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A DSS FOR RISK MANAGEMENT ON DRINKING WATER INFRASTRUCTURES DURING EXTREME EVENTS

Extended abstract

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Background

The safety of drinking water infrastructures is fundamental for economic, social and sanitary reasons, and should be guaranteed both during ordinary service and in case of emergencies. Besides verifying and preventing deterioration and ageing, the response of the system to extreme events should be also carefully analyzed. As a matter of fact, depending on the level of preparedness that water system authorities have adopted, the restoration of system functionality may require days, weeks, or even months.

Water supply systems are vulnerable towards several hazardous events, which can be mainly classified as natural (such as earthquakes, hurricanes, volcanic eruptions, landslides, fires…) or anthropic (both intentional and accidental, such as pollution, operational mistakes, black-outs etc.). Referring to the potential consequences of such events on the system, physical damages consisting in breakage or malfunctioning of one or more elements of the network, should be distinguished from water contamination.

A research activity is being developed by the *Water Research Institute of the National Research Council* (Istituto di Ricerca sulle Acque del Consiglio Nazionale delle Ricerche IRSA-CNR), supported by the *Italian Department of Civil Protection* (Dipartimento della Protezione Civile - DPC), with the aim of defining a strategic Decision Support System (DSS) for efficient and coherent decision-making in case of threats involving drinking water infrastructures. The DSS is based on Bayesian Belief Networks (BBNs), a semi-quantitative probabilistic tool particularly useful for managing emergency situations, characterized by time shortness and information uncertainty. It should be mainly used for detecting potential shortcomings of the system during emergencies, but also for helping water authorities in defining priorities of action, even with reference to ordinary management procedures.

In the following, the methodological approach adopted is firstly presented, with specific reference to the main features of BBNs. Then, the structure of the methodology is described in synthesis. At last, the applicability of the tool is discussed, referring to a couple of real case studies developed with the cooperation of Acquedotto Pugliese S.p.A., an Italian water authority.

Materials and methods

Several risk-vulnerability assessment methods were proposed to investigate the behavior of water supply systems (see for example Rosén et al, 2007; Beuken et al., 2008; Hokstad et al., 2009), although there is a certain lack of operative procedures (Ezell, 2007). Within the framework of available risk management methods, BBNs are identified as effective tools, useful to build a DSS to help in decision processes and in supporting analysis of the consequences of operative choices (Cain, 2001).

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A Bayesian network is a DAG (Directed Acyclic Graph) mainly consisting of three elements, namely "Nodes", "Links" and "Conditional Probability Tables". Nodes are basically the system variables, each one characterized by a set of possible states. Links define causal connections between nodes. When a node has no links from any other variable it is named "parent" and defines an input variable; the destination node of two or more links is termed "child" node. Conditional probability tables (CPTs), quantify the strength of a link through Bayes' theory, and represent the probability of a child node being in a particular state, given the states of its parents.

The most relevant technical features that make BBNs particularly useful for risk-vulnerability analysis (Aguilera et al., 2011) are the combination of qualitative and quantitative aspects, the possibility of reversal inference (from results to causes) and the easiness in getting the ranking of influencing factors, the strong learning ability, the combination of data with domain knowledge; the prediction accuracy even with rather small sample sizes. However, one of the main advantages in adopting BBNs in the water management field is the possibility of integrating different kinds of variables, and several categories of data, information and sources of knowledge.

In the present activity, the knowledge of a group of local experts, both hydraulic structures designers and academics/researchers working in the field of water management, was collected, and represented a basis for model building. Semi-structured interviews were held individually, and aimed at eliciting a broad range of knowledge with a minimum number of interviews.

Model description

The proposed model is based on the definition of different BBNs for each subsystem of a typical drinking water infrastructure, with respect to the occurrences that may potentially affect its functionality. Structural, operational and environmental information are required for compiling the BBNs, and input data can be attributed through GIS functions, or directly inserted by the user. For this purpose, geographical databases as well as data provided by water authorities should be joined and integrated.

Considering the typical structure of a drinking water infrastructure, the following subsystems were included in the vulnerability assessment procedure: a) Water source; b) Intake structures (Wells; Wellspring intake; Dams; River intake); c) Treatment plants; d) Water mains; e) Tanks and storages; f) Pumping stations; g) Control systems; h) Urban distribution networks.

Two hazard classes were considered: a) Physical hazards, associated to the potential damage of infrastructural elements determining limitations on water quantity; b) Chemical, Biological, Radiological (CBR) hazards, connected with the possible contamination of the resource and consequent quality problems.

The most influential variables for each sub-system, with respect to the hazard classes considered, were then detected, and their nature (continuous/discrete, deterministic/probabilistic) also determined at this point. Possible 'states' of these variables were also identified. The graphical conceptual structure was developed at this stage, and the specific role of the variables as well as their reciprocal influence expressed through causal links. A qualitative judgment on the strength of correlations and dependencies between variables was proposed by experts and, when available, integrated with literature results.

The structure of the model is mainly based on expert knowledge, and is therefore affected by a certain subjectivity. The procedures of formal network validation, as well as its calibration, mainly involving the values in CPTs, are fundamental for providing the system with an effective predictive capability. As a matter of fact, once outlined the structure of the model, feedback sessions were also held, involving experts, to ensure that the system had been correctly modeled. The development of real case studies also helped in verifying the applicability of the tool in case of specific occurrences, and the correctness of results. Sensitivity analysis helped in quantifying the specific role attributed to each input variable with respect to the target variable too.

Basically, two BBNs (for physical and for CBR hazards respectively) were developed for each subsystem of a drinking water infrastructure, in order to define a complex probabilistic vulnerability assessment tool from source to tap. An integration between Netica™ software (used for developing BBNs) and GIS tools, for optimizing data transfer and management, was performed and a user-friendly interface is currently being developed. Such integration is particularly helpful with the aim of developing a dynamic vulnerability mapping tool, able to update information from regional databases and to provide a graphical localization of criticalities and weak points in the water supply system.

Model application

The model validation and calibration is being carried out, with the support of Italian DPC and the co-operation of local water authorities. Particularly, there is a scientific agreement between IRSA-CNR and Acquedotto Pugliese S.p.A. (AQP S.p.A.), the local water authority in Puglia region. Different case studies were selected and are being analyzed in order to verify the efficiency of the proposed methodology. In the following, the results of two case studies are summarized.

The first one refers to the Ofanto Aqueduct, one of the most important water mains in Puglia, highly conditioned by landslide phenomena. It has an overall length of approximately 100 km, and is designed for a maximum discharge of 6.5 mc/s. It is made of steel pipes having 2400 and 2000 mm diameter, 20 mm thickness and

16 m long bars. Several damages exist, mainly induced by landslides, and therefore maintenance activities are scheduled and real time monitoring procedures have been already introduced.

The second case study refers to another fundamental drinking water infrastructure in Puglia, namely the 'Canale principale'. It is a gravity water main made of brick laid with cement mortar and designed for a discharge of 6.5 mc/s. Its overall length is approximately 245 km with several segments in tunnels. Designed and built starting from the early 1900s, it is currently the most important drinking water infrastructure in Puglia, although several hazards (mainly a severe earthquake in 1980s) have threatened its functioning in different sections.

Structural information provided by AQP S.p.A. as well as geographical and environmental data available through regional databases, were used to insert input variables. Infrastructural information were provided partially in digital form and partially as hard copy. Regional data were instead available in digital form, mainly through online Web GIS platforms, from local authorities and institutions.

The main results of the case studies are summarized in the following Fig. 1, showing the probabilistic value associated with the state 'high' of the 'breaking vulnerability' variable.

Conclusions were discussed with AQP S.p.A. technicians and model predictions were found to be coherent with the real damage situation. Furthermore, other 'high vulnerability' areas were detected through the model, and thus areas where further analyses should be addressed were identified. The situation of such areas was investigated in details and it was found that several of these sections experienced severe corrosion damages, and that the local influence of environmental conditions has been never carefully taken into account.

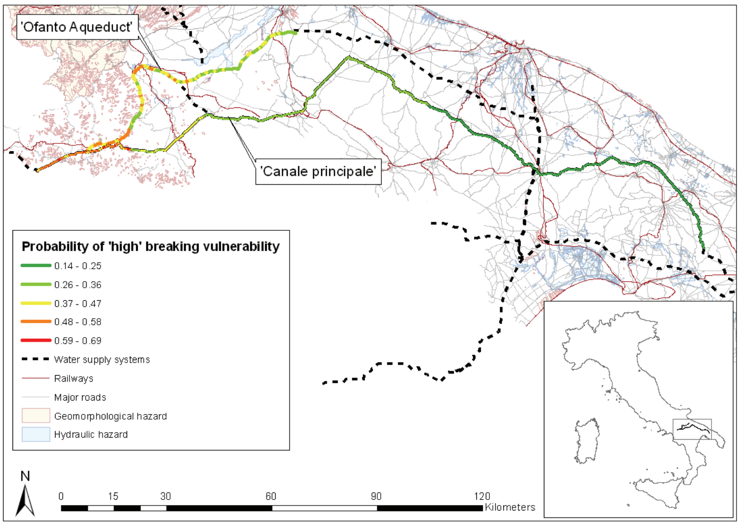

Fig. 1. Results of the case studies

Discussion

The probabilistic vulnerability model briefly described in the present work, was developed in order to support decision-makers during emergencies associated with drinking water networks. Its implementation in real case studies revealed its usefulness and operative simplicity, as well as satisfactory predictive capabilities, although some practical difficulties and approximations emerged too.

The first issue is connected to knowledge acquisition and information reliability. It is worth to remind that the adoption of a probabilistic tool such as BBNs is particularly helpful in order to avoid weighty detailed computations, that may reveal difficult in emergency conditions. Furthermore BBNs allow the integration of different sources of knowledge such as scientific and experiential, revealing particularly useful when fragmented or uncertain data are available. Nevertheless, such feature also constitutes a significant modeling challenge, since knowledge collection and structuring is quite difficult. The phase of data processing may reveal also complex, since data from different sources, available in different form (digital or hard copy), having different nature (numeric or linguistic) and different reliability should be combined and manipulated. It could be therefore useful to develop a preliminary phase of data collection and structuring, especially by local water authorities.

The second issue to be considered is connected with the integration of the vulnerability analysis tool with an hydraulic model, able to support in the investigation of the effects of changes of water quality or quantity on the hydraulic regime of a network. An hydraulic modeling software, EPANET, was used accordingly. The introduction of such tool could reveal fundamental to model the potential effects of hazardous occurrences on hydraulic functionality, thus selecting the most suitable operative strategies. Feedback sessions held with both AQP S.p.A. and DPC technicians underlined the importance of developing a comprehensive DSS, integrating vulnerability, environmental and hydraulic considerations. A user-friendly interface is currently being developed, in order to simplify data transfer and processing through GIS, Netica™ and EPANET.

At last it is worth to notice that, despite the model was primarily developed as a DSS for emergency management, the interaction with technicians of local water authorities revealed another possible field of application. As a matter of fact the tool may be also used for optimizing repair/replace procedures and supporting technicians in scheduling ordinary maintenance, through the mapping of vulnerability and the definition of a hierarchy in operations and interventions needed.

Concluding remarks

The present work summarizes the first results of a research activity oriented to the definition of a probabilistic methodology for the vulnerability assessment of drinking water infrastructures under extreme events. The vulnerability model was developed through the adoption of BBNs. Such vulnerability model was integrated in a more comprehensive framework, including GIS tools and an hydraulic modeling software, in order to provide decision makers with and effective DSS.

In case of extreme events determining a physical damage of the infrastructure or a water contamination, the model should be able to identify the elements of a water supply system that are most likely to fail or being damaged, thus originating limitations in drinking water quantity and/or dangerous quality changes. Hydraulic scenarios should be also modeled, in order to help in correctly selecting operative strategies. Actually, the methodology is being still tested through the co-operation of both researchers and water authorities.

Keywords: Bayesian Belief Networks, Decision Support System, Drinking water infrastructure, Emergency management, vulnerability assessment

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