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CNRS - INP - UT3 - UT1 - UT2J



**Research Report IRIT/RR—2021--06--FR**

**Towards Flash Floods Management Using Temporal Loops**

***Abstract***—Floods, particularly fast ones, are recurrent natural disasters with a large impact on people and infrastructures. To handle such disasters it is needed to combine important quantities of data from different fields. In this article, we attempt to show how data and data-management methods can be used to contribute to the goal of improved disaster and crisis management, especially in the phases of mitigation and crisis response. We propose a concrete methodology to exploit various types of data. We apply it to two floods that occurred in France in 2010 and 2013.

# Towards Flash Floods Management Using Temporal Loops

Patricia Stolf\*, Julian Berthet<sup>†</sup>, Christelle Bosc<sup>†</sup>, Pauline Bremond<sup>§</sup>, Arnaud Ceyte<sup>†</sup>, Victor Champonnois<sup>§</sup>, Anne-Laure Collard<sup>§</sup>, Florent Dubois\*, Georges Da Costa\*, Katrin Erdlenbruch<sup>§5</sup>, Didier Felts<sup>†</sup>, Rémy Gasset<sup>†</sup>, Frédéric Grelot<sup>§</sup>, Christophe Heral<sup>||</sup>, Benjamin Piccinini<sup>†</sup>, Jean-Marc Pierson\* and Amal Sayah\*

\*IRIT Université de Toulouse, France,

<sup>†</sup>Cerema, France,

<sup>‡</sup>Enedis, France,

<sup>§</sup>G-EAU, Univ Montpellier, AgroParisTech, BRGM, CIRAD, IRD, INRAE, Institut Agro, Montpellier, France,

<sup>¶</sup>CEE-M, Univ Montpellier, CNRS, INRAE, Institut Agro, Montpellier, France,

<sup>||</sup>SDIS 31, France

## I. INTRODUCTION

Between 1980 and 2019, worldwide losses due to floods amounted to 1,092 billion US dollars [30]. Only storms caused even more damage than floods. According to the International Disaster Database EMDAT, flood events over the same period triggered over 250,000 fatalities and left 1.2 million people injured (EMDAT [15], last consulted in 2020). In France alone, the mean annual costs of flooding were estimated to amount to 1.3 billion US dollars [16],[1],[29] and every major flood comes with tens of fatalities [45].

The Intergovernmental Panel on Climate Change (IPCC) indicates a likely rise in extreme flash floods and river floods in many regions [23],[30]. In Europe, for instance, such evolutions are likely under current climate change predictions [4]. On the other hand, according to Munich Re [30], flooding is regarded as the natural hazard against which precautionary measures are most effective. Clearly, very many policies and tools to manage floods do already exist at different scales [44]. Yet, improving these tools promises to be effective. This seems all the more important as recent data management techniques and computer-based methods have much evolved over the last decades, allowing to combine important quantities of data from different fields. In this article, we attempt to show how data and data-management methods can be used to contribute to the goal of improved disaster and crisis management.

Disaster and crisis management is described in the literature as a life cycle of four phases [19]: risk mitigation, preparedness, response and recovery. This article focuses on the phases risk mitigation and response. To deal with flash floods, there are two main needs at different time scales. First, there is an operational need during crisis (in the response phase) to help firefighters to prioritize the rescue demands and plan the evacuations. Then in the long term (many years after crisis in the risk mitigation phase), the aim is to avoid future crisis. To do that, institutional organizations have to improve the territory's resilience. In this article we propose to integrate data from different sources at the scale of the territory, we compute different indicators and perform analyses using this data, in

order to improve flood risk management both in the short term and the long term. Based on this knowledge, we respond to the operational needs expressed in the field to provide solutions during the response phase.

More precisely, the questions we answer here are: "How to build a diverse and heterogeneous knowledge base and how to exploit this data for crisis management?"

We propose a concrete methodology to exploit various data described in figure I. The approach could be generalized for any territory, data may be adapted for any specific country.

The hazard has to be described: sensors may collect data on water height, flow, right-of-way of water on the territory. Then, there is a need for data on what is at stake: density of population, enterprises, houses and buildings, network infrastructure...Damage has also to be listed to be able to analyze after crisis how to improve and avoid such situations. The population can also adapt its houses to be better prepared.

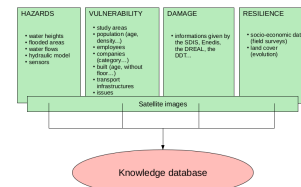


Fig. 1. Data used to feed knowledge database

The main contributions are:

- combine complementary and heterogeneous data to handle crisis through optimisation loops which come from MAPE-K formalism (described later in the article). Insure interoperability and integrate data.
- answer operational needs in crisis management at two timescales: first, during a crisis to prioritize people evacuation to help firefighters during operations; second, to evaluate the territory's resilience in the long term.
- propose a methodology to integrate the different data coming from different scientific communities

- collect complementary data about a territory to have more knowledge and optimize the time to evacuate people.

The remainder of the paper is organized as follows: after a short overview on the related literature in section II and the introduction of the underlying project and the case-study areas in section III, we describe in section IV the data that we deal with, according to the temporalities of the crisis. Data considered is various, including satellite images, data from household surveys and data from qualitative methods and the history of the River.<sup>1</sup> In section V, we explain the underlying models, concepts and methods, which rely on different disciplines, namely hydrology, engineering, applied mathematics, economics, sociology and computer science. In section VI we show how to combine data and methods to improve flood management in the short term, during the crisis. In section VII, we show how to use data and methods to improve the response in the long term, for better risk mitigation and resilience. An integrated risk evaluation is performed. The last section is devoted to the conclusion.

## II. STATE OF THE ART

Based on the needs presented in the introduction to deal with flash floods we present in the following different approaches to manage crisis. There are mainly static approaches build on historic flooding events [37]. Usually, documents that return on experience (REX) are used to analyze in the long term how handling crisis and improve crisis management. Static rules and processes are mainly deduced from historical experiences on the field during crisis.

OSIRIS[17] tackles the issue of data access in the context of flooding but does not offer a solution to deal with this data in the objective to give an answer to this crisis. ANYWHERE (enhANCing emergencY management and response to extreme WeaTHER and climate Events) is an European project that aims at producing a platform for data collection and warnings in the crisis management area without using directly this data to produce directly a decision support tool. This tool is meant to be developed using the output of the network. The GéNéPi [18] project focuses on the right level of granularity needed during crisis management with models of the processes and the cooperation of distributed information systems. This collaborative data platform intends to be used by crisis relief teams to help decision without giving a possible solution itself. Other tools focus on the information system such as Web-GIS [6] a Web-based GIS platform for the monitoring of river flood and risk prediction along the riversides of Arachthos. It displays data from different meteorological stations. In [38] the authors make a literature review and study how information systems research has addressed risk assessment and reduction in natural disaster management.

Several approaches try to predict flood susceptibility [12], [39]. Authors in [12] propose an hybrid intelligence model, based on bagging ensemble and logistic model tree, namely

<sup>1</sup>The article aims to describe all the data useful for crisis management, the associated methodologies, their exploitation within the framework of the i-Flood project.

“Bagging-LMT” model, for flood susceptibility modeling and identifying areas prone to flooding with a case study in Iran. Flood prediction is out of the scope of our proposal. However all the contributions we proposed can be applied on prediction results. In [26] the authors propose to overcome the limitations of hydrological/hydraulic model for ungauged aread or poorly gauged river basins. To do this, they combine artificial neural network (ANN) and GIS techniques and provide the spatial flood hazard.

Many articles try to exploit satellite images to cover the lack of data [2], [28]. In [2], they discuss the utility of applying satellite-based Earth observations for improving flood inundation monitoring over the flood-prone Lower Mekong River Basin. Then present a methodology for determining near real-time surface water extent associated with current and historic flood events. In [41], they utilize the moderate resolution imaging spectroradiometer (MODIS) weekly normalized difference vegetation index (NDVI) product to detect and further quantify flood damages on crops.

Some articles focus on the response phase such as [3]. In [3] authors propose a flow and routing optimization taking into account the congestion on the evacuation network and minimize the evacuation time. Even if this approach can be used in a preventive phase, it does not offer a complete management of the crisis such as our proposal. In [50], authors propose a multi-coverage optimal location model for EMS facilities based on the results of disaster impact simulation and prediction. They propose and formulate a disaster-scenario-based planning and optimal location model that considers the multi-coverage of zones. They ensure in some way a sizing of the emergency infrastructure.

Several operational tools are available to improve the response phase. ResiWater [33] is a suite of models, tools and monitoring infrastructure to improve the resilience of water-related infrastructures.

At a larger timescale, several works evaluate the impact of flooding on the behavior of people. The RETINA project [8] shows several long term strategies implemented following such event. The RAITAP [21] project lists several possibilities to improve resilience and thus reduce the negative impacts of future flooding.

In [48], authors review the crisis management (crisis in general) and resilience literature. They notice that much of the empirical research has focused specifically on the response to crisis events. They propose to link crisis management and resilience in a feedback loop. After experiencing and overcoming a major crisis, there is a feedback loop in which actors’ interpretations of the tasks and relationships they experienced during adversity shape organizing for subsequent adversity.

Some approaches are close to ours but none of them considers at the same time emergency crisis management and prevention, restoration, thus dealing with short-term and long-term problems.

### III. E-FLOODING: PROJECT PRESENTATION

The e-Flooding project aims at modeling flash floods in term of risk management and impact on the infrastructures using data collected by technological or human sensors. The project integrates technical expertise to handle flash floods in crisis management and resilience through an autonomic approach that provides smooth adaptation to the evolution and to the events. The project suggests managing three phases: before, during, and after a crisis in a feedback loop coming from the autonomic field called MAPE-K loop [24, 22] (Monitor Analysis Plan Execute Knowledge). The project<sup>2</sup> is funded by the French Research Agency (ANR).

Two timescales are considered:

- Short-term: aims to optimize the crisis management. During the crisis.
- Long-term: improve territories' resilience for risk prevention. From 5 years after a crisis to 10 years after the crisis

Each timescale is managed with a dynamic approach in four steps by an autonomic approach MAPE-K [25, 22] presented in figure 2. This approach models the dynamics of a system through 4 modules (Monitoring, Analysis, Planning, Execution) and a knowledge base (Knowledge). Usually this approach is used to represent the dynamics of a computing system. The collection of information (Monitoring) leads to an analysis of risks and resilience factors (Analysis), to decide and prioritize actions to be taken (Planning), and finally to execute these actions (Execution). This execution leads to a modification of the system, which therefore closes the loop on information gathering, and so on, while enriching the knowledge of the actions carried out and their cost-benefit ratios. The notion of territorial resilience (identification of vulnerabilities and resilience indicators) is a metric and an objective for rehabilitation. At short-term for example, the Monitor is in charge of the detection of events; the Analysis aims to estimate the consequences of these events; the Plan optimizes the processes to manage the crisis (to evacuate people for example) and the Execute chooses the best process.

The global approach and methodology have been presented in [42]. One loop called *short-term loop* handles the crisis management and the other one called *long-term loop* handles risk prevention.

This article will focus on the Knowledge (the data) which can be used, then the analysis to exploit them. We will present how decisions can be made during a crisis and the feedback after a crisis.

Two territories are used as case studies and are described in the next subsection.

#### A. Study areas

1) *Var flood - June 2010*: Following a strong rainy episode starting on June 15, 2010 in the morning, in the Draguignan sector, the surrounding rivers (the Nartuby, and the streams descending from the Malmont hill) quickly saturated their respective beds, as well as the city's rain networks. It thus

fell, in almost 24 hours, 200 mm of rain on average, and up to 400 mm in places (Les-Arcs-sur-Argens in particular). The peak of flood is reached during the night of June 15 to 16.

Some districts, built in natural depressions, and in particular the commercial area of Saint-Hermentaire in Draguignan, have displayed water heights reaching 4 m. The torrential nature of the flows caused a lot of damage on the town, and those downstream (torn roads, carried cars ...). In addition to the damage to human activities, a large part of the riparian forest was swept along the Nartuby.

This highly artificial sector facilitated the devastating flows on the Nartuby until its confluence with the Argens. From there, the nature of the flood changed to become slower, but more extensive, until the mouth of the Mediterranean. The municipalities bordering these two rivers (the Nartuby and the Argens) have all been impacted, to a greater or lesser extent.

Considering the torrential nature of the flood, and the rapid rise of the waters on the sector just upstream from Draguignan to the confluence with the Argens, it was agreed to focus on this area for the rest of the project (Figure 3).

2) *Pyrenees flood - June 2013*: The second territory chosen is in the Pyrenees, for the devastating flood of June 2013. The event was the result of several causes, which began the previous winter:

- a very significant accumulation of snow at the end of winter: this is due to abundant precipitation (it would have fallen, between December 2012 and March 2013, nearly 800 mm of rain, which represents almost 70 % of precipitation in a year), and temperatures slightly below normal. This resulted in an absence of snowmelt, with snow descending 150 m below, and a snowy mantle of 9 m to 1,900 m and 12 m to 2,500 m.
- an equally cool and watered spring: at the end of May, more than 1,000 mm of precipitation were recorded (91 % of precipitation in a year), with a cumulative snow about 12 m to 1,800 m, 18 m to 2,500 m, and 20 m to the Pic du Midi observatory at 2,877 m (the normal average annual accumulation is 9 m at this location).
- phases of warming up in May and June: they cause an increase in the flow of rivers by snowmelt.
- exceptional new rainfall on June 17 and 18: in less than 48 hours, 180 mm fell in Gavarnie, or 115 mm in Oô. The aquifers are already full, the rivers too. The flow increases (also generated by the steep slopes of the mountain), the water begins to tear off and transport solid materials, which come to create jams on the rivers, favoring overflows. There are 4.80 m in Lourdes. Towns such as Barèges (crossed by the Bastan) are largely devastated (washed-out houses, torn roads, modified riverbed...).

The flood extends over the catchment areas of the Garonne upstream, La Pique, Neste du Louron, and Neste d'Aure (for the Garonne basin), and the catchment areas of Bastan, Gave de Gavarnie, Gave de Cauterets, and Gave de Pau (for the Adour basin), not counting the downstream sectors.

The study area chosen for this flood is concentrated around Bagnères-de-Luchon, along La Pique (Figure 4).

<sup>2</sup><https://www.irit.fr/i-nondations/>

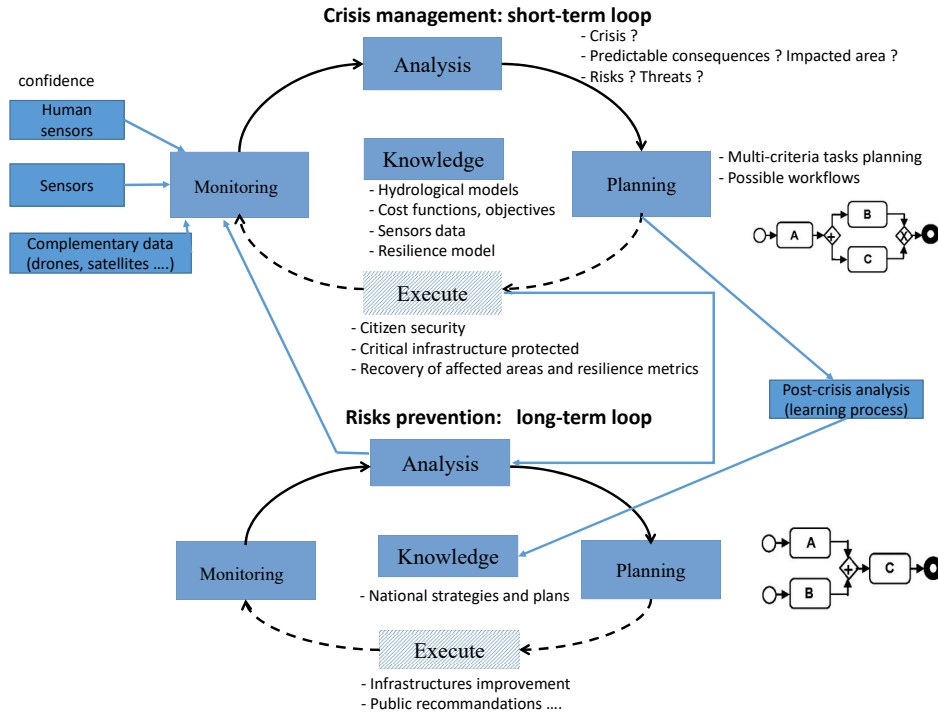


Fig. 2. MAPE-K Loops

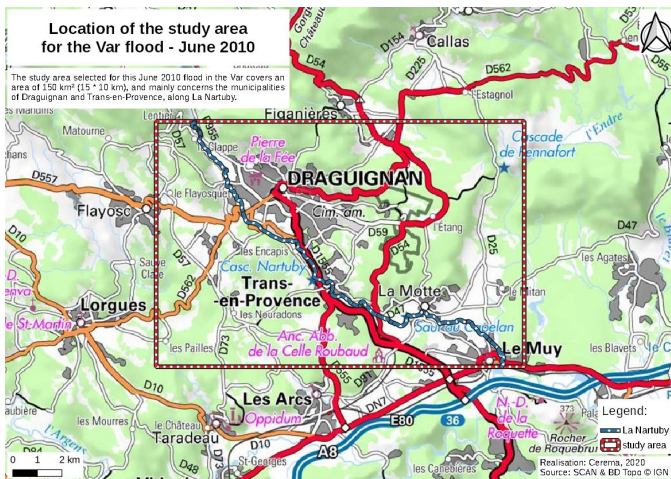


Fig. 3. Study area for Var flood

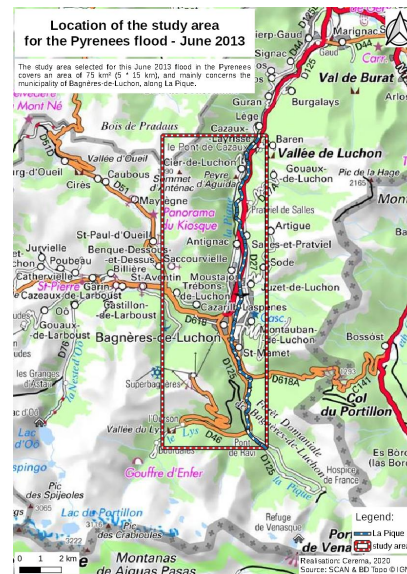


Fig. 4. Study area for Pyrenees flood

#### IV. DATA

Crisis management requires Knowledge. In the context of flood, many kinds of data can be used. This section describes the different data collected which can be static or dynamic. Data are stored in a database called Knowledge in the MAPE-K formalization. This knowledge can be used during a crisis (short term or semi-long term) or in the recovery phase after a crisis at long term temporality. This section presents the Knowledge: we present the data that could be used to manage a crisis, we explain which data is used in the e-flooding project. The Knowledge presentation is structured with it's temporality

usage.

##### A. Static Databases with semi-long term changes

In France there are several institutional databases used in crisis management. They are described below. Most of them are homogeneous and cover all territory.

- BD TOPO: it is a three-dimensional vector database covering France at the scale from 1:5 000 to 1:50 000.

Each year, a new version of BD TOPO is available and produced by National Institute of Geographic and Forest Information. But on average, each point of the territory is updated every 3 to 6 years.

BD TOPO contains:

- road network
  - railway network
  - energy transportation network
  - buildings
  - points of activity or interest
  - named locations (localities, orography, protected natural areas)
- MAJIC is a national database on land data for taxation purposes. MAJIC is managed by Cerema (a French public institution for planning, regional cohesion, and ecological and energy transition) and multiple stakeholders contribute to its production. It is produced each year and allows to access to information on the typology of the buildings (age, size, state, occupation status) or housing (individual, collective, secondary residences).
  - GeoSirene is a database which adds geolocation to the national Sirene database. Sirene is managed by the National Institute of Statistics and Economic Studies (INSEE). It gives a description of all companies and establishments in France. It is updated daily and freely available. Among the information given, the following data are particularly interesting concerning the project, especially when it comes to using damage functions :
    - company addresses
    - APET code: identifier code of 5 characters assigned by INSEE for each company to be listed in the Sirene register.
    - number of employees of the company
  - RPG is a geographical database used for the instruction of the Common Agricultural Policy subsidies by the French Ministry of Agriculture. Since 2015, data produced are at the scale of an agricultural parcel, before 2015, they were at the scale of a cultural block (a set of contiguous agricultural parcels belonging to the same agricultural exploitation). RPG database gives information on the culture of each agricultural parcel or set of parcels such as declared by the farmer.
  - Enedis manages the electricity distribution network across 95% of mainland France and provides data in five fields : energy, environment, infrastructure, electricity markets and operation of electrical power. The map of the electricity network infrastructure is interesting because it contains the 4 main types of electrical network managed by Enedis: underground or overhead electrical network in high voltage or in low voltage. These data are made available for information purposes and not updated regularly. However, it allows to know the location of electrical network and stations where it would be appropriate to place sensors for water height and speed of water flow.

The data contained in all these databases can be used either at short-term to help during the crisis to limit damages and at long-term to study how to improve resilience.

For crisis management in other countries, an important phase of search and collect of data must be realized to fill the Knowledge database.

### *B. Satellite Images: semi-long term and long-term usage*

Satellite images can be used to complete knowledge on a territory or when no institutional database is available.

Usually, there are two ways to get a satellite image: to order archives by visiting the online catalogue from the distributor, or to program the satellite for an acquisition. Also, we can consider satellite image as dynamic data. The advantage of the second way is the possibility to have an image with specific features, but this programming could be constrained by other acquisition requests (that could delay ours few days or weeks after), weather (clouds)... During crisis, satellite images could be acquired in emergency, and made available in 1 or 2 days. Satellite image cost depends on the type of image, the sensor, the area covered... and can be from free (Sentinel data) to several hundreds of euros for optical data or thousands of euros for radar image.

Images acquired during crisis or few days right after, give information on damage and characterization of the flood hazard such as location of flooded areas, isolated areas, land cover of the flooded areas to estimate the presence of persons to be rescued for firemen... Satellite images can be integrated directly in the short/semi-long term loop (to have a vision of the territory, to have a background map), or indirectly with extracted objects or information (as flooded area vector, land cover like build up areas). In this project, 4 satellite images were analyzed: 3 on Draguignan area (one of which is a radar image, the others being optical images), and only one (optical) on Luchon area.

For the long-term usage, only one image by territory was analyzed (optical too). These two satellite images are actually two couples: a couple is a pair of images from the same area, taken at intervals of a few seconds, with two angles of view. This allows to obtain a 3D information, with building and tree height. That covering Draguignan dates from 7 years after the flood (07/13/2017), that of Luchon 1 year and a half (11/02/2014). They could provide information on the evolution of damage or land cover in relation to new land planning following the crisis. These observations make it possible to assess the resilience of the territory, and reduce its vulnerability.

From satellite images, several information can be extracted, which can be classified into 5 themes: hazard, damage, what is at stake, resilience, vulnerability. This will be detailed in the analysis section. Most of these data are obtained by the production of a land cover mapping, which allows the extraction of objects classes (built, roads, bare soil, water, vegetation), and the crossing with other data. According the study characteristics (the spatial resolution of the image, the



study area extent, the kind and complexity of the treatment), the processing time is between few hours to several days.

The land cover mapping is the result of a semi-automatic supervised pixel-oriented classification, and divided into 4 steps :

- 1) image preparation: receipt of the image, assembly and cutting at the right of way of the study area, neochannels computation (NDVI...)
- 2) learning sample preparation: receipt of exogenous data (BD Topo...), assembly and cleaning, random selection to constitute the final sample
- 3) Random Forest classification: the core of the processing, which will assign a land cover class to each pixel of the image
- 4) post-processing: various tasks to improve the result, which can be automatic or manual.

Figure 5 presents an example of a satellite image exploitation to characterize land cover in Dranguignan. The extraction of specific objects of the land cover mapping (buildings or roads for example) allows to update spatial databases (BD Topo or institutional databases).

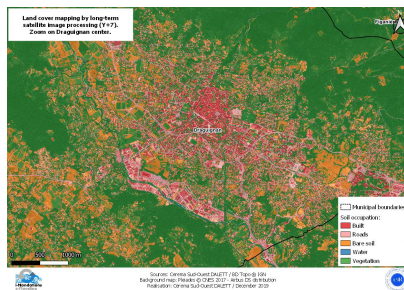


Fig. 5. Land cover mapping on Dranguignan

Orthorectified images acquired from drone or plane can be treated in the same way as satellite images, if they meet 2 constraints: vertical shooting (not oblique), and presence of the same channels (at least, red/green/blue/near-infrared).

### C. Surveys: long term data

We also collected data through surveys. Surveys allow the collection of data that is not readily available in data bases and that cannot easily be measured or observed without talking to people. Data can be static if it makes a picture of a given situation, or dynamic if it gathers repeated information on the evolution of a situation. In quantitative surveys, static data is called cross-sectional data and data over time is called time series data, while the combination of both is called panel data. However, cross-sectional data can refer to different other points in time and hence indirectly capture some dynamic information, for instance, one can ask people about the impact of different flood events in the past; likewise, cross-sectional data can contain some information on possible future states, for example, when people state whether they intent to reduce their vulnerability through future investments. In qualitative surveys, the viewpoints expressed can also refer to a historical

event or describe some evolution and hence contain some dynamic information. Both quantitative and qualitative surveys were implemented in the case study areas. The aim was to collect information to illustrate the long term loop about the evolution of people's vulnerabilities and associated risk prevention measures. The quantitative survey focused on the household level and aimed to understand which households take action to protect themselves against floods and what were the determinants of their actions. The qualitative surveys focused on the institutional level and aimed to illustrate from a long term perspective the determinants and the difficulties of the implementation of the flood management policy in one of the case study areas, the La Pique area. In the following, we describe in more detail the data selection process of the quantitative and the qualitative survey:

- Between April and June 2019, we led a quantitative survey among 418 households in 10 municipalities (Dranguignan, Le Muy, Les Arcs, Trans-en-Provence, Taradeau et Vidauban, Bagnères-de-Luchon, Montauban de Luchon, Saint-Mamet, and Juzet-de-Luchon). Households were selected randomly and surveyed in face-to-face interviews in their dwellings. We collected cross-sectional data on the sociodemographic characteristics of the household, housing characteristics, flood experience, attitudes towards risk and time, flood risk perception, individual adaptation [7, 9, 32, 35] and willingness to pay for individual and collective flood prevention policies [27]. We captured some indirect dynamic effects by asking people about their past flood experience, their current protection and their willingness to protect themselves in the future. The aim was to characterize people's vulnerabilities towards floods and to evaluate the scope for further action, individual and collective, to reduce this vulnerability. We asked respondents about specific individual adaptation measures: slot-in flood barriers, sewer non-return valves, main rooms upstairs and valuables placed upstairs, and electrical fittings set higher up the walls. These are the most common measures, according to previous surveys by [35]. We also asked respondents about their willingness to pay for individual and collective adaptations by presenting two scenarios: the first scenario proposes the implementation of collective flood-protection measures and the second proposes expert assessment and implementation of individual protective measures in the at-risk properties. A further description of the survey can be found in [10] and [11]. The results can be used for two purposes: first, to adjust the damage functions for residential buildings, in order to take into account household's adaptation actions, second to make assumptions on the evolution of the areas' vulnerability in the long-term loops.
- A flood can be defined as a natural and social risk shaped over time by human action [47]. From this perspective, we have traced a socio-history of the hydraulic works at the La Pique River in order to understand the technical

choice made over the last 150 years to control recurrent torrential flood. The aim of this qualitative study is to underline the difficulties of anticipating the next flood event on the territory given the complexity of the dynamics of sediment transfer and soil erosion and the effects of hydraulic works of them. The corpus of data studied is based of 10 qualitative interviews and former technical reports. The interviews have been conducted with some agents of the French torrent control service (in France: Restauration des Terrains de Montagne, RTM) current or retired at the national, regional and local levels. Other interviews have been made with local elected officials; fishermen and river managers. The study of the reports allowed us to identify the arguments and interests that have shape the technical choices from 1865 to the present day.

Section VII-A will present some results of the qualitative surveys in the Bagnères De Luchon area and section VII-B of the quantitative surveys in both study areas.

#### D. Short-term Data: Sensors and Forecasts

Sensors data are dynamic data acquired at runtime and are used for forecasts or at short term temporality during a crisis to collect and analyze the events.

1) *Flood Forecasting Service*: The Flood Forecasting Service (FPS) called in France Vigicrue aims at collecting and predicting flood data. Flood vigilance information consists of qualifying the level of vigilance required, given the phenomena observed or forecast and the associated risks, within the next 24 hours. They use a four-level colour scale: green, yellow, orange and red, going from the lowest to the highest level of risk.

To do that, the French flood prediction service (SPC) has deployed sensors in most of the rivers susceptible to have floodings. These sensors provide water height measurements, and sometimes the water flow as well, every 15 minutes as shown on figures 6, 7. The resulting data can be accessed freely using a REST API with an history of 30 days. In other countries, the same hydrograms are provided.

2) *Sensors*: Enedis, French electricity distribution network, has set up sensors (from Atim<sup>3</sup>) in electrical substations that allow a first management of floods on a water level to optimize its low-voltage grid. Sensors are placed in transformer substations that had been damaged during the 2013 floods in Luchon. On the map in Figure 8, we can see their position in the research area.

Sensors use Sigfox<sup>4</sup> and LoRaWaN<sup>5</sup> wireless low-flow network to transfer data. A water detection verification is performed every 10 minutes. Data is only sent if there is a change in the sensor's state and is proved twice consecutively. The change of state triggers the emission of 5 radio frames every 10 minutes to make sure that information will be

received and processed. Every 24 hours, a frame is sent as a test and every week a feedback is sent to verify the proper functioning of the sensor with the number of messages emitted as well as the state of the sensor. Data is collected and stored for one year.

Example of test frame: 

05	1f
----	----

Frame	Data
05	header
1f	counter from 0 to 255

Example of alarm frame: 

13	06	00
----	----	----

Frame	Data
13	alarm frame
06	counter from 0 to 255
00	lack of water
01	presence of water

Example of feedback frame: 

01	0d9f	0d76	64
----	------	------	----

Frame	Data
01	feedback frame
0d9f	standby voltage
0d76	transmission voltage
64	end of frame

The information provided by sensors will allow the following actions :

- to secure electrical structure at the right time,
- to limit the impact of power cuts,
- to facilitate crisis management with external actors, in particular through precise communication of interventions,
- to ensure better planning and mobilization of teams to rehabilitate the structures.

3) *The Operational Organization*: A fast or torrential flood carries sludge and/or solid materials whose density can be important (transport of rocks of several tens of tons). It is generally very destructive and can lead to catastrophic floods. In order to prepare for and manage an event of this type, the response strategy is based on operational planning. Thus, in France, an ORSEC flooding plan defines the crisis management organisation at departmental level. This plan is designed to mobilize and coordinate, under the sole authority of the prefect, civil security actors when the current or daily level of response by services is exceeded. This plan is completed, at the commune level, by those of the Communal Safeguard Plan (PCS). It defines, under the authority of the mayor, the organisation provided by the commune to ensure the warning, information, protection and support of the population with regard to known risks. The objective of this organisation is to limit damage to persons, properties and the environment.

This crisis management system is based on the activation of several crisis units, the most important ones are :

- the Departmental Operational Centre (COD);
- the Operational Command Post (PCO);
- the Communal Command Post (PCC);
- the Departmental Fire and Rescue Operational Centre (CODIS).

<sup>3</sup><https://www.atim.com/?p=3951>

<sup>4</sup><https://www.sigfox.com/en>

<sup>5</sup><https://lora-alliance.org/about-lorawan>

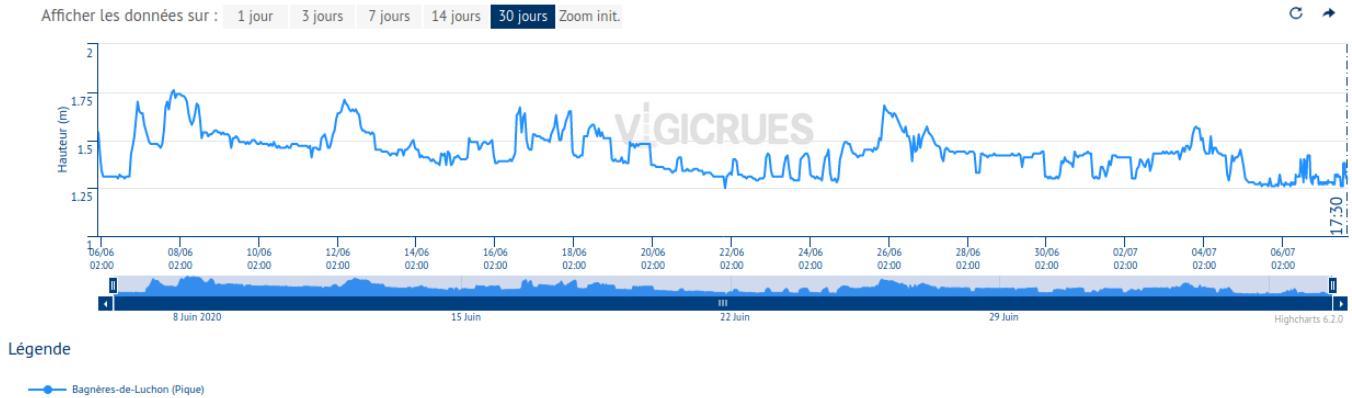


Fig. 6. Example of height measurement for La Pique

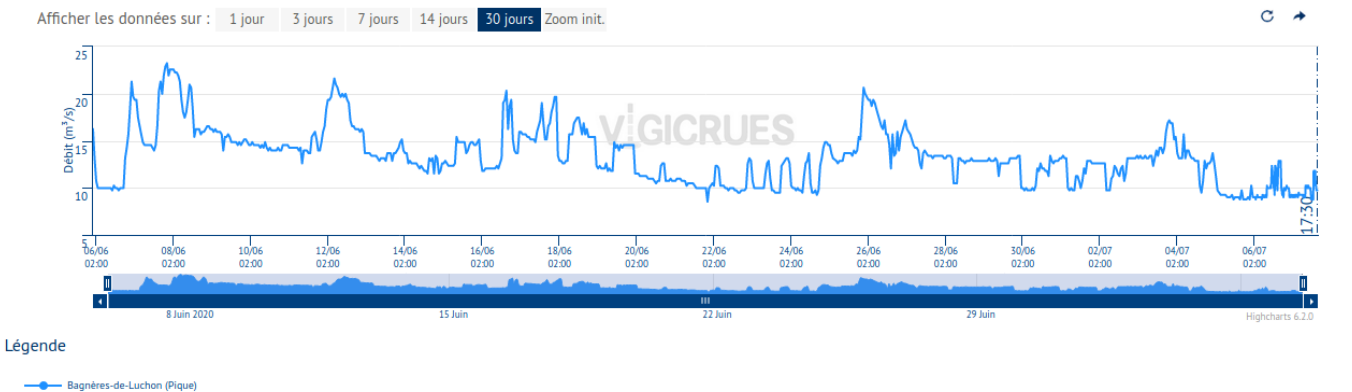


Fig. 7. Example of water flow measurement for La Pique



Fig. 8. Bagnères-de-Luchon area

The Departmental Fire and Rescue Service (SDIS) draws up "Flood Plans" for the main rivers. They define the operational response strategy of the SDIS to the risk of flooding during the different phases of the flood: anticipation, emergency and operational response.

4) *SDIS: the different phases of the flood management:* The different phases of the flood management follow procedures which are described below.

**Anticipation Phase.** The anticipation phase begins as soon as the CODIS receives an alert message sent by a Flood Forecasting Service (FPS). In order to adjust the departmental operational response, the CODIS is activated and collects the data related to this event, analyzes the meteorological data with the mapping of the territory and issues. It draws up and transmits operational instructions to the fire brigades of the fire and rescue centres (CIS) and specialised water rescue teams. These preventive instructions can be sent on the eve of the expected phenomenon or when the climatic phenomenon is predictable with a high confidence index. They are sent without delay in the case of an unexpected flooding phenomenon or one of significant proportions. In particular, they must specify the list of materials to be used for a thorough check and a reminder of the safety instructions.

**Emergency and Operational Response.** In the event of flooding, the operational response of the SDIS is based on the various intervention units, early feedback and the implementation of local command systems. The commitment of the fire brigade is prioritised according to the context, the

location and the issues at stake. The priority is to rescue and protect people, then to safeguard and protect property and finally to assist the population, in support of the other players, towards a return to normal life. Each player in the crisis must invest in the collection, synthesis and feedback of information. The main purpose of this information is to characterise and locate an event, to enable a better quantification of needs and to anticipate the actions to be taken. To do this, the fire brigades go to the field in order to assess the level of risk, its evolution and its impact on people, property and the environment. Depending on the size of the flooded area, a geographical cluster is set up in order to facilitate the operational commitment of the rescue means. The operational management method aims at coordinating the means (vehicles, firefighters...). The coordination is based on the choice of the objectives, the ideas for manoeuvres and the different tasks to be carried out. In the context of a flash flood, the objectives of the SDIS are as follows:

- Accurately monitor the evolution of the rising water level
- Avoid having people blocked by rising water levels in buildings or in vehicles. To do that, a priority is determined for each stake:
  - Can stay in place
  - Must be evacuated within 12 hours
  - Must be evacuated within 6 hours
  - Must be evacuated urgently.
- Limit damage to property (animals, public or private goods...)
- Avoid environmental pollution due to rising water levels

The evacuation problem is described and modeled in section VI-A.

## V. ANALYSIS

Based on the Knowledge collected, different analysis can be conducted to exploit the data during the optimization loops to manage the crisis and ensure a better resilience of the territory.

### A. Hydrological and Hydraulic Models

An exhaustive and precise representation of flood hazard on territories is needed for an accurate behaviour of the MAPE-K loop. Furthermore, the analysis of historical observation has shown that the collected data on flood such a as the one of 2013 may locally be insufficient or could be incoherent, and that this data only applies for the Pique river and a quite frequent flood (with a period of return estimated largely under 100 years), resulting in a lack of information for a rarer - and more problematic- event. A modelling of the rivers are necessary to better predict floods and anticipate the area impacted. Models have been realized for the Pique and Nartuby in the context of the project. A standard approach, using an hydrological model for computing flood generation and a uni-dimensional hydraulic model for flood propagation has been chosen regarding the amount of data available at the beginning of the project. This general approach can be replicated in any basin subject to fast floods with a dominance of fluvial,

with data on topography and historical events. However the type of hydraulic model should be adapted in rivers with a dominance of torrential flows as mechanics, evolutions of the flood and results expected for an evaluation of the risk diverge dramatically.

1) *Bagnères-De-Luchon*: At the beginning of the project, the Pique river's basin was insufficiently gauged to provide an accurate monitoring and good predictions of the river discharge. Moreover, as the only hydrometric station of the studied basin is located after the One-Pique confluence, it was not possible to evaluate the respective contributions of Pique and One rivers, resulting in a poor representation of the flood on the upstream part of Bagnères-de-Luchon urban area (figures 8, 9). An hydrological model, based on the free model ATHYS, has been tested to generate hydrographs for the upstream part of the rivers Pique and One. These kinds of models can be used when monitoring data is not enough. On mountain territory some issues could appear due to the unknown contribution of the snow to the flood.

Free flow modelling of the river Pique, starting upstream of Bagnères-de-Luchon (high slopes with torrential flow) to a narrowing of the Pique valley at Cier-de-Luchon (medium slop with fluvial behaviour) has been made using the 1-D open source modeller Mascaret, developed by the consortium openTELEMAC-MASCARET [31]

It includes a representation of effects of dikes and bridges, as observations of the June 2013 flood tend to prove their important role in flood aggravation or mitigation in Luchon. The modelling was made on a transcritic computation, and by its simple nature provides very fast simulation of the river's flooding, water depths and speeds at a spatial step of 1 to 5 m, enabling an evaluation at a building scale.

Pique's model has been calibrated based on the high water marks and observations of the year 2013 flood, with an objective of residual error under 15cm, reached on more than 90 percent of the urban linear, but with a significantly lower result on the rural and high-sloped areas. A local modification of bridges ramps and roads terrace has also been done to reduce the differences between the flood observations and the model's results. Calibration has also shown an issue in the representation of river's One left bank small protective walls, which have protected the hippodrome and rail station area during the year 2013 flood, while the model predict its flooding.

2) *Nartuby*: A free flow modelling of the river Nartuby with Cartino, a semi-automatic method based on Mascaret, has been realised by Cerema following the 2010 flood in the gauged and monitored basins of Nartuby and Argens [34]. This model has been reemployed for a representations of floods of the nartuby river in ANR e-Floodings project.

These hydrological and hydraulic models are useful for flood mapping and visualizing the areas impacted for different possible flows in the territory.

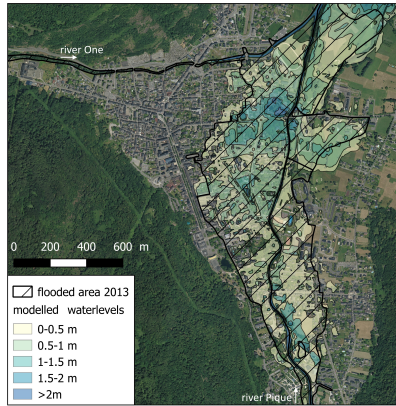


Fig. 9. Final modelling results of the year 2013 flood of the river Pique on Luchon's urban area, compared to the estimated flooded area by Local State Services (based on high water marks, interventions and observations during the flood)

### B. Damage Functions

Damage functions are a simplified representation of the vulnerability of assets exposed to flooding. They allow to combine spatial information on hazard and land use to anticipate potential damage. Within the current project, damage functions are adapted from those constructed for the MTES (Ministère de la Transition Écologique et Solidaire<sup>6</sup>), to be applied in Cost-Benefit Analysis of flood management projects. These damage functions have been developed following a synthetic approach, based on damage and insurance experts knowledge. They are developed for 4 categories of assets (residential housing, economic activities, public infrastructures and cultivated plots), They take into account the water height, season and submersion duration. An example is given in figure 10 for agricultural crops.

Water heights and impacted zones can be computed by the hydrological models above. Classifications for public services, businesses and types of crops reflect those used in the public databases are presented in Section IV-A.

However, it can be noted that these functions have been obtained for classical floods and may not be as accurate for flash floods, in part because they do not cover the potential complete destruction of the asset by the flood.

The adaptation status can also be taken into account in the damage functions. For example, when households prevent water from entering the home (up to a certain height), this will reduce the damage for a given water height and accordingly change the damage function. Similar considerations can be made for the other categories of assets. Overall, damage functions measure the propensity of damage of the main categories of assets for different scenarios of floods and, hence, assess the potential vulnerability of the territory in monetary terms. In the long run, damage functions may be adjusted, for example because adaptations have taken place.

<sup>6</sup><https://www.ecologique-solidaire.gouv.fr/evaluation-economique-des-projets-gestion-des-risques-naturels>

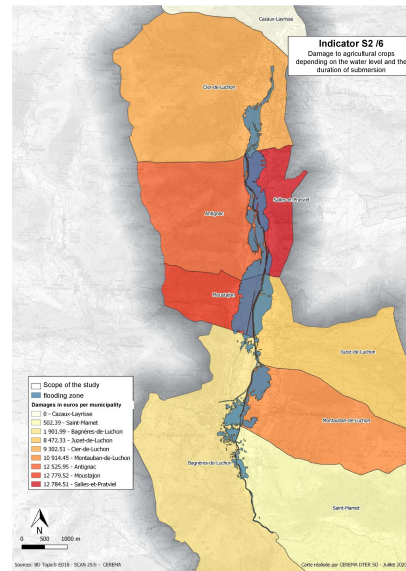


Fig. 10. Indicator S2 /6 Damage to agricultural crops depending on the water level and the duration of submersion

### C. Satellites images analysis

**Hazard characterization.** The hazards theme gathers the production of flooded areas (automatic extraction of water areas, and photo-interpretation, to obtain the maximum water extent), and water height (by crossing this flooded areas data with elevation information). Figure 11 presents an example of a satellite image exploitation to characterize the hazard in Draguignan. Satellite images and their analysis to extract hazard characterization can help to complete hydrological model.

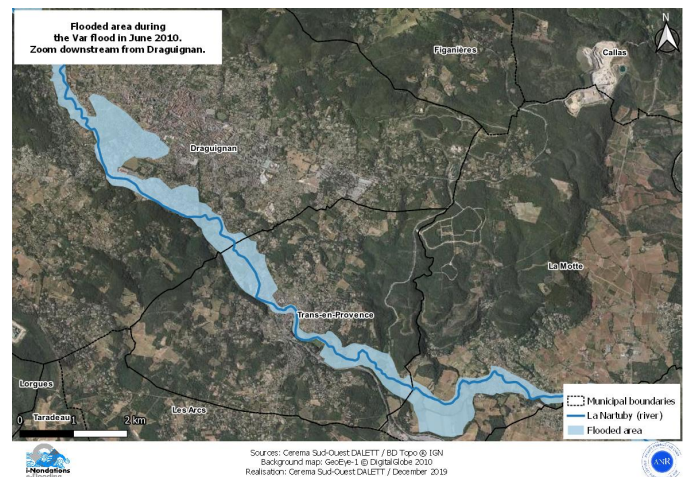


Fig. 11. Flooded area on Draguignan

**What it at stake.** The production of data about what is at stake consists mainly to extract a class of the land cover mapping. They can enrich spatial databases. This updated data could thus be crossed with other data, to locate buildings impacted by the presence of water (by crossing built class with

flooded areas), or to know if a road is passable (by crossing roads class with water height) for example.

**Damage detection.** Damage detection by satellite concerns macro damage to structures such as buildings or roads, or even the impact on crops or vegetation. They can be obtained either manually by photo-interpretation, or automatically by comparing the evolution between two land cover mappings, if we have a mapping before the crisis. Damage detection can help emergency services to locate affected areas, and prioritize interventions according to the level of damage.

**Resilience monitoring.** As with damage detection, resilience monitoring consists of either photo-interpretation of changes, or a comparison between two land cover mappings, in both cases, with an image just after the flood and a second a few months/years after. We can thus see how the territory has recovered, how it has developed to anticipate a possible new crisis, and whether these changes have reduced its vulnerability to floods.

Damages detection and resilience monitoring could be gathered into a macro-theme: change detection (Figure 12).

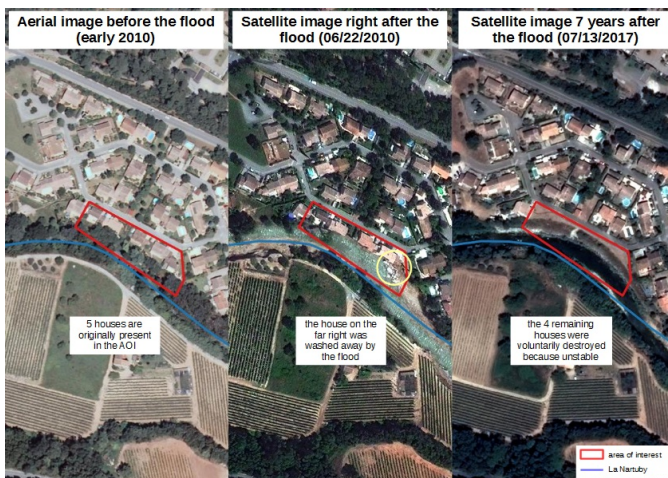


Fig. 12. Example of built changes detection

#### D. Vulnerability Computation

The risk can be defined as a function of hazard, exposure and vulnerability [43, 23]. The IPCC (Intergovernmental Panel on Climate Change) defines vulnerability as the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Knowing and assessing vulnerability is critical for several purposes. Particularly, this information is critical when decision makers have to prioritize between several options [20] as for example prioritizing evacuation of assets during the crisis or prioritizing adaptation options. When it comes to evaluate vulnerability, several approaches can be used. In this section, we present four approaches that enable vulnerability assessment: first with satellite images analysis, second through the computation of indicators, third based on mathematical analysis on a set of data and finally with the damage functions.

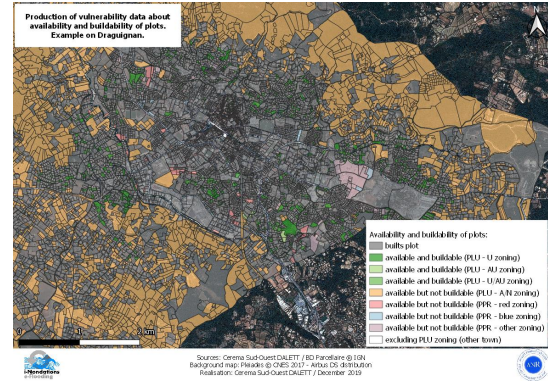


Fig. 13. Availability and buildability plots on Draguignan

1) *Vulnerability characterization with satellite images analysis:* Production of vulnerability data may be based on the national repository of vulnerability to floods (from the french ministry in charge of ecology [46]). Two types of data were produced with satellite images analysis: The first is a location of available and buildable plots, by crossing a plot with built data (from land cover mapping or other source) to get availability of this plot, and by crossing available plots with planning document (like local urban masterplan, or flood risk prevention plan) to know the buildability. The other is about municipal campsites: their location, their capacity, check the presence of refuge space... These vulnerability data are then cross-checked with each other, and with other data, to produce vulnerability indicators.

Figure 13) shows buildings plots in Draguignan obtained by crossing plots with buildings maps, a local urban plan, and a flood risk prevention plan.

Satellite images exploitation gives data about vulnerability and the evolution of land use in the territory, in the short-term it helps to detect damage and in the long-term it helps to evaluate the territory's resilience.

2) *Indicators of Vulnerability:* The implementation of the vulnerability reference framework [46] aims to make a diagnosis of the territory according to three themes: i) the safety of people, ii) material damage to property and iii) the time required to return to normal. The tables I, II and III below describe the sources of vulnerabilities retained within the framework of this project and the acronym corresponding to the data required for its calculation (Zx, Zd, Po6 ...). These data are related to the phenomena studied, population, land use, public action and networks.

This approach is based on a methodology developed in the national vulnerability reference framework as part of the national flood risk management strategy. As an illustration, two maps are presented: one on the source S1/6 - number of roads cut, and the source S1/10 number of dependent people in areas of electrical fragility. These vulnerability indicators can be visualized on maps. Figure 14 shows the linear distance of roads by number and name of lanes, as well as the rail line and marshalling yard area. 38.8 kms of roads and 4.5 kms of

Source of vulnerability	Vulnerability indicator
S1/6	Number of road routes intercepted by hazard zones dangerous to a person
S1/7	Number of inhabitants in areas accessible by dangerous routes
S1/8	Number of people in urbanized areas that have been inaccessible for a long time and are not organized to stay in place
S1/9	Number of people in areas of high density
S1/10	Number of dependent persons in areas of electrical fragility
S1/11	Number of people exposed to over-water related to the rupture of structures
S1/15	Surface of areas undergoing urbanization, intended for housing, and whose accesses are dangerous

TABLE I

INDICATORS OF THE VULNERABILITY REPOSITORY FOR PERSONAL SECURITY

Source of vulnerability	Vulnerability indicator
S2/9	Number of (land) vehicles exposed to the hazard
S2/10	Number of network parts (nodes, links) likely to be damaged by flooding
S2/11	Damage due to network malfunctions (in the case of prior existence of network vulnerability diagnostics) /(subject to method)

TABLE II

INDICATORS OF THE VULNERABILITY BASELINE FOR PROPERTY DAMAGE

railways are intercepted by a dangerous hazard when height is higher than 1 meter or 0,5 meter and for a flow of 0.5 m/s).

Figure 14 identifies the number of vulnerable people for the electrical point of view. Five establishments are concerned in the commune of Bagnères-de-Luchon and the vulnerability concerns 463 persons.

3) *Vulnerability evaluation based on a set of data:* In order to assess the vulnerability of a territory, a synthesis using the following 5 indicators can be made: the urban density, the population density, the building street level, the year of construction, the socio-economic characteristics of the territory. Understanding the impact of this synthesis of criteria on the decision taken is typically the task of a Multi-Criteria Decision Making process. In our context, the MCDM is represented in Figure 16. The vulnerability (the objective) is a function of 5 criteria, themselves divided in  $k$  sub-criteria (i.e. classes, representing a more or less dense criteria); and  $n$  alternatives (a subdivision of the territory in  $n$  tiles) are evaluated against each of the criteria.

Source of vulnerability	Vulnerability indicator
S3/9	Number of vehicles.days hindered on transit networks taking into account alternative paths (degraded operation)
S3/10	Proportion of protective structures not affected by an emergency response system and restoration time (degraded operation)
S3/11	Number of crisis management plans
S3/12	Ignorance of risk by the population (survey)
S3/13	Collective crisis preparedness to limit damage
S3/14	Proportion of the population for which the commune has a communal civil protection reserve

TABLE III

VULNERABILITY BASELINE INDICATORS FOR RETURN TO NORMALITY

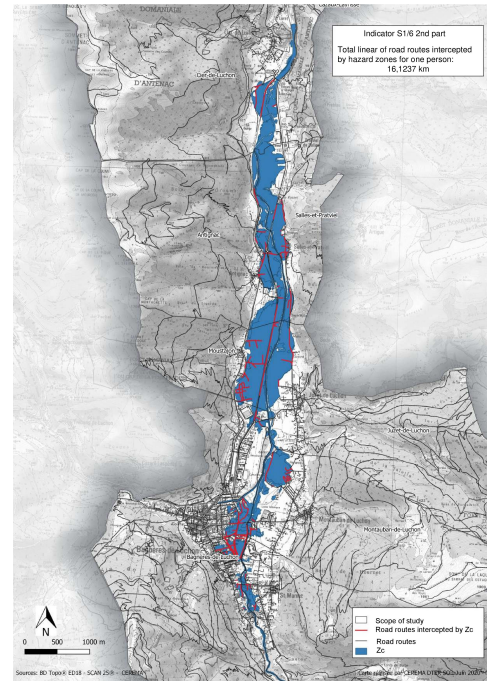


Fig. 14. Map of indicator S1/6 - number of road routes intercepted by hazard zones dangerous to a person in Bagnères de Luchon

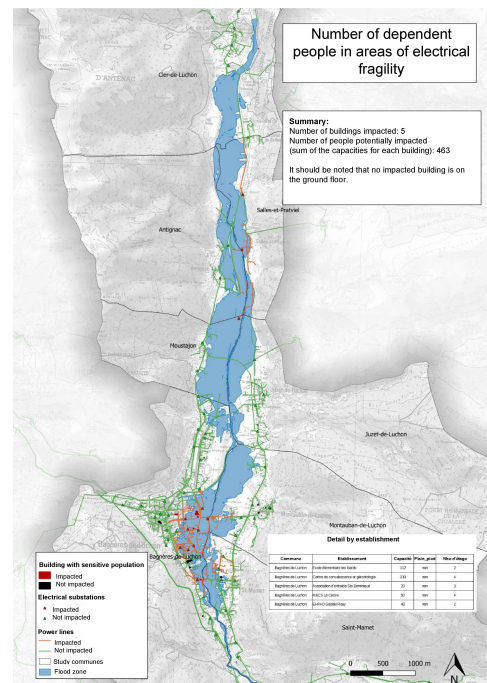


Fig. 15. Mapping of indicator S1/10 - number of dependent people in areas of electrical fragility in Bagnères de Luchon

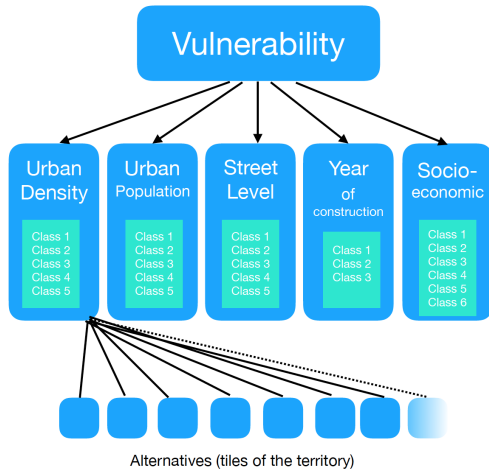


Fig. 16. Vulnerability synthesis based on 5 criteria and their own modalities evaluated for each alternative

Algorithms have been proposed in the literature in the context of the crisis management [14] such as PROMETHEE, ELECTRE, TOPSIS, AHP, ANP, .... We decided to investigate AHP (Analytical Hierarchical Process) [36] for its ease of use and its low execution complexity in the context of this work. The idea of AHP is to transform a complex decision into a series of importance comparisons between each pair of criteria. Moreover AHP comes with a useful indicator able to verify the consistency of relative importance evaluations for assessing the bias in the decision process. AHP is done in two steps: the first step consists in a two-level collection of the experts view on the relative importance between each pair of criteria, using for instance a questionnaire, and the evaluation of the performance of the alternatives (the tiles of the territory) for each criteria. This produces a resulting priority matrix. In the second step, following a diagonalisation process on the priority matrix, we can obtain a vector representing the percentage of importance for each criteria and use this vector in a super matrix (the adjacent matrix of the MCDM) representing the links between each criteria and alternative (see Figure 16, for each alternative -each tile on the territory of study- we can derive finally the vulnerability level).

In our work, we decided to elaborate a number of classes sampling the range of possible values for each of our 5 criteria: 5 classes for urban density, urban population, and building street level ; 6 classes for socio-economic ; 3 classes for year of construction. These choices were guided by reasons linked to the process itself (too few classes would not be very useful in the process), and local knowledge (for instance for the year of construction, some legal aspects changed at certain dates for helping against flood crisis, making easy to classify building according to these legal changes).

As an illustration on the Luchon area, one can see the result in Figure 17 for the vulnerability index. As expected, the most vulnerable places are located along the roads and in the town center (with many people and enterprises).

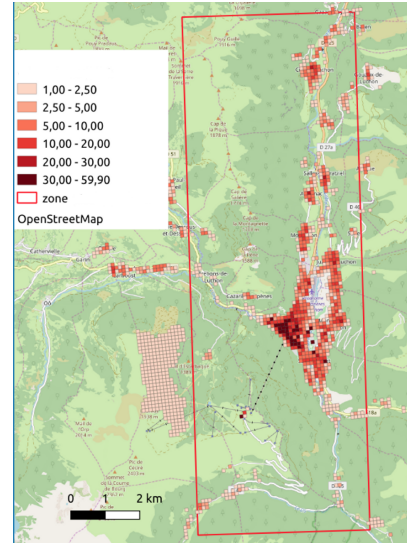


Fig. 17. Vulnerability evaluation

4) *Vulnerability evaluation based on damage functions:*  
Alternatively, the vulnerability of the territory can be evaluated via the damage functions. For each of the categories of assets (residential housing, economic activities, public infrastructures and cultivated plots) one can compute the potential damage, according to different flood scenarios, the sum of which represent the potential monetary damage for the territory. An aggregate indicator can be computed for a range of plausible floods. In addition, in the long-term loop, one can i) make assumptions about the evolution of the spatial distribution of the assets ii) integrate the new adaptation status of the assets, and then compute a new potential damage. The adaptation status of residential buildings and its potential evolution depends for example on the household's willingness to adopt new measures, as has been shown in the quantitative survey. For example: 14 % of the households decided after the flood to take individual actions to protect themselves; hence the future potential damage in the housing sector will be reduced for them. Likewise, more people are considering flood risk when buying, constructing or investing, which can lead to more frequent elevation of ground floors. Implementing the long-term loop on all these changes allows reassessing more correctly the new potential vulnerability of the area.

## VI. DURING A CRISIS: DECISION

During a crisis, hydraulic models can help to compute the impacted area. Then localization of what is at stake can be made. Moreover, the firefighter identify the different demands. The operational methodology for priority rescue and safety missions of the SDIS is based on prioritizing the evacuation of people in flooded areas. The fire brigade carries out evacuation circuits starting from the depot (where the resources are: vehicles...) and the point of demands (nodes where the people to be evacuated are). The circuits end to the location where victims are regrouped.



The problem SDIS 31 is facing when they need to rescue victims from a fast flood can be modeled as a Capacitated Vehicle Routing Problem (CVRP) as detailed in next section.

#### A. Vehicle Routing Problem: Mathematical Model

Few works have been made on Vehicle Routing Problem (VRP) for disaster Management. [49] is a case of use of VRP for disaster management but the capacity constraints are not considered. The same constraint is missing for [40] who focus on earthquakes relief. For the literature on the Vehicle Routing Problem other than disaster relief, the application are mostly commercial applications where time constraints violation is possible under penalties as in [5]. Disaster relief operations cannot afford not to treat demands in time.

This problem is characterized by a fleet of vehicles that need to take action on demand points. We model our problem as a directed graph where every vertex  $i$  is a point of demand where people need to be rescued and the edges represent existing roads that link nodes together. Each of these edges is associated with a cost reduced for our problem to a travel time  $tt_{ij}$ . Each demand  $i$  has a size  $d_i$  corresponding to the number of victims and has a time  $a_i$  for the action to be completed on the node. We are looking for a global optimal solution of a VRP problem for the current state of the problem. Due to the capacity limitations of the rescue vehicles and according to the SDIS 31 expertise, the rescue teams will not have resources to solve the problem with only one passage by the depot. We introduce the tours, which translate the number of times a vehicle go through the depot, we will then solve the problem on several tours. To deal with the capacity limit of the vehicles, we also need to consider that a vehicle  $k$  has a maximum capacity  $Q_k$ . For the purpose of the model we also use  $x_{ij,k}^z$ , a binary variable equals to 1 if and only if vehicle  $k$  visits vertex  $j$  using edge  $(i, j)$  in tour  $z$ . We study a Crisis Management case where people's lives are at stake so we need to determine for the model a way to differ the urgent nodes to be treated in priority from demands that do not need to be treated urgently. To do so, we based our categories of priorities on the ones of the SDIS 31 who use the following scale: (1) Can remain on the spot, (2) Have to be rescued within 12 hours, (3) Have to be rescued within 6 hours, (4) Need to be rescued in emergency. These 4 priority categories are used to characterize the problem with both priority factors and deadlines. For each node of  $i$  we will associate a deadline  $f_i$  and a priority factor  $p_i$ . While the hard deadlines cover the emergency aspect of the problem through, the objective is to minimize the cumulative time for the demands to be treated. We introduce the Flow-time which is the time between reception and treatment of a demand at node. The objective of our optimization is to minimize the total Flow-time weighted by the priority for every demand. The aim of the optimization problem is to assign the demands to the vehicles and to the tours.

However this problem is NP-complete, this induces that the computation time to find the optimal solution will increase

exponentially with the size of the problem. Experimental results showed that the computation time skyrocket from 7 nodes problem size (bigger problem induce to high computation time for the requirements of the relief operations decision support's tool) . According to the experience feedback from SDIS 31 we need to consider over than 50 nodes which means the use of heuristic algorithms are necessary for a real-time solution.

We developed a first heuristic based on First Fit algorithm. First fit is a resources allocation scheme. It is used in the bin packing problem where one must pack different size's items in bins also of different size. The list of items is sorted (in size order) and then items are allocated in order to the first bin in which they fit without consideration of the optimal choice. In our case, items are the nodes with as size the number of victims and bins are the vehicles with their capacity. The list of nodes (demands) with Shortest Distance Insertion (SDI) is sorted first in term of priority and then for the nodes of the same priority in function of their distance from the closest available vehicle. When a vehicle is full it return to the depot and is available for the next turn.

The second algorithm we developed, the Best Flow-time Insertion (BFI) algorithm, is inspired from the best fit algorithm. In opposition with First Fit, the purpose of this scheme is to allocate resources to the most appropriate task (according to the objective) and not to the first one fitting. We allocate the vehicles to the nodes in order to minimize the objective defined on Flow-time. For every demands and for each vehicles we compute the Flow-time score and insert it at the best route.

```

l ← sortDemands(demands);
while l not empty do
    while vehicle available do
        vehicle ← availableVehicle();
        while vehicle not full do
            vehicle ← bestInsertionScore(l[0]);
            assignDemand(vehicle, l[0]);
        end
        nextVehicle();
    end
    nextTurn();
    EmptyVehicles();
end
    
```

**Algorithm 1:** BFI algorithm's structure

These algorithms have been tested on wide sets of randomly generated territories. The results show that we are getting a solution with heuristic algorithms within a second. This highlights the fact that we may have different kind of heuristic algorithms to use according to the needs of the crisis. SDI was developed as a reproduction of SDIS 31 decision process whereas BFI aims at another approach in order to improve the objective in term of Flow-time. Results of this experiments shows an improvements in objective score of 30%

Once the routing problem is solved, the solution is displayed through a graphic interface. We used an existing academic tool

VROOM (<http://vroom-project.org>) and modified it to use our algorithm and show the solution on a map.

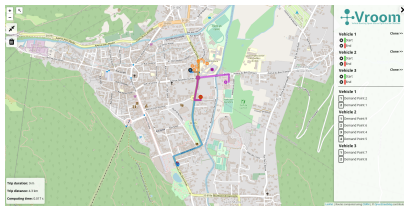


Fig. 18. Example of graphic interface to display computing routes using VROOM

In this example we observe the plan to rescue victims in the municipality of Luchon. It has been computed with 9 demand points in blue, a rescue center in red and 3 vehicles for which the planned routes are displayed in different colors (orange, purple and blue).

## VII. AFTER A CRISIS: FEEDBACK

After a crisis, the knowledge about the new event can be analysed and re-integrated in the analysis and models described above.

### A. Social analysis derived from the qualitative survey

In this section, we present the results of a qualitative survey conducted on Bagnères De Luchon. Since the 19th century, mountain risks are in charge of the RTM service. At that time, civil engineers establish a link between erosion processes and the practices of mountain populations. In order to protect the forest, the authoritarian State deprived them of their land to carry out reforestation actions. The particularity of torrential floods is characterized by the transport of solid materials. Civil works are installed with the aim to prevent them from reaching downstream populations. The hydraulic mastery of La Pique River began in 1865 when the Esbas torrent becomes active. A system of retention check dams are designed to trap sediments, reduce flow velocities and control the soil erosion. Despite those, in 1901, the erosive activity extended to other torrents. New works were designed to stabilize those already in place and continue controlling soil erosion. Until the late 1980s, this technical device is maintained, perfected, solidified under the effect of successive floods. Following the flood of 1925, which caused 7 victims, the Foresters noted that the infrastructures built upstream torrent were not sufficient to contain the sediments. They decided to build some downstream, at the gates of Luchon to block those who continue to pass by. Between 1938 and 1951, the technical paradigm is based on the desire to contain the sediments in the mountain's territories. The use of concrete in the 1940s resolved stability problems of work made of stone and dams with greater retention capacity can be designed. The Castelvieil dam is built according to the logic at the time; for blocking the sediments. But the 1978 flood completely fills the dam earlier than expected. The Foresters can not just longer build new dams, because the institutional context has changed. The Grand Bornand disaster of 1987 put on the agenda the redistribution of

responsibilities of all the actors for the risk management. It concerns particularly the cost of the torrent works which affects technical choices. For political reasons, it is decided that Castelvieil would continue to block the sediments, to avoid letting them pass through Luchon. This decision avoids the need to negotiate with the municipalities about the cost of clearing the riverbed what is their due. Moreover, the new environmental constraints no longer allow the construction of hydraulic works identical to the one in Castelvieil, because they are affecting the environment excessively. This puts an end to a technical model based on the renewal of torrent works. The choice to remove sediments of Castelvieil reflects these two preoccupations (cost and environment). The flood in 2013 fills fully the dam again, which presents a risk. But the past technical solutions became unavailable because the regulatory framework renews the environmental constraints. The Water Acts (1964 and 1992) rules the protection of aquatic systems and particularly the respect of sediment continuity. The environmental argument challenges the technical model adopted over the past 150 years because torrent works have significant effects on sediment transport. Consequently, the sediments contained in the Castelvieil dam cannot be removed and then extracted from the river, but must be re-injected. Moreover, the MAPTAM law (2014) and the NOTRE law (2015) plan the transfer of competences for flood management. Since January 2018, new actors are entering on the risk scene and the transfer of management of Castelvieil from the RTM service to the local collectivities becomes a possibility. In addition, as in the past, the re-injection of sediments will modify the hydromorphology of La Pique in an uncertain manner. The torrent will continue to be a laboratory.

The study has shown different factors, which have changed over time, that have influenced risk management. We have identified three of them: technical choices, costs and environmental protection. These three factors have shaped the definition of torrential risk and the answers given to it. This study provides an understanding of how the dam has been managed in the past, and the problems that currently arise from this. This approach of qualitative analysis on a territory makes it possible to complete the knowledge. As it has been described, the evolution of the institutional context has an impact on the choices made and is difficult to anticipate.

### B. Analysis of household's vulnerability and adaptation from the quantitative survey

In the following, we present the results of the quantitative survey about household's vulnerability and adaptation status conducted in the study areas (areas around Bagnères de Luchon for the Haute-Garonne department and the area between Draguignan and Le Muy for the Var department). The data of the randomly chosen population sample shows that the average respondent lives in a household with 2 or 3 persons, is an owner of their home and has lived in their home for 17 years. These features are quite similar to those of the whole population. However, the age structure in our sample is different, the average respondent is 60 years old. Most of

the respondents (74%) have prior experience of flooding, at least in the municipality, one third live in an area covered by a Flood Risk Prevention Plan. A more detailed description of the dataset can be found in [10] and [11].

Concerning the adaptation of households we can state the following results: 40% of the respondents live in elevated accommodation (with raised floor or crawl space). However, this does not seem to have been an active choice, since respondents rarely took flood risk into account when choosing their home. As shown in our survey, flood risk had a greater influence on property choice prior to 1960, but the receded in the period from 1960 to 2000, only reappearing in 2010. Next to elevated accommodation, a range of other measures could have been taken: 14% of respondents have individual adaptation measures to reduce their vulnerability at home, of which the most common is having placed electrical fittings higher up in the walls, followed by flood barriers, storing valuables upstairs and installing sewer non-return valves or using pumps to hinder water from entering the home. Overall, 9% of respondents have adopted measures themselves. In contrast to results from former surveys in the area [35], almost no respondent has further action planned. This is perhaps due to the fact that the last major floods (2010 for the Var and 2013 for the Haute-Garonne) took place several years ago. Indeed, as shown in our dataset there was a peak in the adoption of new measures in the Var immediately after the 2010 flood, and then a rapid decrease to very low levels.

As reported in [10] and [11], we estimated probit models to analyse the determinants of adoption of individual adaptation measures. The analysis shows that the main determinants are having experienced a flood and the perception of risk, both having a positive effect on individual adaptation. In particular, residents with a very acute perception of risk have tendency to implement measures. Although the overall adoption rate is relatively low, the survey reveals that households are willing to pay for further individual and collective prevention policies. For the whole sample, the mean annual willingness to pay (WTP) for further action is 35 euros for the individual scenario and 46 for the collective scenario. When we remove the respondents with a protest attitude, as usual in the literature, the mean annual WTP increases to 94 euros for the individual scenario and 91 euros for the collective scenario. The revealed levels of willingness to pay are not sufficient to implement cost-efficiently measures such as the complete dry proofing of individual homes. However, they are sufficient to implement cost-efficiently more inexpensive adaptation actions, such as installing sandbag barriers, or storing valuables upstairs. Moreover, they can be interpreted as some willingness to act in the future, in the face of a flood event.

The survey has shown that adaptations are mainly taken in the two or three years after flood events; likewise, flood risks are more often considered in residential choice just after the occurrence of major flood events. It is hence possible to update the information about the adaptation status (number of elevated houses and type of adaptations) some years after an event and to integrate this information in the vulnerability

models described above.

### C. Risk evaluation in a territory

To determine the risk associated to a territory, we use two indicators: the vulnerability of a given territory and the danger related to a flood situation. The combination (multiplication) of both indicators gives the territory risk. The vulnerability can be computed with the different methods presented previously.

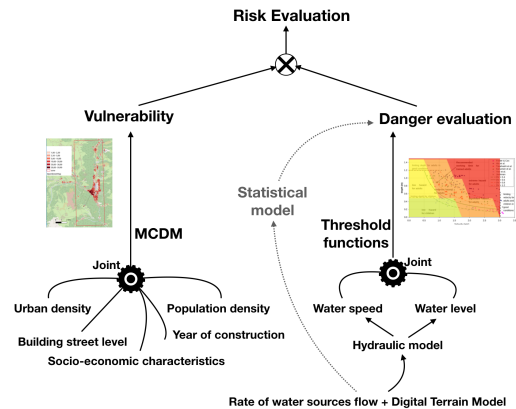


Fig. 19. Risk Evaluation

**Danger evaluation:** A danger is computed according to the level of water coming from the hydraulic model (see Figure 9), for each tile. It is based on the water level and the velocity of the river. Several studies have associated the couple (water level, velocity) to a danger value. We base our study on [13]. In Figure 20 the colors determine the danger (the red is the higher, the green the lower danger). We associate values between 0.25 (green) to 1 (red) based on these colors to determine the danger for each tile (a value of 0 is given when there is no flood, i.e. no flood on that tile).

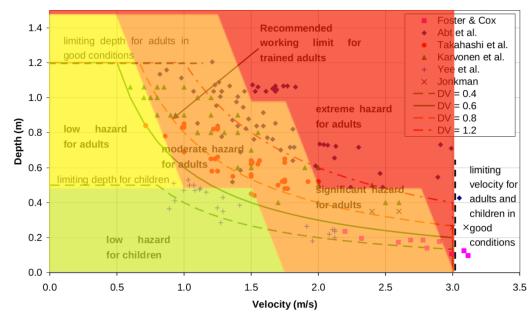


Fig. 20. Danger due to level and velocity of water. Illustration based on the synthesis of works done to assess the danger for people according to water level and velocity developed in Cox et al.[13]. Colors were added to make a clear graphical view of the danger situation.

Finally the risk level for each tile is simply computed by multiplying the vulnerability index and the danger value. At long-term the risk level can be used to evaluate how much the territory and the elements at stake are exposed to floods and to make some choices (or to compare the different choices). Knowing the weaknesses of the territory could help

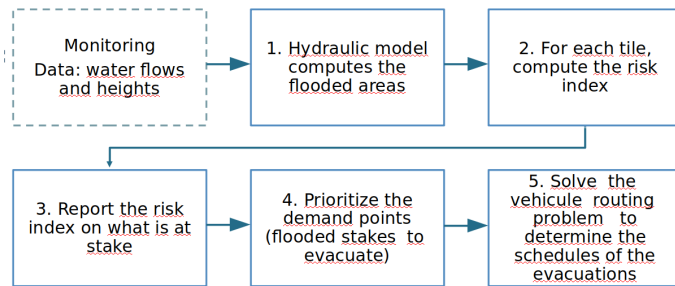


Fig. 21. Complete integration of the contributions

to prioritize what should be evacuated first during a crisis. The next section will present how this risk indicator could be used during a crisis.

#### D. Feedback use during crisis

Some indicators computed at long-term could be used at short term during a crisis to help to manage the crisis, evacuate people and return to normal as quickly as possible. Figure 21 presents the complete integration of the different contributions and shows how a crisis could be managed.

First the hydraulic model can be called based on water levels and flows to determine how the water would flood the territory. The risk index is then computed, one on each sub part of the territory, and applied on the different elements at stake. This knowledge helps to prioritize the demand points (flooded stakes to evacuate). Finally the vehicule routing problem is solved to determine the schedules of the evacuations.

## VIII. CONCLUSION

Current crisis management rely heavily on preparation. Several scenarios are prepared in case of flooding and actors are required to prepare for all possibilities.

In this article we showcase that using the now available ubiquitous data it becomes possible to improve the management of a crisis. A large number of open databases provide information on localisation of what is at stake; models described in this article provide means to compute vulnerability and possible damage taking into account the exact current and the forecast situation; ubiquitous sensors provide real time information on the situation to tune automatically the models (such as hydrological ones); an operational resource optimization system provides the best routes for rescuers.

We also show that these improvements are not only for in-situ reaction to flooding but can also help mitigating long-term impacts and provide feedback. Using similar models augmented by a quantitative survey, we show that the risk evaluation is not static and evolves depending on the management of previous flooding and with socio-economic changes. We also show that the long-term evaluation can be used during short-term crisis to improve the damage evaluation.

We illustrate our approach on two floods in the Var (2010) and in the Pyrenees (2013) using a large number of openly

available data (maps, hydrological models, population data and economic activities, ...) completed by quantitative surveys (2019), data and processes from crisis actors (firefighters, electrical infrastructure manager).

Overall, with the help of aggregation of a large number of heterogeneous data, it becomes possible to improve the decision process while providing actors with enough information for them to keep the situation under control.

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