A SPATIAL DECISION SUPPORT SYSTEM TO OPTIMIZE INSPECTION, MAINTENANCE AND REPARATION OPERATIONS OF RIVER LEVEES

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ABSTRACT

More and more floods occurred over the last decade in France and in the world, causing important damages and significant costs. Moreover, levees are often not well maintained, so they hardly resist to major floods and can break easily.

At French national scale, the length of levees, estimated to 7500 kilometers, and the lack of data all along these infrastructures complicates their management. In this frame, levee managers need approaches and tools in order to be helped in their maintenance decision.

The goal of our research is to develop methods modeling levee failure mechanisms and allowing performance levee assessment. From collected data (detailed visual inspections, laboratory tests, historical data, etc.), we establish indicators able to assess levee condition and performance. These methods integrated in an existing GIS dedicated to levee management will contribute to obtain a spatial decision support system aiding levee managers in their maintenance decision.

Our communication presents in a first part the development of the "Levee GIS" and an example of its current functionalities. In a second part we describe the models that have been set up to assess levee performances and we describe their integration into a new prototype version of the "Levee GIS".

KEY WORDS

Levee, SDSS, GIS, Multicriteria Decision Aid, Model.

INTRODUCTION

In the world as well as in France we observe disastrous river floods. Due to the necessity of new construction, an increasing number of housing units are being built in river flood plains,

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which in turn increases the exposure to floods and their financial impact. Levees, many underdesigned and poorly maintained, have shown their weakness on many occasions. Breaching increases the power of flood waters and may worsen its effects (e.g. Mériaux et al. 2001).

A significant amount of information on levee design and past consolidation works has been lost because of their age and the failure of many owners to carry out rational maintenance. Furthermore, the aggregate length of French levees complicates such work. Owners and the regulatory agencies are fully aware of the importance of maintenance plans that are needed to bring the levees up to modern safety standards. But the mileage involved raises the thorny question of where to begin (e.g. Diab 2002). Owners have finite financial resources and it is important to optimize the money available for planning inspection and maintenance efforts.

To cope with these problems, levee managers need decision-making methods and tools. A Geographic Information System (GIS), named "Levee SIRS[5]", has been developed and is now used in practice within the levee management community (e.g. Maurel et al. 2004). It integrates numerous data about levees structure, networks, desorders as well as surrounding areas. This tool is described in the fist part of the paper.

Our research aims to improve this existing tool and incorporate methods for assessing levee performance[6]. The current goal is to make available a fully-fledged decision-making aid to levee managers for inspection, maintenance, and repair planning. This tool should help them to display and locate the most critical levee sections, which shall be upgraded and maintained in priority. The second part of the paper presents how the current "Levee SIRS" has been improved and the results obtained from a first test on a real levee.

A LEVEE GEOGRAPHIC INFORMATION SYSTEM

THE GIS DEVELOPMENT CONTEXT

Since 1995, Cemagref and several engineering offices have been asked by levee managers to develop and to test levee diagnosis and monitoring methods. Studies results allowed to design field observation protocols for levee diagnosis and to describe and follow-up the maintenance or repair works carried out on the levees.

In parallel, the French Ministry of Environment (Water Directorate) launched in 1999 an investigation to identify levees that protect inhabited places from river floods. Data to be collected relates to levees themselves (described however on a small scale), managing structures and protected area. Cemagref was largely involved in the design of data acquisition protocol and the "DIGUE" database software, support of the investigation. This census thus contributed to develop survey methods to collect relevant information for levee knowledge and management.

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5 SIRS: Spatial Reference Information System (Système d'Information à Référence Spatiale, in French language). We prefer use this acronym as GIS, often considered as a « simple » software application with no consideration of human, organisational and economic aspects of information systems.

6 Performance is defined as the aptitude of the structure to render the service for which it was designed (e.g. for levees: stand up to floods, not fail, protect areas on the landward side).

First works on the “Levee SIRS” started in 1998, upon the initiative of Cemagref, then gradually with other partners. Using a structured approach for analyzing and designing Information Systems (e.g. Rouzet and Labbé 1997), Cemagref financed and carried out a first study - called strategic diagnosis - by interviewing Loire and Vidourle rivers managers on their current practices and their expectations concerning a SIRS (e.g. Belouze 1999). At the end of this phase, it was decided to give the priority to a SIRS focused on the levees and the river bed, at a level of accuracy suited to local managers (1/5000° to 1/10000°). The SIRS should also be able to handle more accurate information (1:500 scale), but just in the form of documents and not of detailed geographic database.

Next step, started in 1999 and completed in 2000, was to assess, from a technical and a practical point of view, the interest of local managers for such a SIRS. With the support of the Ministry of Environment, Cemagref then developed a generic demonstration prototype, on the Cisse river valley in the Loire middle course, to help the managers better understand the potential of a SIRS and thus, better specify their expectations.

In 2001, two local levee managers, each of them managing approximately 250 kilometers of levees located respectively in Camargue and in Isère, joined the project to adopt this modern and innovative management tool.

On the basis of detailed terms of reference for a national call for tenders, a first version of the “Levee SIRS” application was developed and is now fully functional. This application is based on ArcGIS (© ESRI) and Access (© Microsoft) softwares. It intensively uses ArcGIS© dynamic segmentation capabilities to manage, analyse and represent punctual and linear levee informations. Moreover, feeding the SIRS with good quality and complete data was considered as one of the key conditions to make this tool usable by levees managers. A very detailed attention was granted to the field observation cards dedicated to the levee guards who are the main data providers. Our approach consisted in elaborating field survey cards as ergonomic as possible for an operational use in the field, independently from the software application, then to develop on this basis graphic user interfaces for data capture.

“LEVEE SIRS” USE-CASE EXAMPLE

We now present a concrete use-case example of the current “Levee SIRS” version that can be performed by levee managers. This example deals with disorders which can affect levees performances. A disorder is defined here as a defective behavior of hydraulic infrastructures from safety and performances point of view.

A manager walked through his levees portfolio and notes down all the visible disorders on specific field observation cards. The following information can be captured:

- disorder position on levee;
- its localization (either using a GPS, or by linear points of reference);
- disorder characteristics (burrows, vegetation, slope erosion...) while choosing in a preestablished list of possible disorders;
- a photograph of the disorder;

- various comments related to the description and the evolution of the disorder and possible management operations.

Once the levee data collection is completed in the field, an operator then enters data in the SIRS using digital forms, whose design is similar to the field observation cards. The next step, performed by the "Levee SIRS" administrator, consists of validating these new data before making them acessible to final users. Now, levee manager can exploite SIRS data. For example, he may wish to represent on a map the disorders that have just been entered in the database. For that, he just has to choose the topic he wants to represent in the SIRS cartographic application (Fig.1).

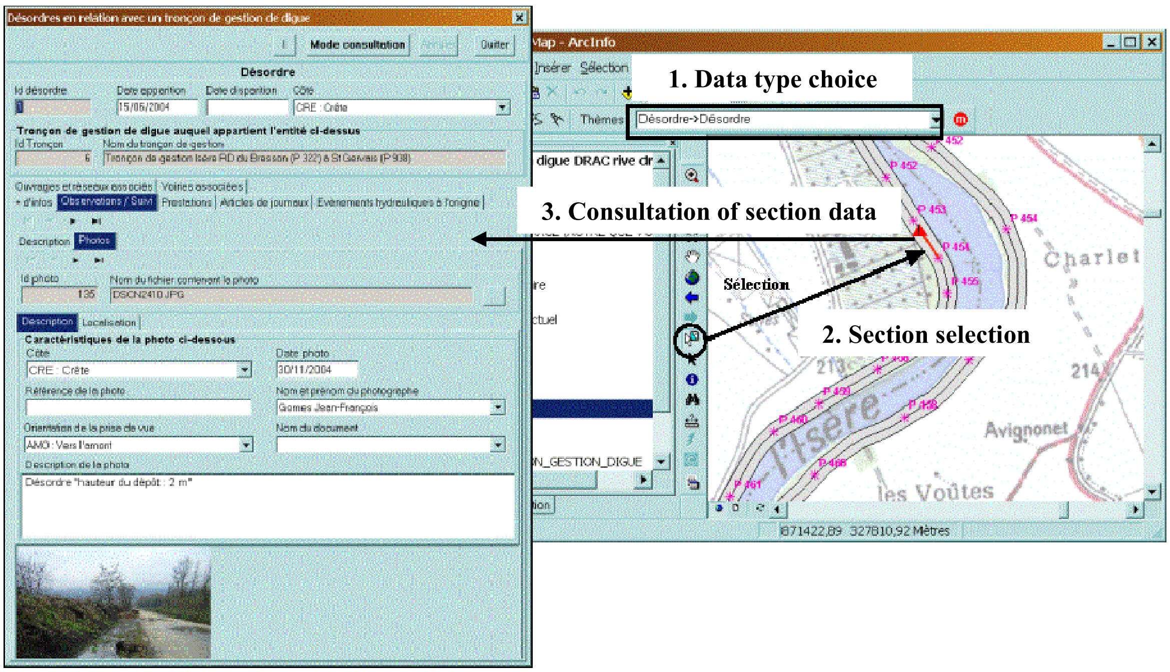

Figure 1: Disorder cartographic representation

In this example, the manager performed that operation between PR 453 and 454. Two disorders relating to the Isère river right bank levee are identified:

- a punctual disorder symbolized by a red triangle meaning "danger";
- a linear disorder symbolized by a red line in levee crest.

The manager can easily get all the information relating to these disorders by double clicking on a specific disorder using the selection tool surrounded on the figure above. By carrying out this operation, he obtains the digital form corresponding to this disorder.

SYNTHESIS

This GIS tool constitutes a significant progress within the framework of levee sustainable management. However the "Levee SIRS", at this time, does not really allow levee managers to optimize their maintenance actions. For that, new GIS functionalities have to be developed, in particular, to provide a synthetic vision of levees conditions and performance all along their length.

TOWARDS A SPATIAL DECISION SUPPORT SYSTEM (SDSS)

SDSS PRINCIPLES

Starting from the 1970's numerous Decision Support Systems (DSS) have been developed to support decision-making with expert knowledge. The most generally accepted definition of a DSS is the one articulated by Sprague (1986): "Interactive computer based systems, which help decision-makers utilize data and models to solve unstructured problems". A more detailed definition is the one provided by Turban (1990): "an interactive system, flexible and adaptable, which uses decision rules, models, databases and suitable formal representations of the decision-makers' requests to indicate specific and applicable actions to solve problems which cannot be solved by the optimisation model of Classical Operational Research. It thus assists complex decision processes and increases their efficiency."

It is usually recognized that a DSS is based on three components:

- a database management system which provides all the functionalities relating to data entry, storage, processing, results editing and exchange with other databases;
- a management system of analytical model database which provides a set of analytical relevant tools, necessary for interpretation and recommendations relating to data, and responding to decision maker needs;
- convivial and interactive user interfaces, which facilitate interactions between decision makers and the DSS.

But, because of the specificity of spatial issues relating to geographical localization, a Spatial DSS (SDSS) needs additional capacities and functionalities (Densham, 1991) for spatial data entry spatial analysis (Laaribi, 2000) and spatial editing in various forms, like maps and charts.

Thus, although innovative in the levee management context, the "Levee SIRS", in its current version, still needs to be enriched with spatial analysis functionalities, allowing levee performance charting, to become a real SDSS.

MODELS FOR LEVEE PERFORMANCE ASSESSMENT

A levee functionnal failure model

Our goal was to develop models able to assess levee performance. The fist step consisted in modeling levee failure mechanisms in the form of scenarios in order to obtain the information needed for assessing levee performance. The model shall include all the failure mechanisms relevant to all types of levees.

We used tools developed in the field of Operational Safety for modelling complex systems and representing the organic links between the sequences of failures in the structures (e.g. Zwingelstein 1996). The functional model representing the mechanisms is built up with the use of functional analysis and Failure Mode and Effect Analysis (FMEA) methods (e.g. Peyras 2003, Serre 2005).

We constructes levee failure scenarios by linking failure causes to failure modes, and then to failure effects. In this way, the failure mechanisms are modelled as series of functional failures representing the relevant physical processes (e.g. Pilarczyk. 1998) taking place within the system and leading to loss or deterioration of function. The scenarios are drawn as causal graphs; each mechanism is modelled in a directed graph describing the functional deterioration processes and sequence of corresponding variables (Fig. 2).

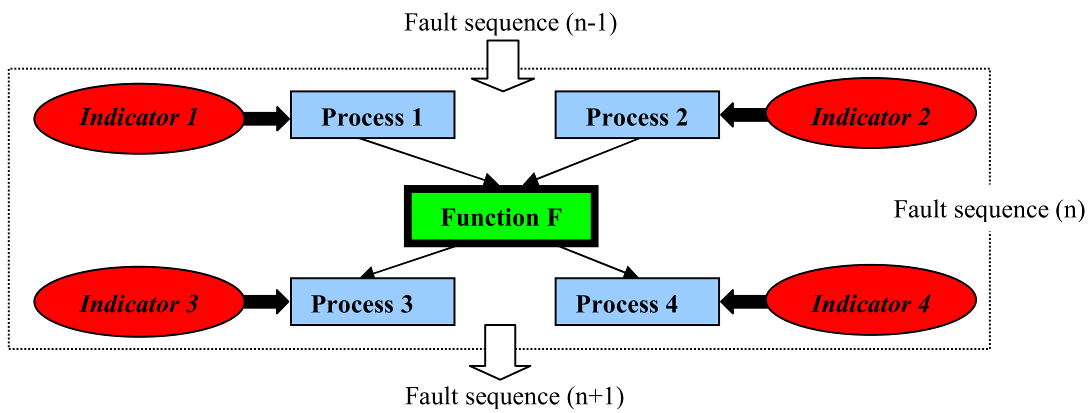

Figure 2: Failure sequence chart derived from FMEA (Peyras 2003)

The functional model representing scenarios includes three categories of variable: function variables corresponding to failure modes, process variables accounting for failure mode causes and effects, and indicator variables corresponding to the outward evidence of processes.

This kind of model offers multiple advantages. It provides a framework of expert knowledge in the form of functional scenarios; it organizes information on mechanisms around three categories of variable (function, process, and indicator) and can account for partial and progressive deterioration in the variables and non-chronological mechanisms.

A levee performance multicriteria assessment model

We focus now on the multicriteria method used to assess levee performance. We have chosen methods that allowed us, on the basis of the modelled failure scenario, to transform the information collected on the levees into scores reflecting the levee performance level.

The first stage of our work consisted in finding a method able to provide a levee performance assessment based on several criteria. Then, we determined indicators used to support the evaluation of each criterion, and to combine these indicators to give an assessment of each criterion (Fig. 3).

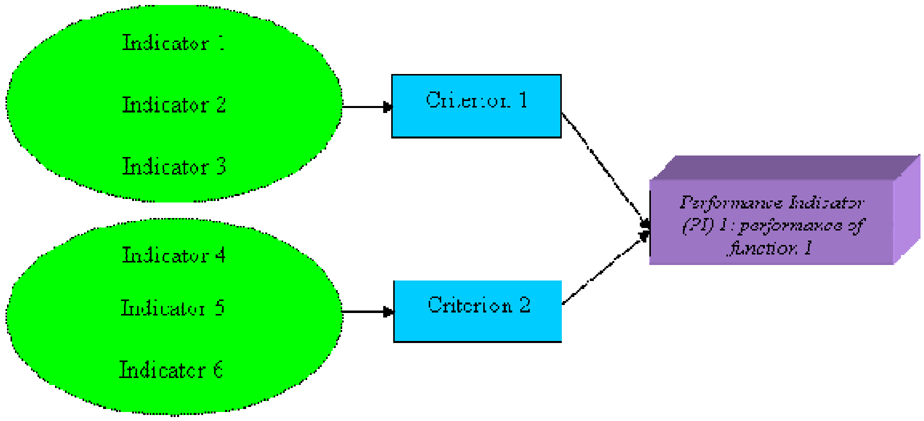

Figure 3: Hierarchy of indicators, criteria and performance indicators

We decided to use an interactive multicriteria method, named "assignment by rules establishment" (Azibi 2003), which alternates stages of calculations and stages of dialogue with the decision maker. This kind of method is well fitted to our complex context of aggregation. Rule-based aggregation consists of a set of "if … then" rules, close to natural language, to express the principles of aggregation (Tab. 1).

Table 1: Example of rules aggregation method (e.g. Serre 2005)

Conditions	Criteria	Scores	Failure mechanism	Performance score	Class assignment
if	Burrows in impervious upstream shoulder	7	Internal erosion of body of levee	9	« bad »
and if	Roots in impervious upstream shoulder	9			
and if	Scour in impervious upstream shoulder	6			
and if	Composition of in impervious upstream shoulder	5			
and if	Pipe through impervious upstream shoulder	7			
and if	Burrows in body of levee	10			
and if	Roots in body of levee	0			
and if	Potential seepage in body of levee	9			
and if	Pipe through body of levee	6			
and if	Composition of body of levee	7			

The condition part (if) concerns the levee assessments on a set of criteria and the conclusion part (then) indicates the total aggregate assessment. This method allows incorporating the preferences of field experts and explaining the synergies and compensations between criteria.

MODELS AND GIS INTEGRATION RESULTS

To integrate our models into the "Levee SIRS", we upgraded the SIRS database model to include all the indicators and criteria needed for each failure mechanism model, and we coded a performance calculation module (Prévot 2005). Then, we assessed the quality of the prototype from two perspectives: first, its ability to reproduce hydraulic infrastructure expert reasoning to assess levee performance as. Second, its ability to provide useful decision support to levee managers.

The prototype was tested on a 2 km levee located in the south of France, near Montpellier. We assessed the levee performance relating to internal erosion failure mechanism.

This operation consisted first in collecting field data on this levee. One day was necessary to gather data needed for performance calculation. The second phase consisted in entering data in the prototype and finally in executing the performance model calculation. A map of the levee performance was produced at the end of the procedure (Fig. 4).

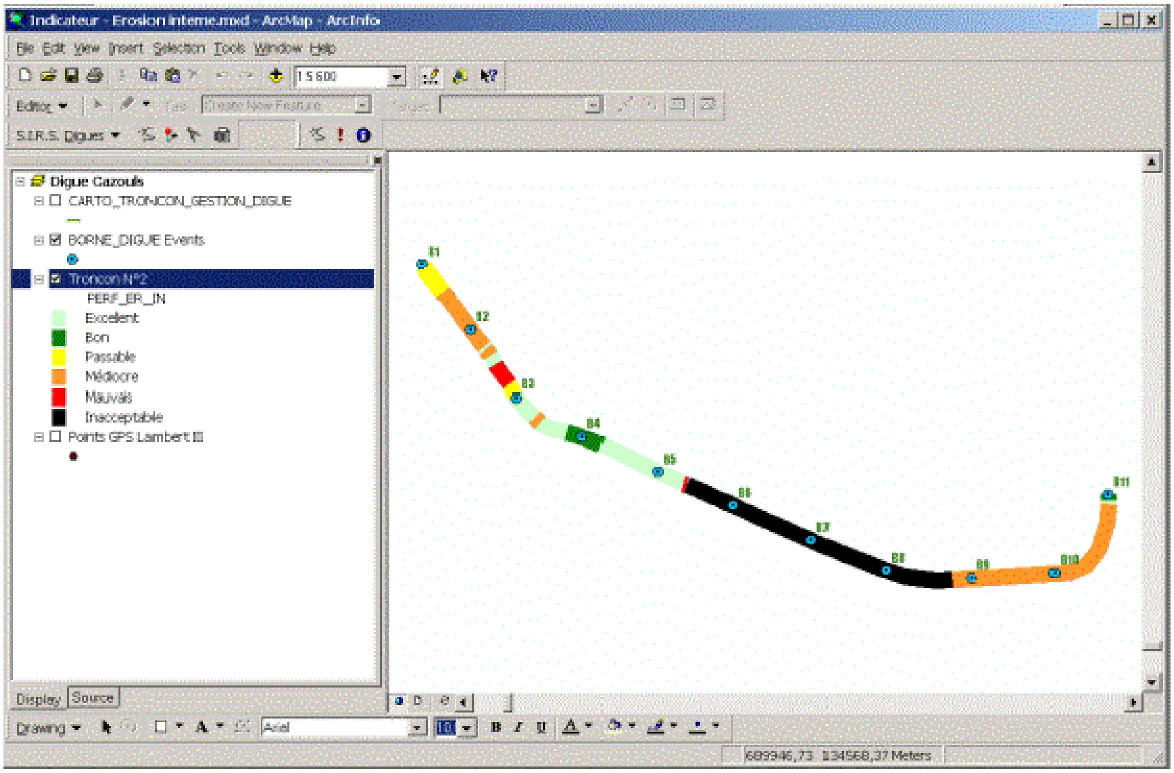

Figure 4: Levee performance map relating to internal erosion failure mechanism

This levee section was well known by several levee experts and reports describing levee performances relating to all failure mechanisms were available. The post comparison of the results obtained with these three approaches (SIRS model, existing reports, expert analysis) leaded to very similar conclusions. Even if these results are encouraging, it is too early to generalise them for all kind of levees yet. Additional tests have to be performed on other kinds of levees and other kinds of failure mechanisms.

About decision aid supplied to levee managers, the contribution of such a tool seems very promising. First of all, performance indicators values can be mapped in a very visual way in the GIS. Furthermore, the prototype allows users to retrieve all indicators and criteria which contributed to each section performance value. Our test also shown that the levee segments, homogeneous in term of performance level, were long enough from operational maintenance perspectives.

SYNTHESIS

Based on functional analysis and FMEA, we proposed a functional model able to represent levee failure mechanisms in the form of scenarios. Analysis of expert knowledge allowed us to assemble and to formalise all available information relevant to levee failure mechanisms. Then, we adopted a based-rules method to assess levee performance, from various indicators and criteria, for each levee failure mechanism. Finally, by integrating these models into the existing “Levee SIRS”, we obtained a SDDS able to supply to levee managers a synthetic view of their levee portfolio performance.

CONCLUSIONS

Our research aimed to produce a method for analysing levee performance and to integrate it into an existing GIS levee application. The work led to several results which made it possible to build up a SDSS prototype for levee managers.

The first stage of the work made use of Operational Safety methods: functional analysis, failure mode and effects analysis, and fault trees. These methods allowed to model levee structures, to understand the design functions of levees and their components, to identify failure modes, and to determine causes and effects. Taking into account all these informations as well as expert knowledge, we modelled as scenarios the most important levee failure mechanisms. In this way, we obtained for each mechanism the indicators and criteria needed for levee performance evaluation. In terms of results, we modelled the principal mechanisms leading to levee failure and determined, for each mechanism, the criteria needed to evaluate levee performance.

The next stage consisted of aggregating the indicators and criteria to evaluate levee performance. The approach used is a rule-based multi-criteria assignment method, combining discussions with a panel of experts and computational activities. In terms of results, this approach led to a set of criteria evaluation and aggregation rules for each failure mechanisms, ultimately leading to a synthetic evaluation of levee performance.

In order to provide levee managers with a practical working tool, we improved an existing GIS, the “Levee SIRS”, in which we incorporated the levee failure mechanisms model and the levee performance multicriteria evaluation model. The prototype is now operational and has been tested on a real levee, producing conclusive performance assessment results for that particular levee. In term of decision-making aid, such tool seems to be very promising for levee managers to determine levee performance and so to optimise their maintenance and repair scheduling. The “Levee SIRS” tends towards a real SDSS as defined by Densham (1991).

The next step related to the development of this SDSS will be to integrate the vulnerability dimension (critical facilities at stake in area protected by levee) and to match it with levee performance to better prioritise management actions.

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