Lessons learnt from the application of a participatory modelling approach in the framework of a river restoration project: case of the Gave de Pau River, Hautes-Pyrénées, France

Rabab Yassine[1,2,3], François Pérès[1], Olivier Frysou[3], Hélène Roux[2] and, Ludovic Cassan[2]
[1]Université de Toulouse, INP/ENIT, LGP, 47, Avenue d'Azereix, F-65013 Tarbes, France
(Tel: +33 5 62 44 27 00; e-mail: rabab.yassine@plvg.fr and francois.peres@enit.fr).
[2]Institut de Mécanique des Fluides de Toulouse (IMFT) - Université de Toulouse, CNRS-INPT-UPS, Toulouse, France (Tel: +33 5 34 32 28 53; e-mail: helene.roux@imft.fr and ludovic.cassan@imft.fr).
[3]Pays de Lourdes et des Vallées des Gaves (PLVG), 4 rue Edmond Michelet, 65100 Lourdes, France
(Tel: +33 5 62 42 64 98; e-mail: olivier.frysou@plvg.fr)

Abstract: Considering the diversity of criteria and stakes, the uncertain and stochastic nature of the physical phenomena and the multi-scale aspects to be taken into account, a river restoration project can be viewed as a complex problem. Many river managers and scientific researchers have been investigating the subject as river restoration projects deal with significant safety, environmental and economic issues. A project manager can hardly be an expert in all the disciplines to consider to come up with the optimal solution that satisfies all the involved dimensions. The integration of both local stakeholders with field experience and technicians and academics with scientific knowledge can hence benefit river restoration projects. The aim of this paper is to present an approach that considers the integration of various stakeholders engaged in river restoration issues to gather their knowledge and define the solutions that offer decent compromise considering all the dimensions involved. To this end, a group of stakeholders identified according to specific selection criteria were engaged in a modeling approach based on Bayesian Networks (BNs). BNs are increasingly being used as tools for decision-making in river management due to their natural ability to adjust to complex multi-criteria systems with multiple interactions. A participatory approach based on BNs that led to the elaboration of causal graphs is introduced in this paper. This study considers the combination of both physical knowledge associated to river systems and the relation constraints to river users and managers. The work is conducted in the framework of the restoration project of the "Lac des Gaves", an artificial lake that undergone years of sediment extractions over the past century and important flood events that highlighted several numbers of impairments.

Keywords: Participatory Modeling, Stakeholders, Bayesian Networks, Multi-criteria, River Systems, River Restoration

1. INTRODUCTION

The ambition of the project in which the work described in this article takes place is to propose sustainable restoration measures of a river disturbed by both natural (floods, river avulsion etc.) and anthropogenic (sediment extractions, hydraulic structures, riprap, etc.) pressures. This operation is considered as a complex problem knowing the diversity of the stakeholders involved, but also the outcomes that will result in terms of potential use or exploitation of the watercourse. It is therefore important to look for solutions that consider the different actors associated with the various phases of the life cycle of the aquatic system.

The normal functioning of a watercourse is defined by a balance between morphological (flow patterns, sediment transport, etc.), granulometric (size and composition of sediments), physicochemical (oxygen level, temperature, etc.) and eco-biological (fish, macroinvertebrates, riparian zones, etc.) factors (Gregory, 2006). The main objective of rehabilitating a river must be to avoid stressing its fragile equilibrium while facilitating the cohabitation with its riverside communities (populations, agricultural lands, urbanised areas, etc.) or its users (farmers, stockbreeders, fishermen, energy users, promoters or protagonists of sports, 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. It has undergone years of sediment extractions which led to a strong hydromorphological imbalance that is disturbing the normal functioning of the watercourse at this are, if we refer to the definitions above. After a major flood event that occurred in June 2013, the lake is almost completely filled with sediments. This may lead to river avulsion in the direction of populated areas and thus increase safety risks. In addition, the weirs caused a sediment discontinuity that led to sediment deficit and thus channel shrinkage downstream that is provoking serious ecological damages and navigation problems.

The aim of this article is to present an attempt to apply a Participatory Modelling (PM) approach with the help of Bayesian Networks (BNs) in order to define restoration scenarios for the "Lac des Gaves" reach. We first tried to unravel the main mechanisms that led to its current situation with the help of local stakeholders coming from different backgrounds to be able to cover the various disciplines involved in this project.

This paper will be divided in 6 parts. In Section 2, we will present the modelling framework ant the methodology, then in Section 3, we will introduce the study area. In Section 4, we will present how we implemented the methodology to the "Lac des Gaves" case study. After that, in Section 5, we will present the results of one of the developed models related to safety issues. We will end this article by a discussion (Section 6) on the advantages and drawbacks of this approach.

2. MODELLING FRAMEWORK

2.1. Collaborative context

As presented above, the search for restoration solutions takes place in a multi-criteria framework that links the needs and constraints of the numerous stakeholders involved. Besides, it also considers a transdisciplinary context that is illustrated by the various disciplines likely to bring knowledge to the definition of operational and sustainable solutions for the "Lac des Gaves" reach. We had first to identify them in order to target the right stakeholders to involve in the study. 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. This can be related to transdisciplinarity, that 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. This notion of transdisciplinarity is fundamental to the approach that we consider. In fact, 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, 2019).
This project considers one of the key aspects of transdisciplinarity, as it involves stakeholders in the search for 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 task. It can require the joint consideration of cognitive, technical, social, economic, organisational, temporal aspects, etc. The consideration of a collective effort can be a response to the complexity of this task. The identified actors 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 collaboration 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

There are various ways of organising such a PM approach and several types of models can be constructed. However, the main 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 forges a common understanding of the system, the problems and the solutions.

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 multiple studies (Carr, 2015 ; Heldt, *et al.*, 2016 ; Hemmerling, *et al.*, 2019 ; Jordan, *et al.*, 2018). Even if we agree on the notion of distinction between Collaborative Modelling and PM Basco-Carrera *et al.* (2017), 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 all 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. BNs as a supporting tool

To overcome the problem of uncertainty handling, we have highlighted that the PM approach has to be instrumented with some tools capable of combining all the possible forms of uncertainties, while providing a supportive framework for the expression of the various stakeholders. For this particular reason, we decided to use BNs. BNs are a modelling tool based on a graphical structure (Fig. 1) and probabilities for the representation of causal relationships among variables (Cain, 2001; McCann *et al.*, 2006). BNs are graphical models designed to formalise 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, characterised by probabilities of occurrence, and a series of observations representing the actual state of the system (Yassine, *et al.*, 2018; Liu, *et al.*, 2016; Villeneuve, *et al.*, 2011).

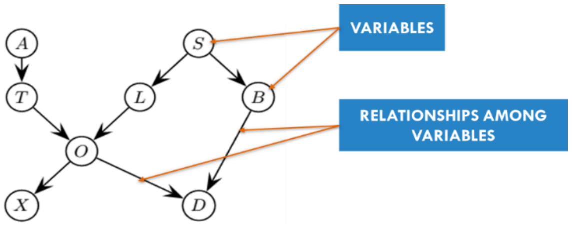

Fig. 1: Example of a BNs structure

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.

2.4. Methodology

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 approach was carried out considering the following steps:

1. **Problem formalization.** It is important to properly characterize 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 definition of the problem can be challenged or modified at the very beginning of the analysis by the various stakeholders once they have been identified.

2. **Stakeholders' identification.** This refers to all individuals and organizations that have something to do with the project. Either they are directly involved in the execution of operations, or they are impacted by the initial problem, or event by the choice of solutions. 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 and (ii) characterizing their level of expertise. The identification of the parties involved must be followed by a stakeholder management plan based on their profile. For some of them, communication tasks have to be planned: detailing the objectives and the chosen method, informing about the progress of operations, preventing a probable risk, the difficulties encountered... Finally, it is advisable to assess the impact and/or support of each party using a power/interest matrix (Fig. 2). This representation provides a synthetic vision of the stakeholders to be taken into account as a priority as well as the type of associated action.

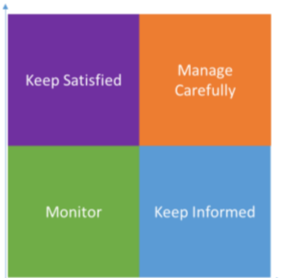

Fig. 2. Power/interest matrix of stakeholders

3. **Definition of the goals to be achieved.** A proper definition of the purpose of the project is a fundamental element for its success. Precise objectives must be set with the stakeholders, in particular: the context, not only the definition of the problem and the objectives but also the reason why this project was initiated and the goals pursued, the constraints and requirements, the deliverables and expected results, the tools and indicators for the results evaluation.
4. **Send surveys and questionnaires to the stakeholders.** This operation must be performed prior to the meetings. The aim is to collect their raw opinion and assess any kind of evolution by the end of the process.
5. **Constitution of working teams.** When there is more than one representation in a given category, an interesting option would be to assign the participants to small groups. The two advantages of this initiative are: (1) working in small groups can be more "manageable" and give the opportunity to all the participants to express their opinion while it can be complicated if the group is too big, (2) it can be interesting to collect the opinion of two participants representing the same category to verify if there are variabilities in perceptions inside of the same category.
6. **Definition of a meeting planning.** The first phase is to divide the project into several stage by the identification of all the tasks to carry out, estimate their duration, identify the sequence of stages, allocating resource and finally modeling this organization on an operational document shared by all the actors involved.
7. **Implementation of the collaborative analysis.** Stakeholders implication can be viewed as an expert elicitation process. Several elicitation protocols have been developed. They generally involve the following steps: (1) explain the nature of the problem and be aware of possible biases due to subjective judgments; (2) specify the elements to be identified or the quantities to be estimated; (3) discuss the state of the available knowledge (strengths and weaknesses of the available data, knowledge gaps, qualitative uncertainties, to name a few); (4) elicit the expertise and verify its correct formalization; (5) decide how to aggregate the knowledge elicited from the stakeholders. In our case, these steps will be implemented as follows:
   - *7.1. Establishment of the key variables.* This analysis can be performed according to (1) a top-down logic starting from the input variables and the explanation of their influence on variables at a lower level, or (2) a bottom-up approach aiming at determining the upstream causes associated to the evolution of an output variable;
   - *7.2. Co-construction of a conceptual graphical model.* This qualitative step focuses on explaining the physical mechanisms. According to the same collaborative principles and once the variables have been identified, the experts may then be asked to group them into families and establish the nature of the causal relations they have with each other;
   - *7.3. Translation of the graphical model into a BN.* The values that can be taken by the variables must be characterized. A continuous variable can be represented by a probability distribution associated to the different values in can take. When the variable is discrete or when the probability distribution is not defined, it is easier to discretize the variable into classes also called modalities;
   - *7.4. Estimation of the variable parameters.* Every variable in a BN has a probability table. When the variable has no parent, the definition of the table will be through marginal laws. When it 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. **Elaboration of the scenarios.**

3. STUDY AREA

The Gave de Pau watershed (Fig. 3) located in the western Pyrenees was severely impacted by a large flood in June 2013. This event have 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 (Fig. 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

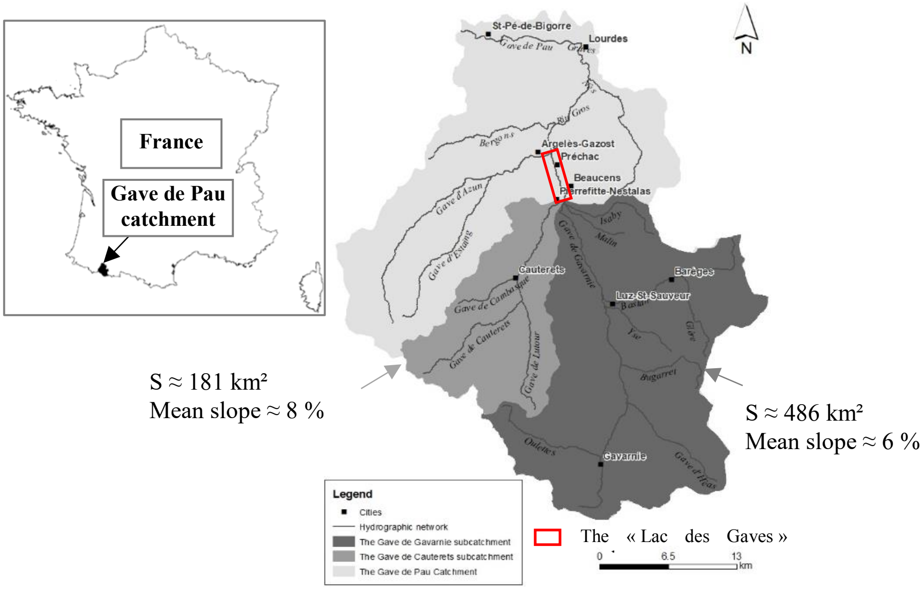

Fig. 3. Presentation of the Gave de Pau catchment and its main upstream subcatchments: the Gave de Cauterets and the Gave de Gavarnie subcatchments

lower than the bed elevation. There is thus a need to come up with an efficient and sustainable restoration solution for this complex reach.

4. MODEL ELABORATION

4.1. 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 approach helped to understand the physical aspects that influence the watershed and hence the study area with precision, 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. Of course, all the data acquired thanks to the physical analysis will serve the PM approach by feeding BNs with reliable data representing the real hydro-morphological characteristics of the study area. Participatory modelling approach. All the steps regarding the implementation of the PM method are developed in the following sections.

4.2. PM approach

Step 1 – Problem formalization

The physical approach helped identifying helped at defining the problem from a hydromorphological dysfunctional point of view. The main physical impairments were identified by comparing the current morphological configuration of the study area to a reference state, considered as the most natural functional condition of the river. 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 were 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.

Step 2 – Stakeholders identification

We selected the participants in such a way that most of the fields involved in the project would be covered. 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 as the number of divergent opinion is likely to rise but the knowledge and the relevant ideas may increase as well. The challenge is then to try to find a consensus.

Five categories of stakeholders were represented (Table 1).

Step 3 – Definition of goals

The general problem of the research project can be defined as the evaluation of the potential efficiency of a functional and sustainable river restoration project. Moreover, the organization of the various sessions devoted to PM lead to the creation of a model for the definition of a functional restoration scenario for the Lac des Gaves. To do so, the participants were in charge of the elaboration of causal graphs translated after into BNs that allow a probabilistic quantification related to the potential consequences of each solution.

Step 4 – Send surveys and questionnaires to the stakeholders

Before the beginning of the process, we sent a survey to all the participants to collect their raw opinion prior to the PM approach. The aim is to assess any kind of evolution by the end of the process. We also wanted to understand their perception of the problem and the relevant restoration measures according to their opinion.

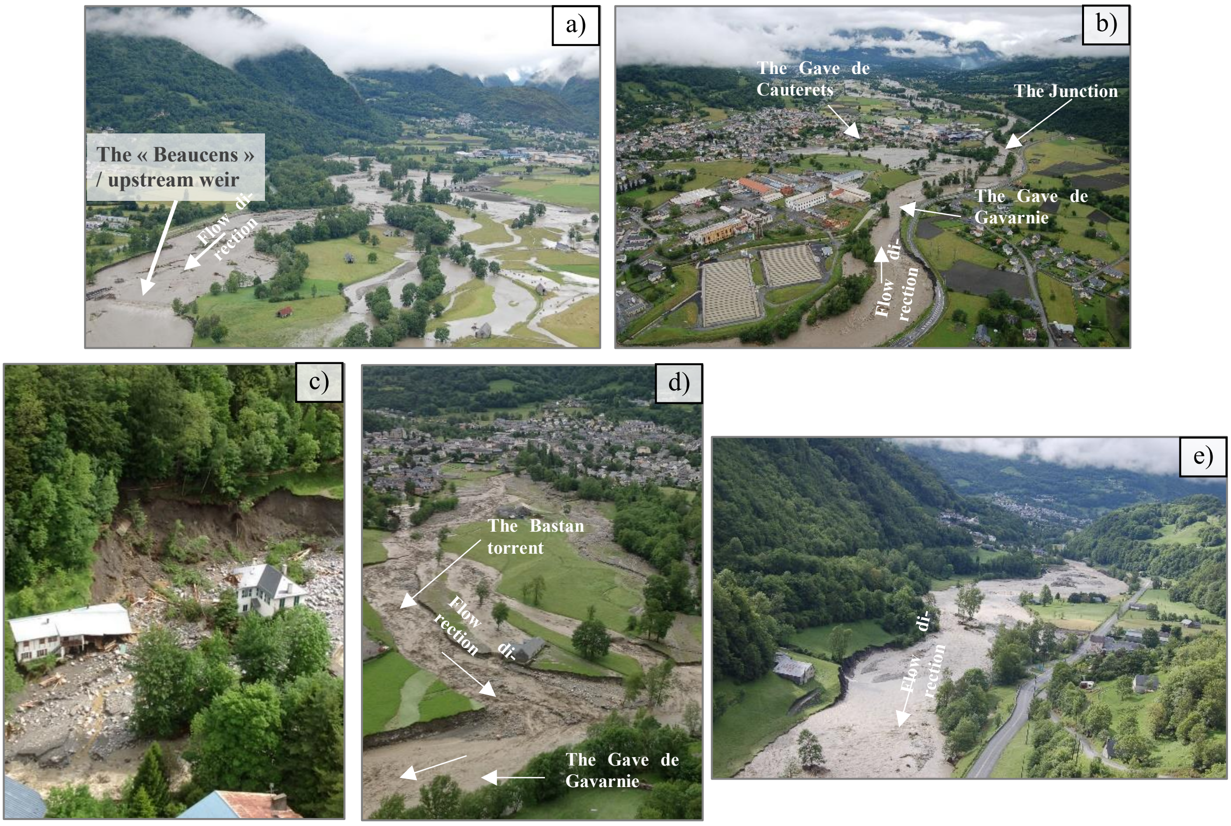

Fig. 4. Some examples of damages caused by the flood of June 2013 at different locations and different streams.

The questionnaire was divided in the following categories:

1. General information about the participant;
2. General knowledge about the study area;
3. Survey on ecological and sediment continuity;
4. Description of the individual or collective uses of the river reach (agriculture, fishing, and tourism).

Step 5 – Constitution of working teams

We separated the participants in three groups not only to facilitate exchanges and consensus building, but also to compare the results obtained by each team for the same restoration scenario (Table 1). The five categories were represented in each group when possible.

Table 1: 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

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.

Step 6 – Definition of a meeting planning

The planning of the PM process was established as follows:

1. Workshop n°1: identification of the key variables that can influence the system;
2. Workshop n°2-3: co-construction of a conceptual graphical model linking all the variables;
3. Workshop n°4: translation into a Bayesian Network;
4. Workshop n°4: filling of the Conditional Probability Tables (CPTs) with the stakeholders;
5. Elaboration of scenarios and modelling.

Step 7 – Implementation of the collaborative analysis

Step 7.1 – Establishment of the key variables

The first workshop was about the identification of all the variables related to the considered system and likely to have a meaningful influence. Each participant had to write on a post-it all the relevant variables that, according to his own experience and state of knowledge, might influence the system. Each variable could be quantitative or qualitative. The research team was there to facilitate the workshop, guide the participants if needed and help them from a technical point of view. A paperboard was disposed in the middle of the room and divided in four categories: (1) Security of goods and people; (2) Ecological and sediment continuity; (3) Economic factors; and, (4) Social factors. This classification gave more clarity to the participants as they were able to visualize the connections among the different variables. Each participant presented his selection of variables and explained to the audience how, in his opinion, each variable interacted with the system. He was then invited to stick his post-it in the adequate category. Discussions were then engaged among stakeholders for a limited amount of time and each participant had the possibility to review his list of variables.

Some participants did not clearly come up with variables but more with problems observed on the ground. Even though this information was very interesting and complementary to our physical knowledge, it had to be translated into qualitative of quantitative variables. This work was achieved between the first and the second workshop. Duplicated variables were deleted and the final list was divided in five categories associated to a colour: (1) Decision in orange, (2) Costs in purple, (3) Causes in red, (4) Physical in blue, and (5) Effects in green.

Step 7.2 – Co-construction of a conceptual graphical model

The final list of the variables and their definition was provided to all the participants in label forms from different colours in accordance to the five categories mentioned in step 5. A causal graph for each group of stakeholders representing their perception of the system depending on a restoration action, was elaborated. In some cases, even information to integrate in CPTs was provided. The research team was here mainly to 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 audience on a paperboard. At this stage, loops and retroactions were allowed.

Table 2: Proposed restoration scenarios

Code	Name of the scenario	Description	Restoration measures
S1	Business As Usual (BAU)	Current conditions	No intervention
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)
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

Step 7.3 – Translation of the graphical model into a BN

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 conceptual model elaborated allowed feedback loops whereas BNs are Directed Acyclic Graphs (DAGs) that cannot handle these kinds of retroactions. After the second and the third workshop, the research team worked on the transformation of the collected conceptual graphs into BN graphs by removing all the loops and retroactions while trying to not change the structure and the meaning of the graphs. The three networks were merged. To keep a reasonable number of combinations for direct elicitation and reduce the computational time, 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 distorted.

Step 7.4 – Estimation of the variable parameters

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 CPTs 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. Socioeconomic variables were defined through discussion with the stakeholders.

The final probabilistic BN for the assessment of the security of goods and people was implemented in Netica (©Norsys Software Corp.) (Fig. 5). 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 encode 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 affect them, and finally, (3) the decision maker's preferences over the possible outcomes of the decision making process. In the present case study, the decision node was attributed to the restoration decision and the utility node to the related costs.

Step 8 – Elaborate scenarios

Restoration scenarios were elaborated with the stakeholders (Table 2). Several scenarios were defined from the worst (in terms of negative impacts) to the best (in terms of positive impacts).

5. RESULTS

The results are presented only for the assessment of the security of goods and people criterion. The final probabilistic BN is presented in Fig. 5. 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 2) are summed up in Table 3 and discussed in the discussion part.

6. DISCUSSION

In this paper, we focused mainly one model representing the impacts of a given restoration scenario on the safety of goods and people. Of course, the obtained results must be replaced in a more global context integrating the other dimensions involved in this project (socio-economic, ecological aspects, etc.) associated with the other developed models. We studied three scenarios (Table 2) 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.

After running the model, the TRW 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

Table 3: Comparison of the impacts of the three different 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

the ground if we consider this scenario. This was very appreciated by some stakeholders as it was shown that it has a positive influence from an environmental perspective as well. The safety results were considered good enough for this scenario (40.2%). However, from a practical point of view, this may seem relatively simplistic if other complementary measures are not carried out. Bank protection measures would, for example, make it possible to avoid severe geomorphological problems (erosions, depositions) before the desired equilibrium is reached. Besides, this scenario appears to be the most expensive one (1 500 000 €) which can make its implementation questionable. For the WL scenario, we only considered the downstream weir intentionally as this was the stakeholders' preferred scenario at the beginning of the workshops. 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, the developed model does not take into account the time component. Thus, 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. CONCLUSION

Knowing the diversity of criteria, stakes and the multi-scale aspects to be taken into account, a river restoration project is constrained by various uncertainties. 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. Our work addressed the problem of selecting the best strategies for the restoration of a river damaged by various pressures. It was very important to spend enough time identifying all of the possible impacts of a given measure and understand the role of each variable in the modification of the studied system. For this reason and because of the large number of variables the BNs were chosen as modelling tools.

The methodology and first outcomes of the hybrid modelling presented in this paper are based on the "Lac des Gaves" 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. Three restoration scenarios were established with the participants and were simulated using BNs. For the security of goods and people criterion, it turned out that the best scenario concerns the removal of the two weirs. However, besides the fact that this scenario is the most expensive one, it 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.

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. An approach based on PM can be applied in such kind of projects was proposed and what benefits can be drawn from it. We 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.

8. REFERENCES

Antunes, P., Santos, R., & Videira, N. (2006). Participatory decision making for sustainable development—the use of mediated modelling techniques. *Land Use Policy, 23*, 44-52. doi:https://doi.org/10.1016/j.landusepol.2004.08.014

Cain, J. (2001). Planning improvements in natural resources management: Guidelines for using Bayesian networks to support the planning and management of development

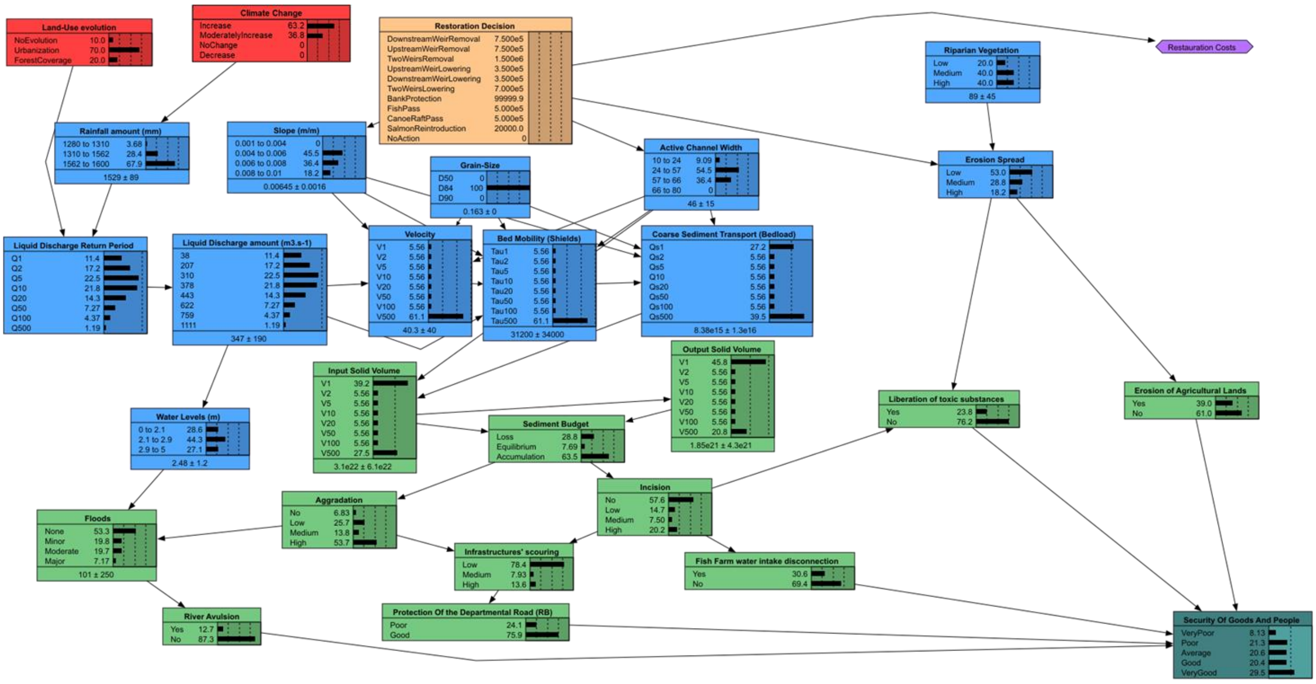

Fig. 5: Final probabilistic BN for the assessment of the security of goods and people

programmes in the water sector and beyond. *Centre for Ecology and Hydrologt, Crowmarch Gifford, Wallingford, UK*.

Carr, G. (2015). Stakeholder and public participation in river basin management—an introduction. *WIREs Water, 2*, 393-405. doi:10.1002/wat2.1086

Gregory, K. J. (2006). The human role in changing river channels. *Geomorphology, 79*, 172-191. doi:https://doi.org/10.1016/j.geomorph.2006.06.018

Heldt, S., Budryte, P., Ingensiep, H. W., Teichgräber, B., Schneider, U., & Denecke, M. (2016). Social pitfalls for river restoration: How public participation uncovers problems with public acceptance. *Environmental Earth Sciences, 75*, 1-16.

Hemmerling, S. A., Barra, M., Bienn, H. C., Baustian, M. M., Jung, H., Meselhe, E., . . . White, E. (2019). Elevating local knowledge through participatory modeling: active community engagement in restoration planning in coastal Louisiana. *Journal of Geographical Systems*.

Jordan, R., Gray, S., Zellner, M., Glynn, P. D., Voinov, A., Hedelin, B., . . . Group, N. S.-E. (2018). Twelve Questions for the Participatory Modeling Community. *Earth's Future, 6*, 1046-1057. doi:10.1029/2018EF000841

Liu, Q., Tchangani, A., & Pérès, F. (2016). Modelling complex large scale systems using object oriented Bayesian networks (OOBN). *IFAC-PapersOnLine, 49*, 127-132. doi:https://doi.org/10.1016/j.ifacol.2016.07.562

Livet, P. (2019). Promoting and Experimenting with Interdisciplinarity. In *Methods and Interdisciplinarity* (pp. 1-21). John Wiley & Sons, Ltd. doi:10.1002/9781119681519.ch1

McCann, R. K., Marcot, B. G., & Ellis, R. (2006). Bayesian Belief networks : applications in ecology and natural resource management. *NRC Research Press*.

Roux, H., Labat, D., P.-A Garambois, J. C., & Drtus. (2011). A physically-based parsimonious hydrological model for flash floods in Mediterranean catchments. *Natural Hazards and Earth System Sciences*.

Schneider, F., & Rist, S. (2013). Envisioning sustainable water futures in a transdisciplinary learning process: combining normative, explorative, and participatory scenario approaches. *Sustainability Science, 9*, 463-481.

Smetschka, B., & Gaube, V. (2020). Co-creating formalized models: Participatory modelling as method and process in transdisciplinary research and its impact potentials. *Environmental Science & Policy, 103*, 41-49. doi:https://doi.org/10.1016/j.envsci.2019.10.005

Villeneuve, E., Béler, C., Pérès, F., & Geneste, L. (2011, 5). Hybridization of Bayesian networks and belief functions to assess risk. Application to aircraft deconstruction . *International Conference on Industrial Engineering and Systems Management (IESM 2011)*. Metz. Retrieved from http://oatao.univ-toulouse.fr/6621/

Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software, 25*, 1268-1281. doi:https://doi.org/10.1016/j.envsoft.2010.03.007

Yassine, R., Pérès, F., Roux, H., Cassan, L., & Frysou, O. (2018). A Bayesian network approach to study hydromorphological modifications over space and time in the framework of a sustainable river restoration project: the "Lac des Gaves" case study. *IFAC-PapersOnLine, 51*, 7-12. doi:https://doi.org/10.1016/j.ifacol.2018.06.191