directorate for hazard knowledge and risk prevention is responsible for flood and coastal risks, natural land risks (such as landslides, avalanches and earthquakes) and the safety of hydraulic structures. It employs about thirty people. Since I started my career, I could see that the collaboration with INRAE scientists was already well established. For us, in the central administration or decentralised services, INRAE is a pool of scientists who carry out demanding and operational research: we know we can count on them to understand and react to complex and rather rare phenomena, as in the recent case of storm Alex, to characterise the hazard, or to construct a socio-economic analysis grid for reconstruction. The agreement that organises the INRAE / DGPR cooperation places a great deal of emphasis on supporting research activities, notably to better understand the various natural hazards. This knowledge is essential for developing the various tools for prevention and protection of populations.

Can it be said that the risk of flooding has increased?

When faced with a rare and intense event, we tend to think of it as "the most" catastrophic ever. In reality, we need to look at the question of risk from a historical perspective: the most recent damaging floods on the Loire and Seine rivers in 2016 and 2018 are nothing like the devastating flooding of the Seine in Paris in 1910. It would also be a shortcut to say that more and more citizens are exposed to flooding. A study by the Caisse Centrale de Réassurance (a reinsurance company) shows that, in fact, prevention tools have made it possible to contain costs and damage. Moreover, we have increasingly reliable models, thanks in particular to the work of INRAE, for forecasting and simulating, an essential step in anticipating action and preventing and limiting damage, particularly to humans.

What are the scientific questions of today and tomorrow?

There are still many questions that require scientific progress. First of all, the characterisation of hazard remains perfectible for several natural phenomena. This is all the more the case when they require a description on a small spatio-temporal scale. For example, while the characterisation of flooding of major watercourses is globally satisfactory, progress is needed to describe and anticipate the risks associated with rapid flooding and even more so with runoff.
As for the future, knowledge of the effects of climate change on hazards is very diverse: while there is a fairly good scientific consensus on the rise in average sea level, it remains difficult to estimate the effects on intense rainfall, particularly in the South of France, and even more so on the resulting floods due to the multiplicity of factors to be taken into account, particularly soil moisture. Beyond floods, the risks linked to forest fires and droughts must be scientifically clarified, and INRAE is working with us on these aspects. The support of scientists is more crucial than ever. The dialogue with this community, which began more than 20 years ago and which works very well, must therefore be pursued.

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Hydrological modelling is essential to anticipate the risk of flooding..

Spotlight on three major projects to improve knowledge of exceptional floods

Extreme floods, such as those that have only a one in 1000 chance of occurring per year, can be devastating. The Floods Directive requires the assessment of the major characteristics of inundations caused by this type of flood. In this context, INRAE is involved in two major projects funded by the ANR:

- The aim of the Extraflo project (2009-2013) was to compare a dozen or so methods used in France to predict extreme rainfall and flooding. The comparisons were translated into recommendations for the services in charge of the execution of risk prevention plans. In the final report, the SHYREG-Pluie and SHYREG-Débit models, developed by INRAE for regional knowledge of rainfall and hydrological hazards, were recommended for their robustness.
- The PICS project (2018-2022) made it possible, by combining models, to develop systems offering up to 6 hours of anticipation on flash floods and representing their impacts on the territories.
  A synopsis of the remarkable floods recorded in mainland France and overseas between 1770 and 2011 was also drawn up by INRAE and an independent historian. It gathers information on the hydrometeorological genesis and impacts of about 175 floods. In 2011, this census, which took almost 10 years to complete, was transposed into a database.

Thanks to this improved knowledge of extreme floods, forecasting models can be adapted to this type of event.

FORECASTING FLOWS IN SMALL RIVER BASINS: A SPECIFIC CHALLENGE

In the early 2000s, the hydrologists of the RECOVER unit in Aix-en-Provence joined forces with the South-East inter-regional management of Météo-France to develop the AIGA method. Fed in real time by rainfall data obtained by radar, the method makes it possible to forecast the flows in small Mediterranean river basins on an hourly basis. These basins are characterised by short reaction times and are often affected by flash floods. These flash floods are particularly deadly and devastating, with several hundred million euros of damage per event.

In 2010, the heavy floods in Draguignan highlighted the need to provide municipalities with a warning tool for small river basins that are not part of the national monitoring system. This is a challenge for research, because it is now necessary to be able to anticipate floods in a few hours, throughout the country, by making the most of the radar rainfall data produced by Météo-France. It is the AIGA method that has made this possible after several years of research and development, primarily thanks to the RHYTMME platform, which distributes anticipation and monitoring maps of hydrometeorological hazards to the 170 subscribed structures in the PACA region, and then at national level via the VIGICRUES Flash service.

The AIGA method is currently used in three operational hydrometeorological hazard monitoring and forecasting systems at a resolution of 1 km2 and a time step of 15 minutes:

1. The national APIC system
   It is a warning system for intense rainfall at the municipal level developed by Météo-France for

Catherine Fouchier
Hydrology researcher, RECOVER unit, INRAE

In the team, we work on the anticipation of flash floods, which particularly affect small unmonitored watercourses. During my thesis, I worked on the AIGA method, which models the flows on these watercourses and estimates the frequency of the modelled floods. The less frequent an event is, the more potentially dangerous it is. In 2017, Schapi wanted a flash flood forecasting system, VIGICRUES Flash, which our experience with AIGA, already deployed in the PACA region, enabled us to rapidly render operational. The subject of flood anticipation is complex and constantly evolving, as is our hydrological model, which is now part of our SMASH platform. It combines hydrological and hydraulic models, allows for their enrichment and testing, and then for their parameterisation so that they reproduce the behaviour of water courses as well as possible. One of the next steps will be to integrate rainfall forecasts. A deployment of SMASH in Réunion Island is also planned with issues specific to the local topography and climatology. All these developments are supported by Schapi.

MUFFINS (2022-2026): for the development of innovative forecasting systems, integrating in particular artificial intelligence

As a follow-up to the PICS project, INRAE is leading the MUFFINS (MUltiscale Flood Forecasting with INnovating Solutions) project. The objective is to develop tomorrow's tools, both multi-scale and cross-disciplinary, for forecasting floods right up to their impacts. The project brings together 9 French partners, operational players or insurance companies, as well as researchers in hydrometeorology, hydraulics and applied mathematics. The project includes in particular the addition of a rainfall forecast to increase the anticipation of flows, an impact model to predict damage and artificial intelligence methods to improve the precise performance of the models.

the Ministry in charge of ecology. It informs the 9,800 subscribed municipalities of the more or less exceptional nature of the rainfall observed in real time;

2. The VIGICRUES Flash service, which monitors 34,000 km of water courses in more than 10,000 municipalities to automatically warn its subscribers of the risk of intense and sudden flooding in the coming hours;
3. Météo-France's extranet for civil security, which provides crisis management services in prefectures with an AIGA Rain map for rainfall within 2 hours . throughout the country and the AIGA Flow map for 15 departments around the Mediterranean belonging to the southern and south-eastern defence zones.

The objective is now to extend the application domain of the tool while maintaining an operational method. A new modelling platform is used for this purpose: SMASH. This platform allows the implementation of different types of models, at different spatial and temporal scales. Modules specific to snow, runoff or underground problems can also be tested. The MUFFINS project financed by the ANR (see box) will also explore the use of artificial intelligence in flow forecasting.

TRANSLATING WATER DEPTHS INTO DISCHARGE: MEASUREMENTS, UNCERTAINTIES AND MODELLING

Scientists have devoted a great deal of attention to the question of flow measurement techniques and have developed software such as Fudaa-LSPIV, created with EDF, to evaluate water velocity and river flow based on video images. This software was supplemented by tools for calculating uncertainties (Oursin and Q+ methods implemented in the QRevInt and Barème operational software), intercomparison campaigns of gauging equipment and alternative gauging techniques.

The BaRatin model, developed by the RIVERLY research unit in Lyon since 2010, makes it possible to estimate the flow of rivers from the water depth measured by a hydrometric station. The statistical approach chosen for BaRatin makes it possible to combine hydraulic information and uncertain gauging to calibrate the parameters of the water depth-discharge relationship and thus quantify the uncertainty of the calculated discharges. Being able to quantify the confidence interval associated with real-time flow measurements ultimately contributes to assessing the uncertainties in flood forecasting. The BaRatin model is used by the VIGICRUES network using its graphical interface BaRatinAGE, and a more general software package, BaM!, offers an extensive catalogue of rating curve models in addition to BaRatin. They are also used by the Compagnie Nationale du Rhône for the operational management of rating curves. All of these advances are being exported internationally, including to the NEON network of long-term ecological observatories in the United States and have been tested by the United States Geological Survey (USGS).

Jérôme Le Coz
Hydrology researcher, RECOVER unit, INRAE

For the past 15 years, I have been developing innovative flow measurement methods for the flood prevention services of the Ministry in charge of ecology. Flow measurements are the first building block of flood forecasting. Models, prevention plans and risk assessment are based on them. These data, which are of great value, are kept in the hydro-portal. France has a solid hydrometric network, with about 2,400 flow monitoring stations, some of which have chronicles exceeding 100 years of observation. The measurement methods are varied and constantly evolving, ranging from propeller-type current-meters to hydro-acoustic profilers and the analysis of videos taken on the ground or by drone. Hydrometry is a field of enthusiasts that brings together engineers from all over the world in a very dynamic network. Beyond the measurement itself, it is also necessary to quantify the uncertainty linked to the conditions and the measurement tool. These are challenges on which France is ahead, thanks in particular to the long-term support of our partners.

Flow rate is a crucial data. Measuring it requires skilled operators, various techniques and sound procedures.

Taking into account the challenges faced by the territories to protect them from floods

The actions carried out to manage urban planning and land use in risk areas are part of flood prevention. This involves defining areas that cannot be built on, or that can be built on subject to compliance with certain regulations, based on a map of areas exposed to flood risk. To create this map, engineers cross-reference the cartography of flooded areas for different reference hazards with that of the stakes and their vulnerability. Usually, they rely on hydraulic flood modelling, which is also used to design any protective structures such as dykes or dams. Assessing the effectiveness of flood risk management measures through prevention or protection obviously also includes an important economic dimension

Frédéric Grelot
Economist, UMR G-eau, INRAE, member of the CBA/MCA working group

Since 2007 and following on from my thesis, I have been involved in the development of the national framework for the economic evaluation of flood management projects, particularly for protection works. With my colleagues at G-eau, we have contributed to developing skills that were previously lacking in France, compared to the United Kingdom or the United States, for example. The challenge was to be able to calculate the amount of damage avoided thanks to the planned projects and to qualify the uncertainties of the economic analysis indicators. On the basis of experts' opinions, we have drawn up usable "turnkey" models, known as "damage functions", for housing, economic activities and cultivated plots. They are recommended by the DGPR in the cost-benefit analysis of projects with the PAPI label. We have also been providing a transfer of knowledge on this subject through continuing education since 2011. The economic evaluation of floods is stimulating, because we have to combine many disciplines such as agronomy, geography, hydrology, sociology and psychology, and extend our understanding of the flood-territory link.

A NATIONAL REFERENCE METHOD FOR THE ECONOMIC EVALUATION OF FLOOD PREVENTION PROJECTS

Quantifying the cost of flood damage is part of prevention and territorial risk management. Since 2010, economic evaluation has been included in the flood prevention action programmes (PAPI). It is mandatory for any project exceeding 2 million euros and takes the form of a cost-benefit analysis. This involves assessing the effectiveness of the proposed measures in terms of their cost and the monetary damage avoided by these measures. For projects over 5 million euros, it takes the form of a multi-criteria analysis, also incorporating non-monetary indicators of effectiveness and cost-effectiveness. These methods help to assess the reduction in vulnerability of the territory resulting from the project. They help in the arbitration between the different land management options for flood prevention.

The cost-benefit and multi-criteria analyses used are national reference methods recommended by the Ministry in charge of ecology. They were developed within the "Flood multi-criteria analysis" working group launched in 2008 following the inventory of socio-economic evaluations of flood prevention instruments (2007, Ministry of the Environment). The group brings together scientific experts (INRAE G-eau, Cerema, DGPR), insurers, and a flood risk prevention and management association (CEPRI) under the guidance of the General Commission for Sustainable Development.

Within this working group, the G-water economists were particularly involved in the development of damage functions for cultivated plots and economic activities. These functions estimate the expected costs of a flood with regard to the characteristics of the stakes (type of crops, nature of the activities) and those of the floods (intensity, time of year). They have also developed a scientifically rigorous and easy-to-implement method for taking into account uncertainties in cost-benefit analyses.

Since 2011, UMR G-eau has also been in charge of continuing training on the methods. Primarily intended for State employees, the training courses are also open to local authorities and engineering offices; each year, they bring together around twenty participants.

Because of their involvement, the economists of G-eau INRAE in Montpellier are regularly asked by the DGPR to assess the quality of the socio-economic analyses of prevention projects.

THE SPECIAL CASE OF FLASH FLOOD PREVENTION IN MOUNTAINS

Flash floods in mountains represent particular hydraulic phenomena in terms of flood prevention. In addition to overflow, they involve in mountain rivers with steep slopes large quantities of sediment transported by the floods. Sediment transport is therefore a very important component in the analysis of flash floods, as sediments can, for example, cause bed and bank erosion, accretion and shifting of the riverbed during extreme events. INRAE provides regular support to the Natural and Hydraulic Hazards Department (SRNH) to improve the prevention of this type of risk, starting with the development of specific hydraulic models capable of integrating this sediment transport component and its influences on the flow laws governing the water-sediment mixture.

Valorisation-transfer actions are carried out such as the publication of a technical guide on the characteristics of flash floods with sediment transport, their morphological effects, the adapted

Being able to predict the evolution of beds allows proposing principles for land use planning.

means of measurement and the existing simulation methods.
Support is also apparent in the contribution to working groups set up by the SRNH. For example, one group has developed the methodological guide "Prevention plan for torrential risks" and a second group has worked on taking into account the specificities of torrential risks in the design of cost-benefit and multicriteria analysis methods. Other actions have led to the design of adapted torrential correction devices, the development of methods for evaluating their effectiveness and the development of maintenance strategies adapted to these particular devices. Finally, INRAE is involved in supporting the Mountain Risk Management and Prevention Strategy (STePRiM), set up by the Ministry in charge of ecology, through the development of initial specifications and decision support for the implementation by candidate communities.

Research that interests insurers

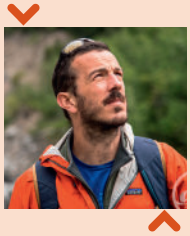
Studies on the risk of intense flooding are of particular interest to insurers, who fund research work.

The MHYST model, which is a simplified steady-state hydraulic model financed by the AXA Research Fund, models floods in a simplified manner in areas with little data, making it a useful complement to conventional hydraulic models.

The Caisse centrale de réassurance has financed work on the analysis and simulation of rainfall on the scale of mainland France and Corsica. A model was adapted to about fifty areas of the territory to simulate the frequency, seasonal, spatial and temporal variability of rainfall over long periods and the associated flood risk.

PROTECTING AGAINST FLOODS WITH NATURE-BASED SOLUTIONS

The development of nature-based preventative solutions is part of the DGPR/SRNH-INRAE programme. In line with the GEMAPI, the aim is to adopt an integrated management approach that takes into account the flood risk and environmental issues: maintenance of flood expansion areas, wetlands and actions to restore natural ecosystems. Recently, the European NAIAD project has made it possible to propose new methodologies for assessing effectiveness and assisting decision-making in implementing nature-based solutions. A methodological note on the biophysical and economic evaluation of nature-based solutions, combining geosciences, ecology and economics, is being drafted with Cerema, as well as a reflection on the coherence of current governance on floods.
Prevention policies against natural hazards were initiated as early as 1858. Successive developments made it possible to build tools and methods that address the various problems of the public actors involved in them. INRAE contributed to the knowledge of phenomena and hazards, allowing them to be taken into account in the development of regulatory risk zoning for natural risk prevention plans from the 1980s. Subsequently, models and tools were deployed to improve flood forecasting and support the services created for this purpose. The expertise of the INRAE teams also contributes to the integrated management of flood risks by proposing methodologies for the cost-benefit analysis of prevention actions included in the PAPI.



Guillaume Piton
Researcher in torrential hydraulics, ETNA unit, INRAE

Originally a hydraulic engineer in an engineering office, I now conduct research on flash floods involving the transport of sediments and driftwood, and on protection strategies against the associated risks. Storm Alex in 2020 caused major flooding and damage due to sediment transport in the Maritime Alps. The DGPR immediately mobilised the IGN to carry out aerial images and a Lidar survey, as well as Cerema, ONF-RTM and INRAE to carry out feedback on this rare disaster. These analyses enabled us to improve our knowledge of sediment and float transport during extreme floods and to inform post-flood reconstruction. In this logic of continuous improvement, the DGPR supports research for action and INRAE, both in our fundamental work on torrential rivers and in our more operational actions. In addition to publications, I contribute to the drafting of guides and notes for government services and technicians, such as the guide for the elaboration of risk prevention plans associated with torrential rivers..

INRAE is already working to address the new challenges that prevention policies will have to integrate, including the impacts of climate change and the resulting uncertainties, as well as improving the way risk is taken into account in territorial management, by involving all stakeholders in order to increase simultaneously the prevention, protection and resilience of the greatest number to flooding ■

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