Participatory Bayesian modelling for sustainable and efficient river restoration projects: Feedback from the case study of the Gave de Pau River, Hautes-Pyrénées, France

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Abstract

Through the diversity of criteria and stakes, the uncertain nature of the entailed phenomena and the multi-scale aspects to be taken into account, a river restoration project can be considered as a complex problem. Integrative approaches and modelling tools are thus needed to help river managers make predictions on the evolution of hydromorphological, socio-economic, safety and ecological issues. Such approach can provide valuable information for handling long-term management plans that consider the interaction and the balance of stakeholders interests and river system functioning. In this paper, we present a probabilistic participatory modelling (PM) method that assesses the effects of given restoration actions, knowing the hydromorphological modifications that they may induce on the safety, ecological and socio-economic aspects with the help of local stakeholders through several workshops. To support this strategy, we used Bayesian networks (BNs) as modelling tools as their causal graphs can combine multidimensional knowledge and data from diverse natures. We introduce the causal graphs elaborated with the help of the stakeholders and convert it into BNs that can assist restoration decisions by considering the available decision and utility functions to provide guidance to decision-makers. This was applied to the "Lac des Gaves" reach in the Hautes-Pyrénées, France, a reach that has gone through severe sediment extractions for over 50 years. Each network represents possible restoration decisions linked to one of the observed issues. The paper demonstrates how BNs used as a decision support system (DSS) can help to assess the influence of given management strategies on the river system with the consideration of stakeholders' knowledge and integration in all the modelling process.

KEYWORDS

Bayesian networks, decision support system, participatory modelling, river restoration, river systems, stakeholders

1 | INTRODUCTION

The ambition of the global project in which the work described in this article takes place is to propose sustainable solutions for the rehabilitation of a watercourse disturbed by events of both natural (flash floods, river avulsion, etc.) and anthropogenic origins (sediment extraction, construction of hydraulic structures, recalibration, dredging, riprap, etc.). This task is made complex by the diversity of the stakeholders involved in the search and implementation of restoration solutions, but also by the outcomes that will result in terms of potential use or exploitation of the watercourse. Therefore, the search for solutions involves different actors associated with the different phases of the life cycle of the aquatic system and requires consequently a deep multi-criteria analysis.

The normal functioning of a watercourse is, first, defined by a sophisticated balance between morphological (flow patterns, flow regimes, sediment transport, etc.), granulometric (size and composition of sediments), physicochemical (oxygen level, temperature, etc.) and eco-biological (fish, macroinvertebrates, diatoms, riparian zones, aquatic vegetation, etc.) factors (Gregory, 2006). The primary objective of redesigning a river must be to avoid upsetting its fragile equilibrium while facilitating the cohabitation with its riverside communities (populations, agricultural land, urbanized areas, etc.) or its users (farmers, stockbreeders, fishermen, energy users, promoters or protagonists of sports, recreational and leisure activities, etc.) (Voinov & Bousquet, 2010).

The “Lac des Gaves” is an artificial lake delimited by two weirs located within the riverbed of the “Gave de Pau” river in the Hautes-Pyrénées department in France and has undergone years of sediment extractions. This led to a strong hydromorphological imbalance that is disturbing the normal functioning of the watercourse in this area, if we refer to the definition above. Today, after a major flood event that occurred in June 2013, the lake is almost completely filled with sediments, which may lead to river avulsion towards populated and thus safety risks. Besides, the sediment discontinuity induced by the weirs, caused active channel shrinkage downstream and sediment deficit that led to serious ecological damages and navigation problems.

The aim of this paper is thus to present an attempt to conduct a participatory modelling (PM) approach with the support of Bayesian networks (BNs) to help us define a restoration scenario for the “Lac des Gaves” reach. We try to unravel the main mechanisms that led to its current situation with the help of local stakeholders from different backgrounds in order to cover all the disciplines involved in this project. Within this context, the paper will be divided into five parts. In Section 2, we will discuss the modelling framework, we will present then in Section 3, the methodology that we decided to follow and how we instantiated it (Section 5) to our case study. After that, in Section 6, we will present the results of one of the developed models related to safety issues to then finish with a discussion in Section 7 on the advantages and drawbacks of this approach and how we can implement it in other areas.

2 | MODELLING FRAMEWORK

2.1 | Transdisciplinary collaborative context

As just sketched out, the search for solutions takes place in a multi-criteria framework, linked to the needs and constraints of the various stakeholders involved, but also in an inter-transdisciplinary context. First of all, the disciplines likely to bring knowledge to the operational definition of sustainable restoration solutions for the Lac des Gaves reach had to be determined. The result is a fertile combination of approaches and outcomes whose aim is to enrich the information collected, and consequently, a more complete, systemic, or even holistic, understanding of the object under study. Interdisciplinarity combines the scientific approaches of each discipline with a common goal of studying the same object, but in a more global perspective. Transdisciplinarity offers the possibility to integrate different perspectives, to go beyond the disciplinary paradigms, to consider the object of study in its entire complexity through a global and systemic view, and to set up a formal platform that provides the opportunity to all the involved parties to participate to the entire process (Graf, 2019; St, Bouchard, Oestreicher, Simon, & Saint-Charles, 2014). This notion of transdisciplinarity is fundamental to the approach considered in this paper as it combines inter-professional expertise, useful for decision-making and scientific requests to take into account the different epistemological angles through which a system should be tackled (Livet, 2020).

The search for a framework favouring transdisciplinarity involves bringing together the different actors through exchanges and discussions. In this organization, the working group is assimilated to a system of permanent interactions in order to go beyond the limits of individual work with the purpose of combining elementary efforts into joint actions. This requires regulation and coordination mechanisms between the different actors. In this sense, each actor of the collective must have a global vision of the working environment in which he participates and interacts. Through this confrontation, it becomes possible to identify the expectations of the other partners and the impact of mutual actions on the environment of concern (Maksimov & Fricker, 2019; Neely & Bortz, 2018). This project considers thus one of the key aspects of transdisciplinarity, as it involves stakeholders in the research of restoration solutions from the identification of the problem to the definition of the objectives and strategies.

The integration of different points of view in investigations for a solution is a complex activity requiring the joint consideration of cognitive, technical, social, economic, organizational, temporal aspects, etc. The collective effort is a response to the complexity of this task. The actors or subjects come from different disciplinary and cultural backgrounds requiring mechanisms of understanding. It is therefore clear that the role of cooperation is crucial in fostering transdisciplinary convergence. This cooperation can take place through several means, but the most effective approach seems to rely on the concept of PM (Schneider & Rist, 2013; Smetschka & Gaube, 2020).

2.2 | Participatory modelling approach

"Participatory modelling is a method that involves a group of individuals in the development of a model to improve understanding of a particular system, its problems and possible solutions, which will directly or indirectly lead to better management decisions. The product of this method is the generation of a collective understanding among the builders of the model, during the process, rather than the model itself" (Crevier & Parrott, 2019).

There are various ways of organizing such an exercise and several types of models can be constructed (Stave, Dwyer, & Turner, 2019), but the overall objectives of such an exercise are as follows:

- stakeholders improve their overall understanding of the system;
- they learn and understand each other's points of view;
- the group hence forges a common understanding (shared by the stakeholders) of the system, the problems and the solutions.

Participatory design (PD) processes have developed in Sweden since the 1970s to address the issue of sharing power between the employer and the union. The tools used were rudimentary and were based on the use of manuals and checklists. In the 1980s, and in order to collect knowledge from users for improving the quality of the final solution, methods for interviewing experts (designer and user representatives) were developed (Lepreux, Kubicki, Kolski, & Caelen, 2012). However, the delegation of knowledge to correspondents was hampered by the fear of its misuse and the methods did not achieve the expected results. In the mid-1990s, the concept of a collective design process emerged. It was based on the principle that all stakeholders are considered experts and their participation is based on their own knowledge rather than on the roles they play or the interest they represent. It is a creative act in a collective process to which all those concerned with the outcome of the process actively contribute with their different expertise. Various techniques have since arisen to instrument this process. We can mention in particular the principles of concurrent engineering, the development of computer (RUP, UML), or methodological tools such as role-playing or the method of moments (Halbe, Pahl-Wostl, & Adamowski, 2018; Ormond, Telhada, & Putnik, 2019).

The principles of PM, including techniques for quantifying stakeholder preferences, the questions raised by this approach and the quality of the results obtained have been the subject of several studies (Carr, 2015; Heldt, *et al*., 2016; Hemmerling, *et al*., 2019; Jordan, *et al*., 2018; Luyet, Schlaepfer, Parlange, & Buttler, 2012; Petursdottir, Arnalds, Baker, Montanarella, & Aradóttir, 2013; Reichert, *et al*., 2007). As the notion of collaboration is considered superior to the sole notion of participation, in Basco-Carrera, Warren, Beek, Jonoski, & Giardino (2017), the authors make a distinction between collaborative modelling and PM. We agree with this notion even if, later in this paper, we will refer to PM to designate the most successful collaborative action leading to decision-making in a highly cooperative framework.

As interesting as these methods may be, they might be irrelevant if they failed to take into account the uncertainties of the problems and the levels of confidence associated with the knowledge introduced.

2.3 | Uncertainty handling context

The PM study is usually carried out in an environment characterized by the presence of many uncertainties (Sear, Wheaton, & Darby, 2007). These may be of different kinds. An objective or residual uncertainty is not avoidable and persists even after all efforts to gather all possible information have been made and are not sufficient to reduce it. Subjective uncertainty on the other hand is linked to a lack of knowledge of the system under study or a mistrust in a decision-making process.

Perpendicular to this dichotomy, and in a matrix view, it will be useful to distinguish three forms of uncertainty. State uncertainty refers to a situation where the variables that describe a system are well understood, but their value is unknown. Effect uncertainty refers to a situation where the variable is considered relevant to a particular problem, but the nature of its impact is unclear. Finally, response uncertainty refers to an absence of solutions or the inability to predict the likely consequences associated with a choice or a decision (Bond, Morrison-Saunders, Gunn, Pope, & Retief, 2015).

The PM approach needs to be able to deal with this uncertain context. It is a question of characterizing objective uncertainty while attempting to reduce subjective uncertainty through confrontation between stakeholders and collaborative knowledge generation. It is also necessary to identify the variables and their parameters in order to define confidence intervals for the evaluation of state and effect uncertainties and to prepare the ground for a creative process of searching for answers when all possible options are not known.

The treatment of uncertainties in PM approaches can be handled in different ways. For the characterization of uncertainties associated with qualitative variables, tools such as mind maps, questionnaires, and pedigree matrices can be used (Meselhe, *et al*., 2020; Petursdottir et al., 2013; Röckmann, *et al*., 2012). Other studies are based on multi-criteria studies and in general the Multi-Attribute Value and Utility Theory (MAVT/MAUT) (Langhans & Lienert, 2016). For certain quantifiable technical information, the use of frequentist techniques is appropriate. In some cases, other advanced modelling tools can be used to support collaboration between actors. This is the case, for example, of system dynamics (Pagano, Pluchinotta, Pengal, Cokan & Giordano, 2019; Scolozzi, Schirpke, & Geneletti, 2019), or multi-agent systems (Pluchinotta, 2014) for instance.

2.4 | Bayesian networks as supporting tool

To overcome the problem of uncertainty handling, we have highlighted that the PM approach had to be instrumented with some tools capable of embracing all the forms of uncertainty previously mentioned, while providing a supportive framework for the expression of the various stakeholders. To underpin this process, we decided to use Bayesian networks (BNs). BNs are a modelling tool based on a graphical structure and probabilities for the representation of causal relationships among variables (Cain, 2001; McCann, Marcot, & Ellis, 2006). BNs are graphic models designed to formalize knowledge with the purpose of reasoning about a problem. Bayes theorem is central in the mechanism of inference in BNs. It makes the link between a series of hypotheses, characterized by probabilities of occurrence, and a series of observations representing the actual state of the system (Liu, Tchangani, & Pérès, 2016; Villeneuve, Béler, Pérès, & Geneste, 2011; Yassine, Pérès, Roux, Cassan, & Frysou, 2018) (Figure 1).

Several reasons motivated the choice of BNs:

- ability to break down a problem into elementary variables (each actor can integrate its own parameters into the model)
- multidimensional, multi-scale and dynamic modelling of the different dimensions of a problem (each actor can position himself on the dimension of his interest)
- possibility to combine tacit (expertise), explicit (real field data), or analytical (physical laws) knowledge
- upward or downward propagations of the uncertainties associated with the different variables for the establishment of a diagnosis or prognosis (each actor can visualize the risk or confidence thresholds associated with his own uncertainties about the achievement of a result taking into account the uncertainties of the other actors)
- possibility to introduce decision and utility nodes in the model to assess the trustworthiness of different alternatives or scenarios.

Attempts to use BNs in support of the PM approach can be found in the literature with, in particular, a predominant field of application being that of environmental sciences. In Shenton, Hart, and Chan (2014) and Glendining and Pollino (2012), the authors deal more specifically with the problem of river restoration. These works are most often based on the use of simple BNs (Chan, Ross, Hoverman, & Powell, 2010; Salliou, Vialatte, Monteil, & Barnaud, 2019; Stewart-Koster et al., 2010; Zorrilla et al., 2010), but also, sometimes, dynamic or object-oriented (Molina, Bromley, Bromley, García-Aróstegui, Sullivan, & Benavente, 2010). In Salliou, Barnaud, Vialatte, and Monteil (2017), the authors use BNs to address problems of ambiguity and to try to explain the points of divergence between stakeholders in order to better solve them later on.

Our work was mainly inspired by the aforementioned studies. However, in this paper, we considered the notion of decision and utility nodes in our causal diagrams. This orientation allowed us to propose to river managers the best restoration scenario based on the available data, stakeholders' opinion and the elaborated BNs. We describe the key steps and tools in the process to integrate their knowledge and finally give some possible ways to improve this approach.

3 | METHODOLOGY

In the context mentioned above, modelling the restauration project of a river turns out to be complex due to the multidisciplinary nature of the actors and the differences of opinion likely to appear around the issue under study. A specific modelling framework is needed to compare opinions on both the structure of the network (qualitative variables and interactions between variables) and the evaluation of their modalities (nature and values of quantitative parameters).

The PM approach took the form of an interactive co-learning/co-construction participation, which meant that the stakeholders had to share their diagnosis and any kind of useful information. This led to involve the participants at all levels of the PM BN model construction. The PM steps considered in this study are presented in Table 1.

4 | STUDY AREA

The Gave de Pau watershed (Figure 3) located in the western Pyrenees was severely impacted by a large flood in June 2013. This event has demonstrated the major influence of sediment transport on the hydromorphological dynamic of the catchment's streams. As a matter of fact, an extreme hydrology combined with a very high rate of sediment delivery from the upstream catchments, exposed the downstream fluvial system to great danger characterized by very important sediment depositions, serious bank erosions that caused the collapse of roads and buildings, destruction of hydraulic structures' foundations and significant ecological damages (Figure 4).

The Lac des Gaves was particularly impacted by these events as it acted like a sediment trap. During the event, it intercepted almost all the sediment coming from the upstream catchment. Today, the lake is considered to be almost completely filled and avulsion risks are observed, as the left bank elevation is lower than the bed elevation. There is thus a need to come up with an efficient and sustainable restoration solution for this complex reach.

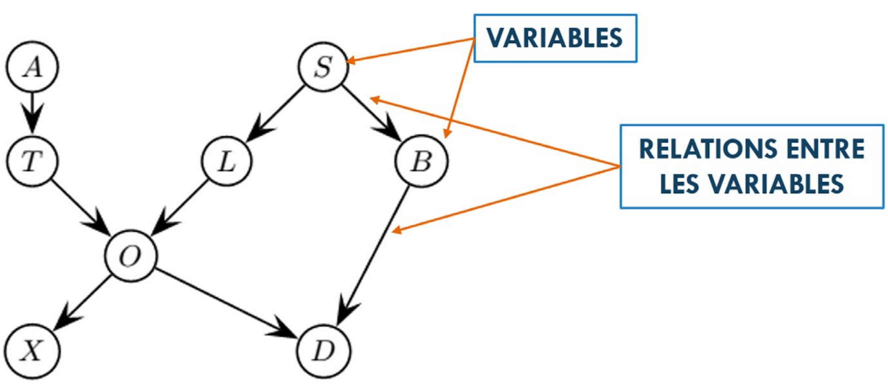

FIGURE 1 Example of a BNs structure [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 PM steps

1. **Formalize the problem:** The first step is to properly integrate the ins and outs of the issue to be solved. It is particularly important at this level to be careful not to confuse the problem with its symptoms. The issue must be addressed to fully understand all its dimensions and gather as much information as possible to facilitate the search for causes. Depending on the extent of the problem, staff from different departments may broaden the perspective on the issue. The classic trap would be to rush headlong into the realization without having taken the time necessary to analyse and fully understand the explicit (and sometimes implicit) needs, the real issues (financial but also strategic, human…), the project environment, etc. It is about making sure that everyone is on the same page and shares the same diagnosis. To overcome this risk, the definition of the problem can also be challenged or modified at the very beginning of the analysis by the various stakeholders once they have been identified (Nyberg, Marcot, & Sulyma, 2006).
2. **Define the goals to be achieved:** The purpose of the project is a fundamental element for its success. It takes shape in the setting of precise objectives associated with this future work. The definition of objectives is closely linked to the needs expressed. They bring this link between gross need and operational expression that will allow teams to get to work knowing exactly what they need to produce, when and at what cost. In a conventional way, the specifications drawn up must specify not only the objectives but also the reason for the existence of the project and the goals pursued, the constraints and requirements, the deliverables and expected results in qualitative and quantitative terms with the associated deadlines, the tools and indicators for evaluating the results.
3. **Identify the key stakeholders.** This refers to all individuals and organizations that have something to do with the project. Either they are directly involved in the conduct of operations, or they are impacted by the initial problem (Figure 2). A distinction should be made at this level between (i) defining the nature of the skills expected that will make it possible to identify the different stakeholders in the problem and (ii) characterizing the level of expertise of the latter. On this second aspect and insofar as the participants are external, it is very difficult to evaluate their expertise and their level of knowledge. It is still possible, however, to determine upstream some characteristics of the expected profiles by specifying a degree of requisite competency. The identification of the forces involved must be followed by a stakeholder management plan based on their profile (Molina et al., 2010).
4. **Surveys and questionnaires to the stakeholders** prior to the meetings to collect their raw opinion. The aim is to assess any kind of evolution of their beliefs/knowledge by the end of the process. It can also be interesting to understand their perception of the problem and the possible restoration measures that seem to be well suited according to their vision (Jähnig et al., 2011).
5. **Constitute working teams.** If there is more than one representative in a given category, an interesting option is to assign the participants to small groups. There are two advantages to this initiative: (1) working in small groups can be more "manageable" and give the opportunity to all the participants to express their opinion whereas it can be complicated if the group is too big, (2) collecting the opinion of two participants representing the same category can be interesting to verify if there are variabilities in perceptions inside of the same category.
6. **Define a meeting planning**. To achieve the goals set, planning is an essential phase. Classically, its objective is to organize the progress of the project stages over time, which is a fundamental task for deadline control. The first phase consists in dividing it into several stages (identification of all the tasks to be carried out), estimating their duration, identifying the sequence of stages (including those that can be carried out in parallel—task scheduling), allocating resources and finally modelling this organization on an operational document shared by all the actors concerned to optimize the progress and monitoring of the implementation (Molina et al., 2010).
7. **Implement the collaborative analysis**. Stakeholders' consultation can be considered as an expert elicitation process whose aim is to obtain subjective judgements. It is commonly used in quantitative risk analysis to quantify uncertainties in situations where there is no or too little direct empirical data available to infer uncertainty. In the context of uncertainty quantification, expert elicitation aims to obtain a credible and traceable account of the specification of probabilistic information about uncertainty in a structured and documented manner. Several elicitation protocols have been developed (Hemming, Burgman, Hanea, McBride, & Wintle, 2018). The expert elicitation protocol generally involves the following steps: (i) explain to the expert the nature of the problem as well as the assessment procedure and make sure about awareness of biases in subjective judgements, (ii) specify the elements to be identified or the quantities to be estimated and choose a scale and unit familiar to the expert, (iii) discuss the state of knowledge on the quantity at hand (strengths and weaknesses in available data, knowledge gaps, qualitative uncertainties), (iv) elicit the expertise and check about its correct formalization, (v) decide whether or not and how to aggregate the knowledge elicited from other stakeholders. In the PM-based building of a BN, these steps will be implemented to:
    - 7.1 *Establish the key variables* likely to drive the model being built. More specifically, it is necessary to determine which input variables are most important to influence the outcomes of the model and to what extent the variation in model outputs can be explained by these variables. The analysis can be conducted according to (i) an inductive or top-down logic starting from the input variables and aiming to explain their influence on variables at a lower level, or (ii) via a deductive or bottom-up approach seeking to determine the upstream causes associated with the evolution of an output variable. In a "meet in the middle" approach, both methods can be combined (Voinov & Bousquet, 2010);
    - 7.2 *Co-construct a conceptual graphical model*. The qualitative approach focuses on predicting and explaining the behaviour of physical mechanisms. Causality intervenes as a theory linking structural and functional reasoning. According to the same collaborative principles and once the variables have been identified, the experts are asked to group them into families and establish the nature of the mutual relations they have with each other (existence of a link and its direction) (Antunes, Santos, & Videira, 2006);
    - 7.3 *Translate the graphical model into a BN*. The values that can be taken by the variables must then be identified. When the variable is continuous, it can be represented by a probability distribution associated with the different values it can take. When the variable is discrete or when the probability distribution is not defined, it is easier to discretize the variable into classes (or modalities). For the definition of the complete graphical model associated with the BN, the experts are then invited to identify the different classes and to estimate their range of definition based on qualitative (e.g. high, medium, low) or quantitative values (e.g. 10 to 20, 20 to 50, 50 to 100) (Salliou et al., 2017);
    - 7.4 *Estimate the variable parameters*. Each of the variables in a BN is associated with a probability table. When the variable has no parent, these will be marginal laws. The experts must then express their opinion on the probability value associated with each modality. If the variable is a child variable, then it is a question of identifying the conditional probability tables characterized by the values likely to be taken by all possible combinations of the modalities of its parents.
8. **Elaborate scenarios**

5 | MODEL BUILDING

5.1 | Physical approach

A diachronic analysis was conducted based on an important amount of historical data (such as flow data, aerial photos, field data, etc.). The aim of this work was to study the hydromorphological evolution of the river from its natural state to its current modified state. Next, a numerical approach coupled with an experimental approach at the catchment scale were then performed relying on the physically based hydrological model MARINE (Roux et al., 2011) at the catchment scale and a 2D model at the reach scale. Even if the physical

FIGURE 2 Power/interest matrix of stakeholders [Colour figure can be viewed at wileyonlinelibrary.com]

approach helped to thoroughly understand the physical aspects that influence the watershed and hence the study area, other aspects were not considered such as the economic development of the area, the eventual loss of activities, tourist frequentation, etc. To cover these issues, a complementary analysis including PM was considered (Figure 5). It is evident that all the data acquired thanks to the physical analysis will serve the PM approach by feeding BNs with reliable data representing the real hydromorphological characteristics of the study area.

All the steps regarding the implementation of the PM method are developed in the following sections.

5.2 | PM approach

The different steps of the methodology described in Section 2.2 were instantiated to the case study in order for the decision-makers to take advantage of the diversity of standpoints considered by the different stakeholders.

5.2.1 | Step 1 – Formalize the problem

As described in section 4.1 and illustrated in Figure 5, the physical approach helped at defining the problem from a hydromorphological dysfunctional point of view. We identified all the physical impairments by comparing the current morphological configuration of the study area to a reference state where we consider that the river is

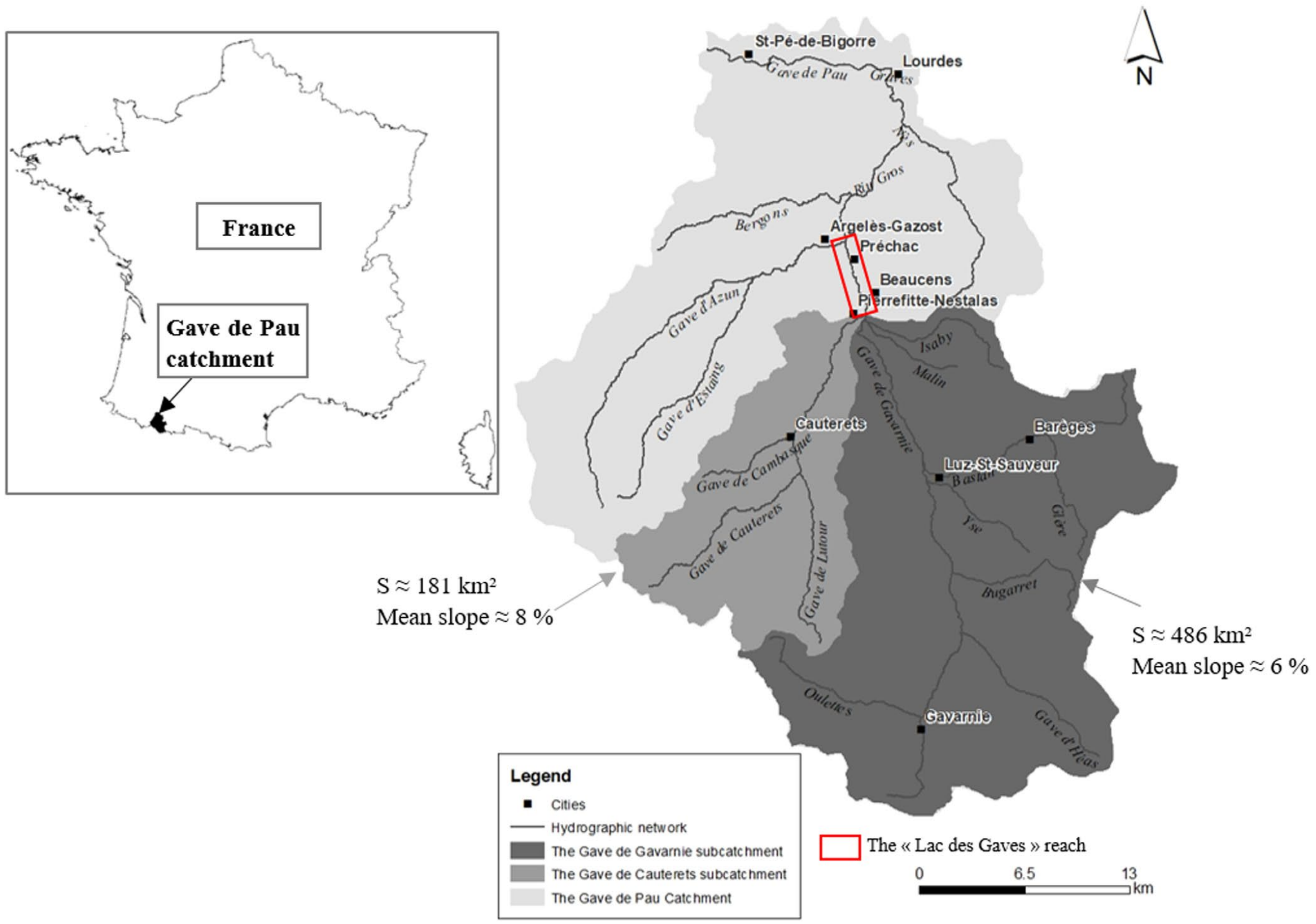

FIGURE 3 Presentation of the Gave de Pau catchment and its main upstream subcatchments: the "Gave de Cauterets" and the "Gave de Gavarnie" subcatchments [Colour figure can be viewed at wileyonlinelibrary.com]

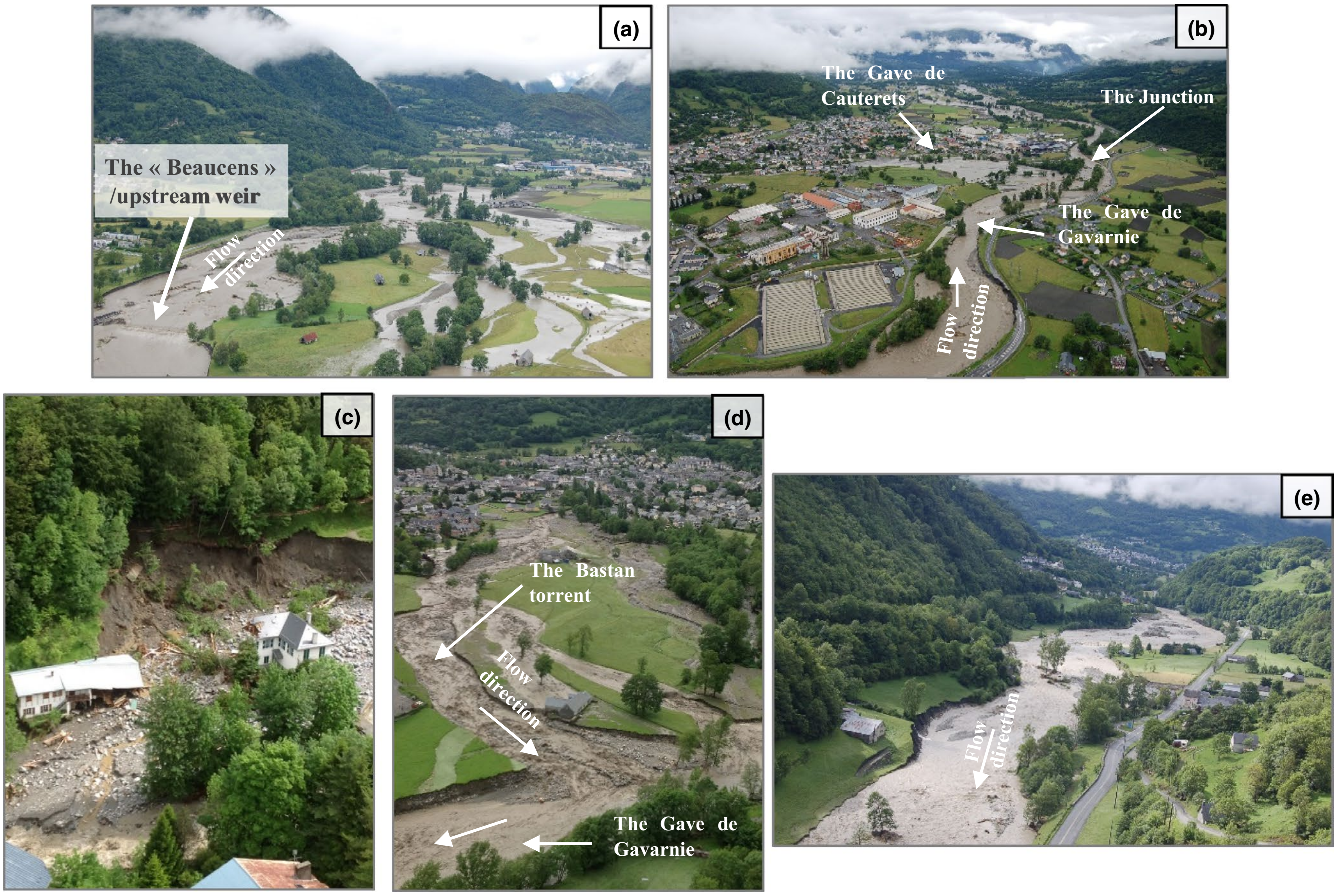

FIGURE 4 Some examples of damages caused by the flood of June 2013 at different locations and different streams [Colour figure can be viewed at wileyonlinelibrary.com]

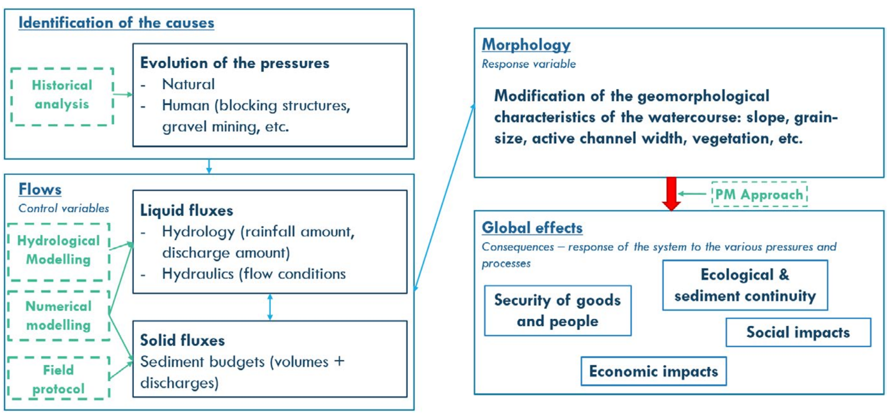

FIGURE 5 Main steps considered in the restoration project of the Lac des Gaves reach [Colour figure can be viewed at wileyonlinelibrary.com]

at its most natural and functional condition. We also compared the morphological characteristics of the reach before and after the 2013 flood to understand the impacts of such kind of events. This step helped at acquiring precious information about the reach's behaviour and evolution from a physical and ecological point of view; however, information about the security, the social and the economic impacts was still missing. By involving stakeholders in the framework of the PM approach, we were able to complete the missing pieces and link the provided information to the physical impairments previously identified. The issue was hence formulated in a holistic way considering the problems at different levels/scales and covering all the involved dimensions.

5.2.2 | Step 2 – Define the goals to be achieved

The general problem of the research project can be defined as the evaluation of the likely efficiency of a project for the functional and sustainable restoration of a watercourse. More specifically, the organization of the various sessions devoted to PM aimed to create a model for the definition of a functional performance of a development scenario for the Lac des Gaves. Within this framework, the objective assigned to the participants was to build the causal graphs and then the BN allowing a probabilistic quantification for the characterization of the potential consequences of each solution and the assessment of the levels of vulnerability of the stakes (human, material or environmental) and the risks induced by the architecture of the studied system.

5.2.3 | Step 3 – Identify the key stakeholders

The participants were selected in such a way that most of the fields involved in the restoration project would be covered. They were all described according to their function and their level of knowledge on a specific topic (Table 2). The idea was to cover the wide range of topics that a river restoration project can bring into play. However, involving stakeholders from different backgrounds can also be quite challenging. Indeed, by doing so, the number of divergent opinions is likely to rise but the knowledge base and the relevant ideas also increase. The challenge is then to try to find a consensus.

Five categories of stakeholders were represented. The first category was the elected politicians, like for instance the mayors of the impacted municipalities. Social representatives were mostly represented by landowners. The professional category included the "water users" such as fishermen, kayak or rafting amateurs or professionals who have sometimes troubles crossing the reach and are forced to disembark at the downstream weir and re-embark after. The technician category represented all the engineers and technicians that are experts in river management and know very well the study area. Finally, the government services are the ones that control the respect of local regulations and the funding of river management projects.

5.2.4 | Step 4 – Survey the stakeholders

Before the first workshop, a survey was sent to all the participants to collect their opinion prior to the PM approach and assess any kind of evolution by the end of the process. The aim was also to understand their perception of the problem and the possible restoration measures that seem to be well suited according to their vision. After having presented briefly the study area and recalled the aim of the PM approach and the objective of this survey, the questionnaire was divided into several categories listed below:

1. General information about the participant;
2. General knowledge about the study area and opinion about the current state;
3. Survey on ecological and sediment continuity;
4. Description of the individual or collective uses of the river reach.

TABLE 2 Stakeholders working groups

Stakeholders profession	Group 1	Group 2	Group 3
Elected politician	1	-	-
Social representative	1	1	1
Professional/association representative	3	2	2
Technician	2	2	3
Government services representative	1	1	1

5.2.5 | Step 5 – Constitute working teams

The selected participants were separated into three groups. The purpose was to work with small teams to facilitate exchanges and consensus building on the one hand, but also to compare the results obtained by separate teams for the same study scenario (Table 2). The five categories were represented in each group when possible.

Thirty-two participants attended the kick-off meeting; twenty-nine were present in the first workshop, twenty-one in the second and fifteen in the third.

5.2.6 | Step 6 – Define a meeting planning

The planning of the PM process was established as follows (Figure 6):

1. Workshop n°1: identification of the key variables that can impact in one way or another the system with the stakeholders;
2. Workshop n°2–3: co-construction of a conceptual graphical model linking all the variables;
3. Workshop n°4: translation of the graphical model into a BN;
4. Workshop n°4: Filling of the conditional probability tables (CPTs) with the stakeholders (quantification scales: qualitative or quantitative; justification of the discretization steps and the possible states that a variable may be in);
5. Elaboration of scenarios and modelling.

5.2.7 | Step 7 – Implement the collaborative analysis

Step 7.1 – Establish the key variables

After an introduction of the objectives of the project and an explanation of the principles of the PM approach, each participant had to write on a post-it all the relevant variables (quantitative or qualitative) that, according to his own experience and state of knowledge, might have a role to play in the current or future behaviour of the system. During this exercise, the research team was there to facilitate the workshop, guide the participants and help them if they had any technical question. A paperboard was installed in the middle of the room with four different categories: (1) security of goods and people; (2) ecological and sediment continuity; (3) economic

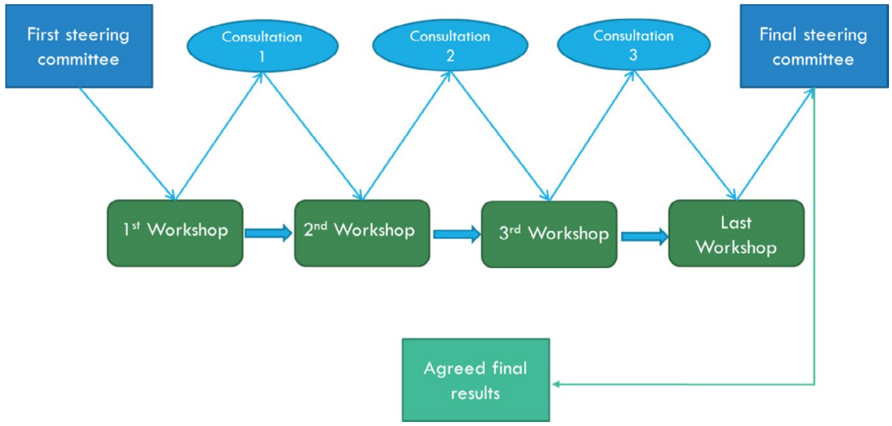

FIGURE 6 Global organization of the PM process [Colour figure can be viewed at wileyonlinelibrary.com]

factors; and (4) social factors as they represented the main category of issues identified by the stakeholders. This classification gave more clarity to the participants as they were able to visualize the connections among the different variables. Once they were done, each participant presented his selection and explained how, to his opinion, each variable interacted with the system. He was then invited to stick his post-it in the adequate category (Figure 7). After that, discussions were engaged among stakeholders for a limited amount of time and each participant was entitled to review his list of variables.

However, some participants did not clearly come up with variables but more with problems observed at the reach level. While this information was very interesting as it completed our knowledge about the study area (see Section 5.1), the collected information had to be transformed into variables between the first and the second workshop. Duplicated variables were deleted and the final list was divided into five categories with an associated colour: (1) decision in orange, (2) costs in purple, (3) causes in red, (4) physical in blue and (5) effects in green. The list of variables is given in the Appendix S1.

Step 7.2 – Co-construct a conceptual graphical model

Several transdisciplinary approaches such as Adaptive Environmental Assessment and Management (AEAM) or Integrated Assessment and Modelling (IAM) considered the integration of multiple sources of information and expertise in the model building process, for example, in the study of an overexploited hydrogeological system (Molina et al., 2010); in the elaboration of a management plan of a coastal wetland (Videira, Antunes, Santos, & Gamito, 2003); or in the framework water resources management for wetland degradation and conflicts mitigation (Zorrilla et al., 2010). In our case, we considered stakeholders not just as clients; we collaborated together in the development of the model about the specific identified problems in a series of workshops supported by the research team who acted as a facilitator. This chosen methodology of PM is also called mediated modelling (MM) described in more detail in Antunes et al. (2006).

The final list of the variables and their definition was provided to all the participants. They did not have to use all of them. The variables were deposited on a table in label forms from different colours according to the five categories mentioned in step 5. From the exchanges and discussions within each group of stakeholders (Table 2), a causal graph representing their perception of the system according to a restoration action was constructed, and in a few cases, some information to integrate in CPTs was provided. To be able to verify their understanding on the potential impacts of a restoration solution, they were asked to work on several prospective restoration measures. The research team was here to facilitate the workshop,

FIGURE 7 Results of the variables definition process [Colour figure can be viewed at wileyonlinelibrary.com]

manage conflicts and help with the understanding of the physical variables. The three groups worked simultaneously on the causal graphs and a representative of each group presented the results to all the participants. At this stage, loops and retroactions were allowed.

Step 7.3 – Translate the graphical model into a BN

The transition from the conceptual model to the BN structure can be tricky. In fact, the conceptual model elaborated allowed feedback loops whereas BNs are directed acyclic graphs (DAGs) that do not allow these kinds of retroactions. After the second and the third workshop, the research team worked on the transformation of the collected conceptual graphs to BN graphs by removing all the loops and retroactions without changing the structure and the meaning of the graphs elaborated by the stakeholders. The research team merged the three networks elaborated by the teams. In order to keep a reasonable number of combinations for direct elicitation, we proposed the division of the graphs into small BN structures so that they can stay manageable. The final BNs were proposed to the stakeholders that had to verify that their opinion was not deviated from its former meaning. The obtained graphs are presented in Figure 8 for the assessment of economic impacts, Figure 9 for social impacts, Figure 10 for the security of goods and people, Figure 11 for ecological continuity and Figure 12 for sediment continuity.

The final probabilistic BN for the assessment of the security of goods and people was implemented in Netica (©Norsys Software Corp.) (Figure 13). After having developed the BN connecting the causes and the effects of restoration measures proposed by the stakeholders, we transformed the BN into an Influence Diagram (ID). IDs are a general-purpose extension of BNs for helping to think about links between objectives, alternatives and consequences. They can provide a shared understanding of "how things work" and how various factors influence others. An ID encodes three basic elements of a decision: (1) available decision options, (2) factors that are relevant to the decision, including how they interact among each other and how the decisions will impact them, and finally, (3) the decision maker's preferences over the possible outcomes of the decision-making process. These three elements are encoded in IDs by means of three types of nodes: decision nodes, typically represented as rectangles, random variables, typically represented as ovals, and

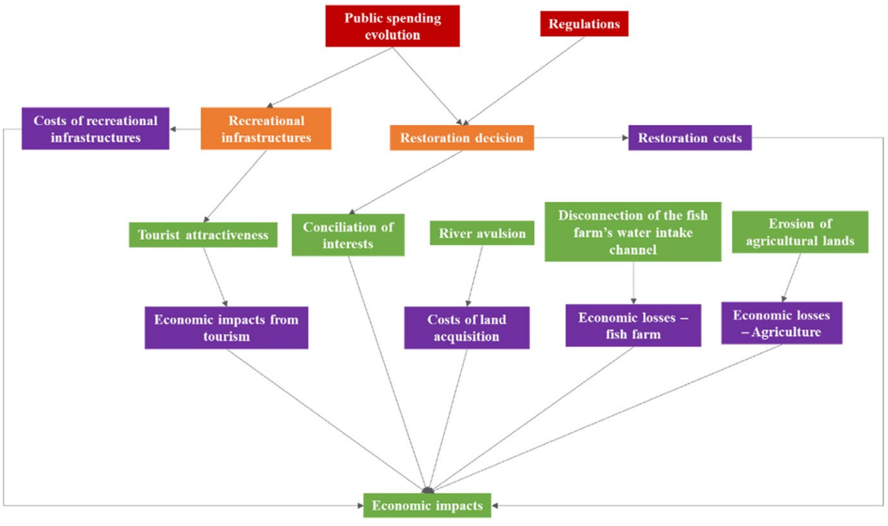

FIGURE 8 Causal graph for the assessment of economic impacts [Colour figure can be viewed at wileyonlinelibrary.com]

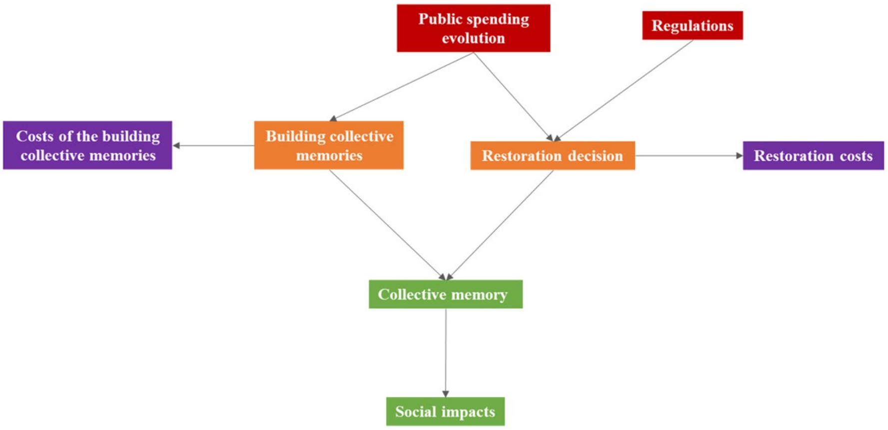

FIGURE 9 Causal graph for the assessment of social impacts [Colour figure can be viewed at wileyonlinelibrary.com]

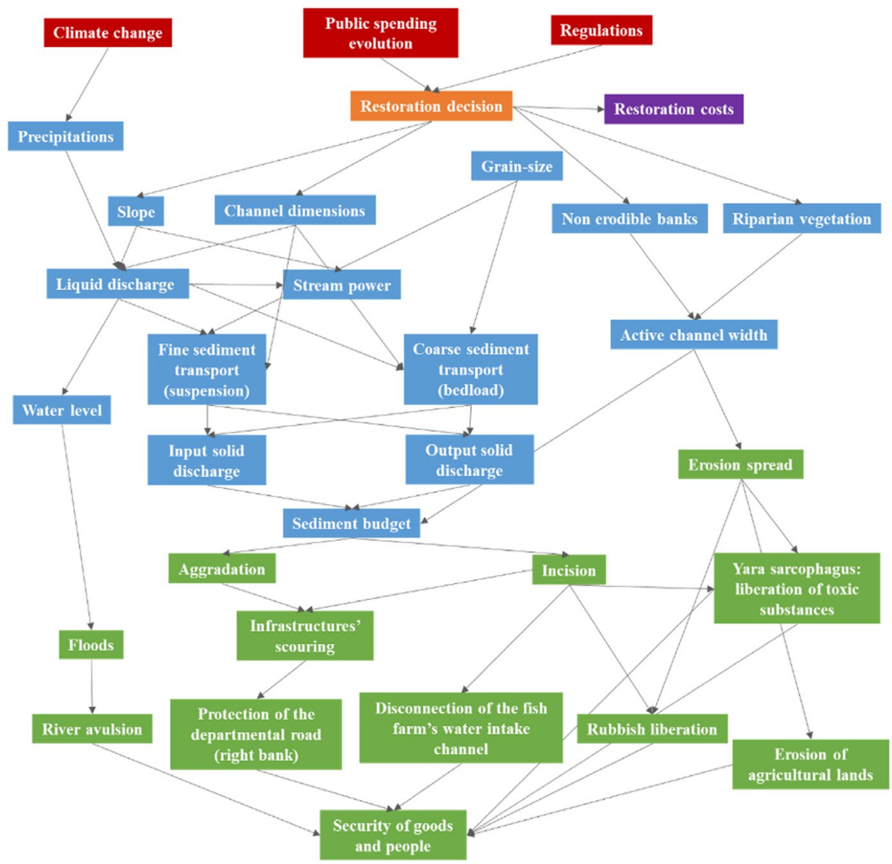

FIGURE 10 Causal graph for the assessment of the security of goods and people [Colour figure can be viewed at wileyonlinelibrary.com]

utility nodes, typically represented as diamonds or hexagons. In the present case study, the decision node was attributed to the restoration decision and the utility node to the related costs (Figure 13).

Step 7.4 – Estimate the variable parameter

The elaboration of CPTs started at the end of the third workshop. The process of defining variables and corresponding parameters is a long-term process. With the data obtained from the physical approach and information collected in the workshops, some variables states and conditional probability tables had already been completed.

Most of the CPTs of physical variables were also defined using data obtained from the output of hydrological and 2D hydraulic models as well as the results of the historical analysis. Socio-economic variables were defined through discussion with the stakeholders.

In this paper, we limited our contribution to the assessment of the security of goods and people issues as it was the top priority model and was the first to be addressed according to stakeholders' wishes. The exhaustive list of variables and their states for the assessment of security of goods and people is presented in Appendix S2.

5.2.8 | Step 8 – Elaborate scenarios

Restoration scenarios were elaborated with the stakeholders. Three scenarios were defined from the worst (in terms of negative impacts) to the best (in terms of positive impacts). The considered scenarios are presented in Table 3.

6 | RESULTS

All the causal graphs elaborated with the stakeholders are presented in Figures 8, 9, 10, 11 and 12.

As mentioned in Section 5.2, step 7.4, the results will be presented only for the assessment of the security of goods and people criterion. The final ID is presented in Figure 13 and the probabilistic BN in Figure 14. With the help of the ID, it becomes easy to compare the different strategies/scenarios considered on each of the identified performance criteria and to decide on the best restoration solution. The results of the simulation performed on the three proposed restoration scenarios (Table 3) are briefly commented below under the sole criteria of safety and summed up in Table 4.

6.1 | BAU scenario – Business As Usual

The Business As Usual (BAU) scenario resulted in 38.8% of chances of giving poor safety issues and 20% of chances of reaching satisfactory security performances. This scenario illustrates important flood risks (major: 37.2%, moderate: 28.9%) as there are great chances of sediment accumulation within the lake and thus higher risks of river avulsion (54.1%). This scenario and the following ones were simulated for

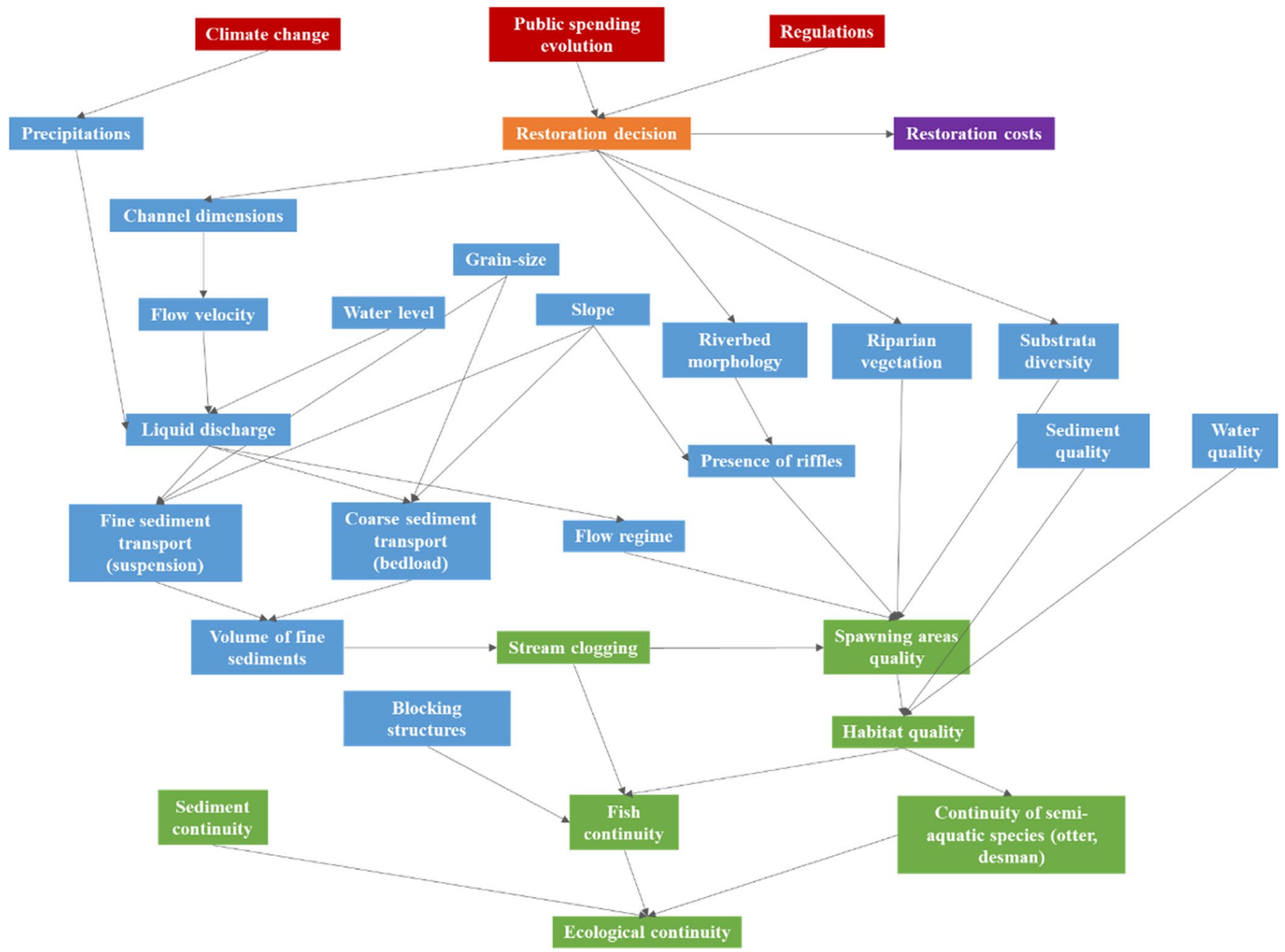

FIGURE 11 Causal graph for the assessment of ecological continuity [Colour figure can be viewed at wileyonlinelibrary.com]

the worst-case climate change scenario (% annual rainfall increase), an evolution of the land-use towards urbanization (increase of the imperviousness of the soils) and thus for high discharges (> Q_{20}).

Even if the weirs are not removed, there is still a risk of agricultural land erosion (65%). This was proved by a recent flood event (06/2018) that induced severe erosions at certain locations upstream the "upstream weir." This was confirmed by the farmers who attended the workshops and complained about this phenomenon. On the other hand, the protection of the side road turns out to be good (89.2%) and there are low risks of fish farm water intake disconnection (25%). As no restoration action is performed, the cost of this scenario is also zero.

6.2 | WL scenario – Weir Lowering

The weir lowering (WL) scenario resulted in 46.5% probability to reach poor safety results and 13.5% to reach good performances. However, for this scenario, there is 87% chance of erosion of agricultural lands and 66% of toxic substances liberation exposure. We found out also that the fish farm water intake is very likely to be disconnected for this scenario (70%). The positive point is that the risk of river avulsion is low (16.6%) as sediment aggregation in the lake decreases. The side road is also considered as protected for this scenario (62%). The cost estimation of this operation is about 350,000 €.

6.3 | TRW scenario – total removal of Weir

The last scenario regarding the total removal of the two weirs (TRW) gave the best results with 40.2% chances of succeeding at protecting goods and people. For this restoration measure, the model estimates that the protection of the side road located in the right bank is good (86%). This scenario considers that the water intake of the fish farm should be out of danger (25% disconnection chances) since the river is supposed to reach a new equilibrium. In fact, the model can be used to predict the sediment budget ($out - in$) and thus the potential risks of aggradation or incision. Model results show that if both weirs are removed an equilibrium slope should be reached which means that the effects of erosion and aggradation processes are expected to counterbalance each other. The restoration costs related to this solution are estimated to be over 1,500,000 € which makes it the most expensive solution.

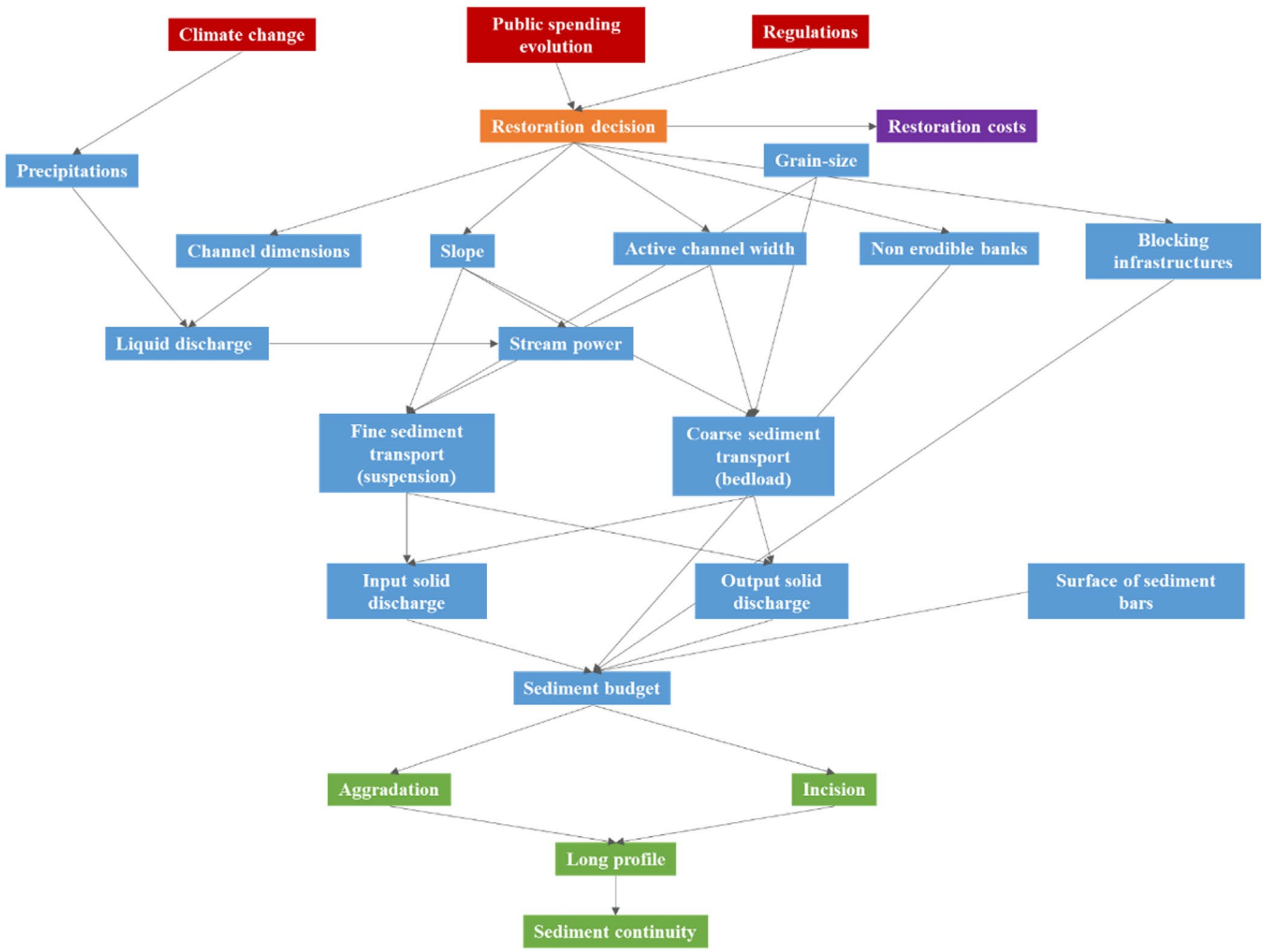

FIGURE 12 Causal graph for the assessment of sediment continuity [Colour figure can be viewed at wileyonlinelibrary.com]

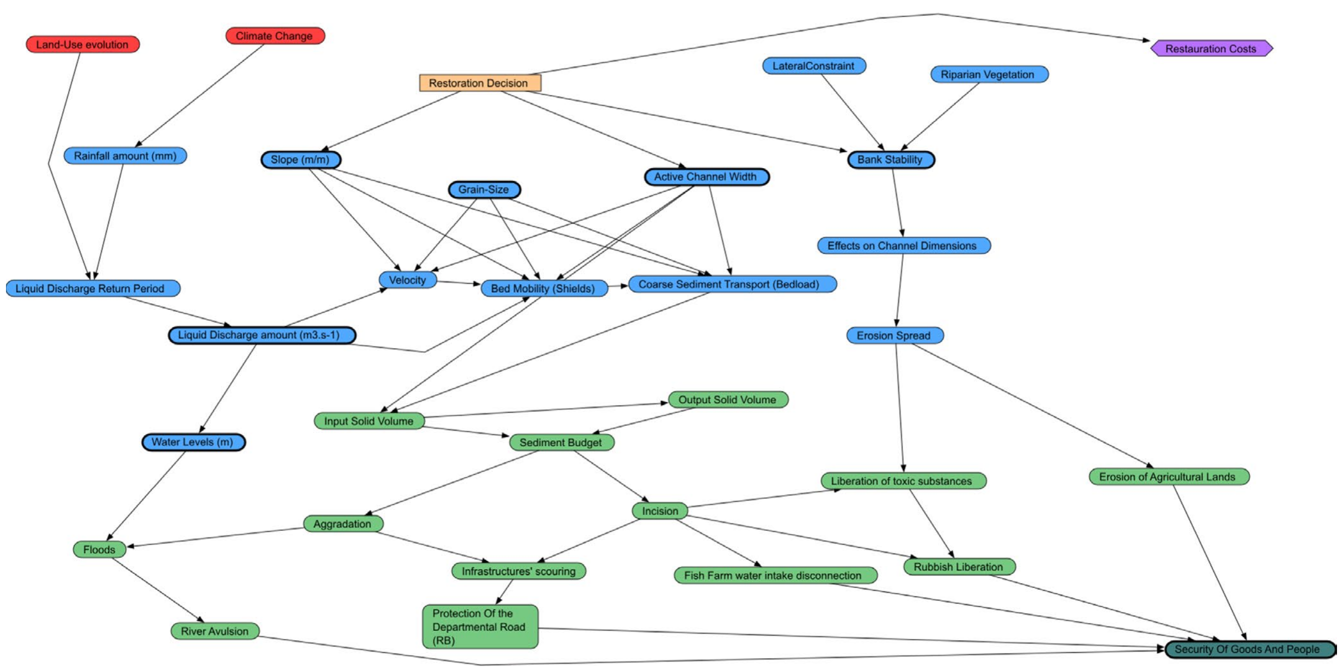

FIGURE 13 Final influence diagram for the assessment of the security of goods and people [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Proposed restoration scenarios and interventions

Code	Name of the scenario	Description	Restoration measures	Expected consequences
S1	Business As Usual (BAU)	Current conditions	No intervention	Accumulation of sediments River avulsion Incision aggravation Sediment discontinuity Increased flood risks
S2	Weir lowering (WL)	Modification of the topography of one of the two weirs in the hydromorphological 2D model	Lowering of one of the two weirs (−2 m)	Better sediment transit Decrease of river avulsion risks Increase of erosion and incision risks upstream the downstream weir Better sediment continuity (short term) Decreased flood risks upstream Increased flood risks downstream Disconnection of the fish farm water intake
S3	Total removal of the two weirs (TRW)	Removal of the weirs by modifying the topography in the 2D model	Total removal of the two weirs in the objective to come back to the initial state	Better sediment transit Decrease of river avulsion risks Return to an equilibrium slope Strong erosions, incisions and depositions before reaching an equilibrium Better sediment continuity Decreased flood risks upstream Increased flood risks downstream

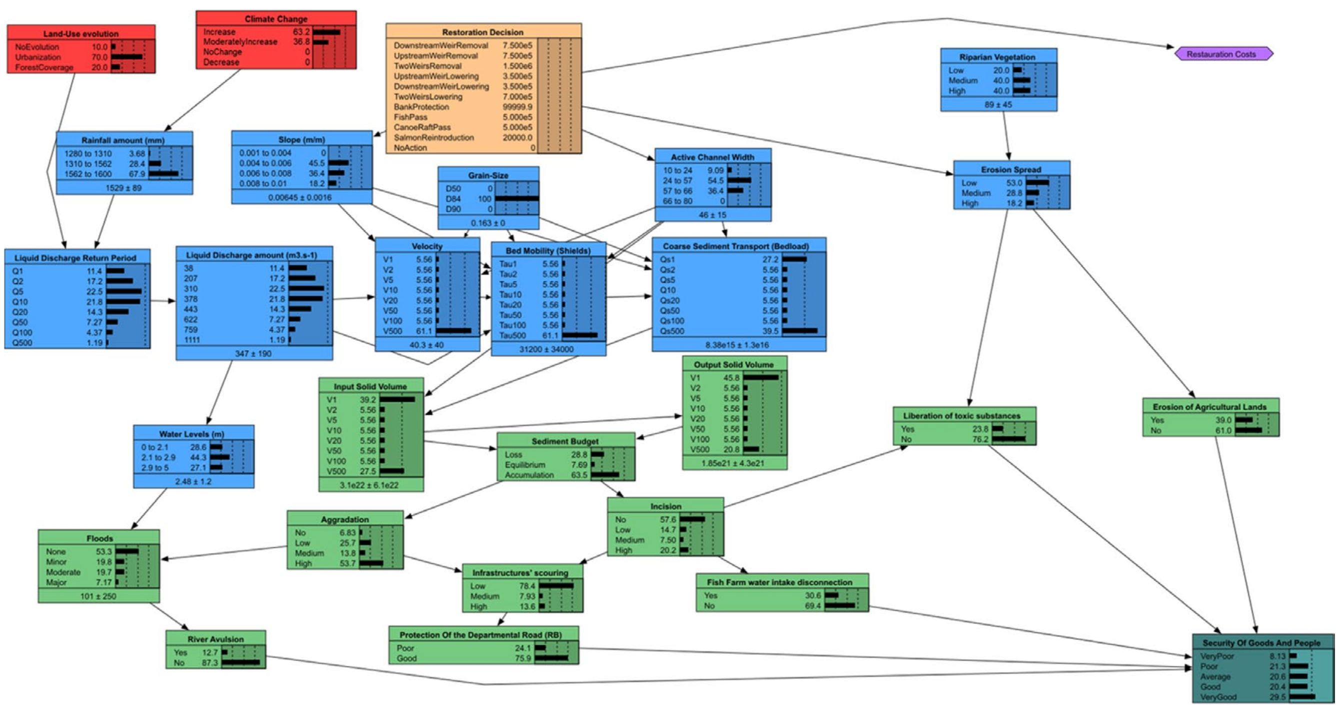

FIGURE 14 Final probabilistic BN for the assessment of the security of goods and people [Colour figure can be viewed at wileyonlinelibrary.com]

6.4 | TRW scenario – total removal of weir

The last scenario regarding the total removal of the two weirs (TRW) gave the best results with 40.2% chances of succeeding at protecting goods and people. For this restoration measure, the model estimates that the protection of the side road located in the right bank is good (86%). This scenario considers that the water intake of the fish farm should be out of danger (25% disconnection chances) since the river is supposed to reach a new equilibrium. In fact, the model can be used to predict the sediment budget $(out - in)$ and thus the potential risks of aggradation or incision. Model results show that if both weirs are removed an equilibrium slope should be reached

TABLE 4 Comparison of the impacts of the three restoration scenarios on the security of goods and people

Intervention scenario Main issues	States	BAU	WL	TRW
Flood risks (%)	None	17.7	60.5	47.6
	Minor	16.1	20.5	19
	Moderate	28.9	15.2	18.2
	Major	37.2	3.8	15.2
River avulsion (%)	Yes	54.1	16.6	28.4
	No	45.9	83.4	71.6
Protection of the main road (%)	Poor	10.8	38.0	14.0
	Good	89.2	62.0	86.0
Fish farm water intake disconnection (%)	Yes	25.0	70.0	25.0
	No	75.0	30.0	75.0
Liberation of toxic substances (%)	Yes	32.0	66.0	43.0
	No	68.0	34.0	57.0
Erosion of agricultural lands (%)	Yes	65.0	87.0	87.0
	No	35.0	13.0	13.0
Security of goods and people assessment (%)	Very Poor	12.9	31.7	11.1
	Poor	38.8	46.5	37.4
	Average	19.7	7.50	7.69
	Good	20.0	13.5	40.2
	Very Good	8.59	0.85	3.67

which means that the effects of erosion and aggradation processes are expected to counterbalance each other. The restoration costs related to this solution are estimated to be over 1 500 000 € which makes it the most expensive solution.

7 | DISCUSSION

7.1 | On the participatory aspect

This study gives an overview of how PM tools can be applied to create a reliable knowledge model for the assessment of impacts of river restoration actions in a multi-risks area. Most of the stakeholders considered the methodology to be innovative and useful as it helped them to acquire a better understanding about the Lac des Gaves system, its complex morphological configuration, the large amount of variables that can change its behaviour and the vulnerability of the stakes located nearby. The elaboration process of the model has thus proved to be a valuable social learning tool. Besides, the participatory framework helped at cultivating personal relations among key stakeholders who have been able to engage into free and honest discussions about hydromorphological issues. This aspect is a very positive contribution given the conflictive nature of interests in this basin. The PM process also helped developing a better understanding of the complexity of the issue and the challenge to find a solution that can satisfy all the dimensions involved. In addition, stakeholders were able to recognize the uncertainties associated to river management in the concerned area and that restoration actions can have positive impacts on a given criteria but negative consequences on others.

The participation rate of stakeholders attending each workshop turned out to decrease considerably from the first to the third workshop. This may lead to questions about the level of satisfaction and response to expectations provided to those who decided to no longer participate in the sessions. Once the participants left the process, it turned out very difficult to have their feedback to understand the reasons explaining their choice. However, some hypotheses concerning the causes can be explored based on similar studies (Salliou et al., 2019; Videira et al., 2003; Voinov & Bousquet, 2010). The first reason could be that the stakeholders were not satisfied with the process or that their expectations were not in line with the objectives assigned to the sessions they had attended. This was the case especially for a few landowners or members of environmental associations who were waiting to take the opportunity of these meetings to argue about past restoration mistakes (and in particular the emergency measures decided upon after the 2013 flood) rather than to discuss future improvements. Second, the timing of the workshop (during the mornings) seemed to make it complicated for voluntary participants or elected representatives holding a mandate in parallel with another professional activity to drop work duties and support the travel costs to attend the meetings.

7.2 | On the model results

In this paper, we focused mainly on the security model and the impact of certain remediation solutions on the safety of goods and people. The results obtained must be replaced in a more global context integrating the other dimensions (socio-economic and ecological aspects, etc.) associated with the other models we worked on. We deployed the three scenarios presented in Table 3 to assess the model's ability to reproduce consistent outcomes. We believe that our model was able to give coherent results in agreement with the provided data and the knowledge we acquired on the studied reach. The application of our model on the Lac des Gaves watershed shows that the results can provide useful information for rehabilitation planning.

After running the model, the removal of the two weirs delineating the Lac des Gaves reach turned out to be the best option. In fact, the model predicts correctly the slope recovery to its equilibrium level according to historical information on the ground if we consider this scenario. This was very appreciated by some stakeholders as it was shown also that it has a positive influence from an environmental perspective. The safety results were considered good enough for this scenario (40.2%). However, from a practical point of view, this may seem relatively unrealistic or even ineffective if other complementary measures are not carried out. Bank protection measures would, for example, make it possible to avoid severe geomorphological problems (erosions, deposits) before the desired equilibrium is reached. Besides, this scenario appears to be the most expensive which can make its implementation questionable.

For the weir lowering scenario, we only considered the downstream weir intentionally. In fact, at the beginning of the workshops, this was the stakeholders' preferred scenario. However, historical data and previous geomorphological expertise performed in the physical approach demonstrated that the removal or lowering of only one weir might lead to just shifting the problem to the second weir. This turned out to be the worst of the three scenarios as it led to 46.5% of poor safety performances. The presentation of these results proved to be essential in that they contradicted stakeholder's intuition that this scenario was by far the best of all and clearly demonstrated the need for further action on the second weir. The outcomes of this calculation highlighted the complex nature of the studied reach and the related influencing hydromorphological processes. This appeared to be a very positive feedback.

For the BAU scenario, which corresponds to the current situation of the studied reach, the model performed good calculation as the results were in accordance with what was observed in the field. The river avulsion risks were properly reproduced (54.1%) through the aggradation phenomenon currently occurring in the lake and mechanically enhancing the relative risk of flooding. However, since the developed model did not take into account the time component, it was not possible to consider the situation in which, maybe some years from now, the lake would be completely filled. This would mean that the natural hydromorphological equilibrium of the studied would have been reached.

7.3 | On the performance of BNs as modelling tools

BNs turned out to be interesting tools to use in this framework and their graphical structure was the most appreciated aspect by the stakeholders. Another attractive aspect of BNs is that they allowed the participants to use various kinds of data. In fact, the development of the model relied mainly on stakeholders' expertise for some qualitative nodes as well as real field data and even physical laws for sediment transport estimations. To our opinion, this is one of the most positive aspects of these tools as no physical model confronts its results to other nonquantifiable information. Finally, the opportunity to use IDs by introducing utility and decision nodes in the model was a real added value.

In terms of downsides, the use of BNs made appear some drawbacks. The fact that they do not allow mutual interactions between variables can question the validity of the results from a physical point of view. This aspect was strongly debated with the participants, as they did not always agree with some simplifications made for the transformation of the conceptual graphs into BNs. Besides, the consideration of the temporal aspect is complicated, which constrained us on approaching the river system as a static one. Let's note that the use of dynamic BNs to support the next steps in modelling could provide some response to the two previous criticisms.

7.4 | On the PM approach in general

Finally, the first positive feedback suggests that PM paid off in enhancing stakeholders' knowledge about the river they live nearby or they work on. They are now fully aware of the main variables that have an impact on the system and acknowledge the uncertainties that hamper river management.

In this paper, only the safety criterion was addressed in quantitative terms. It is clear that the global approach will have to, through dedicated multi-criteria analyses or by the means of an extended view of the Bayesian model, incorporate all the dimensions of the problem (ecological continuity, sediment continuity, economic and social issues) in order to define the choice of the optimal scenario.

Besides, the proposed restoration scenarios take only one action into account. Considering the combination of various restoration measures can lead to better and more realistic results. This can be also another avenue to be addressed.

Even if the approach considered is on the whole positive, it is important to mention that other difficulties related to the use of this approach can be reported: (1) the approach is time-consuming, especially if data are not available. Field experiments, hydromorphological modelling and sediment transport calculations had to be performed to enhance the physical understanding of the system before even thinking about restoration solutions. This took almost two years. In addition, there is the time needed to organize meetings and to work out the results. (2) The lack of data may lead to the use of only expert knowledge if the project period is very short which might result in a partially subjective model; (3) The financial costs of this approach (data collection, physical modelling, meetings organization and the acquisition of the software licence) are important and have to be considered in the initial financial budgeting of the restoration project (Cain, 2001); and finally, (4) in some confidential cases, PM approaches cannot be applied or can be considered only with a limited circle of stakeholders working in the same team which can question the transdisciplinary aspects and plurality of opinions.

8 | CONCLUSION AND PERSPECTIVES

Knowing the diversity of criteria, stakes and the multi-scale aspects to be taken into account, a river restoration project is constrained by growing uncertainties. While it is unrealistic to assume that these uncertainties can be completely removed, the participatory exercise presented in this paper shows that including stakeholders in the modelling process in combination to suitable technical tools may prove beneficial in reducing uncertainties and improving stakeholders' knowledge about the difficulties associated to river restoration projects. Besides, a PM approach offers the opportunity to consider results from not only physical models but also economic and social factors. Within this framework, our work addressed the problem of selecting the best strategies for the restoration of a river damaged by past flash flood events. Since the 2013 flood, no restoration action has so far been performed in the study area as the issue is very complex and there is a high degree of uncertainty concerning the decision-making process. A given restoration measure can have strong impacts at various dimensions. It was therefore very important to spend enough time identifying all of them and understand the role of each variable in the modification of the studied system. For the aforementioned reason and because of the large number of variables, the BNs were chosen as modelling tool.

The methodology and first outcomes of the hybrid modelling presented in this paper are based on a case study. PM workshops helped defining in collaboration with the stakeholders all the variables involved in this multi-criteria restoration projects. The exhaustive list covered physical aspects as well as socio-economic impacts. The states of the variables were developed in collaboration with the stakeholders and helped filling the CPTs. The PM approach resulted in the elaboration of several causal graphs each one assessing the potential impacts on a given criteria. Three restoration scenarios were established with the participants and were simulated using BNs. We presented the results related to the security of goods and people assessment. It turned out that the best scenario from a physical point of view concerns the removal of the two weirs. However, it is also the most expensive one, which may question the feasibility of its implementation. Besides, this scenario might be considered as "extreme" if not accompanied with other complementary restoration measures such as bank stabilization or progressive sediment delivery to the downstream fluvial system. We also proved that the initially preferred scenario (lowering/removal of the downstream weir) was not the best one in terms of goods protection. This particular information convinced the stakeholders about the fact that river systems are very complex and that definition of an optimal restoration solution turns out to be very delicate.

Finally, this paper provides a practical demonstration of how a PM approach based on BNs may be used to support river restoration projects decision-making process. A simple methodology explaining how PM can be applied in such kind of projects was proposed and what benefits can be drawn from it. It has been demonstrated that BNs have the advantage to balance in a same approach the socio-economic factors versus the physical aspects. The results presented in this paper provided some answers to river managers that acquired a better knowledge on the hydromorphological processes influencing the river system they work on. However, this process takes time, and there is a need for an important amount of data to be able to propose consistent restoration solutions. Finally, the main feedback of this PM process is that stakeholders' participation is the key to achieve validation of these kinds of models while strengthening collaboration and creating a relevant interface with managers and researchers.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.