Spatial Management of Risks
Spatial Management of Risks

Edited by
Gérard Brugnot
# Table of Contents

## Introduction

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2. GIS and public security</td>
<td>3</td>
</tr>
<tr>
<td>1.3. Examples of applications for public security</td>
<td>8</td>
</tr>
<tr>
<td>1.3.1. SIGASC application</td>
<td>8</td>
</tr>
<tr>
<td>1.3.2. Application</td>
<td>12</td>
</tr>
<tr>
<td>1.3.3. SIG CODIS application</td>
<td>15</td>
</tr>
<tr>
<td>1.4. Prospects for development</td>
<td>18</td>
</tr>
<tr>
<td>1.5. Conclusion</td>
<td>19</td>
</tr>
<tr>
<td>1.6. Bibliography</td>
<td>19</td>
</tr>
</tbody>
</table>

## Chapter 1. From Prevention to Risk Management: Use of GIS

Sophie SAUVAGNARGUES-LESAGE

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2. GIS and public security</td>
<td>3</td>
</tr>
<tr>
<td>1.3. Examples of applications for public security</td>
<td>8</td>
</tr>
<tr>
<td>1.3.1. SIGASC application</td>
<td>8</td>
</tr>
<tr>
<td>1.3.2. Application</td>
<td>12</td>
</tr>
<tr>
<td>1.3.3. SIG CODIS application</td>
<td>15</td>
</tr>
<tr>
<td>1.4. Prospects for development</td>
<td>18</td>
</tr>
<tr>
<td>1.5. Conclusion</td>
<td>19</td>
</tr>
<tr>
<td>1.6. Bibliography</td>
<td>19</td>
</tr>
</tbody>
</table>

## Chapter 2. Coupled Use of Spatial Analysis and Fuzzy Arithmetic:

Assessing the Vulnerability of a Watershed to Phytosanitary Products

Bertrand DE BRUYN, Catherine FREISSINET and Michel VAUCLIN

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Introduction</td>
<td>23</td>
</tr>
<tr>
<td>2.2. Construction of the index</td>
<td>24</td>
</tr>
<tr>
<td>2.3. Implementation of fuzzy calculations</td>
<td>26</td>
</tr>
<tr>
<td>2.4. Application to the watershed of Vannetin: vulnerability to atrazine</td>
<td>28</td>
</tr>
<tr>
<td>2.4.1. The research site</td>
<td>28</td>
</tr>
<tr>
<td>2.4.2. Parameters of the watershed</td>
<td>28</td>
</tr>
<tr>
<td>2.4.2.1. Pluviometry</td>
<td>28</td>
</tr>
<tr>
<td>2.4.2.2. Anthropogenic sub-index</td>
<td>29</td>
</tr>
<tr>
<td>2.4.2.3. Pedology</td>
<td>29</td>
</tr>
<tr>
<td>2.4.2.4. Summary of data common to the entire watershed</td>
<td>29</td>
</tr>
</tbody>
</table>
Chapter 3. Agricultural Non-Point Source Pollution

Philippe BOLO and Christophe BRACHET

3.1. Introduction ............................................ 39
3.2. Mapping non-point source pollution phenomenon . .......... 40
  3.2.1. Mapping principles ................................... 40
  3.2.2. Description of the research phenomenon ................. 41
  3.2.3. Mapping steps ....................................... 41
3.3. Territorial database building rules ........................ 42
  3.3.1. Choosing software programs ........................... 43
  3.3.2. Design of the implemented GIS ........................ 44
  3.3.3. Organizing and creating geographic information layers .... 46
    3.3.3.1. Implementation of a conceptual data model .......... 46
    3.3.3.2. Digitization of paper-based document ............... 46
    3.3.3.3. Digital data import ............................... 47
    3.3.3.4. Controlling the geographic data integrity .......... 47
  3.3.4. Organizing and creating attribute tables ............... 47
    3.3.4.1. Implementing a conceptual data model ............... 47
    3.3.4.2. Creating a data dictionary ........................ 47
    3.3.4.3. Thematic data processing or import ................. 48
    3.3.4.4. Controlling the attribute data integrity .......... 48
3.4. The data sources used .................................. 48
  3.4.1. Identifying the available information .................. 48
  3.4.2. Soil-related data .................................. 49
    3.4.2.1. Surface texture of the soils ...................... 50
    3.4.2.2. Soil hydromorphy ................................ 51
    3.4.2.3. Soil textural differentiation ..................... 51
  3.4.3. Topography-related data ................................ 52
    3.4.3.1. The slope ....................................... 53
    3.4.3.2. Slope orientation ................................ 53
  3.4.4. Land use-related data ................................ 54
  3.4.5. Land planning-related data ............................ 56
    3.4.5.1. Hedges ......................................... 56
    3.4.5.2. Ditches ......................................... 56
    3.4.5.3. Agricultural land drainage ........................ 57
### Table of Contents

3.5. Pollution risk zoning .................................. 58  
3.5.1. Treatments to be performed ........................ 58  
3.5.1.1. Zoning of the potential for pollution .......... 58  
3.5.1.2. Vulnerability zoning ........................... 59  
3.5.1.3. Risk zoning .................................. 59  
3.5.2. An example of risk zoning .......................... 60  
3.5.2.1 General presentation of the research area ....... 60  
3.5.2.2. Knowing the risks ................................ 60  
3.5.2.3. Transfer diagnosis ................................ 64  
3.5.2.4. Risk management ................................ 65  
3.6. Risk zoning applications ............................... 66  
3.6.1. Risk knowledge applications ........................ 67  
3.6.2. Spatial planning applications ........................ 67  
3.6.3. Applications related to monitoring water quality ... 68  
3.7. Conclusion ........................................... 69  
3.8. Bibliography .......................................... 70

Chapter 4. Cartographic Index and History of Road Sites
that Face Natural Hazards in the Province of Turin ............ 71
Paola ALLEGRA, Laura TURCONI and Domenico TROPEANO

4.1. Introduction ........................................... 71  
4.2. Principal risks ........................................ 73  
4.3. Research area ......................................... 74  
4.3.1. Geological insight .................................. 74  
4.3.2. Morphology of the research areas ................. 75  
4.4. Working method ....................................... 76  
4.5. Computer-based synthetic analysis and transcription of historical data and information collected on the research area .......... 78  
4.6. First results .......................................... 80  
4.7. Structure of computer thematic mapping ............... 82  
4.8. Application and use of the method ...................... 84  
4.9. Bibliography .......................................... 85

Chapter 5. Forest and Mountain Natural Risks: From Hazard
Representation to Risk Zoning – The Example of Avalanches ....... 87
Frédéric BERGER and Jérôme LIÉVOIS

5.1. Introduction ........................................... 87  
5.1.1. General information on forests ....................... 87  
5.1.2. The protective role of mountain forests ............. 88  
5.2. Identification of protective forest zones ............... 90  
5.2.1. General principle .................................... 90  
5.2.2. Methodology ....................................... 90
6.2.2.2. Implementing traditional spatial analysis tools to assess forest fire risks ................................................. 132
6.2.2.3. Coupling to models ........................................ 135
6.3. Using GIS to map forest fire risks .............................. 137
6.3.1. Forest fire risk assessment and mapping in the Massif des Maures (Department of Var): raster GIS ................................ 138
   6.3.1.1. Analytical approach: the example of fire propagation hazard .... 138
   6.3.1.2. Towards a global approach: characterization of interfaces with the use of remote sensing ............................ 141
6.3.2. WILFRIED – fire fighting support (coupling GIS and model) ... 143
   6.3.2.1. Model systems and knowledge-based systems for the processing of knowledge ........................................ 143
   6.3.2.2. WILFRIED, a PSE dedicated to forest fire prevention ....... 144
   6.3.2.3. Partial conclusion ........................................ 147
6.4. Conclusion ....................................................... 147
6.5. Bibliography ..................................................... 148

Chapter 7. Spatial Decision Support and Multi-Agent Systems: Application to Forest Fire Prevention and Control .......................... 151
Franck GUARNIERI, Alain JABER and Jean-Luc WYBO

7.1. Introduction ...................................................... 151
7.2. Natural risk prevention support and the need for cooperation between the software programs ........................................ 152
   7.2.1. The cooperation issue between the information systems ...... 152
   7.2.2. The various approaches aiming at facilitating this type of cooperation .................................................. 153
7.3. Towards an intelligent software agent model to satisfy the cooperation between the decision-support systems dedicated to natural risk prevention ............................................ 154
   7.3.1. The multi-agent paradigm ................................... 154
   7.3.2. Intelligent software agents .................................. 155
   7.3.3. A proposed intelligent software agent model ............... 157
7.4. Experiment in the field of forest fire prevention and control ...... 158
   7.4.1. Context of the experiment ................................... 158
   7.4.2. The experiment scenario .................................... 160
   7.4.3. First part of the scenario .................................... 160
   7.4.4. Second part of the scenario ................................ 161
   7.4.5. An example of problem solving ................................ 165
   7.4.6. Conclusion of the scenario .................................. 166
7.5. Conclusions and perspectives .................................... 166
7.6. Bibliography ..................................................... 167
Chapter 8. Flood Monitoring Systems ................................. 169
Jean-Jacques VIDAL and Noël WATRIN

8.1. Introduction .................................................. 169
8.2. Flood monitoring and warning ................................ 170
8.3. Situation diversity .......................................... 171
8.3.1. Spatial information for a better understanding of the phenomenon 173
8.3.2. Spatial information for flood impact assessment .......... 174
8.4. Technical answers ........................................... 175
8.4.1. Hydrological observing networks .......................... 175
8.4.2. Data processing ........................................... 176
8.4.3. The integration of acquired knowledge in the natural hazard prevention policy ........................................... 178
8.5. Conclusion .................................................... 178
8.6. Bibliography .................................................. 179

Chapter 9. Geography Applied to Mapping Flood-Sensitive Areas:
A Methodological Approach ........................................ 181
Christophe PRUNET and Jean-Jacques VIDAL

9.1. Introduction .................................................... 181
9.2. A geographic analysis of flooding .............................. 182
9.2.1. Intensity .................................................... 182
9.2.2. Frequency .................................................. 182
9.2.3. Extension ................................................... 185
9.2.3.1. Extension of the flood-sensitive alluvial plain .......... 185
9.2.3.2. An accurate analysis of the fluvial landform development 185
9.2.3.3. Locating water projects .................................. 186
9.2.3.4. How does society use space? .............................. 186
9.2.3.5. Extension of liable-to-flooding riverside areas lacking hydrological monitoring ..................................... 187
9.3. A concrete example ............................................. 188
9.4. Bibliography .................................................. 190

Chapter 10. Information Systems and Diked Areas:
Examples at the National, Regional and Local Levels .......... 193
Pierre MAUREL, Rémy TOURMENT and William HALBECQ

10.1. Context ....................................................... 193
10.2. Analysis of the current situation for the management of diked areas 195
10.3. Spatial dimension and integrated management of diked areas 197
10.4. Examples of information systems dedicated to diked areas ........ 198
10.4.1. An information system at the national level for dike inventory 199
10.4.2. An information system at the regional level to analyze dike failure risks in the Mid-Loire region ........................................... 200
10.4.3. An information system at local level for the integrated management of diked areas ...................................................... 203
  10.4.3.1. Functional analysis of the diked system ....................... 203
  10.4.3.2. Conceptual modeling and prototyping ......................... 204
  10.4.3.3. Examples of results ............................................. 209
10.5. Recent progress and perspectives ...................................... 212
10.6. Bibliography .................................................................... 213

Chapter 11. Geomatics and Urban Risk Management: Expected Advances ................................................................. 215
Jean-Pierre ASTÈ

11.1. Towns, risks and geomatics .............................................. 215
  11.1.1. An overview ......................................................... 215
  11.1.2. City: a much sought after security area ....................... 216
  11.1.3. Risk: a poorly understood notion ................................ 217
  11.1.4. Geomatics as a data structuring and management tool .... 217
11.2. Prevention stakeholders: their responsibilities, their current resources and expectations ................................................... 218
  11.2.1. Ordinary state or emergency state ............................. 218
  11.2.2. Government and institutional stakeholders .................... 218
  11.2.3. Municipal stakeholders and the populations they represent ... 219
  11.2.4. Operational and technical stakeholders ......................... 220
  11.2.5. Insurance agents .................................................... 220
  11.2.6. Scientific stakeholders ............................................ 221
  11.2.7. Compelled to live with an identified risk ...................... 222
11.3. Today’s methods and tools: strengths and weaknesses .......... 223
  11.3.1. Urban reference systems and the expected connection with the digitizing of cadastral maps .......................... 223
  11.3.2. Managing experience ............................................... 224
  11.3.3. Knowledge and modeling of phenomena ....................... 226
  11.3.4. Monitoring phenomena ............................................ 227
  11.3.5. Reducing vulnerability ............................................. 227
  11.3.6. Risk assessment .................................................... 228
  11.3.7. Macro and microeconomic approach ............................ 229
  11.3.8. The means of exchange of experiences, skills and knowledge. ................................................................. 230
  11.3.9. Consultation, public information, training and culture ........ 230
11.4. New potentialities using geomatic methods and tools .......... 232
  11.4.1. Geomatics ......................................................... 232
  11.4.2. Acquiring and structuring spatial and temporal data .......... 233
  11.4.2.1. Data for territories .............................................. 233
11.4.2.2. Data of phenomena ........................................... 233
11.4.2.3. Data related to exposed elements. ......................... 234
11.4.3. Modeling phenomena and behaviors. .......................... 235
11.4.3.1. Modeling phenomena. .................................... 235
11.4.3.2. Vulnerability assessment. ................................. 236
11.4.3.3. Understanding social and economic behavior .............. 236
11.4.4. Task analysis and support to complete and control them ..... 237
11.4.5. Managing experience and knowledge .......................... 238
11.4.6. Quantified and hierarchical appreciation of the risks involved . 239
11.5. Some ongoing initiatives since the beginning of 2001 .. 240
11.5.1. Examples from Lyon: the information system of the service of Balmes and the GERICO project .................................. 240
11.5.2. An Alpine concern: avalanche risk management. .......... 242
11.5.3. Risk management and natural or man-made subterranean caverns, mines and quarries. ................................. 243
11.5.4. The RADIUS project of the international decade for natural disaster reduction (Décennie internationale pour la prevention des catastrophes naturelles (DIPCN)) .......................... 243
11.5.5. Bogotá and its risk and crisis information system (SIRE) .... 244
11.5.6. The CŒUR project in preparation between the Rhône-Alpine and Mediterranean cities ................................. 244
11.5.7. The Base-In project of recording Grenoble’s historical floods . 245
11.6. Assessment and outlook: fundamental elements of future systems .......................................................... 245
11.6.1. Territory ...................................................... 246
11.6.2. Phenomena .................................................... 246
11.6.3. Stakeholders .................................................. 247
11.7. Bibliography ..................................................... 247

List of Authors ............................................................ 249

Index ................................................................. 251
Introduction

Geographic Information, Land Use Planning and Risks

Risks, a growing issue

As clearly asserted by the titles of two books written by the German sociologist, Ulrich Beck, we have entered into a risk society (1992), and more recently we could even say that we have entered into the world risk society (2000). Risk is omnipresent in our daily life. Now, the question is naturally raised whether we are living in a more “risky” society than ever before. This statement can be analyzed in two ways. On the political level, which we will not enter, risk acts as the social cement of a “society without enemies”. On a more prosaic level, regarding our daily life, it is now commonly asserted that risk consists of the combination of a hazard (sometimes called danger, threat, etc.) and vulnerability. This analysis needs to be more comprehensive to paint a more accurate picture of reality, but it gives us something to work with.

This definition raises many difficulties, for it seems only to apply satisfactorily to the situations in which a phenomenon, totally independent from human activity, could assault people or damage their goods. In fact, this is true but only in borderline cases, such as, for instance, natural hazards related to crustal motions. Generally, we are both agent and victim, which means that not only do we not protect ourselves sufficiently from phenomena posing risks, but we create them. If this contrast appears artificial, yet we can more satisfactorily attest that risks can often be

Written by Gérard BRUGNOT.
explained, whatever the real cause may be, such as poor use of land planning. This poor planning does not, in this case, stem from ill will, but from a lack of knowledge of spatial phenomena and issues. The territory, and the society that exists within it, is bounded by risk and every risk is written in the land.

As a result, the application of spatial analysis to any type of risk remains limited. The choice to give very concrete examples of spatial analyses led us to consider only certain types of risks with strong spatial logic. Therefore, we have focused on natural hazards, while some other risks, though important on the socio-political agenda, play less of a part. For example, food safety and health risks do not lend themselves to spatial analysis, although we do believe that the relatively small number of such analyses carried out on these phenomena is due to some other reasons.

**The contribution of spatial analysis to risk analysis and prevention**

According to our previous definition, threatening phenomena and human stakes are both clearly spatialized. For this reason, it is easy to see why spatial analysis is an indispensable tool for those in charge of risk management.

Risk management in large communities makes spatial analysis particularly relevant, since a high level of vulnerability is to be found there, and most large European cities have the necessary geomatic tools. Nevertheless, one of the major problems in large urban concentrations is that, although vulnerable concentrated elements are well known, hazards may originate from outside the urban territory – for example, water-related risks, whether they have to do with the quality (pollution) or the quantity (floods).

The chapters in this book have been chosen to illustrate various situations. Phenomena generating risks are quite diverse. Even though natural hazards make up the largest proportion of such applications, we have tried to compare other factors. This is the reason why some chapters focus on applications and others on theories.

Moreover, the examples given not only refer to prevention, but also to crisis management and feedbacks. Some chapters present urban applications with very highly spatially concentrated vulnerability, while some others present rural applications with more diffuse vulnerability and possibly more diffuse phenomena. It is certainly in the latter kind of case, which involves slow-dynamic phenomena, that spatial applications, which increasingly turn to temporal factors, are hugely beneficial to society, since they can detect both dangerous and irreversible slow changes on large territories. In this case, we can assert that spatial analysis is a tool serving sustainable development.
All the contributions in this book share a common point: they are all presented from a risk representation perspective, and not only from a potentially dangerous phenomena perspective. In all cases, human stakes are weighed against these phenomena and, even if, in most examples, we do not (yet) have an integrated risk management system, we do have an information and decision support tool. There is no doubt that the future, thanks to the expected continuing advances in software and equipment, will see the development of more and more sophisticated spatio-temporal interoperable systems. The field of risk management will probably welcome these systems more than any other field, since it requires the manipulation of numerous spatio-temporal objects, so as to support more and more complex decisions.

Presentation of chapters

In Chapter 1, the author gives a comprehensive summary of GISs used in crisis management. The spectacular evolution of problem management environments over the last 15 years is illustrated with the example of forest fire management performed by civil protection. The example of forest fire is particularly relevant to emphasize the obvious importance of spatial tools supporting risk management. Indeed, this natural hazard is very sensitive both in a temporal (the effect of a bucket of water after a minute of combustion is equivalent to the considerable means deployed an hour later) and spatial sense (not only for the management of preventive measures on vegetation and access, but also for pre-positioning of fire fighting and the conduct of fire-related operations). Two other examples are presented: one deals with the transportation of dangerous substances, while the other is about crisis management. In the first example, we discover a very concrete application, which takes special care to describe the notion of vulnerability. The second example introduces a very generic application that requires efficient telecommunications management. It enables the real-time acquisition of data on incidents and the issuing of the instructions necessary for implementing corrective actions.

Chapter 2 is dedicated to even more anthropogenic hazards, that is to say pollution risks generated by plant protection products. This type of pollution is widespread and related to agricultural practices that the so-called reasoned agriculture is willing to minimize. Yet, without further advances to improve water quality, it is necessary to implement and manage health information. To do so, the authors suggest the use of overall quality indexes to identify pollution levels in the logic of spatial representation. This index combines the determinants of pollutants leaching to ground water aquifers and waterways; these factors characterize the contaminants, the types of soil and rain. An original element of this contribution is the use of fuzzy numbers to list the results and reveal the inaccuracies related to spatial representation in general, especially when the purpose of the indicators is
more to reflect the variation of phenomena in a space, rather than to represent them with precise physical parameters at each point. An example is given to illustrate the method and to test management actions aimed at controlling water pollution from atrazine.

In Chapter 3 we remain in the field of risks related to farming practices, for which the implementation of a space observatory is proposed, so as to monitor water pollution, in all its forms (pesticides, fertilizes, solid objects), as well as soil erosion. The authors’ approach rests on what they call process mapping, which corresponds to conceptual modeling. Their ambitious project led them to build a very comprehensive spatial database, consisting of elements related to topography, vegetation cover, structures (ditches, hedges, etc.) and to ground conditions. A risk/vulnerability analysis emphasizes the most exposed areas and proposes, as in the previous chapter, complementary management actions to improve the situation.

Chapter 4 was written in Italy, more precisely in the Piedmont region, and we would like to thank the authors who made the effort to write in French, for this book was first published in French. This chapter is an introduction to natural hazards and, in particular, to extremely severe events of nature. North-west Italy was hit very hard in October 2000, to such an extent that it led to the development of a spatial information and representation system. It lists a certain number of natural events characteristic of mountain zones near the Mediterranean Sea, and which are poorly defined by the French classifications. These phenomena correspond to flooding, landslides and torrential runoffs (formation of lavas). They are caused by heavy and long-lasting rain in geologically unstable areas, which generate several runoffs that sometimes stay away from thalwegs and carry huge amounts of solid objects, which can entail deposits exceeding several meters in thickness. Chapter 4 shows how these phenomena are inventoried through a specific survey, and then processed in a GIS, which in turn provides numerous information layers, among which the most prominent is related to the road network, assessing how vulnerable it is to these hydrological and geological phenomena through a list of accounted damage.

Chapter 5 also deals with mountain areas, albeit more peaceful mountain areas, with colder but less excessive climate conditions: the Northern Alps of France. In this area, the forest is a real protection structure that can be considered as ecological, because it is not natural, and results rather from an intensive gardening of the slopes, sometimes very steep, and dating back to very ancient times. The authors describe a very sophisticated multilayer spatial analysis system that makes it possible to emphasize the interactions between the forest and the various events disturbing it, and against which it provides protection: avalanches, rockfalls and landslides. This Geographic Information System highlights the weak areas in the forest ecosystem, where the slightest mistake, the slightest delay in terms of intervention could make whole areas at the foot of slopes unsuitable for building purposes. This type of
concern explains the reason why this chapter was written by a researcher and a practitioner, who developed a method that can be used and is operational to draw up risk prevention plans (plans de prévention des risques, PPR).

As in Chapter 1, Chapter 6 presents an application for forest fire management. It is also similar to Chapter 5, in the sense that it focuses on prevention via natural habitat management. Naturally-caused forest fires are often contested, because the majority of fires are caused by human activities, whether intentional or unintentional. The authors analyze the constraints related to this type of situation in terms of risk definition: the forest, but also humans are both risk creators and victims. Natural habitats are strongly affected by this phenomenon, which is not, ecologically speaking, completely negative. Moreover, forest fire being a physical phenomenon, its propagation suffers from greater uncertainties than rockfalls or avalanches influenced by slope inclination or even rivers running down their beds. All these circumstances make forest fire risk zone mapping very delicate. This explains why there are very few “forest fire” PPR. The authors propose to develop an interesting hazard mapping support system for the Massif des Maures, based on physical characteristics such as wind, slope or vegetation, to assess fire risks and fighting conditions. The application is presented in a very educational way, and comments and illustrations are provided for all the development phases of the spatial information system.

Chapter 7 also deals with forest fires and confirms the fact that this phenomenon is particularly relevant, due to its complexity and numerous feedbacks, to test the most sophisticated spatial analysis systems. The author thus proposes a very ambitious and very generic approach to spatial and temporal multi-agent risk management that integrates some decision support aspects in situations of uncertainty. He gives concrete examples of wind intensity changes, and especially of wind direction that can greatly endanger the resources deployed in the field. This type of management, which is highly decentralized in a multi-agent context, gives the author the opportunity to present distinctive theoretical results from a multi agent system. ISA are neither firemen nor a new kind of forest firefighters, but intelligent software agents exchanging information and coordinating their actions. The author gives a concrete example of crisis management to illustrate how such tools could foster theoretical developments that are not discussed in this volume, which is dedicated to the presentation of applications.

Chapters 8 and 9 describe applications used in the case of a specific phenomenon that no region of our country is immune from, even if it takes different forms according to geographic location (climate): floods. Brittany, Aude, Somme, Meuse and Var are among the most recently disaster-struck and/or susceptible regions, which does not mean that the next flood will necessarily occur in one of these specific locations of which, among others, the Loire and the Seine are not included.
As is clearly explained in Chapter 8, flood hazard management, and especially flood hazard warning largely depends on the size and slope of watersheds. Entering the geographic information field with great care, and staying away from debate among hydrologists, and even farther from political considerations regarding land planning, such analyses should enable us to define flood control measures that could be implemented to the entire French territory, and especially, to stay in the realm of GI, lead to the development of spatio-temporal information systems adaptable to local climatic and geomorphic conditions. The system presented by the authors in this chapter is used to manage the watersheds that drain into the Garonne, for though they are large, they are vulnerable to heavy rainfall. The authors also describe the meteo-hydrological forecasting chain, as well as the spatial tools supporting crisis managers. As in the previous chapter, we focus on short-range forecasting (nowcasting). Unfortunately, a disciplinary and administrative barrier between hydrologists and meteorologists has limited the advances necessary to reach the level of the application dedicated to forest fires presented in the previous chapter.

Chapter 9 is less ambitious, in the sense that it only targets the representation of historical floods. Yet, this inventory is very topical since we are in a field where spatial analysis uses both proven tools and large surfaces of buildable or already built zones. It concretely illustrates the risk issue, the assessment of which is based on a study of the phenomena that must be extremely accurate due to the economic stakes involved, as well as relevant when delivering results. To illustrate this, the author not only provides an inventory of the questions raised and the methods used in flood mapping, which is very valuable, but also an example relating to the Garonne river.

Chapter 10 is also dedicated to flooding, but its approach is very different from those used in the previous chapters. It describes a comprehensive project with ambitious plans to inventory and diagnose river dikes over the whole national territory. Above all this, this chapter is particularly fundamental in this volume because it provides an example of a major spatial system that integrates all the characteristics of a comprehensive public decision-support system. The average time for such projects is 10 years, and the proportion of resources necessary to carry it out is similar. The genesis of the application (the Camargue flooding and the concerns with the Loire embankments) is interesting, because it is based on the Government’s willingness to find a long-term solution to this problem, and because it conducted a thorough analysis to identify the needs of a multi-scale spatial information system in nature, according to the variety of the objects involved. In the end, this system integrates the notions of hazard and vulnerability, from the most concrete and accurate geotechnical aspects related to dikes (e.g. rabbit burrows) to the most realistic scenarios of vulnerability, such as what if (e.g. what would happen if such a dike, which had received a diagnosis of weakness, finally breaks).
Chapter 11 concludes a volume essentially devoted to natural risks, or at least risks related to vast territories of low-density occupation, with an overview of spatial information systems dedicated to urban risks. This chapter is presented in a course format, which completes the volume by addressing spatial risk issues in a conceptually clear manner, by discussing alternatively application questions and examples, which will enable readers to shed new light on some developments already presented in the previous chapters. The author provides many different examples, including space risk management systems developed by the Urban Community of Lyon, which are, with those developed in Marseille, the most ambitious of their kind. He sets all the tools used in a public political context, which concludes the volume with an emphasis on the social and political nature of risk, as expressed at the beginning of our introduction.

Conclusion

Risk analysis involves a fundamental spatial component; there is no need to demonstrate this point again. The chapters of this volume illustrate the possible uses of spatial analysis tools. Without some of these tools, many delicate issues relating to land planning would be impossible to manage at the political level.

Some may be surprised from the above statements that our conclusion is actively pessimistic. Viewed more broadly, spatial risk analysis appears to be poorly developed in France. It is scarce in numerous fields, and a little more developed with respect to country-related risks, due to the agro-rural tradition of our society that some bodies, sometimes academic bodies, have acquired.

Nevertheless, we are still unable, for instance, to overlay natural hazard-related information layers, such as floods, with other information layers illustrating land use in urban and peri-urban environments. Moreover, information on flood damage is managed independently and its spatialization is not on the agenda, at least for now. Therefore, we are still unable to integrate the drainage system to a digital elevation model.

Many examples could be given to demonstrate how important it is for major managers of spatial databases, without whom applications would only remain academic monographs or systems of local interest, to provide quality and economic research products, such as topographic, land use, physical or economic databases. Some areas of study are still wide open, such as the creation of areal postal codes as in the UK, and the georeferencing of vulnerable components.

These issues can only be addressed with political support. They are a fundamental ingredient to the development of interoperated land use management systems, without which no risk integrated management is possible; only partial
management, often implemented in catastrophic events, which can lead to disappointing results, let alone negative results.
Chapter 1

From Prevention to Risk Management: Use of GIS

1.1. Introduction

Territory mapping has always been of paramount importance for society [IGN 90].

Since ancient times, maps have had a functional role:

– “route” maps, in ancient Rome and the Middle Ages, such as the Tabula Peutingeriana;
– commercial maps during the 15th century and the long voyages around the world;
– military maps, of which the most significant development occurred at the instigation of Napoleon.

It was at the beginning of the 19th century that Napoleon formalized the fact that knowing the terrain was a necessary condition for victory. He created the 1:80,000-scale ordnance survey maps produced by the military services. They were high-precision maps providing detailed information on relief, remote communities, bridges, vegetation, etc. Moreover, such maps enhanced the necessity for regular updates.
During the two World Wars, maps progressively became an obvious decision-making support tool for crisis management:

- road maps appeared with the transport revolution, but their use was adapted to the needs of World War I, that is, to follow the evolution of the Front with nearly real-time updates;
- the French National Geographic Institute (IGN) was created in 1940, and replaced the Army Geographic Service that had been dismantled by the Germans;
- Michelin provided the French, English and American armies with maps to drive their troops.

Some of the working conditions of firemen are similar to the context of conflict, and this is why they have always paid great attention to prior knowledge of the terrain. Maps have always been critical for any type of response (emergency relief to people, flooding, accidents on transportation linkages, etc.). However, they are mainly used to locate an event, to dispatch the resources, to know about the crisis area and emergency plans (prevention, aid). When responding to a disaster or an accident, this knowledge is determinant in order to take the right and most appropriate decisions given situational factors. The time to plan a response is limited to the few tens of seconds between the moment the call is received and the movement of the emergency team.

In the case of toxic gas dispersion, for instance, it is essential to know the environment in order to take action, such as the confinement or evacuation of people.

In March 2000, in Saint-Galmier (Loire), a train hauling highly toxic substances derailed, thus releasing a gas cloud. The operational analysis carried out just after the event revealed that, among the elements that had supported the decision-making process for the rescue of people, accurate knowledge of land use had been fundamental [GRI 00]. In such contexts, the most comprehensive and synthetic tool to picture land use is the map.

The use of “conventional” topographic maps, which was dominant for a long time, progressively turned to “profession” maps targeting specific issues. The need for “profession” maps produced for a particular theme increased more and more:

- maps dedicated to urban public security and defense management [CHE 00];
- maps to prevent and fight forest fires [JAP 00];
- maps for the management of dangerous goods transportation-related accidents [GLA 97].
Nowadays, the most effective tool to answer these needs is a Geographic Information System (GIS). The evolution of its use over time will be discussed using examples of existing applications.

The features related to the complex issue of updating data will not be dealt with in this chapter.

1.2. GIS and public security

Within their respective sphere of competence, the French Fire and Rescue Department Services cover the following missions: public security risk prevention and assessment, planning safeguards and implementing emergency measures, life, property and environment protection, emergency assistance to people who have suffered an accident, damage or a disaster as well as their evacuation [SNO 00]. These missions are grouped into three themes:

– prevention: gathering the measures implemented to prevent a disaster occurring again or becoming worse;
– forecasting: to know and forecast the initial conditions and evolution of a disaster;
– operations: the implementation of disaster control measures.

Three main reasons account for the increasing importance of GISs in the execution of public security plans:

– GISs are involved in each of the missions mentioned above;
– the professional profile of those using the GIS tool;
– the role of GISs in decision-making processes in crises.

In the field of forest fires, in which mapping is a fundamental tool, the missions of the French Fire and Rescue Department Services are characterized by [DSC 94]:

– forest fire prevention or protection (DFCI), which includes, among others, forest massif management, monitoring (patrols and fire towers) and public outreach;
– forecasting, aiming at assessing local risks of forest fire outbreaks and spread, based on meteorological and vegetation condition parameters;
– fighting, which consists of coordinating land and air resources to stop the fire from spreading and to extinguish it.

During these missions, firemen make considerable use of mapping. Indeed, it is quite impossible to manage disaster control measures without information on the surface topography, road transportation systems, populated areas, etc. Maps are a privileged tool at the heart of decision-making processes.
At the beginning of the 1970s, a reform of the forest fire control mechanisms was launched in the South-West of France. This reform entailed several consequences such as the creation of new agencies aiming at implementing actions to protect forests from fire, the creation of a statistical database on forest fires and forest fire control structures, such as tracks, water points, forest towers, etc. [KER 99].

In 1987, DFCI maps appeared, that is, maps specifically produced for forest fires control and prevention practitioners. Provided by the IGN, these maps were based on 1:25,000 and 1:100,000-scale topographic maps [RON 87]. They display, in superimposition, the specific coordinate system (bikilometric DFCI grid) and all of the DFCI structures.

![Figure 1.1. Initial organizational chart of DFCI map production](image-url)

Figure 1.1 presents the organization in 1987. There were, however, some disadvantages to these maps [SAU 97]:

- the cost: the IGN spent hundreds of thousands of Euros to produce 1:25,000 and 1:100,000-scale DFCI maps just for medium-sized departments;
- information update: a year after the production, the maps were no longer operationally usable.

The development of GISs was then mainly limited to the research sphere [DID 90], and their market reflected “their youth by its instability and lack of maturity” [POR 92].

In 1992, a first attempt to implement a geographic information system dedicated to public security was made in the French Mediterranean zone. The purpose was to deploy an operational coordination information system for public security integrating messaging capabilities, databases, mapping and decision-support [MAR 93]. Yet, the lack of geographic digital databases (both in terms of costs and of
geographic coverage of the Mediterranean zone) led to the suspension of the mapping dimension of this tool, and consequently of the use of a GIS.

The interest in using a mapping information tool was renewed in 1995. At the national level, this date also seems to be an important step in the use of GISs by firemen [SDI 00].

In the French Mediterranean zone, this was illustrated by the SIGASC application project (GIS applied to public security). The objectives of this application emphasized GIS functionalities so as to achieve several goals. Indeed, SIGASC must [SAU 97]:

- produce up-to-date paper maps;
- provide a constant knowledge of the DFCI structures across a specific area;
- manage and plan forest massifs to help control forest fires.

A transfer of expertise regarding paper maps can be observed, from the “conventional” producers to the users (see Figure 1.2).

End users (firemen) seek to develop the necessary skills to manage their own mapping production. Moreover, the routine use of GISs introduces users to more complex functions, which creates new needs: data processing, spatial analysis, quantitative analysis, geographic database management, etc.

![Figure 1.2. Introduction of GISs aimed at firemen](image)

A major step was taken with the introduction of the automated processing of geographic data: *geomatics*.

GISs were then actually used to gather, store and manipulate heterogenous data that, once they were made coherent, could be restored in various forms: reference maps, thematic maps, reviews and tables (see Figure 1.3).
The developments and use of GISs continued in two major areas [SDI 00]:

– functional developments: the use of spatial analysis capabilities, the production of new information, the use of technologies producing geographic information (remote sensing, GPS);


GISs also became support tools for the retrieval of simulated processing. These functionalities are especially related to the following areas:

– forest fires [SAU 98],
– technological risks [DUS 97],
– radiological risks [PRE 00],
– floods [COR 99].

Their use remained especially focused on prevention and prediction for, even though the functions gained in complexity, the core purpose still remained the production of maps.
It is only recently that this purpose has evolved [SDI 00]. Today, GIS is at the core of an increasingly complex organization (see Figure 1.4).

This organization makes it possible not only to produce thematic maps from a variety of sources, but also factual maps [FOR 98], which will be progressively introduced in operational areas responsible for risk management.

Today, GISs have become tools processing information to achieve an immediate objective, such as maps on demand, mobile tracking, etc. They are more and more involved into decision-making processes in emergency situations, for they provide the required information with almost real-time refresh rate [GAL 96, SAU 00].

Today, there are a growing number of GIS applications integrating the principles of telegeomatics [OLI 99]: the communications between operational areas and command posts in situ are essentially cartographic in nature: the resources implemented in the field include geographic information survey tools (GIS, GPS, cameras, etc.) allowing the edition of maps “on demand” to track an event [BOU 01]. These maps are then transmitted to the command post in the field to plan or modify fighting tactics, or to the operational area to anticipate the actual requirements in terms of resources.
Yet, despite their increasing use in public security, GISs are still basically used by *in situ* commanders to acquire and manage as much information as possible to make the best decision they can.

GISs, and more particularly the maps they produce, are information-sharing tools fundamental to decision-making.

The strength of GISs is related to the fact that the volume of information, its level of synthesis and the typology of the information on the map have greatly increased.

### 1.3. Examples of applications for public security

The role of GISs within departments responsible for public security is illustrated in the three following examples of existing applications.

#### 1.3.1. SIGASC application

Formalized in 1995, the objectives of the SIGASC application were determined by the necessity of supporting forest fire management and prevention [SAU 98].

The main purpose was to provide the 15 Departmental Fire and Rescue Services of the south defense zone (Languedoc-Roussillon, Provence-Alpes-Côte d’Azur, Corsica, Drôme, Ardèche) and the public security and defense top managers of the south zone with a GIS-based tool and methodologies applied to public security practitioners of the French Mediterranean zone, and mainly to forest fires.

Defined in collaboration with the users, this application always provides an updated vision of the field. The large geographic coverage (the 15 departments of the Mediterranean front) requires homogenous information across the research area in terms of content and cartographic representation.

Such a work required establishing a certain number of working groups, consisting of users and GIS specialists. Indeed, the Departmental Fire and Rescue Services are financially independent, and consequently, they could not all afford the purchase of the necessary data or the services of a specialist to carry out this work [SAU 00].
The work was organized through thematic groups (application architecture, financial negotiations with the IGN, acquisition of specific data, cartographic production, etc.), and thus, all the Departmental Fire and Rescue Services could benefit from the results.

In order to meet the intermediate objectives presented in Figure 1.5, several steps were achieved:

– to define precisely the computer support (hardware and software) according to the needs;
– to identify a common cartographic reference system that would address both the information and visualization expectations;
– to identify as accurately as possible the availability of specific mapping, and to assess discrepancies;
– to standardize the definition and the representation system of specific geographic information;
– to provide the technological and methodological resources to have constantly updated maps and to be able to edit an annual departmental atlas.

To fit the departmental and zonal use, the common cartographic reference system was chosen on a small or mid-scale.

**Figure 1.5. General structure of the SIGASC application**
The following choices were made:

- **BD CARTO®** of the IGN (digital vector products that include all the information present on 1:100,000-scale maps, providing decametric precision), because of its availability across the research zone and its adaptability to the research field;

- **Scan25®** and **Scan100®** products from the IGN (raster digital products resulting from the scanning of paper maps at different scales, from 1:25,000 to 1:250,000, to be used exclusively as base maps), so as to keep what we already had, as well as the comfort while reading maps at both scales.

With the appearance of **DFCI** maps in 1987, the use of specific maps to serve public security was assigned differently within each department, and soon, discrepancies came to light. An overview of these discrepancies is presented in Figure 1.6.

These results led to the writing of a standards guide [DPF 97] to lay down the fact that: “every piece of field equipment used by the DFCI corresponds to a specific standards category that enables its symbolization and production on maps”.

The geographic information specific to public security services being precisely defined, the technology and methodology dedicated to the acquisition of these data were identified in their turn.

The problem relating to data acquisition is a major issue. There is a lot at stake, the reason for producing maps for public security being twofold [SAU 98]:

- to provide a comprehensive knowledge of the field, so as to optimize decision-making at the different levels of operational command;

- to ensure, with a minimum amount of risk, the veracity and relevancy of the elements represented.

With respect to specific data acquisition, a brief comparative study was carried out between the traditional methodology for surveying geographic information (compass and decameter) and the methodology using GPS [SAU 00]. The results emphasize a factor of 10 between these two methodologies regarding the time for survey and mapping transfer.
Figure 1.6. Examples of symbols used before the standardization

The SIGASC application was implemented in 1997 in some departmental fire and rescue services.

In the Department of Gard, a protocol was established between the National Forest Office, the Departmental Fire and Rescue Service, the Agriculture and Forestry Departmental Directorate and the General Council. It aims at creating a common pool of DFCI data, for which the processes of initial GPS acquisition, of management and processing, of update and mapping are jointly carried out by the four signatory organizations. The target here is the homogeneity of DFCI data across the department, the constant updating of DFCI 1:25,000-scale mapping and a cost-effective production.

A structure (DFCI GIS cell) and a specific vehicle with a GIS and a GPS on board (DFCI four-wheel drive liaison vehicle) were implemented. The DFCI GIS cell consists of a joint-team of some staff from the National Forest Office and firemen. Their objective is to perform a GPS-based survey of all the DFCI structures to map them and characterize them.

The GPS-surveyed data are then sent to the administrator, the DDAF (Agriculture and Forestry Departmental Directorate), who structures them and integrates them to the departmental database. The resulting DFCI database thus conforms in all respects to the requirements of the standards guide. This database is then transferred to the signatory organizations of the convention.
In summer, the systematic GPS-based survey of DFCI structures stops. The DFCI four-wheel drive liaison vehicle is then mobilized for forest fires to map in real-time the starting point and successive contours. The maps produced can be printed in situ. This also contributes to the development of a cartographic database for forest fire annual reports.

The SIGASC project gave birth to many others: working groups are carrying out more research into the use of GIS for public security, with additional technologies (aeronautical application of GISs) and other risks [MIS 00].

1.3.2. Application

The SIGRISK project (GISs related to the risk of transporting dangerous substances applied to public security) is part of the implementation of an operational tool to support decision-making in times of crisis. This tool meets the needs related to public security preparedness in the face of accidents resulting from the transportation of dangerous substances.

Dangerous substances transportation risk is characterized by random occurrence both in space and time. This specific risk presents two major categories of uncertainty related to risk assessment and quantification, and to environmental variability [DUS 97, GRI 99].

Among the specificities of typical accidents resulting from the transportation of dangerous substances [LAG 95], we find:

– kinetics, which varies a lot according to the type of transportation, the type of goods and the type of accident;
– the necessity to understand very quickly the environment (human, physical, natural) where the accident occurs.

Within the very first minutes following an accident resulting from the transportation of dangerous goods, it is of an absolute necessity:

– to know, even generally, about the kinetics of the accident, and its possible spreading, for instance how a toxic gas cloud might disperse according to weather conditions [FUL 96];
– to have as much information as possible on the population, the potential presence of public assembly buildings, of industrial sites at risk, of drinking water installations, nature of the surface, of the subsurface, of the road network, etc. [GRI 00], so as to assess as soon as possible the direct risks as well as the potential indirect impacts.
Consequently, the objective is to design a GIS-based computer tool enabling us to:

– quickly assess the consequences of a dangerous goods transportation accident via effect distance calculations;

– identify and quantify the vulnerability of the area impacted from a human, material and environmental point of view; vulnerability levels previously determined and translated into a map.

These objectives include some intermediary steps described in Figure 1.7.

Assessing the consequences of a dangerous goods transportation accident is achieved using OSIRIS. This software was developed in collaboration with the Ecole des Mines d’Alès and firemen from the Department of Gard. OSIRIS is “capable of providing information relating to the safety of individuals during dangerous goods transportation accidents” [OSI 00]. It is a crisis management training software program that informs, with baseline figures (on meteorology, type and quantity of spilled material, etc.), on the consequences (rate of flow, of evaporation) and effect distances for various types of accidents: explosions, toxic gas dispersion, and hydrocarbon fires [DUS 97].

OSIRIS is coupled with a GIS software to transfer onto a map the effect distances previously calculated. The spatial analysis capabilities of the GIS are then used to emphasize the information relevant to crisis management.

With the GISRISK application, the effect distances of sample accidents are cross-referenced with a vulnerability map [GRI 01].

The term map refers to the need for digital geographic information. The term vulnerability refers to land use knowledge.

The production of a vulnerability map consists of several steps.

The digital mapping of land use is the first to be edited from [GRI 01]:

– SPOT satellite images providing a land use overview adapted to the selected issue. This map is based on a nomenclature derived from CORINE land cover (www.ifen.fr) to emphasize the important elements to the assessment of vulnerability;

– other data sources (urban databases, National Institute for Statistics and Economic Studies, etc.) add more accuracy to specific points previously edited, for instance, the localization of public assembly buildings, schools, etc.
At that point, the land use map contains all the elements necessary to the assessment of human, material and environmental vulnerabilities, with respect to dangerous goods transportation risks.

The next step, which consists of the production of the vulnerability map, requires the development of a method to identify the potential targets, their sensitivity to a certain type of accident and their degree of exposure to potential hazards.

Among the information edited on the land use map, human targets (dense or dispersed residential developments, healthcare facilities, etc.), environmental targets (intensive agriculture, wetland, etc.) and material targets (water installations, commercial stocks, etc.) are identified.

Subsequently, these targets are characterized according to:

– the potential effects of accidents to which they are sensitive (thermic, toxic effects for instance);

– the foreseeable consequences (difficulty to evacuate people, financial depreciation, etc.), possible indirect consequences (psychomedia impacts, daily life impacts, etc.).

Then, all these parameters are structured in a hierarchical format using a multi-criteria decision-making method [SAA 80]. This step aims at drawing attention to

**Figure 1.7. GISRISK application architecture**
the targets showing some kind of sensitivity, for all endpoints, rating high in terms security of people, property and environment.

The results are finally edited on a map using five categories (which are the five legend keys). This final vulnerability map will support preparedness and response.

Tackling extreme situations, this tool provides the public security services with the capacity for quicker access to specifically processed information.

1.3.3. SIG CODIS application

The third application presented here is an illustration of the current use of GISs for crisis management.

Indeed, it is the increased knowledge of GIS capabilities that led to the implementation of this application in operational areas [SDI 00].

This tool was designed to address a certain number of constraints entailed by the operational management of alerts, whatever the type of accident (forest fire, emergency relief to people, road accident, etc.):

– localization of the event,
– to send the rescue resources to the scene of the accident,
– knowledge of the environment of the site,
– to anticipate the possible increase of the emergency requirements, by knowing the evolution of the event.

The purpose is to provide a tool that improves response time. The users are those in charge of processing alerts and of the operational management of the event.

The application is not dedicated to one type of risk, but makes it possible to manage any operational contexts.

Developed on the basis of the consultation version of a GIS software program, the first version of the SIG CODIS application was very simple. This was to prevent any corruption of the databases due to misuse.

Initially, the application provided users with a reference database consisting of BD CARTO®, SCAN 25® and SCAN 100® from the IGN, as well as with rapid locating functions, using information such as the name of the district, the road number, etc.
Today, this tool has evolved, and its current design is more complex (see Figure 1.8).

Familiar with the system, users developed it further to meet their own needs. A large bibliographical study was carried out in parallel to give an overall vision of GIS usage in French operational management, but also in the world [CAI 01]. The intersection between the vision of what already exists and the users’ needs determines the objectives guiding the improvement of this tool.

Figure 1.8. SIG CODIS application architecture

Today, the specific interface of the SIG CODIS makes it possible to locate an event with the information acquired during the initial alert: the name of the district or of the crossroads, road number, intersection of roads, highway kilometer post, emergency phone boxes, DFCI track number, DFCI coordinates, etc.

The system then provides an immediate determination of the area of intervention (sphere of competence of each emergency center) and of the highway intervention zones (that may be different according to the direction of traffic), and the nearest access route.

Being one of the tools involved in operational management, the constraints related to this application are particularly severe [SAU 98]:

– the validity of the database, which has to do with the accuracy of the location of the information, especially when this information concerns the dispatching of rescue resources (access route for instance), descriptive data (access to a trail with heavy equipment), and also updating data;
the integrity of the database, which has to be absolutely ensured, since many operators use it;

– the timelines of the system, which must be coherent with the very short time elapsing between the moment the call is received and the movement of the emergency team.

Figure 1.9. Possible evolution of the SIG CODIS application

On the basis of the current application, the possibilities for further development are still numerous. There are three main research directions:

– evolution of the database content through the integration of large-scale databases [CHE 00];

– technical evolution through the integration of telecommunication devices to exchange operational cartographic data between a command post at the scene of a disaster, equipped with a GPS, and an operational area; or through the integration of devices to locate mobile stations on land or at sea from the operational area [BOU 01];

– evolution of the functions, such as the development of a real-time route planner using driving accesses, whether on open roads or through forests [SDI 00].

Applications could possibly evolve towards a structure such as that presented in Figure 1.9.
1.4. Prospects for development

The three examples presented above reveal that the development of GIS applications for crisis prevention and management seems to turn towards:

- the integration of “professional” databases (management of forest fires, dangerous goods transportation, emergency relief to services, etc.), which are also multi-scale and constantly updated (interagency conventions, telecommunication technologies for data acquisition);
- the sharing of a single database among a number of users (implementation of cartographic databases servers);
- establishing connections between the field and the operational area for the transmission of different types of data (data, voice).

GIS first appeared in public security as a computer-based mapping tool. Later on, it was used for its ability to perform spatial analysis operations, in particular for the development of forecast and prevention documentation. Today, it has entered operational areas thanks to its interactive capabilities in managing alerts and specific interventions.

Current developments seem to be heading towards tools providing a direct interactivity between the crisis management area and the field, the scene of a disaster:

- access to databases from central servers, shared among many different users. Data, and more generally maps, are produced on demand according to the field and situation conditions;
- direct observation of the event by the transmission of georeferenced images (visible or infrared) taken from the ground or from the air;
- knowledge of the intervention processes and progress by the transmission of cartographic data providing information on the fighting tactics and resources implemented to carry out each action;
- accurate location of the resources dispatched to the scene, whether on the ground or in the air, by the transmission of data pinpointing the site of these resources.

With respect to this evolution, real-time and telecommunication functions are becoming more and more important within GIS applications, which consequently results in a more complex organization of the system as a whole, as presented in Figure 1.10.
1.5. Conclusion

Public security-related professions are expanding massively at present. Among the numerous development spheres, geographic information practitioners predominate.

Indeed, in most services, geomatics and telegeomatics tools are increasingly used by firemen who, for the most part, also take part in the interventions.

Having a double vocation, these firemen can identify and formalize their needs, carry out or follow the development of specific applications and maintain the data.

1.6. Bibliography


Chapter 2

Coupled Use of Spatial Analysis and Fuzzy Arithmetic: Assessing the Vulnerability of a Watershed to Phytosanitary Products

2.1. Introduction

The intensive use of agricultural land entails many environmental disruptions. Water resources, both groundwater and surface water, are particularly impacted. For example, phytosanitary products, used for achieving better agricultural output, are carried by runoff and contaminate wetlands such as marshes or floodplains.

Two main approaches enable us to assess the impact of a disturbance on an environment.

The first approach, based on equations governing transfers of water and chemical substances, provides generally complex mechanistic models. Indeed, apart from the difficulty performing certain calculations (highly non-linear and coupled phenomenon), they usually require large amounts of data (input variables, parameters) to such a point that they are generally underestimated. These models are precious research tools [VAU 94], but when used to simulate or forecast large-scale behaviors, several difficulties arise related to variations in the availability of data and to the inaccuracy of some of their parameters due to spatio-temporal variability of the environment.

Chapter written by Bertrand DE BRUYN, Catherine FREISSINET and Michel VAUCLIN.
The second approach consists of the use of indexes or indicators. Used for a long time in many different fields, they answer simply and concisely the increasing demand for information about the situation of any type of system (stock market index, fertility index, etc.). For the last few years, the environmental sphere has also witnessed the emergence of indicators dedicated to the assessment and monitoring of natural and anthropized habitats: the standardized global biological index [AFN 92] to assess the biological quality of surface water habitats, DRASTIC1 [ALL 85] or AF (Attenuation Factor) [FRE 99, RAO 85] to assess the intrinsic or specific vulnerability of groundwater to phytosanitary products.

To date and as far as we know, very few tools of this kind have been developed for surface waters, even though they are also very sensitive to crop protection products that are increasingly used. Therefore, we propose a new indicator, called VESPP, designed to assess the vulnerability of surface waters to phytosanitary products2.

It is above all a comparative tool applied to an agricultural watershed, and it has the ability to produce, for a specific product, vulnerability maps of the research area, taking into account its main characteristics (climate, topography, pedology, vegetation cover, anthropization level, etc.). Assessing this indicator is heavily dependent on the accuracy with which parameters are known or estimated. The resulting inaccuracy is taken into account here with an approach based on the fuzzy subset theory. This emerging method within the field of environmental sciences [BAR 95, FRE 97] provides a range of possibilities for the parameters. The fuzzy computation provides the possible values for the index and, coupled with a GIS, enables us to compare the results on the research area.

2.2. Construction of the index

The OECD (Organisation for Economic Cooperation and Development) recommends the use of indicators. It also gives their construction outlines: they must meet three basic criteria: simplicity, reliability and accuracy [OEC 98].

---

1. Depth to the water table, net Recharge, Aquifer medi, Soil media, Topography, Impact of the vadoze zone, hydraulic Conductivity.
2. The “Environment, Life and Society” program launched by the CNRS (National Center for Scientific Research) and the Rhône-Alpes Regional Council provided us with the resources to carry out this study. ALCATEL Space supplied us with the satellite data relating to crops.
A study of the phytosanitary product transport and persistence mechanisms in surface waters highlights the main parameters of the research problem [DEB 99b, LIE 98]. They can be grouped into three categories representative of the dominant mechanisms:

– Intrinsic characteristics of the environment:

\[ \text{Im} = \frac{P \cdot Ld \cdot C}{L} \]  

where \( P \) (%) is the average slope of the ground surface; \( L \) (m) is the length of the slope; \( Ld \) (m) is the length of the hydrographic network that drains a specific surface; and \( C \) (-) is an index characterizing vegetation covers.

– The phytosanitary product persistence parameters:

\[ Ip = \frac{M \cdot T_{1/2}}{f} \]  

where \( M \) (-) defines its application mode. It varies from 0.1 for moderately transferable products to 5 for highly transferable products. \( T_{1/2} \) (day) is the half life of the product and \( f \) (day) the average time of dry periods in the month following the application of the product.

– The parameters related to the dissolved and particulate transport:

\[ It = \frac{Kd}{100} \cdot R \cdot PAE + \frac{100}{Kd} \cdot R \cdot PAR \]  

where \( Kd \) (l.kg\(^{-1}\)) is the absorption coefficient of the product on the ground, which is calculated as the product of the fraction of organic carbon from the soil: \( f_{oc} \) (-) and of the sharing factor of the phytosanitary product: \( K_{oc} \) (1.KG\(^{-1}\)).

\( R \) (-) is the rain erosivity index, the product of the two sub-indexes \( n_p \) and \( n_s \). \( n_p \) is the number of days per year when rainfall exceeds the threshold \( s_p \) and might entail runoff \( (s_p=10\text{mm/day}) \) while \( n_s \) is the percentage of annual precipitation height of daily rainfall higher than the threshold \( (Pu) \) compared to the total rainfall height \( (Pt) \) \( (n_s=100 \cdot Pu/Pt) \).

\( PAE \) (-) allows us to take into account erosion control practices that might have been implemented. The variable \( PAE \) equals 1 when these practices are not implemented, and the minimum value equals 0.6 when these practices are intensive.
PAR (-) refers to the presence of water control practices (ditch, drain, etc.). It equals 1 when there is no such practice and 0.6 if these practices are important.

Analogous to the multiplier index DRASTIC [ALL 85] of underwater intrinsic vulnerability, the VESPP index relative to surface waters is defined by the product:

\[ VESPP = lm \cdot Ip \cdot It \]  

[2.4] 

Consequently, according to equations [2.1], [2.2] and [2.3]:

\[ VESPP = \left( \frac{p \cdot Ld \cdot C}{L} \right) \cdot \left( M \cdot \frac{T_{1/2}}{f} \right) \cdot \left( \frac{K_f}{100} \cdot R \cdot PAE + \frac{100}{K_d} \cdot R \cdot PAR \right) \]  

[2.5] 

The parameters used for the VESPP index characterize the physics or chemistry of soil and products, as well as the watershed studied. Some of them are known or can be accurately assessed, whereas some others (such as \( T_{1/2}, C_f, K_f \)), due to their variability and other constraints, cannot be accurately determined and are quantified using a fuzzy approach.

2.3. Implementation of fuzzy calculations

The fuzzy logic approach appeared at the end of the 1960s to answer the needs of automation and computer science [ZAD 65]. During the 1990s, it was increasingly used for environmental issues [BAR 95, FRE 97, HIG 96].

The fuzzy subset theory broadens the classical concept of set. Classic mathematical sets only propose two choices: an element either belongs or does not belong to a given set. The fuzzy subset theory allows an element to belong only partially to a set, and furthermore, to belong to its complement at the same time. (Therefore, a person who is 5’9” tall belongs to the tall set at 70% and to the small set at 30%.)

This theory is different from mathematical probability since a person cannot have 7 chances out of 10 of being tall and 3 chances out of 10 of being small, but this person is both tall and small (depending on appreciation).

Fuzzy arithmetic follows from fuzzy logic. It uses fuzzy numbers represented by a membership function, which is the range of values that these numbers can have [KAU 85].
Common mathematical calculations (sums, products, etc.) can be processed with fuzzy arithmetic, which enables us to integrate the inaccuracy of some parameters to the calculation.

**Figure 2.1.** Example of membership function: isosceles triangle fuzzy number (here the half-life time of a phytosanitary product). In this case, the value for which the membership function equals 1 is the mean value.

![Figure 2.1](image1)

**Figure 2.2.** Example of membership function of the VESPP index calculated with fuzzy input parameters in isosceles triangle form. In this case, the value for which the membership function equals 1 is the mean value.

![Figure 2.2](image2)

The inaccurate parameters are transformed into fuzzy numbers before calculating the indicator. The little we know about the distribution of the possible values of the parameter implies the use of a simple membership function. Our choice (which in fact has no real impact on the result [DEB 99a]) was an *isosceles triangle function,*
with an apex pointing to the strongest possible value (in our case the parameter mean value) and a base corresponding to the uncertainty interval (see Figures 2.1 and 2.2).

2.4. Application to the watershed of Vannetin: vulnerability to atrazine

In order to improve the readability of the results, calculations were carried out with a GIS (MapInfo). The results are represented on a map picturing the watershed in which the set of plot units appears.

2.4.1. The research site

The research site, the watershed of Vannetin to the East of Paris, is a small agricultural basin of 35 km². It consists of an even topography and open field agriculture. Cereals, sugar beets, peas and corn dominate the cropping pattern. The research area was divided into 83 square plots 678 meters on a side. Each plot is associated with a set of characteristics of its own (mean parameters, fuzzy parameters) and the VESPP fuzzy number (see equation [2.5]) is calculated so as to define the vulnerability of surface waters contained in each plot. The 83 fuzzy numbers thus calculated enable us to compare the watershed plots with each other. Atrazine is an herbicide used on corn crops.

2.4.2. Parameters of the watershed

Here, these parameters are believed to correspond to a unique value for the whole watershed.

2.4.2.1. Pluviometry

Pluviometric data are the only climate parameters useful to the VESPP indicator calculation. We have used the mean of these data over several years, but the study can be carried out on a particular year.

The value of these parameters is deduced from the rainfall records available for this watershed. Therefore, the number of rainless days following the application of atrazine \( n \) is 18.2; the number of rainy days that might start runoff \( n_p \) equals 14.2; the annual average rainfall \( P_t \) equals 933 mm, and heavy rain \( P_u \) is 488 mm.

Relating to the physico-chemical data of the research product, two intrinsic parameters of phytosanitary products are taken into account:

– their sharing factor \( K_{oc} = 100 \pm 78 \text{ g/cm}^3 \);
– their half life $T_{1/2} = 60 \pm 32$ days.

These two parameters are considered as highly uncertain.

The indicator also takes into account the product application process ($M$). It is advisable to apply atrazine in an oil-water emulsion. This type of application leads to $M = 2$.

2.4.2.2. Anthropogenic sub-index

Two parameters enable us to take watershed management into account: $PAE$ and $PAR$. Initially, we considered no management, either for erosion or runoff management: $PAR = PAE = 1$.

2.4.2.3. Pedology

The organic carbon fraction ($f_{oc}$) is the soil characteristic relevant to the calculation. This characteristic is highly variable within each plot, consequently, it was allocated the same inaccurate value over all the watershed: $f_{oc} = 2.5 \pm 0.8$.

2.4.2.4. Summary of data common to the entire watershed

In this case, the values of the parameters common to all cells are gathered in Table 2.1.

<table>
<thead>
<tr>
<th></th>
<th>$n$</th>
<th>$n_p$</th>
<th>$P_u$</th>
<th>$P_t$</th>
<th>$K_{oc}$</th>
<th>$T_{1/2}$</th>
<th>$M$</th>
<th>$PAR$</th>
<th>$PAE$</th>
<th>$f_{oc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>18.2</td>
<td>14.2</td>
<td>488</td>
<td>933</td>
<td>100</td>
<td>60</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>Variability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\pm 78$</td>
<td></td>
<td>$\pm 32$</td>
<td></td>
<td>$\pm 0.8$</td>
</tr>
</tbody>
</table>
the distance between them. The values of the slope are in the range 0.15% to 4.43% on the watershed.

The drainage length $L_d$ is determined by adding the distance between the cell and the nearest stream to the slope length.

These data were obtained using 1:25,000 maps produced by the IGN, but a digital elevation model with a known accuracy would do perfectly well.

### 2.4.3.2. Vegetation cover

Vegetation cover index $C$, determined by satellite images, is taken into account using a simple relationship: the plant species present in the research area, the surface they cover and the bare soil period (see Figures 2.3 and 2.4). For example, if in the research area, there is a wheat field of 10 hectares and a corn field of 20 hectares, account is taken of the fact that corn is twice the surface of wheat, and that wheat crop leaves the soil bare 250 days a year, whereas corn crop leaves the soil bare 260 days [SOG 61].

Satellite images have been combined with land surveys and recognition algorithms to produce a high-resolution vegetation cover map picturing the research area (pixels are 5.13 meters wide and 7.6 meters long). This is a reliable technique, yet inaccurate for two reasons: the confusion in the classification of pixels (wheat with barley, etc.) and the incorrect evaluation of the number of pixels within the same zone (the surface covered by a field). A table (error matrix [SAS 98]) puts into perspective these two aspects of inaccuracy and enables us to determine the inaccuracy of the vegetation cover index $C$.

### 2.4.4. Fuzzy parameters

Not all the parameters should be handled in the same way, because some of them are well-known (e.g. annual pluviometry), and others enable us to modify the scenario (such as $PAE$ or $PAR$). Therefore, here are the parameters chosen for our study:

- half life of the product ($T_{1/2}$);
- vegetation cover index ($C$);
- the soil organic carbon fraction ($f_{oc}$);
- the absorption coefficient poor in organic carbon of the product ($K_{oc}$).

These inaccurate parameters have been converted into fuzzy numbers to be integrated into the calculation of the indicator.
2.4.5. Representation of the indicator and of its related inaccuracy

It is difficult to create a representation of fuzzy numbers. However, it is possible to choose a subjective degree of likelihood that reflects the reliability of results. For example, there is a generally agreed-upon limit that corresponds to a 0.5 degree of
likelihood [BOU 95]. In order to avoid this subjective approach, we preferred to use *Mean Interval Confidence*: MIC [HIG 96, KAU 85]. The MIC takes into account the shape of the membership function. The lower boundary (see Figure 2.5) is calculated by deducting from the mode (the likelihood value of 1) the surface bounded by the membership function that is to the left of the mode. A similar calculation is applied to the upper boundary, by adding to the mode the surface at its right. Both values (lower and upper boundaries of the interval of confidence) are associated with the highest likelihood value: the mode itself.

These values are used to build three different maps: one relates to the lower values of the interval of confidence of the *VESPP* index for each watershed plot, a second relates to the upper values and the third one provides the maximum likelihood values (see Figure 2.5).

Figure 2.6 displays the differences of vulnerability to atrazine between the plots of the watershed of Vannetin. The watershed’s upper limit and the drainage system are also represented.

The results obtained are in accordance with the expected vulnerability. Indeed, the most vulnerable plots are located on the valley floor, near the drainage system.

The upper and lower boundaries of the interval of confidence provide a more accurate vision of the research area which, moreover, is consistent with the expected results. They lead to better information in support of decision-making, given that they identify the areas requiring further analysis for improved accuracy.

On the basis of the above, it is possible to build maps for other phytosanitary products or other climatic conditions (dry or wet year).

It is also possible to test “virtually” the impact of various development scenarios of the watershed (strips of grass, edges, etc.). As an example, Figure 2.7 displays the results relating to the watershed where erosion (*PAR* = 0.6) and runoff (*PAR* = 0.6) control practices would have been implemented on the most vulnerable plots. Compared to the results of Figure 2.6, it appears that a third of the cells have moved to another category, which proves that developing the most sensitive plots reduces the vulnerability of the watershed to atrazine.
2.5. Conclusion

The VESPP index, which enables us to assess the vulnerability of surface waters to phytosanitary products, is designed to be easy to use and to represent, as closely as possible, the transfer mechanisms of these products into the environment. It was shown that the coupled use of fuzzy arithmetic (to take into account the inaccuracy of some parameters) with a GIS for the index calculation is a simple way to assess the vulnerability of surface waters. Even without knowing the exact values of certain rates, it can inform us of the disparities of a watershed.
Figure 2.6. VESPP Mean Value or Mode (b), with the lower (a) and upper (c) limits of its related interval of confidence. All the areas are classified according to the same scale on the three maps (from the lighter to the darker): from 0 to 12,100 (low vulnerability); from 12,000 to 23,400 (vulnerable); 23,400 to 34,700 (mean vulnerability); from 34,700 to \( \infty \) (high vulnerability); E is the outlet of the watershed.
When applied to the basin of Vannetin, the VESPP index enabled us to identify the most sensitive areas and to visualize how certain developments could impact the vulnerability of only a part, or the whole research site.
Even though the results obtained appear consistent with respect to the trends, it is clear that vulnerability mapping, here produced on the basis of the *VESPP* index, must be cross-checked with observations at various points of the basin.

### 2.6. Bibliography


This page intentionally left blank
3.1. Introduction

The agricultural use of land to produce cereals and root crops (corn, beets, potatoes and oilseed and protein crop) can damage the physical environment with the appearance of different types of pollution within the local water resources. There are three main sources of disturbance:

– first of all, the socio-economic context of contemporary agriculture focuses on high levels of performance. Consequently, running field crops requires the use of inputs to manage soil fertility and plant health. These allochthonous substances are one of the sources of pollution contaminating downstream waters;

– secondly, the vegetal production-related cycles entail variations in soil cover that remains bare from seeding to germination or during intercrop periods. Bare soils are more sensitive to rain, which increases the likelihood of contaminant mobilization through runoff;

– thirdly, the optimization of agricultural production resources implies land reorganization (especially land development and drainage), which in turn tends to redefine the hydraulic operating rules of agricultural landscapes in watersheds.

The combination of these causes results in an accumulation of negative effects and generates different kinds of pollution, and many of them are widely covered by the media: water contamination by pesticides, fertilizers and sediments.

Chapter written by Philippe BOLO and Christophe BRACHET.
This chapter intends to demonstrate GIS operationality to manage different kinds of agricultural non-point source pollution. The potentialities of the tool, diagnostic approach and decision-making support are available using territorial data management. This management is presented and commented upon using the know-how resulting from studies carried out in this field by AQUALIS and ISL, two engineering firms.

Two types of water pollution are dealt with in this compendium of experience:
– water contamination by pesticides or fertilizers used for crop tending;
– water pollution by sediments due to soil water erosion.

From now on in this chapter, soil erosion process will be considered as non-point source pollution associated with agricultural activities.

The following considerations are particularly adapted to temperate-zone forests, but can also be generalized to other situations, such as erosion control in arid areas.

3.2. Mapping non-point source pollution phenomenon

3.2.1. Mapping principles

The nature and objectives of data processing introduced in this chapter provide information that can be used for a territory diagnosis approach: relative knowledge, at the watershed scale, of the zones of common influence of the various factors involved in pollution.

A GIS-based analysis of this phenomenon requires the mapping of the involved factors and processes.

The term mapping was voluntarily chosen, rather than modeling, in order to clearly define the potentialities of processing. Mapping refers to qualitative land evaluation, but does not provide any quantitative calculations on pollution. Indeed, quantitative pollution management requires mathematical models of production and transfer that are often difficult to build because of the important amount of data necessary to their calibrations.

Modeling approaches are particularly useful to study and better understand mechanisms. In this case, they can be applied to small areas. On the contrary, mapping offers an easily replicable qualitative diagnosis that can be generalized.
3.2.2. Description of the research phenomenon

Agricultural pollution of surface and underground waters directly results from the mobilization and transport of contaminants through runoff and infiltration. Figure 3.1 pictures water dynamics at the origin of pollutant transfers.

![Figure 3.1. Water dynamics at ground scale](image)

At ground scale, water can take many different paths:

– surface runoff appears when water storage is saturated, in the case of waterproof topsoil (surface sealing) or after heavy rain. Then, dissolved substances are carried away, and sometimes with erosion soil particles are detached (energy of the sheet of water is intense enough to detach particles from the soil surface);

– infiltration occurs when soil conditions allow vertical water flows to seep into the ground. Infiltration then consists of the migration of the mobilizable substances that were present on the land surfaces washed off by runoff, towards the saturated soil storage (and consequently into underground waters).

The parameters of the physical environment that influence the dynamics entailing surface water pollution are numerous and relate to various research fields:

– pedology (soil surface texture, hydromorphy, texture differentiation);

– topography (slope, presence of thalwegs).

Other anthropogenic parameters can be added to this list as they impact water transfers in watersheds (plot drainage, enclosure landscape management, soil work orientation, etc.).

3.2.3. Mapping steps

The physical processes at the origin of water pollution due to agricultural activities being known, we must now define the information mapping rules in order to integrate them into a GIS.
All the factors involved in this phenomenon are, on the first occasion, translated into a map. This step initiates the building of the territorial database and requires a preliminary strategic thinking to achieve success [AQU 98].

The system is designed to be multi-task (able to carry out different types of analyses without any intrinsic limitation to the data available in the base). The amount of processed data must also optimize query and processing response times. The system openness and usability are closely linked to the characteristics of a map (scale, graphic accuracy, legend entries, etc.) as well as to the method chosen to integrate them into the GIS.

Understanding the phenomenon of pollution enables us to understand the interaction modalities of the constituents of the database information layers. The nature of these interactions determines the characteristics of potential treatments.

The phenomenon of pollution thus corresponds to the combination of two distinctive and successive processes: the production and transfer of pollutants.

Production depends on the soil propensity to mobilize contaminants. In order to analyze production, relevant factors are chosen and conditioned by the type of non-point source pollution studied: pollution induced by agricultural inputs or by eroded sediments.

Transfer is determined by the hydraulic path taken by water between the producing area and the water resource. Accounting for preferential flow routes (ditch network and thalwegs) and runoff screens (grass buffer strips, edges and forested areas) led to transfer diagnosis.

3.3. Territorial database building rules

Here is a comprehensive description of the steps taken to build an operational territorial database for non-point source pollution risk diagnosis and management.

This database must be structured so as to make sure it will be used for territorial information exchanges between different decision-making structures (local authorities, public institutions, local environment and agriculture administrations, etc.). The implementation cost of such a database is rather high and its sustainability ensures a fast return on investment.

1. In the case of nitrate or pesticide pollution, this statement is based on the assumed reasoned use of inputs.
Before designing the database, it is of absolute necessity to account for various aspects that are at the very basis of any risk expert works.

3.3.1. Choosing software programs

GISs are information systems characterized by their ability to integrate a spatial dimension. The data to be processed do not only consist of attribute data but also of geographic data (being represented as points, lines or polygons). This characteristic can be managed with two different tools:

- GIS tools, for the management of digital graphic and cartographic objects;
- “relational database management systems” (RDBMS) software, for attribute information management.

Moreover, choosing two different tools ensures optimal use of their respective specificities and functionalities relating to information processing.

GIS software programs rely on conditional and function operators to carry out calculations and queries adapted to the graphic feature of the data:

- “object1 contains object2”;
- “object1 within object2”;
- “object1 intersects object2”;
- geometry calculations functions (distance, length, surface, etc.).

GIS software tools also offer functionalities to produce maps with thematic analyses (coloring and symbolization of objects via the analysis of the values taken by one of their descriptive variables).

RDBMS software programs are specialized in tabular data structuring and management. Their use enables us to develop search screens (reduction of data entry mistakes) and data integrity control functions. RDBMS have specific selection and aggregation operators, as well as functions adapted to statistical processing of information:

- “select expression1 from file where condition1 {=, <, > or <>} condition2 group by expression2”;
- the conditions can integrate different functions (statistical, mathematical, character string operators, etc.);
- statistical calculation functions (minimum, maximum, mean, standard deviation, etc.).
Choosing two software systems does not prevent us from combining graphic and tabular information if non-equivocal join fields characterize each entry in both respective areas.

3.3.2. Design of the implemented GIS

Figure 3.2 provides a summary of the recommended steps to build the databases necessary to the processing of information related to agricultural non-point source pollution.

All the graphic data are processed or imported into GIS ArcView\textsuperscript{TM} or MapInfo software. Access\textsuperscript{TM} or Excel\textsuperscript{TM} software programs integrate and manage the descriptive information of the map objects. These office automation tools were chosen because they are extensively used, which compensate for their lesser power compared to professional tools such as ArcInfo\textsuperscript{TM} and Oracle\textsuperscript{TM}.

This bipolar organization of information implies specific information structuring in order to ensure:

– operationality, usability and fast processing method;
– long-term sustainability and evolution of the system;
– compatibility with other GIS.

Geographic databases are structured into homogenous information layers. One layer can consist of a group of one type of objects (points, lines or polygons) describing a theme: therefore, they are digital files corresponding to collections of even map objects.

The attribute data are organized into tables. Such tables are a tabular representation, associated with a GIS layer, describing recorded features using several fields. A record (a row in the table) is associated with a map object of the corresponding GIS layer. The link between the record and the object is achieved using a non-equivocal identifier (each object and each record has a unique identifier within all of the GIS databases).
Figure 3.2. A model to structure information into the GIS
3.3.3. Organizing and creating geographic information layers

Two major steps ensure the integration of territorial information into the GIS:
– digitization of paper-based documents;
– digital data import.

These two methods are used to develop information layers associated with the agricultural non-point source pollution factors.

3.3.3.1. Implementation of a conceptual data model

This model defines how territorial information layers are integrated and organized into the GIS. Two parameters give each object a place in the overall model organization:
– its nature (the object can be represented by a point, a line or a surface);
– its theme (the object describes a specific type of information).

3.3.3.2. Digitization of paper-based document

Digitization targets all the factors for which there is a paper-based cartographic representation available, but no digital version. It is important to check, on every map, if there is any information relating to the map projection system (accurate identification and presence of control points) for they are essential data to be integrated into the GIS, and thus to be digitized.

The process used is as follows:
– to position the paper-based document on the digitizing table using coordinate points known by the map projection system chosen;
– to digitize objects. Digitization must be carried out according to the type of objects (points, lines or polygons) and take into account their thematic classification.

Digitization can be achieved “on the fly” (the model is called “spaghetti”): the lines and polygons are then digitized via straight and curved line segments the extremities of which meet or intersect. A specific processing corresponding to the topological construction is carried out on this raw file; it generates polygons and lines by deleting the overlapping extremities (deleting dangle arcs) and by merging the extremities of polylines with a distance lower than a threshold set by the user.

This topological construction also enables us to generate an information layer with a structure adapted to GIS-based usage.
3.3.3.3. Digital data import
Imports are used for the integration of territorial information layers that were managed and produced in other GIS projects. Imports relate to raster data (SCAN25® from the IGN, digital elevation models, scanned and georeferenced aerial photographs, satellite images, etc.) or to vector data (soil cover, land use, agricultural parcels, etc.).

3.3.3.4. Controlling the geographic data integrity
A series of controls have to be carried out to ensure the quality (in respect of the conceptual data model, this is particularly important) of developed or imported GIS layers. The most widely used tests are:
– checking the topological homogeneity of information layers;
– searching for double entries;
– calculating surface areas, perimeters, centroid coordinates;
– checking the non-equivocal nature of the map object identifier;
– validating the links with the associated attribute table.

3.3.4. Organizing and creating attribute tables
A table is created for each GIS layer.

3.3.4.1. Implementing a conceptual data model
The conceptual data model is used to characterize the links between the various tables. The links existing between the GIS layers are implicit since the software programs dedicated to their management can combine them in one geographic space.

The development of the conceptual data model consists of optimizing the structure of the attribute database. This optimization is essential to ensure the efficiency of the queries (by avoiding redundant information storage that monopolizes disk space and increases access time).

3.3.4.2. Creating a data dictionary
The data dictionary provides definitions of all the fields contained in each table of the attribute database. These definitions relate to the following points:
– the name of the field and a literal definition of the associated information;
– the type of variable used (integer, character, date, etc.);
– the list of modalities (with discrete information distribution) or the extreme values (with continuous information distribution) associated with the field;
3.3.4.3. **Thematic data processing or import**

Table records are based on the information processed from the paper documents (e.g. map legends) or imported from already existing digital files. The system proposed here is compatible with the most widely used formats: spreadsheets (xls files), databases (mdb or dbf files), word processing (ASCII files).

When necessary, data entry masks are developed with Access™ so as to facilitate the integration process of information.

3.3.4.4. **Controlling the attribute data integrity**

As for graphic data, a series of tests is carried out on each table in order to ensure its validity. These tests consist of:

- searching for double entries;
- checking formats and spelling;
- checking processing uniformity;
- checking the non-equivocal character of the record identifier;
- checking the links with the associated GIS layer.

3.4. **The data sources used**

3.4.1. **Identifying the available information**

Territorial data are not easily available. This is a priority issue to be resolved, and all the existing information related to the research site must be gathered prior to data integration [DUB 98]. The use of GIS techniques requires the availability of information sources or information that is readily transferable to a map.

The need for a map is determined by the results of an analysis carried out on various characteristics:

- the scale of the document;
- the system of map projection used, as well as the georeferencing capabilities (presence on the paper-based document of tick marks and figures associated with a grid);
- date of the information in the case of evolutionary data;
- complementary information to better understand the legend;
- the resolution of data stored in *raster* format (e.g. digital elevation models).
The identification of sources of usable information does not only depend on the characteristics of available maps; it also depends on various project-related parameters:

– the size of the research area delimiting the territory on which information are gathered;

– the plotting scale of the maps to be produced. The graphic accuracy of the input data must be compatible with this scale. Table 3.1 provides the range of scales compatible with the input data that are relevant to zoning risk projects.

<table>
<thead>
<tr>
<th>Plotting Scale</th>
<th>Minimal</th>
<th>Maximal</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Scale</td>
<td>1:1,500,000</td>
<td>1:1,000,000</td>
</tr>
<tr>
<td>1:1,000,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regional Scale</td>
<td>1:250,000</td>
<td>1:50,000</td>
</tr>
<tr>
<td>1:100,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local Scale</td>
<td>1:50,000</td>
<td>1:10,000</td>
</tr>
<tr>
<td>1:25,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Local Scale</td>
<td>1:25,000</td>
<td>1:5,000</td>
</tr>
<tr>
<td>1:10,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1. Range of scales compatible with project inputs and outputs

The input scale must also be coincident with the resolution of the raster plans developed to map risk zoning. The graphic quality of the edited maps directly depends on this resolution. Optimal quality is reached when the pixel size is less than a millimeter on the final maps; formula [3.1] determines the resolution to be chosen according to the plotting scale (where \( Re \) and \( Ec \) respectively correspond to the resolution expressed in meters and at map scale, a 1:25,000 fraction).

\[
Re \leq \frac{1}{1000.Ec}
\]  

3.4.2. Soil-related data

Some of the soil-related information is necessary to the schematization of water dynamics illustrated in Figure 3.1.
Data describing the types of soils present on a watershed are usually difficult to acquire; only a 1:1,000,000-scale cover describes all of the French territory (French soil database from the Agronomic Research National Institute – INRA). Apart from this single national source of information, scattered research, more or less accessible and varying in scale, can be used.

If there are no local soil maps available, it is then possible, within the limits of the characteristics that are relevant to risk zoning (surface texture, hydromorphy and texture differentiation) to extrapolate information with the support of an expert and relying on different documents (topographic and geological maps) and on some analysis-based recognition.

A survey was carried out among different competent authorities (Departmental and Regional Chambers of Agriculture and Forest, Agronomic Research National Institute, etc.) to identify the information sources that could potentially be used; their analysis quickly emphasized their operational nature.

The cartographic document selected was integrated into the GIS under the form of a vectorial layer describing the limits of the different soil units. Then, this baseline is converted into three vectorial geographic information layers defined in the following sections.

3.4.2.1. Surface texture of the soils

The surface texture of the soils is a key parameter for runoff diagnosis. The texture is used to quantify the vulnerability of the soils to smearing.

Soil smearing is characterized by the sealing of the surface microporosity resulting from the impact of rainfall. The kinetic energy of raindrops falling on the soil entails projections of the finest surface particles all around (splash effect). The sedimentation of these particles in the runoff flow occurring in the low areas of soil micro-relief results in the formation of a thin waterproof layer. Soil smearing vulnerability (especially defined by its silt content) impacts the outcome of water and runoff.

The use of a smearing calculation formula implies that we have information available on soil size distribution and on organic matter content (information punctually known from analyzing soils).

Therefore, characterizing soil smearing depends on the surface texture analysis. The method consists of identifying, according to the Jamagne triangle, the texture classes that are most likely to cause smearing (Figure 3.3 contains definitions for soil smearing: predominantly silty textures).
3.4.2.2. Soil hydromorphy

Hydromorphy is integrated into the processing to simulate surface runoff that will form on the surface of soils during long rainy periods. Hydromorphic soils are characterized by surface runoff since they are saturated and do not allow water to infiltrate the ground (saturation of the active storage).

A soil is said to be hydromorphic as soon as it shows signs of hydromorphy (occurrence of redox reactions under reduced conditions and associated with clogging) under 30 cm deep.

3.4.2.3. Soil textural differentiation

Textural differentiation enables us to integrate in the analysis the soils with a profile characterized by discontinuities in the permeability. This vertical variation results in a subhorizontal circulation (hypodermic runoff) at the permeable subsurface horizon (e.g. at the less or low permeable horizon interface). This phenomenon entails changes in vertical water transfers that change direction towards surface waters.
The causes inducing textural differentiations related to soil profile are numerous:
- physico-chemical alteration of the bedrock entailing the formation of a horizon containing more clay;
- outcropping, below the topsoil and the bedrock (this is the case for thin soils developing on slopes and on little altered and waterproof substratum);
- deep leaching of clay during the pedogenesis process;
- deep soil compacting induced by the agricultural works in large cropping farms.

This last point results from anthropogenic activities that are impossible to identify with only a soil map.

Valley floor soils must also be mentioned, for through their hydraulic relationships with nearby streams (leveling the water table during periods of high water) they follow the same process. Even though these soils do not present texture differentiations, it is important to take them into account so as to integrate the existence of horizontal underground circulation, associated with table water dynamics into the schematization.

### 3.4.3. Topography-related data

Topography is integrated in the analysis via a digital elevation model (DEM) in raster format. The related file provides the altimetric information in a raster model. Considerations relative to the choice made for the DEM resolution have been discussed in section 3.4.1.

There are different ways to obtain a DEM:
- the processing of contour lines and spot elevations transferred on the 1:25,000-scale IGN maps or integrated into the BD TOPO®;
- ordering DEM produced by the IGN (BD ALTI®) and available with different resolutions (50 m, 75 m, 100 m, 200 m, 250 m, 500 m or 1,000 m);
- field measurements carried out with the use of tacheometry of Global Positioning System (GPS) technologies;
- stereoscopic processing of aerial or satellite photographs;
- flying over the research zone and measuring the altimetry via a laser scanography.

Choosing one of these methods depends on the size of the research area, the expected accuracy and the budget available to carry out the non-point source pollution diagnosis.
The issues associated with agricultural non-point source pollution management are usually tackled with DEM resulting from the processing of IGN 1:25,000-scale map information. The advantage with medium-scale topographic information is that it is available nationwide.

Vectorial contour processing, required to produce raster DEM, is carried out by applying an algorithm developed by AQUALIS and ISL. It performs an interpolation for each node of the mesh model, of the information given on all the contours. The algorithm makes a choice between two interpolators according to the topographic position of the point analyzed:

- in slope areas (hills, thalwegs, etc.), altimetry is obtained by linear interpolation based on the slope line (established on the four axis directions of the Cartesian system and on their bisecting lines);
- in low slope areas (valley floor, plateau, etc.), altimetry is obtained by polynomial interpolation. Polynomial constants are calculated, based on the four directions defined previously, by adjustments to the contour lines and constraint lines (drainage system and reference ridge lines). A weighting is applied in order to obtain one single altitude value among the four interpolated results.

Altimetry is not directly used in the diagnosis and management process of agricultural non-point source pollution. Two derived raster plans, described below, were produced to analyze the phenomenon.

3.4.3.1. The slope

Unlike floodplain mapping due to overflowing watercourses, it is not the altitude accuracy, but slope accuracy that determines the relevance of the results obtained.

The notion of slope enables us to account for the impact of the terrain gradient on runoff, and thus the transfer of pollutants in surface waters. The slope value accentuates the runoff phenomenon but is not universal and must be reassessed according to the characteristics of the basin studied. The choice for a critical value must also rely upon previous works, as well as upon local experts’ advice.

3.4.3.2. Slope orientation

The slope orientation makes it possible to assess the evolution of runoff generated in a watershed. The slope orientation, obtained from the DEM exploitation, takes into account only the natural terrain and excludes all the

\[1\text{. It is important to precise that there is a fee to be paid to the IGN for scanning or vectorizing.}\]
topographic micro-variations related to human activities (bank, orientation of the water furrows or rows, paths, roads, etc.).

Using DEM integrating macro- and micro-topography requires deploying technical and financial means that are not in accordance with the global and integrated approach presented in this chapter. Yet, the production of such DEM is an interesting source of information for research works applied to limited areas and focusing on the involved physical mechanisms.

The slope orientation is also used in the production of the vectorial plan representing the thalweg-related flow model. This information layer identifies all the runoff concentration axes and completes the permanent or temporary water system transferred on the 1:25,000-scale IGN maps. Knowing these concentration axes is essential to assess risks related to non-point source pollution. Indeed, they represent priority pollution transfer pathways and axes of erosion occurrence.

3.4.4. Land use-related data

The land use-related vectorial plan is produced through the interpretation of aerial photographs. Satellite images and existing databases (e.g. BD CORINE land cover® provided by the French Institute for Environment) can be substituted for aerial photographs. Each source of data has its own characteristics (acquisition cost, necessary technicity to ensure integration and processing, graphic and thematic accuracy). Here, it is also imperative to choose the most suitable information.

All of the French territory is covered by a more or less recent aerial photo gallery (updated about every five years) of various scales (usually 1:25,000 and 1:30,000).3

The different land use stations can be identified through photo interpretation. The quality of the photos and the type of film used (panchromatic, color, black and white or false-color infrared) impact mapping quality. An optimal discrimination of agricultural posts (differentiation of the different field crops from permanent and temporary meadows) can be achieved with the parallel use of photographs on different supports and at different dates.

Two techniques can be used to integrate photo-interpretation works:

- Graticulation consists of reporting, on layers superimposed over aerial photographs, photo-interpreted graphic elements. The IGN base map (produced from SCAN 25® files for instance) is printed on the layers at the photo scale. This base map is then used to position the layer on the photographs with the points of reference that are common and identifiable on both documents. The land use limits are drawn within equal-sized virtual squares dividing the photograph. This approach involves geometric correction to avoid intrinsic distortion of aerial photographs

3. Searchable and available at the national photo library of the IGN.
(distortion due to the camera optics and the pitch and roll of the plane). This draft map is then digitized following the procedures described in section 3.3.3.2 and based on the ticks of the map projection system that can be seen on the IGN base map;

- creation of digital orthophotography in order to ensure computer-based photo interpretation. First of all, this technique requires the digitization of the aerial photographs. Then, the generated files go through a series of processings (geometric corrections, georeferencing and then mosaicking) that are achieved by specialized software programs. At this stage, the land use limits can be directly drawn on the screen, manually or automatically according to the GIS software capabilities.

Both techniques provide a good graphic accuracy of the land use map if the critical steps are carefully carried out (draft map digitization or georeferencing according to standard procedures). The quality of the accuracy can be compared to the scale of the photographs used.

The photo-interpreted land-use map does not single out graphic units associated with cadastral parcels but groups all the adjacent surfaces that are used identically during an agricultural season (these homogenous units are defined as “cultural units”).

The stations identified according to the territory land use must support risk management and diagnosis. This is why it is important to distinguish between annual field crops and temporary or permanent meadows.

Field crops are associated with surfaces where ground care products and plant protection products are used and which, if they are mobilized, contribute to surface water pollution. Field crop parcels are also vulnerable to runoff and to the resulting water erosion (and consequently to the transfer of sediments to surface waters).

On the contrary, permanent meadows are watershed surfaces that participate in the reduction of agricultural non-point source pollution transfer.4

Temporary meadows are surfaces covered with grass during crop rotation. Registering their position allows us to identify the associated areas such as zones where the risk level might undergo relatively long-term changes. This process is the reverse for field crops, for which the diagnosis of non-point source pollution identifies risk situations that can only decrease due to grass-cover.

Forest areas are also important surfaces to be taken into account since they participate in controlling the non-point source pollution phenomenon as they constitute a shield to runoff in the whole watershed.

4. The pollution associated with the waste of animals grazing in pastures is not taken into account in this chapter.
The thematic database associated with the land use map can be completed with
information useful to the analysis (row orientation, planting of a catch crop, plot size
– notion of slope length – use of simplified cultural techniques, etc.). The use of
such information is not systematic and depends on their availability, the size of the
research area, the targeted objectives, etc.

### 3.4.5. Land planning-related data

Forested and grass-covered areas have been introduced as elements involved in
controlling pollutant transfer from the growing areas to the surface water resources.
Other elements from the territory also play a similar role in contributing to the
reduction or increase of water connections within watersheds. These land planning-
related elements are presented in the following sections.

#### 3.4.5.1. Hedges

Hedges act as barriers to runoff. It is absolutely necessary to take them into
account (through the creation of a geographic information vector layer) in order to
identify future water transfers.

Hedge surveying is achieved using interpreting aerial photographs, but it is
impossible to classify them according to a typology associated with features
concerning runoff interception (hedges planted on raised beds or on flat ground,
planting density, etc.). Identifying these features entails a time-expensive
observation of the terrain (the necessity of which depends on the objectives and
context of the study).

#### 3.4.5.2. Ditches

The creation of ditches for water drainage or runoff discharge must be
considered as preferential flow and transfer routes towards aquatic resources.

Ditch surveying (in order to produce a vector information plan) is often difficult
to carry out.

These land planning elements are not visible on aerial photographs that are
available at the scales of 1:25,000 and 1:30,000. Their photo-interpretation requires
the use of photographs gathered during flight observations specifically planned for
the study and at the minimum scale of 1:2,500. This condition can only be satisfied
for some specific studies.

Another source of information, useful for locating ditches, corresponds to the
study reports dealing with reparcelling works. These documents are not
systematically available for several reasons:

– certain real-estate clauses used in reparcelling (e.g. exchange of rural
  immovable property) do not need specific studies;
the first regrouping of land parcels occurred before diagnosis on parcel planning was required by law. Since 1976, an impact analysis has been a prerequisite. Since the Water Act in 1995, it has been necessary to add a section detailing the initial state prior to the regrouping of land;

After a variable delay, the analysis records are transferred to the departmental archives, and then become difficult to search;

acquiring information on the ditch network after the regrouping of land requires access to the as-built drawings of the waterpower developments related to land assembly.

The key to comprehensive surveying of ditches consists of observing the terrain (the use of this approach also depends on the context and objectives of the study).

3.4.5.3. Agricultural land drainage

Agricultural drainage is a disruptive development for natural water flows at the scale of agricultural plots. The network of subsurface drains diverts a large part of the water flows running in the soil (which is one of the goals of such agronomic drainage techniques of wetlands).

Inventorying drained lands is a difficult process since the process is not recorded in any database. The use of aerial photographs is possible if several conditions are met:

- photographs taken at a specific date allowing the visualization of the drain-related impacts on vegetation;
- photographs taken before the outward signs of drain developments on the soil surface disappear;
- use of photographs at a scale greater than 1:10,000.

These requirements are never fully satisfied with available aerial photographs taken during the summer to benefit from optimal lighting and visibility conditions. If the planning of a specific flight mission is not affordable, aerial photographs should not be used.

A more reliable technique dedicated to the positioning of drained plots is based upon the knowledge of local experts (farmers, presidents of official drainage trade union organizations, agricultural contractors, and state services). These experts are able to locate drained plots with only a limited accuracy because:

- they are not always regular users of IGN or cadastral maps;
- collective memory is not always reliable.

Therefore, it is essential to assess the accuracy of the drainage map produced. This can be done by comparing the part of the used agricultural area drained and recorded in the local or departmental statistics available from the rural development
services of the agricultural administration. The General Farm Survey carried out in 2000 is very useful to define the extent to which the drainage survey is exhaustive. The resulting mapping is then used to build the vector plan describing the drainage pattern.

3.5. Pollution risk zoning

First the diagnosis, and then the management of agricultural non-point source pollution at the scale of a watershed is based on the localization of risk areas. Various risk scenarios can be analyzed:

- surface water pollution risks arising from the transfer of pesticides or nitrates;
- risk of surface water quality degradation arising from the transfer of sediment mobilized by soil water erosion.

Other types of risk, which are not detailed in this chapter, can be analyzed with similar approaches. For instance, risks related to soil “patrimony” loss (e.g. in vineyards) or to floods due to mudflows [ISL 01]. Risks regarding aquifers can also be analyzed.

3.5.1. Treatments to be performed

Risk zoning consists of combining, with the help of a GIS, territorial information describing non-point source pollution production and transfer processes.

Therefore, risk zoning results from a treatment chain characterized by three main steps:

- zoning of the potential for pollution;
- vulnerability zoning;
- geographic combination of the potential for pollution and vulnerability defining risk.

3.5.1.1. Zoning of the potential for pollution

Zoning of the potential for pollution seeks to divide the research watershed territory into homogenous geographic units on the basis of the accumulation of factors contributing to non-point source pollution.

The first step characterizes the potential for pollution. It requires a clear list of the factors contributing to the production of the pollution at stake (silt soils, hydromorphic soils, slopes exceeding a critical threshold, etc.).

The information layers associated with the selected factors are transformed into raster plans, and then reclassified on a binary scheme: zones without factor (0), and zones with factor (1). At this stage, zoning the potential for pollution is obtained through the addition of all the raster information layers. The result of this addition,
calculated at each node of the matrix model, is called the score. The score defines the number of factors involved in the production of pollution (a score of 3 consists of an accumulation of three factors).

Scores are grouped into classes (e.g. low, mean or high potential) so as to achieve mapping.

When pluviometry is taken into account, it is possible to translate the potential for pollution into hazard. The latter emphasizes the random nature of the water contamination phenomenon that is governed by statistical temporal distribution laws of pluviometry. Consequently, knowing the hazard requires a hydrological analysis, as well as a rainfall frequency analysis.

3.5.1.2. Vulnerability zoning

Different kinds of vulnerability can be defined according to the type of pollution studied. Vulnerability relates to surface waters in the case of pollution by pesticides, nitrates or sediments (alteration of water quality due to contamination). In other contexts, vulnerability can also be related to:

- cultivated soils in the case of water erosion (decrease in the agronomic value of eroded soils);
- property and persons (buildings, roads and other infrastructures) in the case of floods due to mudflows.

Paths are an important element to take into account, as they constitute, depending on their slope inclination, preferential flow vectors.

With regard to studies targeting river pollution, vulnerability zoning aims at identifying the watershed areas that have hydraulic connections with surface waters (drained plots; terrain on which runoff flows into the hydrographic network, thalweg or ditch beds, etc.). This identification allows us to integrate the notion of pollution transfer with vulnerability.

Areas having hydraulic connections with the hydrographic network are delimited through the simultaneous processing of slope orientation and of information plans illustrating flows (edges, ditches, thalwegs, etc.).

3.5.1.3. Risk zoning

Pollution risk zoning is obtained through the combination of the potential for pollution and vulnerability.

Risk zones are territory areas where the pollution produced is transferred to surface waters from the moment rain induces the mechanism.

Different risk levels can be mapped by defining adequate grids combining the pollution potential and vulnerability.
3.5.2. An example of risk zoning

The potentialities introduced in the previous sections will be illustrated through the results of work carried out by AQUALIS for the regional chamber of agriculture in Pays-de-la-Loire [AQU 01].

3.5.2.1 General presentation of the research area

The research area is the watershed of Montanger, which has a total surface of 655 hectares. Montanger is an influent of the right bank of the Mayenne, which is 2 km north of the town of Mayenne (the sub-prefecture of the department holding the same name).

The type of agriculture practiced in the watershed consists of field crops (cereals, colza and corn silage) and meadows dedicated to pastures for dairy herds.

These vegetal crops grow on silty soil surfaces resulting from Brioverian schist degradation (Precambrian rocks). This situation characterizes more than 80% of the soil in the watershed.

The topographic relief is uneven (extreme altitudes range from 85 to 175 meters) with a succession of narrow plateaus indented by thalwegs where a temporary or permanent water network runs. Steep slopes are associated with this relief; 6% slopes are the most common, and, but 80% of the territory consists of slopes exceeding 4%.

Pluviometry measured on this northern part of the Mayenne rises to 830 mm for 175 rainy days (averages calculated between 1965 and 1994). The annual rainfall pattern is characterized by a typical particularity of the regions of the Great West: pluviometry observed in May is comparable to the winter months.

Findings related to agriculture, soil, topography and pluviometry reveal that the watershed presents favorable conditions to the emergence and transfer non-point source pollution. The following sections will demonstrate how the implementation of a GIS enables us to analyze and manage this risk situation.

3.5.2.2. Knowing the risks

Zoning of the potential for pollution is obtained by combining geographic information plans in a grid described in Table 3.2.

This grid outlines the pollution phenomena that occur from the beginning of October to the end of March (water storage is saturated due to a surplus in the water budget). In order to build a representative scenario of runoff resulting from heavy rainfall on non-saturated soils, factors and marks are modulated. Similarly, combinations can be carried out so as to take into account the pesticide chemical properties for instance (dissolved or absorbed transfer) [AOU 99b].
Table 3.2 illustrates a scenario that discards anthropogenic amplification factors (especially the localization of field crops). On account of this, the grid here only displays the risks representative of the physical environment. Taking into account anthropogenic factors has the disadvantage of freezing risk zoning in time through a correlation with crop rotations described in land use maps. Yet, this problem can be overcome by integrating the crop rotation practices on the research area.

The values of the scores (the sum of the marks) range from 0 to 4 (absence to presence of all the factors taken into account). The raster plan resulting from the combination of the four information layers characterizes the pollution potential through the following codification:

- score = 0, very low potential;
- score = 1, low potential;
- score = 2, average potential;
- score = 3 or 4, high potential.

5. The mark illustrates the contribution of the modality to the potential for non-point pollution production.
Vulnerability is obtained by combining slope orientations with descriptive information plans:
- hedges;
- meadows;
- woods;
- thalwegs;
- water areas;
- hydrographic network;
- drained plots.

Ditches are discarded because the information necessary to their localization is not available for the Montanger watershed.

The result of the calculation leads to the identification of specific zones of the territory that have hydraulic connections with waterways: runoff transferred to rivers through clear routes at a working scale of 1:10,000. Figure 3.4 provides the location of vulnerable zones, the total area of which is 257 hectares (39% of the watershed surface).

Risk zoning is obtained by combining the potential for pollution and vulnerability. The first step defines the combination interpretation rules of the two raster plans (see Table 3.3).
Risk zoning is obtained by combining the potential for pollution and vulnerability. The first step defines the combination interpretation rules of the two raster plans (see Table 3.3).

<table>
<thead>
<tr>
<th>Potential for Pollution</th>
<th>Vulnerable Zone</th>
<th>Non-vulnerable Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
<td>No Risk</td>
<td>No Risk</td>
</tr>
<tr>
<td>Low</td>
<td>Low Risk</td>
<td>No Risk</td>
</tr>
<tr>
<td>Average</td>
<td>Average Risk</td>
<td>No Risk</td>
</tr>
<tr>
<td>High</td>
<td>High Risk</td>
<td>No Risk</td>
</tr>
</tbody>
</table>

Table 3.3. Risk zoning grid

Figure 3.5 presents the risk zoning map resulting from the treatment previously described.

Figure 3.5. Risk zone map
Zoning is first used for risk class planimetry (see Table 3.4).

<table>
<thead>
<tr>
<th>Risk Class</th>
<th>Surface (hectares)</th>
<th>Part of the Watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>27</td>
<td>4%</td>
</tr>
<tr>
<td>Average</td>
<td>120</td>
<td>18%</td>
</tr>
<tr>
<td>High</td>
<td>103</td>
<td>16%</td>
</tr>
</tbody>
</table>

Table 3.4. Risk zone surface

3.5.2.3. Transfer diagnosis

The vulnerable zone map identifies the areas having hydraulic connections with surface waters. It can also be processed to display the transfer routes (runoff heading straight through surface waters, transit via a thalweg or the subsurface drain network).

On the contrary, the non-vulnerable zones emphasize the areas in which exported runoff meets with an obstacle during its course, such as a hedge, a wood or a meadow. This information is very useful to diagnose the structure of the enclosure landscape. Table 3.5 provides the surfaces of the pollution zones intercepted by each type of shield.

<table>
<thead>
<tr>
<th>Pollution Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low</td>
</tr>
<tr>
<td>Shield</td>
</tr>
<tr>
<td>Hedges</td>
</tr>
<tr>
<td>Meadows</td>
</tr>
<tr>
<td>Woods</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

Table 3.5. Influence of obstacles regarding the control of the potential for pollution

6. IS for Intercepted Surface.
7. Tot % for percentage of the total of the potential class.
The previous statistics are useful for the diagnosis of the enclosure mesh pattern through various indicators:

- meadows appear, under the column Shield, to provide the most efficient control to the potentials for pollution (all classes taken together);
- the combination of hedges and meadows intercept the flows occurring on 56% of the watershed territory;
- the “high” potential for pollution remains quite uncontrolled by the combination of the three types of shield against runoff.

It is essential to stress the fact that the conclusions drawn here are only valid at the chosen working scale (here 1:10,000) and without taking into account the ditch network. The real situation is certainly more complex for ditches, which bypass the flows that the map identifies as converging toward a specific shield.

However, this approach should be considered as helpful in the assessment of the potential effects of different management and development scenarios of the enclosure landscape. This tool also enables us to emphasize problems through the identification of certain zones that requires terrain investigations to make an informed decision on restructuring the enclosure landscape.

3.5.2.4. Risk management

Risk zoning is especially used to formulate management measures [AQU 00]. Recommendations must be applicable at the scale of the agricultural plot (an agronomic production unit that can gather several cadastral parcels). In-field measures are not economically adapted; apart from the solutions available with precision farming.

The definition of the risk to the plot precedes any recommendations. Figure 3.6 is an example of parcel risk map.

Zoning discretization is achieved by associating each plot with the most widespread risk factor to be found in it. A code completes the graphic information by identifying the production and transfer factors behind the risk.
The first part of the code is related to the risk (low $f$, average $m$ or high $Fo$). The second part, a succession of four figures (0/1), indicates the presence (1) or absence (0) of the factors governing the production (in the following order: slope greater than 3%, silty soils, hydromorphic soils and presence of a waterproof horizon). The last part deals with the outcome of runoff (thalwegs $t$, hydrographic network $h$ or water area $pe$) and with the potential presence of drainage $d$.

These codes are used to associate each parcel with suitable recommendations: to use simplified cultural techniques, to plant catch crops, to establish strips of grass, etc.

The validation of the recommended guidelines is obtained by assessing the raw water analysis results at the watershed outlets. The study of the evolution of the concentration of various parameters in time confirms the forms of pollution, as well as the forms of recommended guidelines.

3.6. Risk zoning applications

The main objective of risk zoning is to provide synthetic information for agricultural non-point source pollution diagnosis and management. This information
is synthetic since it results from the combination of different information plans describing the mechanisms involved in the phenomenon.

The diagnosis consists of evaluating the risk intensity and spatial pattern. Management must provide various solutions to reduce the watershed-related overall risk.

### 3.6.1. Risk knowledge applications

Knowledge of the characteristics of the risk zones is the first application of the results obtained. It is the fundamental preface to the definition of corrective measures by acting on the “production” component of pollution.

Mapping the risk zones can be completed with information provided by the GIS. Then, on the basis of land use knowledge, it is possible to promote parcel measures to be applied to “field crop” surfaces, so as to reduce the non-point source pollution consequences:

- phytosanitary treatment planning to limit the potential transfer to surface waters;
- establishment of a vegetative cover in intercropping system to reduce winter runoff impacts;
- adoption of simplified cultural techniques to protect soil structure, and thus, reduce erosion risks.

The value of GIS-based data processing lies in the possibility of calculating statistics that describe the different risk classes, according to variable geographic aggregation scales (sub-watershed, district, perimeter protection, etc.).

### 3.6.2. Spatial planning applications

Risk zoning is also a key element in supporting the assessment of the effects of the corrective measures proposed to act on the pollution “transfer” component.

The control of transfers is based on a catalog of specific measures [SOL 01]:

- establishment of strips of grass, or meadows (grassed buffers);
- establishment of wooded zones or hedges (wooded buffers);
- establishment of retaining walls and small ditches (hydraulic buffers).

In extreme situations with mudflow events, the complementary building of bigger structures such as retention ponds might become an absolute necessity.

In order to be optimized, the buffers mentioned above must be positioned in a topographic situation corresponding to zones of flow transit or concentration (bottom of plots, thalwegs, water banks, etc.).
The theoretical efficiency of a buffer can be assessed based on the knowledge of the areas where it intercepts the flows. This analysis is obtained by simultaneously exploiting the DEM and plans displaying the location of flow routes and buffers in the field. The risk zone area, calculated within the zone controlled by the buffer, allows us to evaluate the efficiency of the latter. Several positioning scenarios are compared to decide upon the most effective one.

The study of the impacts of buffer reorganization to control runoff can be carried out similarly (comparing vulnerable zone areas before and after developments). The use of GIS provides numerous perspectives to support decision-making relating to the establishment, reorganization and upkeep of runoff buffers [AQU 99a].

3.6.3. Applications related to monitoring water quality

The patrimonial management of surface water resources is based on the deployment of measuring station networks dedicated to monitoring quality over time.

Regular tests on raw water samples in each of these stations allow us to measure the different parameters behind quality assessment. Determinations are expensive (particularly pesticides) and the adequacy of the measures implemented, in terms of qualitative management of the resource, is closely linked to the positioning of the stations.

The samples collected correspond to the waters that drain the watershed, connected to the hydrographic network above the stations. The substances sought in raw waters, which can be quantified, reflect the activities and phenomena observable at the scale of this hydrologic coherent unit.

It reveals how important the position of the measuring stations is. They must be representative of the territory on which can be found the practices behind the water quality degradation.

When the stations are non-oriented (e.g. established regularly along the hydrographic network) they may bring to light different forms of pollution. This strategy has the potential to excessively exacerbate certain problems and, on the other hand, to obviate some others.

The use of GIS is very helpful in this field. It is possible to calculate, for a hypothetical localization of a station, an overall risk level associated with agricultural non-source point pollution. Then various positioning scenarios can be considered and compared on the basis of the statistics provided by the tool. Finally, the most representative situation of the research environment will be chosen.
3.7. Conclusion

Due to agricultural activities, the pollution of aquatic resources is governed by different factors related to physical environment (pluviometry, topography and pedology) and anthropogenic actions (land use, parcel characteristics and hydraulic developments). These factors are characterized by spatial variations; evaluating their combined influence is complex but facilitated by the implementation and use of a GIS.

This technical solution suggests we take a close look at the key steps, which are decisive in the success of the projects.

The analysis zone and the required accuracy allow us to define a working scale determining the effort of research, of compilation and of integration of information in the GIS.

The adequacy of the diagnoses carried out is directly related to the selected scale. Indeed, there are some inaccuracies in the cartographic representations of the themes integrated into the GIS and their causes are manifold:

- data variations can appear according to spatial extensions, which make their cartographic representation impossible at a given scale;
- the limits of the homogenous unit are of relative accuracy.

These uncertainties entail errors in the risk map, but can be bypassed by choosing an appropriate scale representing the results obtained.

Information accuracy impacts the interpretation of the results. Thus, assessing the effects of runoff buffers is a primary step, and does not dispense from complementary expertises. For instance, DEM created from the contour lines of 1:25,000-scale IGN maps only display the topographic variations associated with the regional relief. Micro-variations are not taken into account even though they do impact water flows.

Consequently, the results provided by the GIS should be considered as part of an approach supporting the overall management of pollution at the watershed scale. It thus becomes possible to:

- locate the main risk zones;
- define the risk area components;
- know about the associated land use.

The hydrographic research unit can be thus divided into sub-basins that will be managed differentially according to their respective risk levels. Complementary inquiries can be carried out on the sub-basins having the most important high-risk surfaces.
Indeed, GIS tools elevate the analysis above the channels defining policies dedicated to the restoration of surface water quality.

3.8. Bibliography


Chapter 4

Cartographic Index and History of Road Sites that Face Natural Hazards in the Province of Turin

4.1. Introduction

When investigating themes such as land management and physical planning, there is an ever growing interest in road safety issues related to potential risks of landslides, snow avalanches and flash floods. Indeed, in recent years in Italy, statistics have revealed a significant increase in victims of road accidents related to natural factors, often said to be “unpredictable”, such as fast-evolving landslides, sudden severe floods and river flooding. These facts mainly result from the growing number of road users who increasingly drive to get to work or to leisure activities.

Roads are the sites the most vulnerable to exceptional fluvial and torrential events, and to slope dynamics. Moreover, roads, and especially secondary tracks, which are the most developed type of road in mountain valleys, are highly complex infrastructures difficult to protect satisfactorily. This issue is even more important in the sense that in the early stages of the crisis, these secondary tracks might be the only route to reach the disaster-stricken isolated communities.

Chapter written by Paola ALLEGRA, Laura TURCONI and Domenico TROPEANO.
Figure 4.1. Examples of torrential risks threatening some stretches of mountain roads: (a) a road covered with floating debris after a flood due to overflows; (b) a road covered with large debris carried by torrential lava; (c) road washed out by lateral erosion
4.2. Principal risks

In all alpine valleys, along the tributaries of the main stream, torrential events often occur, during which one of the key roles is played by the substantial amounts of solid materials carried by the floodwaters. Overall volumes are difficult to predict because very few measurements have been achieved with appropriate instruments. Many a time, the maximum height reached by liquid and solid mixtures was 4-5 times higher than the predictions obtained through calculation processes used in flood forecasting, which did not take into account any solid flows. For decades, drainage channels have been calibrated according to the liquid flood flows, but they are wrongly believed to be adapted to their functions at all times. The mechanisms at the origin of the torrential processes in low-rank watersheds are not well known and accurate hydrometric data, necessary to develop forecasting models, are rarely available. This is the reason why the proper sizing of torrential watercourse crossings, which sometimes carry large solid debris, is very challenging in the planning phase of projects (see Figure 4.1).

With respect to slope instability (road alignments on the valley floor and especially at mid-slope) a key security issue is related to the occurrence of fast-evolving landslides. In most cases, mudflows and superficial landslides result from severe and/or persistent rainfall. In such situations, the adverse meteorological conditions deter people from driving, and fortunately, automobile accident data reveals very few serious injuries to passengers. On the contrary, large rockfalls caused by the collapse of rock walls or scree slides are largely unpredictable and occur unexpectedly along various road alignments.

Moreover, as demonstrated in many other cases, roads can negatively impact slope instability [FRA 69, TRO 83], valley floors and stream crossings [ANS 80]; this is the paradox of roadways: a source of damage rather than a strategic and reliable means for the first respondents to reach the accident site.

Our research study includes a collaboration, which started in 1998, between the CNR/IRPI of Turin and the civil security service of the administration of the province of Turin [ALL 98]. We understood the urgency of the need to develop a research method dedicated to provide simple and flexible means, through scientific knowledge, to plan the management of roadway sites vulnerable to natural hazard-related risks at the scale of the territory. The main objective of this mission was to ensure the security of roadway structures in the alpine region of the province of Turin. To do so, we developed a spatially referenced database on the basis of 1:10,000-scale engineering maps providing the following elements: date of event, typology, location of the phenomenon, size and consequences, as well as indications on its spatial and temporal frequency. All the sites, recorded in the historical knowledge base, reporting damage at least once and/or more severe than others are
identified. Then, they are compared with the current situation and the required developments to make roads fit for traffic, so as to make informed decisions on necessary interventions to implement security, that is, to reduce potential risks to an “acceptable” level. This last step is carried out using probabilistic considerations related to scenarios based on geomorphological and geotechnical data.

4.3. Research area

The study focuses on several watersheds in the Western Piedmont Region, which, according to their geological, geomorphologic and land use characteristics, are representative of the instability phenomenon described above. The research area includes the Lanzon valley (Val Grande, Val de Ala and Val de Viù), Val de Suse, Val Sangone, Cluson and Germanasca valleys, and Val Pellice. These valleys are very different from one another, and this is why they were chosen to represent the different issues in this territory. All these valleys are run through by a main stream towards which many tributaries converge, carrying large amounts of water and solid materials. In doing so, these tributaries greatly increase the main stream flow and cause, within the limits of carrying capacity of the stream bed, significant changes in the solid load distribution within the bed itself.

4.3.1. Geological insight

In the Western Alps, between the Lanzo and Pô valleys, there are two geologically distinctive zones: the Dora-Maira Mountains and the green Calschists complex or Piedmont zone. The Dora-Maira Mountains spread from the Eastern plain to the Western Piedmont area, and are bounded to the north and south by the Dora and Maira rivers. This consists of varied metamorphic rocks; among the predominant types of rocks, gneiss and micaschists can be found, associated with quartzites, marbles and a few amphibolites. The Piedmont zone also consists of heterogenous metamorphic rocks, which vary in age and chemical composition from those found on the Dora-Maira Mountains.

Three sequences, differing in lithological composition and structure, can be distinguished within the Piedmont area: a carbonatic series of the Triassic formation, a strong carbonatic and clay series of Jurassic age and an eruptive sequence consisting of green ophiolites (or green rocks) usually associated with calschist (or shiny schist). The Triassic sequence, which is more or less present all along the connection between the Dora-Maira Mountains and the green calschist, reaches its major expansion in the Pellice-Pô divide. In the Piedmont area, during the alpine orogenesis, the ophiolitic sequence was broken up, which profoundly modified the rocks, with respect to their mineralogy and structure. Four successive phases of
folding were identified and two separated orogenic metamorphic events, which resulted in the transformation of basaltic rocks into prasinites, of gabbros into metagabbros and of peridotites into serpentinites.

The rocks of the Dora-Maira Mountains and of the Piedmont area are not always visible on the surface; they are often covered with a thin layer of physico-chemical weathering materials and soil slaking. They are also covered by thick layers of glacial drift, sheet scree, alluvial fans and of alluvial deposits on valley floors. The research area is also characterized by a particularly thick and continuous detritic layer, resulting from the decomposition of calschist and mica-schist, which is at the origin of most rockfalls due to heavy rains.

4.3.2. Morphology of the research areas

The geographic research area is bounded on the north by the Stura de Lanzo River and on the south by the Pellice torrent. The various valleys and downstreams present an extreme variety of characteristics in this region.

The Stura de Lanzo valley consists of three large watersheds (Val Grande, Val de Ala and Val de Viù) that all converge above the town of Lanzo, at an altitude of 500 m. The steep sides of the valleys, which contain small snow and ice deposits, are furrowed by secondary torrents that flow down into the watersheds, which, even after a small planimetric enlargement, are often characterized by peak flows and erosion damaging the infrastructures of the valley floor.

The Doire Ripaire, or Suse valley, is the largest in the Piedmont area; it connects the Piedmont and France via three accesses: the Montgenèvre pass, the Fréjus tunnel and the Mont Cenis pass. The strategic location of this valley generated, in the past and even more today, the development of major lines of communication in the valley floor: highway A32, national roads 24 and 25, double tracking between Turin and Modane. From a morphological point of view, the Suse valley presents highly variable characteristics. Indeed, it is usually divided into two areas: the upper valley above the town of Suse and the lower valley between Suse and the outfall in the plain. The upper valley exhibits all the features of an alpine valley: narrow and with steep sides, whereas the lower valley has a smoother morphology and the valley furrow is much wider. However, the Doire river is characterized by minor tributary basins, usually small but running on steep inclines, which considerably impacts the slope stability, and consequently threatens the security of the infrastructure in the valley floor. For major tributaries such as the Mont Cenis torrent (Cenischia) and the Doire river of Bardonnèche, the situation is very different. Their dimensions constitute deep valley furrows, with stability issues similar to those of the main stream.
The Cluson torrent, the drainage basin of which is adjacent to that of the Doire Ripaire river, outfalls above Turin, in the Pellice torrent. The area above the town of Pignerol is defined as a mountain valley. Like the Suse valley, it is connected to France, since it gives access to the village of Cesana Torinese by national road 23 and then to the Montgenèvre pass. The Cluson torrent flow is steady; the longest tributary is the Germanasca torrent, which furrows the valley holding the same name and outfalls in the Cluson torrent near the inhabited zone of Perosa Argentina, at 630m high.

4.4. Working method

The method implemented to carry out the computer-based survey on the damaged roads of Turin – due to natural hazards – is divided into several successive steps. This approach is necessary for a spatial analysis of the interactions between the instability phenomenon lato sensu and road works. Figure 4.2 summarizes the main steps of the method, as well as the successive applications on the territory. The first step consists of a general retrospective analysis of the historical information relating to damaging natural hazards in the research area, then follow inspections of the ground and aerial photograph analysis so as to identify the frequently damaged sites. On the basis of the above synthesis thematic maps are developed with georeferencing and typological specification of the phenomenon studied. Each phenomenon displayed on the maps is uniquely linked to an event sheet. This sound scientific basis enables us to identify priority sites where we can ensure road security or, at least, to reduce the potential risks to an acceptable level. Moreover, priorities for adapted action plans can also be defined. Once the necessary developments on the sites are achieved, technicians will have to monitor in time the success and efficiency of the works completed.

Instability phenomenon on slopes and all along the water network are likely to occur again in space and time, and following the same process as before. This is the reason why we have chosen to start with historical analysis to gather knowledge of instability phenomenon, the consequences of which might be grouped under the Italian term of “dissesto idrogeologico”, meaning “hydrogeological disturbance”. The first working step is thus related to research, the selection and collection any information dealing with instability phenomenon that have caused stoppage of the traffic flow, because of torrential activities and/or slope dynamics.

This has been possible thanks to the huge amount of data that the CNR-IRPI of Turin has been collected since 1970 in southern Italy. The coherence of the available information is especially due to the unpublished materials selected and reproduced on the basis of state records and those provided by the main engineering offices, of over 10,000 publications and news from 250 newspapers and periodicals. It amounts
to hundreds of thousands of pages and paper-based materials. The collected information gives an account of the landslide and exceptional flood events that have occurred for the last 500 years and, in a more homogenous and comprehensive way, for the last two centuries. This information is organized in a historical record, a chronicle and a specialized library. Data not only refer to the phenomenon, but also to the resulting damages; in order to have accurate information on the typology and nature of the instability processes, as well as on the situation of the vulnerable infrastructures. As far as the research area is concerned, we have considered the amount of data collected from records and unpublished materials sufficiently exhaustive to provide comprehensive event sheets.

![Diagram of the research method]

**Figure 4.2. Sequenced steps and objective of the research method**

Most of the events recorded in the Province of Turin occurred during the last 50 years (60%), but a certain amount of information dates back to the first half of the 20th century (35%) and all the other events are from the early 18th century. The large amount of data related to the second half of the 20th century is the result of the major floods that occurred on the 23-24 September 1947 and on 13-14 June 1957.

The second step is dedicated to inspections of the ground and aerial photograph analyses so as to carry out a general study to identify issues relating to slopes and
water streams likely to interfere with the existing roadways in the research area. In
doing so, it becomes possible to identify the sites where instability phenomena
threatening road serviceability are the most likely to occur.

4.5. Computer-based synthetic analysis and transcription of historical data and
information collected on the research area

To do so, we have developed a sheet on a scientific basis but with the priority of
facilitating its interpretation and optimizing the management of risk situations, or
providing a crisis management system whenever there is a need for it. Moreover, we
have defined a typology of the information identifiable in the records of the IRPI to
be able to extrapolate the necessary information contained in the materials, taking
account of the fact that they had to be homogenous and comparable with one another
for a hierarchical assessment of the phenomenon reported.

The terminology used to develop the sheet is not characterized by a highly
specialized vocabulary, because the document is not only aimed at technical officials
but also at operational people. The first column of each sheet collects the data
necessary to describe the phenomenon and the site. The key-words are as follows:

- **ISTAT code/event code**: this is the ISTAT code (four digits) of each district,
  followed by a sheet number (three digits), (ISTAT stands for Italian national
  statistical institute);

- **location code**: a complementary code, represented by a letter, indicating
  chronologically different events that occurred in the same location. We can thus
  accurately determine if a site is particularly vulnerable to a specific instability
  phenomenon;

- **district**: name of the district;

- **location/route**: we enter the place name of the site or of the closest locality to
  the damaged site and the optimal route to get there;

- **number of the provincial road**: the official reference number indicated on the
  Carta della Provincia di Torino (1:15,000, January 1991 edition);

- **kilometer post and altitude**;

- **main/secondary hydrographic basin**: the main basin is where the phenomenon
  occurred, whereas the secondary basin is the one in which the first basin outfalls;

- **date phenomenon**: the precise date (year, month, day) of the phenomenon is
  entered if known; otherwise, we enter the date indicated in the report, which is in
  this case the ante quem;

- **description of the phenomenon (historical data)**: we enter the main
  characteristics of the phenomenon. For waterways it can be a flood, aggradation,
lateral erosion, etc., whereas for slope dynamics we describe the nature and kinematics of the phenomenon and possibly the relevant geological formations;

- **description of the phenomenon (ground reconnaissance):** the information collected from the reference records might not be updated. This category is used to make a short description of the new phenomenon that could have been observed during inspections of the ground;

- **description of potential phenomenon:** once again, based on investigations of the ground, new instability phenomenon or sites can be identified, or even some former phenomenon might recur;

- **type of phenomenon:** for reasons related to data transposition in the computer-based system, it was necessary to assign a digital code to each type of phenomenon (1: fluvial dynamics, 2: slope dynamics, 3: avalanche);

- **damage type:** in this category, we describe the damages recorded in roadway infrastructures, related works and/or protection structures; if there is any damage to property or adjacent grounds they are also added;

- **anthropogenic and/or natural causes:** here, we specify, if needed, the nature of the causes that gave rise to a given phenomenon, and we check, if possible, how anthropogenic actions might have impacted its evolution;

- **rainfall 3/15 days before the event:** the amount of precipitation (mm) prior to the phenomenon is important, especially when talking about major rockfalls. It is therefore, calculated here. With regard to fluvial and torrential dynamics, it is relevant to calculate the amount of precipitation 3 days before the event, while for slope dynamics (landslides), it is necessary to go further back in time (at least 15 days). In the latter situation, understanding the interrelations between precipitation and the emergence of the phenomenon is a complex task, yet this data is an indication and each phenomenon should be analyzed thoroughly. For each event, we have collected the necessary information from the closest precipitation stations; and if there were several stations, we chose the closest to the stoss side;

- **type of intervention carried out:** this heading gathers the planned potential works, or those achieved after the damage;

- **adapted and efficient intervention:** both of these terms were used to identify the type of intervention performed. This category is usually completed with data from site surveys. The term “adapted” refers to how appropriate the intervention was on the site, according to the type of instability phenomenon that was to be tackled; while the term “efficient” refers to current state of the situation and the functional efficiency of the works carried out. On the basis of the above, it is possible to determine whether a given work is useful to a roadway infrastructure or not;

- **source or the data and/or date of the field control:** the number assigned to the document used from the IRPI records is a digital code;
notes: further comments can be made, for instance to mention old toponyms that are no longer visible on the current map, or suggestions regarding the content of the document (defect in the accuracy, contradictory information), etc.

4.6. First results

In accordance with the classification established for the IRPI records, historical background data were analyzed according to their class within the geographic limits of each district. 92 districts were selected for the study, of which 39 were in Val de Suse, 2 in Val Sangone, 14 in the Lanzo valleys, 11 in Val Pellice, 20 in Val Cluson and 6 in Val Germanasca.

The total number of district-sheets generated is 2,213 and 83% were actually exploited. The remaining 17% refers to dual phenomenon that cannot be specified or to hydraulic and forest developments and/or to some other developments to rectify the geometry of a channel affected by floods or rockfalls.

Natural phenomenon affecting road usability in the alpine valleys mentioned above were classified into two main categories, whether they were related to slope dynamics or to fluvial dynamics. Yet, sometimes, based on the description of the original document, some of the events generically called landslides were reclassified into torrential lava phenomenon (which in this particular case, were affected in the aggradation category). Moreover, we have highlighted the avalanche sites even if they were only few of them.

Slope processes were characterized according to their rate of evolution, as slowly developing landslides (e.g. subsidence of roads) and rapidly developing landslides (collapse, earth slide).

With respect to fluvial dynamics, we have established three main categories of phenomenon (lateral erosion, aggradation and flood) even though their impacts are often cumulative; for this reason we have always based the subsequent analysis on the main phenomenon.

Among all the events documented, 83.3% are related to fluvial dynamics and only 17.3% to slope dynamics (see Figure 4.3). In this phenomenology, sudden and unexpected rockfalls appear to be the most dangerous and frequent events, usually caused by the structural instability of rock piles (especially in Val Sangone, Val Cluson and in the Lanzo and Germanasca valleys; see Table 4.1).
In the geological and morphological contexts at stake, aggradations represent an average of 35% of the phenomenon (the percentage rises to 45.5% only in Val Pellice). Some comparable percentages then follow: floods and lateral erosions (24.5%).

All of the communal territories studied were divided into two sectors, upper and lower, according to the morphological characteristics of the valleys, so as to highlight the percentage variations of the phenomenon mentioned above: it appears that aggradations substantially increased and rapidly developing landslides doubled (see Figure 4.2).

Table 4.1. Percentage distribution of the different event categories

<table>
<thead>
<tr>
<th>Valleys Analyzed</th>
<th>Number of Sheets</th>
<th>Slowly Developing Landslides %</th>
<th>Rapidly Developing Landslides %</th>
<th>Aggradations %</th>
<th>Lateral Erosion %</th>
<th>Floods %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanzo Valleys</td>
<td>260</td>
<td>10.7</td>
<td>13</td>
<td>25.7</td>
<td>29.9</td>
<td>19.5</td>
</tr>
<tr>
<td>Val de Suse</td>
<td>625</td>
<td>5.1</td>
<td>8.2</td>
<td>30.2</td>
<td>27.8</td>
<td>28.3</td>
</tr>
<tr>
<td>Cluson and Germanasca Valleys</td>
<td>512</td>
<td>6.2</td>
<td>13.8</td>
<td>37.2</td>
<td>19.1</td>
<td>23</td>
</tr>
<tr>
<td>Val Pellice</td>
<td>391</td>
<td>2.3</td>
<td>6.6</td>
<td>45.5</td>
<td>19.7</td>
<td>25.8</td>
</tr>
<tr>
<td>Val Sangone</td>
<td>42</td>
<td>7.1</td>
<td>33.3</td>
<td>9.5</td>
<td>45.2</td>
<td>4.8</td>
</tr>
<tr>
<td>Total</td>
<td>1 830</td>
<td>5.71</td>
<td>10.7</td>
<td>34.4</td>
<td>24.4</td>
<td>24.5</td>
</tr>
</tbody>
</table>

Figure 4.3. Percentage distribution of landslides, avalanches and torrential processes that entailed damage to road usability in the past in the Suse, Lanzo, Cluson, Germanasca, Pellice and Sangone valleys (province of Turin)
### Table 4.2. Percentage distribution of the different types of events in all of the territories of the upper and lower valley

<table>
<thead>
<tr>
<th>Valleys Analyzed</th>
<th>Number of Sheets</th>
<th>Slowly Developing Landslides %</th>
<th>Rapidly Developing Landslides %</th>
<th>Aggradations %</th>
<th>Lateral Erosion %</th>
<th>Floods %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Sector</td>
<td>1,596</td>
<td>5.8</td>
<td>11.5</td>
<td>35.8</td>
<td>23</td>
<td>23.5</td>
</tr>
<tr>
<td>Lower Sector</td>
<td>234</td>
<td>5.1</td>
<td>5.6</td>
<td>24.8</td>
<td>32.9</td>
<td>31.2</td>
</tr>
</tbody>
</table>

4.7. Structure of computer thematic mapping

Choosing a GIS-based software program for historical data processing was quite a delicate problem [PAN 96]. Indeed, we had to take into account the fact that our structure did not have the necessary professional skills to develop some specific software capable of solving the problems we face daily in our profession. We based our choice on the transfer of knowledge, that is to say, what would be most beneficial to external users? Moreover, the working method had to be user-friendly and flexible enough so that operators could quickly acquire the necessary skills to carry out the working processes. These are the reasons why we chose Arc/View 3.1 developed by ESRI. This software falls under the category of programs specific to geographic and text data processing. It provides interesting operational capabilities, as well as an excellent presentation of the various commands. Among our operational priorities, the selection and transcription of historical data to facilitate their computer processing were at the top of the list. However, processing information with Arc/View 3.1 was just a way to achieve our project objectives. This operational option allowed us to fulfill all of our targets without altering the quality of the geographic and historical information, which encouraged the bodies, who ordered the study, to develop a sense of ownership of the project. Moreover, these operational choices will provide data which is easy to update, and ensure the continuation of the project through similar working methods but on wider territories.

The information first collected and then organized in the event sheets was transferred to a digital mapping system using the software mentioned above, via an Excel spreadsheet so as to facilitate the management of all the information related to instability phenomenon. Spatial data positioning was achieved using kilometer

---

1. This section was written in collaboration with Franco GORDONE.
points or the toponymic indications relating to the site where the phenomenon occurred. Damages are represented with appropriate graphic conventions, that is, using lines with adapted thicknesses and different colors to differentiate fluvial dynamics from slope dynamics. Each event sheet uses particular and punctual symbols so as to immediately identify the map layers containing the information related to the phenomena represented (see Figure 4.4).

The necessity of a simple and immediate interpretation of the information related to damage that might affect the roadway system implied the use of automated techniques applied to mapping. The initial material consists of a regional technical map at the scales of 1:10,000 and 1:5,000, scanned at 200 dpi in TIFF format, along with geographic referencing information in UTM coordinates. The organization of work adopted, the amount of historical data processed for the research area, the characteristics of the geographic data used and the level of preparation by the personnel allowed us to use common calculation tools such as a PC. In order to increase graphic quality and accuracy, we used high definition screens. In the near future, we plan to analyze territories of thousands of km\(^2\), with much more information, which will involve upgrading the computer network and acquiring high-speed working stations capable of storing large amounts of data.

Automated mapping can be used through a variety of means: maps can be printed at any appropriate scale, with a focus on zones that suffered damage, and be used by operational teams in the field. Moreover, the map databases integrated with the information on the damage will be available to the offices in charge of monitoring the roadway system of the province of Turin. This, added to graphic software programs, will enable us to manage potential emergencies in the road system through the use of chart information completed with damage-related data.

This project provided users with conventionally formatted results, that is, paper-based thematic maps and raster maps built with graphic themes in vector format, and supplemented with historical information directly accessible in video. In the near future, the project will aim at expanding the operational potential of the method through the implementation of an Internet connection between our working team and the user desktops. This working method will enable the immediate use and, consequently, the review of the data entered into the system by the end users. Therefore, apart from historical information, representations of natural events that occurred in the research areas could be provided.
4.8. Application and use of the method

The process described above allowed us to identify hydrological and geological instability phenomenon affecting the roadway system of the province of Turin. With respect to the database, the applicability of the sheets developed is extremely wide, as there is no particular constraint imposed on their use whatever the morphological or geological situation, even though the current sheet is not adapted to such versatility as it was developed specifically for road safety issues.

The method proposed here is characterized by a wide applicability that can cover, at the territorial and morphological level, plain areas, mountain areas, zones with limited concentration of residential and road infrastructures, or even areas where there is a very high level of interaction between man and nature. Therefore, the results to date can validate a basic tool for all completed studies on land planning, whether for development projects or for prevention.

This methodology generates a computer territorial database enabling information management with a computer or land surveys. Such a project requires considerable effort to enter data and produce the corresponding maps, a point that should be brought to the attention of anyone willing to use this methodology for land planning and crisis management. Another important point relates to the fact that raw data, that
is, the archive documents, must be transcribed, but also must be translated in order to fit the technical configuration of the file. Consequently, caution should be exercised when interpreting the content of the document, and our experience, while preparing the file, confirmed the necessity of combining the geologist’s qualifications with the historian’s expertise. The next operational step is the planning of preventive actions so as to protect areas identified as vulnerable. These actions involve various highly specialized skills, along with intervention projects specific to each vulnerable road section. Moreover, apart from the geological and geomechanical characteristics, it is important to know the kind of damage, the degree of intensity and of frequency of the events compared to what is at stake, which can be easily expressed in terms of traffic flow.

4.9. Bibliography


This page intentionally left blank
5.1. Introduction

The methodology developed by Cemagref for the classification of forests according to their protective role relating to natural hazards has been parameterized and is operational for north-alpine forest stands. This methodology can be transposed to other mountain ranges only if the classification grids used in the north-alpine methodology are adapted to the new geographic conditions. This chapter introduces the works carried out in France during the natural hazard zoning actions, and which focused on forests playing a protective role against avalanches. The main objective of these works was to achieve a transfer of knowledge and qualifications to public services in charge of natural hazard zoning and the management of protective forests.

5.1.1. General information on forests

Needing the forest, man has exploited it regularly by giving it specific roles (production, protection, recreation, etc.). The forest evolves (dynamic) and only a few phases of its natural development accomplish the functions we expect from it.
The notions of sustainable development, biodiversity and multifunctionality have become a key element in the management of natural habitat. Yet, applying the sustainable yield principle to forest management, in the sense that exploitation is limited to what the forest can provide, is no longer satisfactory to meet the requirements of these new tendencies [BER 00].

5.1.2. *The protective role of mountain forests*

Forests can partially or totally control the consequences of various hazards by holding back rock slides, fighting erosion and surface landslides, preventing avalanches from starting, etc. A forest stand takes different actions according to the type of phenomenon, its location in the research area and the scale of analysis (at the level of the trees, of the slopes and of the water basin). The forest cannot stop every danger, but at least it uses the “divide and rule” tactic to fight any type of hazard. Table 5.1 provides an overall picture of this ability to control, as well as the current state of scientific knowledge on this subject [BER 99].

This protective role also depends on the forest characteristics (diameter, age, etc.) and on the spatial organization of the trees. Some forest types better withstand certain kinds of hazards compared to other types, and vice versa. For instance, maple and tamarack are less vulnerable to moving blocks of rock than spruce which, on the contrary, better withstands snowpacks.

Some forest structures, particularly old stands, can have a negative impact on specific hazards or, at least, give only the appearance of providing effective control. For example, large-diameter unstable trees can initiate rockfalls. A mere gust of wind can also result in the fall of such trees, the consequences of which could be disastrous near human developments. Hazard control sustainability is linked to the control of forest stands. A sustainable stand is considered as “stable”. Consequently, forest stability relies on the capacity of the forest stands to withstand biotic and abiotic risks. Today, the inefficiency of plain forestry in mountain areas has been largely demonstrated in terms of forest stand stability. On the other hand, a management approach in tune with natural forest dynamics optimizes the stability of protective mountain stands [BER 97].

Yet, the relative loss in timber value entails a reduction in or even abandonment of silviculture in various mountain areas. Therefore, essential protection functions might no longer be provided by forest stands that are roughly exploited or poorly maintained.

The Mountain Land Protection Service (RTM) has developed inquiries regarding protection development planning. They are based on the combination of data
pertaining to natural phenomena and to threatened issues. This is how the level of natural hazard is being assessed for each research risk area. These risk-issue analyses do not take into account the protective role that forest stands can provide. It is only when these stands disappear that managers evaluate their protective roles.

<table>
<thead>
<tr>
<th>Natural Hazards</th>
<th>Location</th>
<th>Overall Scale</th>
<th>Local Scale</th>
<th>State of Scientific Knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avalanches</strong></td>
<td>Start zone</td>
<td>Recognized</td>
<td>Recognized</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Transit or/and end zones</td>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td><strong>Rockfalls (unit volume &lt; 5 m³)</strong></td>
<td>Start zone</td>
<td>Recognized</td>
<td>Recognized</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Total volume &lt; 100 m³</strong></td>
<td>Transit or/and end zones</td>
<td>Recognized</td>
<td>Recognized</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Surface Landslides &lt; 2m</strong></td>
<td>Start zone</td>
<td>Recognized</td>
<td>Recognized</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Major Landslides &gt; 2m</strong></td>
<td>Start zone</td>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Transit or/and end zones</td>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td><strong>Torrential Hazards</strong></td>
<td>Start zone</td>
<td>Recognized</td>
<td></td>
<td>Low to Average</td>
</tr>
<tr>
<td></td>
<td>Transit or/and end zones</td>
<td></td>
<td></td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 5.1. *The capacity of forests to control natural hazards [BER 00, FRE 99]*

In order to anticipate these dramatic evolutions and to be prepared for emergency situations, it is necessary, with minimal management, to accurately target the place and type of actions to be taken [BER 96].

This is the reason why the “mountain forest” team from the Cemagref of Grenoble, France, has developed a zoning methodology of forests providing protection against natural hazards. This team also studied the structure and natural dynamics of mountain stands so as to support a natural-mechanism-based silviculture.
This chapter introduces this zoning methodology of protective forests, and also how it is transferred to the Mountain Land Protection service (of Haute-Savoie) of the National Forest Office using a specific example.

5.2. Identification of protective forest zones

5.2.1. General principle

The “Ecosystems and mountain landscapes” research unit from the Cemagref of Grenoble has developed a method to priority-rank protective forests derived from the issue-risk analyses carried out by the Mountain Land Protection service of the French National Forest Office (ONF). This method takes into account the nature and importance of natural hazards (avalanches, rockfalls, etc.), the dendrometric structure and parameters of forest stands and the vulnerability of the threatened issues. It enables us to define determination criteria for zones where avalanches could potentially start under forest canopy, as well as for the possible end zones of these phenomena. All these criteria are used to complete a map, which only identifies reported phenomena, with all possible avalanche sites.

On the basis of the above, the most objective rating possible is then established for homogenous territorial units, in real value, with respect to the level of protection provided by forest stands. This rating allows us to identify priority areas for forestry actions (ZIFP), which constitutes a real programming tool to quantify the cost of the silvicultural practices costs necessary to the sustainability of the forest stands and to their protective role against natural hazards (see Figure 5.1).

These areas are characterized by a notion of priority according to the nature of the infrastructures and lives that are threatened, and by a notion of emergency according to the level of stability of the forest stands (capacity of a stand to resist against biotic and abiotic stresses).

5.2.2. Methodology

In order to implement this priority ranking methodology, a certain amount of cartographic data must be compiled (see Figure 5.2).

Therefore, it is necessary to:
– make an inventory of the cartographic documents and studies achieved that list and describe the natural hazards, the forests, the socio-economic issues of the research area;
– complete or build these documents, if they are fragmentary or do not exist at all;
– compile various cartographic data so as to determine rating keys.

Compiling maps and zoning protective forests were achieved with the geographic information system Arc/Info.

![Diagram](image)

**Figure 5.1. Principles of classification of priority areas for forestry actions [BER 98]**

5.2.3. **Building up a synthesis map of natural hazards**

Before introducing the principles that were used to build up the synthesis map, some specifics on mapping natural hazards should be provided to the reader. Consequently, we will present the general process of mapping avalanches, which can easily be applied to other types of natural hazard.
5.2.3.1. General information on the process of mapping avalanches

An avalanche path consists of three different zones: the start zone, the avalanche track and the end zone. The start zone is the point at which the snowpack breaks off, provoking an avalanche. The avalanche track is where the snow slides down at a high speed ranging from 20 to 50 ms$^{-1}$. The end zone is the place where the avalanche slows down and eventually stops, leaving a deposit. An avalanche path depends on the terrain and snow features.

Mapping avalanches is a very old process in France. All the avalanches recorded and documented are represented on a map giving the likely position of avalanches, referred to as the CLPA, managed by Cemagref. Figure 5.3 is an example of avalanche mapping in France.
Figure 5.3. An example of map giving the likely position of avalanches [BER 99]

To date, mapping avalanches has been based on a multidisciplinary approach that combined often incomplete information obtained from various sources.

Topography is the first to be analyzed. If the slopes are very steep, the potential risk of an avalanche cannot be discarded. If the slope is long enough, major avalanches must be taken into account. The existence or otherwise of a wide start zone is another parameter enabling us to refine the analysis. Moreover, it has been noticed that certain steep slopes might never produce avalanches for reasons of topography, vegetation or climate.

Vegetation is the second most important data. Indeed, vegetation directly informs the path and extension of an avalanche according to the damages it can cause to a stand. This is the reason why the impact of avalanches on vegetation has inspired many studies on various mountains in the world. Through these studies, researchers have attempted to find a connection between the frequency of avalanches and the distribution of forest species in avalanche terrain.

Some instances used dendrochronology as a dating tool for past avalanches. This type of analysis often assessed when new avalanches could strike again. The power of this science has been demonstrated. For instance, in order to map major avalanches in Colorado (United States), Ive [BER 99] used historical data, vegetation analysis, dendrochronology, infrared aerial photographs, as well as damaged trees.
Although these methods are widely used and major progress has been achieved, there are limits. First of all, long field investigations are necessary to gather information on past events, the topography and the vegetation. Secondly, some avalanches occurred long ago and their tracks, both in collective memory and in the vegetation, have disappeared. Finally, it is difficult to map areas where avalanches occurred when there is neither historical event nor any track in the forest, or when no event happened at all. Indeed, in the latter situation, there is no sign of avalanche extension. Mapping such areas is subjective and inaccurate. New advances are necessary to overcome these problems. Recent developments of statistical and digital avalanche models, along with the widespread use of GISs, offer a favorable framework for resolving these difficulties.

5.2.3.2. General principles to build a synthesis map of natural hazards upon existing cartographic documents

The purpose is to obtain, for a given research area, a map listing all the zones subject to one or several natural hazards, and to determine which hazard is the most important, the degree of importance resulting from the cross-tabulation of frequency and intensity. Then, after having made an inventory of the present risks, a synthesis is necessary in order to divide the research area into homogenous territorial units, according to the nature and importance of the natural hazards.

This synthesis map is obtained using the compilation of all the cartographic documents listing the natural hazards present in the research area. Different documents might exist:

– maps giving the likely position of avalanches (CLPA). These are developed by specialists from the Cemagref of Grenoble. They only list the phenomena that were detected and observed during field investigations and/or during photo-interpretation studies. During the field investigation phase, the event sheets are completed. CLPA (through analyzing investigation sheets) only informs us regarding the frequency and intensity of the avalanches detected while investigating the area. In order to build a synthesis map of natural hazards it is necessary to obtain the same information for all the avalanche zones mapped on the CLPA that were not part of the field investigation. This information can only be collected in surveys local managers;

– maps listing other natural hazards (rockfalls, torrential flows, etc.). Most of these are developed by the Mountain Land Protection services, and they provide information on the frequency and intensity of mapped phenomena, as well as potential and active phenomena.

Each existing map is scanned (if it does not yet exist in digital format) in order to be integrated on a GIS-based platform, and thus obtain the geographic extent of the natural hazards. Considering the geographic extents of all the natural hazards, we...
have chosen to work in vector format and to use the Arc-Info GIS software. In this system, each map corresponds to a single information layer. Then, descriptive information related to the natural hazards are processed into the GIS database. Importance is calculated for each hazard, and a coding system is proposed for categorizing the hazards according to their nature (avalanche: 1, rockfalls: 2, etc.). Then, we proceed with the cartographic compilation work. All of the information layers are compiled to produce a set of polygons containing all the information collected from the different layers. The last step consists of defining the nature of the hazard with the highest importance value in each zone [BER 97].

5.2.3.3. A method to characterize potential avalanche terrain

We have explained above that the CLPA, contrary to other existing documents, does not list potential avalanche zones. This is the reason why managers should be provided with a method to characterize and locate avalanche prone areas, along with tools to assess the geographic extent of such phenomena. In other words, the CLPA must be completed with potential avalanche areas.

However, it must be kept in mind that the method that we are about to present here is only a supporting tool for expert evaluation. Indeed, this method is based on the use of models, and however robust the different models might be, they only use a certain amount of data, and consequently, they are and will remain a simplified vision of the complexity of reality. Therefore, a model must remain an assessment support tool and the expert must not take any of the modeling-based result for granted. Experts should cast a critical eye on this type of result, and only use them to inspire their reflection.

Managers should be provided with a model referred to as a “release” model, which makes it possible to give the position of potential start zones. They also need principles of use of flow simulation models based upon information produced from the release model.

5.2.3.3.1. A proposed “release” model

Snow avalanche defines a rapid downslope movement of snow due to the effect of gravity. It covers a range of various phenomena.

By simple shear, the ground on which the granular material (snow) lies exerts a strain force that holds the snow pack in place. This anchoring is expressed by a critical limit strain. This anchoring breaks if this strain is exceeded. A slope failure (convex) applies a slight tension on the snow pack, and thus increases the probability of avalanche release.
The critical strain values combined with the potential existence of a convex slope failure have been selected as avalanche release criteria, which are defined as follows:

– search for the areas located on 28 to 55° slopes [FRE 87] [OFE 96];
– search for the traction areas in the snow pack (convex zones).

Since there is no scientific study on this subject, the slope failure value used to characterize the convex zones was established at 10°. However, depending on the evolving state of the art in this field, experts might need to change this value [BER 99].

![Image](caption)

**Figure 5.4. Criterion for locating potential avalanche start zones [BER 99]**

Yet the use of topographic criteria is not enough. Indeed, for an avalanche to occur, large amounts of snow are necessary. Consequently, topographic criteria were combined with:

– a criterion for altimetric location, which was determined at 1,000 m and more for the Northern Alps, and which corresponds to the likelihood of acquiring sufficient snow material [BER 99];
– a criterion defining the minimal surface of a start zone that could potentially produce an avalanche. Taking into account Swiss researchers’ works, the minimal surface recorded is 500 m² (a zone of 10 m in width and 50 m in length along the slope line) [BER 99].

The zones satisfying all these four criteria (see Figure 5.4) correspond to the currently active zones (where avalanche releases have already been observed) and to potential avalanche start zones (where no avalanche release has yet been observed). Consequently, two types of zones are to be differentiated. When the CLPA is available, it provides the necessary information to classify these two types of zones through cartographic cross-referencing: each zone satisfying the four criteria and
included in the geographic extent of the CLPA is characterized as an active zone. On the contrary, all the other zones are characterized as potential avalanche zones.

This method has been used to check the validity of the criteria we had established [BER 97]. If the CLPA is not available, a cross-reference information is necessary and achieved through field investigations. Please note that these criteria do not yet take into account slope angle, wind action, as well as nivo-meteorological conditions. As a consequence, the manager will have to use his own knowledge of the research area so as to cast a critical eye on the zones provided with our model for locating potential avalanche start zones. Indeed, depending on the local weather (prevailing winds, sunshine, snow cover), very few of the zones provided by the model can be kept for consideration. These criteria offer the advantage of being easy to use for managers. In fact, all a manager needs to calculate these four criteria is a topographic map and a ruler. Moreover, the nature of these criteria makes them compatible with the use of a GIS integrating module to create and analyze a digital elevation model (DEM), which makes the process of locating the zones satisfying the criteria automatable. The general principle allowing us to identify these potential avalanche start zones using a GIS is presented in Figure 5.5.

The main advantage of these criteria is the ability to evaluate potential avalanche hazards when the forest cover disappears in currently forested areas. At this point of the research, we are able to provide a tool to locate potential avalanche start zones (also called potential triggering slabs). However, we are not able today to assess the run-out distance of an avalanche in one of the potential start zones. To do so, we would need a simulation model of avalanche flow.

Figure 5.5. General principle allowing to identify potential avalanche start zones using a GIS [BER 96]
5.2.3.3.2. Choosing a flow model to assess run-out distances

The first step consists of choosing a model, as different approaches have been and still are used in the field of avalanche flow modeling.

Regionalized variable topographic type of statistical modeling:

Initially developed by Norwegians [LIE 80], this empirically-built model is based on:

- topographic considerations: the avalanche path is characterized by a parabola (see Figure 5.6). This approach is particularly adapted to avalanche tracks in Nordic countries, but is difficult to apply in Alpine countries. Indeed, in Alpine countries some avalanche tracks can be described by successions of parabolas, which implies solving the problem related to the model chaining (successive use of a single model, by using the results of the first simulation as input data for the second simulation, and so on);

- regional considerations: the avalanche end zone is given by an angle determined through regional statistics. This approach necessitates homogenous and comprehensive historical databases related to the geographic research area.

![Figure 5.6. Longitudinal profile and estimators of the various parameters of an avalanche path, according to [ADJ 94] and [LIE 83]](image)

The topographic parameters used in this method are:

- $\delta$: angle of the fracture zone;
- $\beta$: the mean angle of the area drawn from the fracture point to the point on the longitudinal profile where the slope equals 10° (beyond this point avalanches are supposed to slow down);
- $H$: the change in elevation between the fracture point and the lowest known point in the end zone;
- $y''$: second derivative of second degree polynomial adjusting the land profile.
With these parameters, the authors who have developed this method propose a model assessing the angle drawn between the fracture point and the end point. In the end, this model provides, for an avalanche terrain, the probability that an avalanche flow reaches a given point.

G. Adjel proposed an application of this method in French avalanche terrain complying with the requirements of this Norwegian model (an even profile that can be adjusted to a second degree polynomial). He shows how the angle $a$ is accurately evaluated for a change in elevation $H$ greater than 500 m and an angle of the avalanche debris zone (angle between the $10^\circ$ point and the extreme point of the end zone) in the range of $0^\circ$ and $10^\circ$. For further information relating to this method, please read G. Adjel’s paper [ADJ 94].

**Digital modeling of avalanches**

This consists of solving, through powerful computations, the equations resulting from conservation laws and behavior laws of the flowing material. There are two major model categories: models coming from point mechanics and models coming from the continuum theory [NAA 98].

For dense avalanches, the models resulting from point mechanics have been developed through simulating the avalanche with a sliding bloc [VOE 55] down a slope. Two friction forces slow down avalanches: ground friction, which is proportional to the avalanche weight and to the solid friction coefficient; and the friction resulting from the interaction with air, which is proportional to the square of the speed of the avalanche. The only driving force is weight. Figure 5.7 is a representation of this model.

![Figure 5.7. Conceptual diagram of the block-type model [NAA 98]](image-url)
Applying the conservation of momentum enables us to determine the evolution of speed and of the position of the block over time. These model parameters, called *Voellmy parameters*, were empirically established while using this model in many studies.

For aerosol avalanches, the AVAER model developed by Pierre Beghin [BEG 79] simulates the aerosol avalanche with an ellipsoid, the volume of which increases during the flow. Extension rates depend on the slope of the terrain. Extension coefficients are obtained through laboratory experiments [BEG 86]. Applying the conservation of momentum law enables us to determine the position, speed and dimensions of an avalanche over time.

On the basis of the laws resulting from continuum mechanics, equations of the motion of an avalanche are digitally developed and solved. There are models for dense avalanches, powder avalanches and mixed avalanches.

Dense avalanches are described by Saint-Venant equations and a behavior law resulting from the granular media theory.

Powder avalanches are analyzed as a turbulent suspension. They are described by Navier-Stokes equations and a turbulence model.

Mixed avalanches consist of two layers. The lower layer, the most concentrated one, acts as a dense flow, whereas the upper layer, with low concentration, characterizes the aerosol development resulting from the erosion occurring at the top of the moving dense layer.

This type of avalanche is analyzed using a theory similar to the one used for wind transportation of snow, called the *saltation theory*. The mass flux exchanged between the two layers is proportional to the separation between aerosol loads and pull-out strengths of the particles in the dense flow. The erosion model is completed with a deposition model, which is used when the flow turbulence decreases.

The equations related to the three different types of avalanche are digitally processed on a 2D-grid taking into account the complexity of the topography [BER 99, NAA 98].

While developing our zoning methodology relating to the protective role of forests, we have decided to work with tools and data easy to use or to collect by managers. This choice reflected our desire to transfer the assessment-support tool we proposed to develop.

This is why we decided to use the statistical model, presented above, so as to determine end-to-end distances. This method, called the *Norwegian method*, offers
the advantage of discarding flow parameters or friction coefficients that are often difficult to estimate.

5.2.3.3.3. Guidelines for using the flow model with a GIS

Longitudinal profiles are necessary to use the Norwegian method. Once again, we have used the GIS functions of Arc/Info. Indeed, the triangulation module allows us, apart from the production of digital elevation models, to provide longitudinal profile along with their 3D-coordinates.

Based on the potential start zones, it thus becomes possible to select a longitudinal profile network, and then to provide the flow model with the 3D coordinates of these profiles. Consequently, the model determines the location of the fracture and end points for the confidence interval established by the computer.

Figure 5.8. Principle of proposing potential avalanche terrain zoning through coupling the mathematical model and a geographic information system [NAA 98]
We propose using two confidence intervals, that is to say, those characterized by an end point for 9 avalanches out of 10 and an end point for 99 avalanches out of 100. Once placed on the profiles, these points enable us to propose an avalanche activity zoning of the researched path or slope. As a consequence, the start and transit zones are determined, as well as end zones according to the confidence interval chosen (90% or 99%); see Figure 5.8.

5.2.4. Building up the forest map

This map aims at locating the administrative boundaries of the forest research area, as well as those of the territorial units where forest stands are homogenous regarding forest stability conditions (two categories: stable or unstable), forest cover (= 30%, 30%< = 70%, 70%<) and species (coniferous, deciduous, mixed). This map is built up, on the one hand, from the transfer onto the National Forest Office’s base maps of the information issued from the photo-interpretation study of the research area; and on the other hand, from the results of the fieldworker survey describing forest stands. For each homogenous territorial unit, managers must provide, if applicable, the costs of the work necessary to the forest stand sustainability (to obtain stable stands). After the codification, all the descriptive information relative to forest stands is entered into the GIS database.

5.2.5. Building up the natural forest-hazard synthesis map

This map results from the combination of the forest cover map and the natural hazard map. It enables us to determine homogenous territorial units threatened by one or more natural hazards. An index for controlling natural hazards via forest stands is calculated for each of these units.

This hazard control index consists of the formulation, expressed as a rate, defining the capacity required to control hazards, which was presented in the first section of this chapter. Relativity is due to the fact that a rating of 6 characterizes a forest stand with a better control capacity than a stand rating 1, but not that it is six times better. Figure 5.9 shows an example of this index in the case of avalanches. This index is automatically established by the GIS in the information layer resulting from the cartographic combination of forest cover data and natural hazard data.

However, before establishing hazard control indexes for each forest stand present in the research study, it is necessary to assess potential avalanches under forest canopy. In other words, it is necessary to assess potential avalanches in case the forest canopy disappears. If the stands are located in potential start zones, they are given the highest hazard control index number. At this stage, the threatened issues of
the research area are not taken into account. Figure 5.10 presents the principle of determining the presence of potential start zones under forest canopy.

Figure 5.9. *Key to hazard control index assignment in case of avalanches [BER 96]*

5.2.6. **Building up the map of socio-economic issues and vulnerability**

Socio-economic issues result from human activities that might be, sooner or later, threatened by one or several natural hazards. Therefore, they include all housing types, all industrial-related infrastructures, all transportation linkages, as well as equipment and leisure and outdoor activities, etc.
The socio-economic issues map provides the geographic locations of these issues according to their nature. They are organized into a hierarchy according to their protection priorities in order to build up a vulnerability map assigning to each issue a vulnerability grade. To do so, information characterizing their nature and importance must be collected. IGN maps provide the geographic location of the socio-economic issues, but the knowledge of their nature (e.g., permanent or seasonal housing) and importance (e.g., traffic volume on a road) can only be acquired through analyzing and adapting, if applicable, the survey data relating to the RTM service’s action planning, or through field investigations.

**5.2.7. Building up the priority areas for forestry action map**

The cross-referencing of the forest natural hazard map and the map dealing with the vulnerability of socio-economic issues enables us to obtain a map displaying the forest units threatened by one or several natural risks. Indeed, a natural risk only exists if a socio-economic issue is threatened by a natural hazard. With respect to the forest stands located in potential avalanche start zones, it is necessary to evaluate if the phenomena that might strike in these zones could represent a threat to the lives and infrastructures present in the research area. To do so, we use the method involving the Norwegian model described above.

Figure 5.11 presents how to use this method to propose a forest stand zoning depending on the protective action of the stands (strong in start zones, and low in end zones).
This method, enabling us to locate the potential avalanche triggering slabs under forest canopy and to assess the potential extension of these phenomena in case of deforestation, has been tested and validated on several research areas. Figure 5.12 presents the results obtained in the Chornais site, for illustrative purposes.

When using, for a given forest unit, the index grade relating to the control of the hazard, with the index grade of the vulnerability of the issues threatened by the natural hazard and finally with the stability grade of the forest stand, it is possible to identify priority forestry actions.

At this stage, managers can produce a map displaying forest units into a hierarchy according to their protective role against natural risks. Both actions (organizing into a hierarchy and priority order) led to the creation of a classification key within forestry action zones. This key is not described in this book, so, for any further information please see [BER 99].

This zoning method, along with the classification keys associated with it, has been validated in many different ways. The indexes, proposed in these keys, provide managers with the possibility to perform simulations according to chosen scenarios (modification of the indexes according to the evolution of the forest stands, of the risks, of the economic conjuncture).

5.3. Perspectives

One of the first possible benefits provided by this zoning method, apart from forest developments satisfying forest management practices, is that it can be used for planning hazard prevention. This is the reason why we have decided to analyze, in partnership with the Mountain Land Protection service of Haute-Savoie, the use of the results produced by this type of zoning, and the development of forestry
prescriptions and recommendations in risk prevention plans. Moreover, there is an increasing social demand in this field.

![Image of triggering slab map and selection of trajectories]

**Figure 5.12. Example of implementing the method used to assess avalanche potentials under forest canopy [BER 96]**

Indeed, the elected representatives from municipalities and the Ministry of the Environment want future risk prevention plans to produce practical and workable guidelines that apply to the management of protective forest management. These guidelines should, in a first instance, relate to forest cutting and the creation of paths, and their main objective would be the preservation of forested areas. They would apply to both forests that are subject to forest management practices and those that are not. The integration of private forest areas will surely raise a certain number of problems (owner identification, operating constraints, etc.), and these problems might only be solved through a consensus-building policy among the various stakeholders [BER 98].

### 5.4. The creation of green zones in risk prevention plans

#### 5.4.1. Natural hazard prevention plans

**5.4.1.1. Objectives**

Since 1984, the French government has started a posting policy to provide information on predictable natural risks. First appeared the risk exposure plans (plan d’exposition aux risques (PER)) and then, since 1995, risk prevention plans (plan de prévention des risques (PPR)). The evolution of the vocabulary reflects the political
progress. PER were mainly to help town planning to protect risk target areas. Red zones corresponded to areas where no building was allowed, and blue zones to areas where each individual had to passively protect his existing or future property.

PPR, without discarding the prevention aspect, has added a new feature: hazard source areas. This evolution reflects the rehabilitation of active defense. This is how the government emphasized the functions dedicated to the protection of natural habitats, which are classified as ND (nature protection zones) on the land use plan [BER 98, LIE 96].

5.4.1.2. Tools

The hundreds of opposing documents composed during fifteen years of practice over the ten high mountain municipalities revealed that the notion of dialogue is the key element from the beginning of the process up to the final acceptance of the document.

The elected representatives from municipalities are the key informants. This territorial policy is always based on maps (localization of historical phenomena, definition of hazard areas, zoning conforming to the regulation, etc.). The regulatory document is accompanied by a text listing the prohibitions, but it also gives a lot of advice on the possibilities for each owner to improve the functions of his property [LIE 96].

5.4.1.3. A necessity

Similarly to road or health prevention, we want anyone to have access to risk culture, and to acquire prevention skills, which is the key to success.

5.4.2. Transfer from researchers to users

Inspired by the Cemagref research themes, with respect to GISs and mountain forest stand dynamics, the national delegate for Mountain Land Protection actions (RTM) proposed applying a transfer from researchers to users in these fields.

Therefore, we have come to the conclusion that, if it was beneficial for the RTM to have access to the knowledge, methods and tools developed by Cemagref, it would be just as beneficial for researchers to gain hands-on experience, to have relations with the public, to begin the practical process of implementing prevention measures. It is thus with a long-term perspective and with a constant concern to optimize the public administration investments, that is, the Ministries for Agriculture and Environment, that we became involved in this process [BER 00].
5.4.3. The method used

We first selected an average mountain local authority characterized by varied activities, hazards and large forest areas. Faverges is a local authority located at the south-eastern corner of the Annecy valley, in Haute-Savoie (between Bauges and Bornes), and which combines all these characteristics. Moreover, the municipal team is strongly in favor of an improved integration of the natural habitat into the socio-economic life of the local authority. As for the PPR standard, we have first analyzed the records and carried out a systematic field investigation. Then, we have built up a map to locate historical phenomena, as well as a hazard map accompanied by a text justifying the classifications and describing the issues. Finally, we have proposed a regulatory zoning relating to land planning (see Figures 5.13 and 5.14).

A group of elected and former representatives have assiduously participated in this work. Figure 5.15 presents the general guidelines of the usual method to implement a PPR. We have added some additional processes through this method: the extraction of hazard source zones, the description of the forest cover and of its dynamics on various territories (see Figure 5.16). These wooded areas, which are located in hazard source zones, are integrated into the PPR as “green zones”. The resulting zone corresponds to a wooded area having, for a given hazard, an acknowledged control ability, and which imperatively needs some forestry maintenance (see Figure 5.17). Finally, in parallel with the town planning regulations, we propose a form of forestry management for these green zones. This type of management consists of minimal and fixed maintenance of the conditions to potential silvicultural and exploitation actions, so as to maintain or improve protective functions.

Figure 5.13. Example of a hazard map in a PPR
Figure 5.14. Example of a regulatory zoning map in a PPR

Figure 5.15. Usual method of implementing a PPR [BER 98]
Usual method of implementing a PPR

- Building up the hazard map
- Extraction of the source zones
- Description of the forest cover and of its dynamics
- Regulatory proposal of a forestry management “green zone”

Tested method for a better integration of the forest

- Administrative procedures

**Figure 5.16.** Test method for a better integration of the forest in the PPR, according to [BER 98]

---

Shaded zone: wooded area having a control ability on a given hazard, and that imperatively needs some maintenance

Prescriptions and advice establishing maintenance processes

This map is also a regulatory document

6: leads to the description of forest stands, of prescriptions and maintenance advice in the text of the presentation document

**Figure 5.17.** Example of a green zone map in a PPR
5.4.4. Consequences of these works

As we have explained above, the forest and its protective role were not integrated in any of these plans. Considering these works, and the related results, the new bill relating to forestry orientation and modernization in France stipulates that “predictable natural risk prevention plans [...] may provide for forestry management and exploitation rules within the risk zones they have identified. Land owners and forest operators, as well as authorities in charge of approving forestry management documents, must comply with these approved regulations [...]”. If the recognition of our work provides practitioners with a legislative framework enabling them to see forests as natural protective mechanisms, then it is to be hoped that the new measures will receive enough financial support to be followed by actions.

5.4.5. Reflections and perspectives

The cross-pollination between researchers and users represents a real learning opportunity. It should not stop there but should build on these promising beginnings. Moreover, the use of common tools such as GISs facilitates these transfers. The only shadow is a legislative obstacle. Actually, the method we have presented in this chapter integrates the use of a flow simulation model. To date, there is no legal context, in France, establishing any regulatory use of this type of model to develop PPR. Therefore, the situation should be examined, taking into account the experience of the Swiss, Italians and Austrians.

Native inhabitants and tourists alike are more and more concerned with the non-directly productive roles of natural habitats. Local representatives overcome this problem by requiring the integration of the protective function in the predictable natural risk prevention plans; they even expect strong arguments to be able to justify the communities’ commitment to these issues. There remains a serious barrier: who will provide financial support for this protective function? Which network could this management of forested and natural areas be integrated into? Some avenues are already being explored: local tax on vulnerable areas, RTM regional credits, budget of the ministries in charge of forests and land planning, agricultural landscape contracts, rural area management fund, European funds for undervalued areas, fiscal incentive for minimal management, etc.

Evidently, there will be many different financial networks, and consequently, after naturalists and sociologists, economists will be necessary to guide this reflection towards hazard source zone management.
5.5. Conclusion: general recommendations

Protective forests must be considered as real protective structures. Therefore, they are part of the constitutive elements of a protective legacy. As a result, a strategy for the maintenance of these natural structures must be outlined. This is why, an improved incorporation of the protective function of mountain forests into land planning implies a preliminary zoning of these functions. The latter must define several objectives. The choice of the silvicultural methods or techniques to achieve these objectives must be entrusted to the foresters of the research area. Moreover, this zoning and the objectives relating to protective forests must be accessible and understandable to all the stakeholders of the research area. There again, tools such as GISs and the Internet providing the opportunity to put maps and simulation models on-line (forest evolution, natural hazard propagation, economic scenarios, etc.) will, in the near future, help facilitate the work of natural risk managers and the transfer of this knowledge to the public.

This is how it could become possible to develop a true risk co-management. Alone, the practitioner is inefficient if the different specialists, all the political figures, the land managers and the public of a given area do not voluntarily contribute to these dynamics but with clearly identified roles.

Moreover, a better management of protective forest (hazard control capacity optimization search) suggests we control the land tenure of the hazard-stricken zone and to have the necessary means to determine the management objectives and to control their achievement. It seems that only the public authority (at the departmental, regional and/or national level) can appropriately manage protective forests. Yet, if the public authority establishes objectives, it must not forget to define the rules required for completing them.

5.6. Bibliography


[OFE 96] OCFIM, Soins minimaux pour la fôrets à fonction de protection. OFEFP, 1996.


This page intentionally left blank
Chapter 6

GIS and Modeling in Forest Fire Prevention

6.1. Understanding forest fire risks

Natural hazards cause a lot of damage. Today, natural phenomena (landslides, floods, earthquakes, forest fires, etc.) threaten over 22,000 districts in France. On the basis of the observations made on the department files on major risks (DDRM), these districts are subject to one or several risks, half of which involve strong human stakes (source: French Ministry for Land Planning and the Environment).

Natural hazards slow down social and economic development. No sustainable development can be undertaken without taking into account these phenomena. This is the reason why the conference paper on natural hazard prevention, landscape management and sustainable development (Paris Declaration, June 17-19, 1999), recommends the integration of preventive measures into land-planning and development policies for a sustainable management of human infrastructures and habitats, considering their increasing vulnerability.

With respect to forest fires, they deeply affect, each year, the economy and ecology. For instance, the fires that took place during the summer of 2000 devastated the Western United States (1.6 million hectares were destroyed). During the same period, several thousand hectares of forest suffered a similar fate in Europe, causing serious damage (buildings were destroyed, a number of roads were

Chapter written by Marielle JAPPIOT, Raphaële BLANCHI and Franck GUARNIERI.
closed, people were evacuated in Spain) and resulting in the death of seven people in Greece.

Forest fire is a natural risk causing socio-economic repercussions. It brings about major damage, due to both its nature and extent, to people and property, particularly when located at the wildland-urban interface. Should we consider our societies to be more vulnerable to forest fires? It seems so, and this is especially due to the land use evolution and changes in social processes (increase of urbanization, return to nature, agricultural undervalue, increase in forest areas). Nevertheless, with respect to forest ecosystems, fires can be beneficial for they regenerate wooded areas, even though too high a frequency increases forest vulnerability and causes ecological disasters.

6.1.1. Risk

Risk exists only to the extent that, when a phenomenon or an event occurs it affects populations [FAU 90]. More precisely, a risk is generally described as the result related to the probability of an event happening and the specific consequences induced by this event. In the field of natural risks, this led to a two-fold conceptualization of risk: hazard and vulnerability [ERC 94, OBE 93].

A hazard is defined as the probability of a natural phenomenon of a given intensity happening in a given place.

Vulnerability refers to the consequences, that is, the harm and damage afflicted according to the stakes present in the zone. More precisely, it refers to the exposure of elements to a hazard, and to the resources available to face it [TOR 93].

Forest fires are part of the ecosystem, but they become a risk when they occur too frequently, which deteriorates forests, and especially when humans and their related activities are threatened.

6.1.2. Description of the phenomenon

A forest fire is “a combustion that cannot be controlled in time and in space” [TRA 89].

The probability of a fire starting and extending in a forest stand is never zero. Vegetative and climatic characteristics can create favorable conditions for the development of fires. This is how nearly 7 million hectares are subject to forest fires in France, including 4.2 million in the Mediterranean region and 1.2 in Aquitaine, that is to say 13% of the national territory.
Some vegetation types are more vulnerable to fire than others. For instance, moors and scrubland are more fire-sensitive than forest areas. This is due to the difference in composition of these types, as well as to the climatic conditions they are exposed to. Fire-susceptibility of vegetation types is very much related to their moisture content, which is determined by overall drought conditions (air temperature, lack of rainfall, wind events).

These conditions are not constant in time. They evolve due to, for instance, the conditions of the vegetation, which depend on its natural dynamics, silvicultural practices, and fires that might have occurred in the area. In an exceptional year (as in 1976), vegetation types might be more vulnerable in the north than in the south of France.

Forest fires depend on natural determinants such as vegetation, climatic conditions and topography, but they are mainly related to human activities, which highly impact fire ignition and growth. This man/nature interaction makes this type of risks very specific.

6.1.3. Particularities of fire risk

The very nature of fire makes it a specific risk. As a result, forests are both “vectors and victims”, for they provide the fuel and they get destroyed. Forest fires consequently impact property and people, as well as the natural heritage constituted by these areas.

Studies on the particularities of forest fires address several aspects, such as the forest fire hazard, the actions undertaken relating to the phenomenon and what is at stake.

6.1.3.1. Forest fire hazard

The mechanisms controlling the ignition and growth of a natural phenomenon, whatever it is, are very complex. Several determinant factors must be considered, and notably natural and anthropogenic factors. Forest fires involve both of these aspects, with, however, some significant distinctions. First of all, they depend on a certain number of natural parameters and they are thus called natural hazards. Secondly, they are very closely related to human activities. Whether they start or stop, they are subject to human action, and are thus called human hazards.

6.1.3.1.1. A natural hazard

Contrary to other natural risks, forest fire determinants depend on several natural parameters, such as vegetation characteristics, climatic and topographic conditions.
Vegetation factor

It is usually impossible to determine a precise ignition zone. They depend on the presence of fuel, and the vegetal cover of the French territory being sufficient enough so that fire ignition probability can never be zero. Yet, when this type of hazard is being analyzed more comprehensively, it appears that some areas are more fire-prone than others, according to the flammability and combustibility of vegetation (such as Mediterranean forests or the Landes). Indeed, ignition probability, that is to say the factors favorable to the ignition of a fire, depends on the flammability of plant material, in other words, on its ability to catch fire. The latter depends on its moisture content, as well as on the plant chemistry. Propagation risk, the propensity of fire to spread, is also closely related to flammability, and combustibility, which is the ability of a plant to propagate fire. It depends on the structure (horizontal and vertical distribution) and on the species composition of a stand. These characteristics will determine the type of fire and thus its intensity.

Climatic factor

Meteorological parameters, notably abrupt changes in climatic conditions, also affect fire by influencing flammability, combustibility of vegetation and fire behavior. This is how temperature, rainfall, relative humidity and wind impact the moisture content of plants (drying out of plants), which will consequently be more or less fire-prone. Moreover, the wind plays a specific role in the drying out of the vegetation, and is largely involved in the spreading of fire (providing oxygen renewal, transporting glowing particles). Consequently, wind speed is usually correlated with fire propagation speed (which determines fire extent), and wind direction controls the final fire shape (notion of windward and leeward areas). In the end, any climatic change can very quickly modify fire behavior: a rapid decrease in the relative humidity and the rising of strong winds, for instance, will directly impact fire risk.

Landforms

Finally, topography influences fires. Two important parameters are noteworthy: slope and exposure.

The slope affects the relative inclination of the flames with respect to the ground, and facilitates upstream heat transfers when fire moves up a slope. Therefore, fire propagation is very different whether the fire moves up or down a slope: steep slopes contribute to fire spread, whereas fire propagation is slowed down in descending slopes. Moreover, analyzing exposure allows us to determine the areas receiving different proportions of sunshine and wind. As a result, exposure has an indirect role in the opposition between the sunny side and the shady side, the vegetation being often more flammable on south-southwest slopes. Furthermore, fire spreads more easily on windward slopes than on leeward slopes.
The anthropogenic component must be considered in addition to all these key natural factors. They largely affect forest fire ignition and propagation.

6.1.3.1.2. An anthropogenic hazard

Contrary to other natural risks, forest fire, and more particularly its ignition, is closely related to man. Therefore, this type of hazard is defined as being fundamentally dependent on human activities.

The ignition of a fire results from the conjunction of a combustible – presence of vegetation – and of a heat source, usually human-made. Indeed, the statistically highest ignition factor of forest fires is man. Human presence and activities in areas adjoining forests are responsible for, voluntarily or otherwise, about 96% of forest fires (see Figure 6.1) in the Mediterranean region (Prométhée file). Lightning is the only natural cause of fire ignitions. It only accounts for 4% to 7% of the number of Mediterranean fire ignitions (this rate can rise to 20% in the Landes).

As for fires caused by human activities, we use the typology established in the Prométhée database (see Figure 6.1) which is based on a four-fold classification scheme of the nature of the causes:

– accidental causes (related to installations: electric lines, railroad, waste landfill, etc.);
– intentional human causes (malevolence: conflict, interest, pyromania, etc.);
– unintentional causes, related to trade works (forestry operations, farming, etc.);
– unintentional causes, related to individual people (work and leisure).

Man is a victim of the natural hazards he endures, but sometimes, through his actions and land use, he does affect risk, and therefore the consequences that go with it. Actually, infrastructures affect land use, and consequently the risks by modifying natural phenomena, that is to say hazards or vulnerability (increasing or reducing the risks).

Two major events tend to increase fire severity, both regarding intensity and damaging consequences: agricultural undervaluation and growing urbanization at the forest edge:

– desertion of rural areas, reclaimed by forest, results in the constitution of a forest continuum, there is no more empty space to prevent fires. Contrary to common belief, the Mediterranean forest is not threatened by extinction; quite the opposite, it rather tends to grow out of control due to agricultural undervaluation and migration of people. Forest areas increase at an annual average rate of 30,000 hectares;
– growing numbers of developments in wooded areas, resulting from the spreading of towns and villages, but also from people’s desire to live closer to nature, increase the fire ignition probabilities.

Figure 6.2. Scattered housing in forest (department of the Bouche-du-Rhône). Source: Catherine Nouals (Cemagref Aix)
Constructions in forests outline more or less accurate interface areas, depending on these construction layouts in space. The term interface relates to the notion of frontier, separating more or less accurately natural spaces (vegetation) from anthropogenic spaces (buildings, leisure areas, etc.).

The interface (see Figure 6.2) can be materialized into a clear boundary line (dwellings clustered at the edge of a natural area) or into a transition space (American notion of mixed interface). It can also delimit more complex spaces in which natural and anthropogenic elements are tangled up (scattered housing).

Therefore, rurban areas can be described as still rural but operating more and more like urban areas [BER 99].

This interweaving between natural and anthropogenic elements of land use worsens the risk of fire, for it increases both the fire ignition probability and the vulnerability of the houses in contact with a highly combustible vegetation.

6.1.3.2. Human response to the phenomenon

As for other natural hazards, fire severity varies considerably, from newly-formed fires, quickly brought under control, to ordinary fires that can be controlled only if the specific support arrives promptly on the scene, to fire disasters. The fire fighting measures employed by civil defense are very important. This type of response results in a reduction of the damage and consequences entailed by forest fires.

Prevention measures also impact on the hazard, through identifying fires from other risks. Indeed, the more efficient the prevention and fighting actions, the more protected the forests, but the larger the quantity of combustible, thus increasing progressively the risk of large fire events (fire disasters), against which man is powerless. The smaller the number of medium fires, the higher the risk of large fires. Such fires, which occur in exceptional climatic conditions, account for the destruction of the highest number of hectares of forest [ALE 91].

6.1.3.3. Specific issues

Forest fire specific issues can be related to the forest and its use. Forests are often destroyed by fires, significantly affecting the ecosystem concerned. Moreover, the growing urbanization in or at the edge of forests, added to the development of green tourism, will only result in greater risks in the future.

As a whole, forest fires have caused fewer casualties than many other natural hazards. This is mainly due to prevention and fighting efforts implemented to limit damage to people and property. The expenditure necessary to support these
prevention strategies is difficult to assess. However, it would be interesting to assess the value of what is at stake, of what is to be protected so as to prioritize protection to the areas with much at stake, that is, vulnerable.

6.1.4. *A spatio-temporal variation of forest fire risk*

Forest fires are characterized by a high spatial and temporal variability: it is impossible to identify precisely a point of origin of a fire, nor an exclusive period of time for it to break out.

Therefore, fire risk management requires two different but complementary approaches: a temporal assessment and a spatial assessment.

Fire risk varies in time according to meteorological conditions, and plant drought conditions. Several studies have been carried out to determine the importance of meteorological factors on the ignition and spread of large fire events (relative humidity, temperature, speed and direction of the wind are taken into account). More particularly, research has been achieved on the combustible (vegetation), the purpose was to determine the state of the vegetation so as to assess its flammability (assessment of moisture content). During the whole fire season, the planning of periods of risk enables the proactive mobilization of fighting resources on the areas identified to be at high risk. This is how fires can be detected early and plans of action quickly deployed to stop newly-started fires, which limit their propagation. We are talking here about temporal risk prevention. However, some difficulties have to be mentioned: obtaining data, and the interpolation of the meteorological parameters obtained punctually. With respect to satellite data, usable data are not always available.

Moreover, risk is not homogenous across the territory, at an average or at a given time. Its related intensity depends on the conditions of the natural habitat and on land use. For instance, some parts of the territory are characterized by: high fire ignition probability, favorable habitat conditions for propagation, and critical stakes at risk. To ensure prevention, these specific areas must be identified. We are talking here about spatial risk assessment. Such assessment can evolve over time according to the development of new human activities or to the dynamics of vegetation.

This prevailing need for spatial risk assessment must also consider a slower temporal evolution (at the scale of forest growth and according to population development), while the accuracy of such studies varies with their objectives (from European scale to communal scale). These methods address the propensity or probability of an area to burn or the difficulty of protecting this area. They emphasize hazardous areas and target forest management and land planning.
Forest fire-related risks should not be treated as an inevitability. It is possible to manage and prevent forest fires, so as to mitigate their damaging effects on people and property.

A risk management policy generated many efforts in this regard. This policy includes: prevention (from expectation to prediction), preventive information, land planning (town planning and building regulations), development of emergency and crisis management plans (fire suppression), and rehabilitation after fire.

First of all, prevention policies require all kinds of information related to risk, which suggests the gathering of knowledge on the phenomenon and its related damaging consequences [BLA 01]. The processes and mechanisms implemented culminate in the assessment and localization of the natural risks, as well as in their transfer onto maps.

Assessing risk largely depends on spatial representation, which remains an easy-to-use and convenient tool for managers facing many problems regarding the organization and identification of relevant data. The description of spatially referenced data and their mapping using GISs represent tools for knowledge simplification, synthesis and communication.

In the field of forest fires, GIS are increasingly used.

6.2. Forest fire management: risk mapping and the use of spatial analysis

6.2.1. Requirements with respect to forest fire risk assessment

At present, there is a very high demand for fire risk mapping. This demand reflects a large variety of requirements with respect to applications (town planning, land planning, etc.). However, research on the subject is quite heterogenous, and the concepts used often convey very different significations (notion of risk, of hazard, of vulnerability, etc.). Consequently, it was necessary to look at the demands and needs for risk knowledge and mapping, then at how the answers were provided, and finally at the lessons learned from these answers.

6.2.1.1. Chronological evolution in the field of forest fire risk mapping

The first maps appeared less than 10 years ago. Before, there were mainly descriptive approaches such as past event history (records, remote sensing, etc.), differentiation of the various types of vegetation (flammability, combustibility, etc.) or an inventory of preferential ignition sites (“powder keg”).
From the end of the 1980s, the notion of risk began to be integrated into land planning, especially to regional plans (forest fire management regional plans, SDAFI) and inter-municipal plans (forest protection and management inter-municipal plans, PIDAF). Risk consideration initially resulted from a streamlined approach, usually using a vegetation map.

![Figure 6.3. Progression of the number of risk mapping studies since the 1970s](image)

This type of risk consideration, with respect to protecting forest from fires (DFCI), still exists today. It has not been as clearly applied for the last few years, except for some regional and departmental approaches (particularly during the review of the regional forest orientations). Nowadays, when the notion of risk is taken into account in forest fire fighting management plans, the methods implemented are usually more sophisticated, because the authors aim at synthesizing several information layers through a GIS.

Figure 6.3 reveals a very sharp increase in the number of risk studies since the 1990s. By the middle of the last decade, the dominant focus shifted towards studies with concerns about town-planning (a subject that had never been taken into account before, except for a few methodological or prospective works).

Two main requirements have been identified with respect to risk mapping: needs for town planning and management DFCI. The other requirements will be briefly defined if needed. This inventory of the requirements was drawn from the risk mapping study [JAP 01].

6.2.1.2. Town planning requirements

These needs, expressed by the departmental directorates for agriculture and forest (AFDD) and the directorates for infrastructure (DDE), are very strong in the South-East and South-West departments of France where buildings in forest areas are already a major issue (especially if they have recently been threatened by a fire).
These requirements are two-fold:

– at the departmental level (see regional): the purpose of the map is to identify a priority zoning to establish future PPR. The memorandum of July 2, 1999 specifies that the primary objective of such a “departmental strategic document” is to “identify the sites to which the PPR processes seem to have provided an interesting contribution” and to focus the local governments’ funding “on the securing of the fire-disturbed sites”. At this level, future requirements with regard to town planning will probably address planning projects with a specific concern for fire risk: basic infrastructures, technical and administrative measures, etc. These needs are not specific to the Mediterranean region for they are expressed in the same terms all along the Atlantic coast;

– at the local level (one or several districts): the requirements are essentially those generated by the major natural risk prevention plans, achieved within risk basins theoretically determined at the departmental level.

One of the goals is to build up the hazard map and the regulatory zoning. Another goal is to analyze the current prevention and fighting devices (study of the private or collective equipment, requirement to clear brushwood).

6.2.1.3. Forest management requirements

Today, two events are militating in favor of taking risk levels into account for the management of DFCI: a context of budgetary restrictions and the necessity to maintain or bring the existing network to standard.

Therefore, at the departmental level, sometimes at the regional level, the purpose is to establish a priority zoning that takes into account the notion of risk. The aspects involved are: the reabsorption of accidental disturbances, forest monitoring, preventive mobilization and the equipment (or maintenance) of fire fighting installations. The memorandum of July 2, 1999 mentions the notion of strategic departmental document making it possible to “focus the Mediterranean Forestry Conservation body’s funding to the benefit of all operations aiming at protecting forests, especially in induced-risk zones”. At this level, future requirements will probably also relate to regulatory obligations, particularly those associated with the granting of European support.

Within forest areas, that is, at the district or inter-district level, there are also more operational needs, usually defined in a document such as a PIDAF (forest management inter-municipal plan), for instance: support dedicated to the implementation of new equipment, selection of patrol routes, locating fuel breaks, etc. The validation of already existing installations (or possibly to be established) is also required. Sometimes, digital simulation is used as a new means to satisfy this
type of requirement, but such applications are not really representative of risk mapping.

6.2.1.4. Other requirements

You will find below other needs that have been identified:

– forest policy: to determine what vegetation type should be planted in a reforestation program to make the new forest stands less flammable and less combustible, possibly more fire-resistant. How and where to reforest after a fire.

– ignition prevention: based on the knowledge of the causes of fire ignitions, it enables us to determine a spatial logic of fire ignition distribution that can be linked to anthropogenic activities;

– monitoring and detection: a currently negligible requirement, due to the fact that most monitoring networks are already in place. Yet, monitoring could be focused (or strengthened);

– preventive mobilization and fighting: the taking into account of risk levels is an integral part of the decision-making process to initiate the sending of the aerial or ground combat-ready force. In the South-East, for instance, risk is assessed daily at the regional level;

– preventive information: to inform the public on risk areas and on the safety measures available to protect themselves. This type of information is released at the communal level. The purpose is to develop a simple method to credibly “express the risk” to the populations involved;

– insurance: knowing the risk (outbreak fire and potential damage) so as to determine the insurance amount. Here, the prospective needs must be analyzed, considering the particular case of forest fires that are assimilated to urban fires. For insurance agents, forest fires are covered by the standard warranty (property insurance).

Whatever the needs in risk assessment might be, an analysis must be carried out. Our purpose is not to propose a risk assessment and mapping method, but rather to describe a generic approach requiring the use of spatial analysis.

6.2.2. Forest fire risk assessment and mapping: the use of geographic information systems

Risk does have an obvious spatial dimension: the source is located, the phenomenon is distributed in space, and its impacts are also diffused in space due to the interactions of the phenomenon and to the exposed systems affected by this phenomenon. Whether it is to inform, to recommend or to regulate, natural hazard mapping has become a key tool in decision making and consultation support.
Fire risk assessment cannot be analyzed separately from its form of representation. Therefore, forest fire risk mapping requires powerful computing capabilities (GIS software or other types of software applications) considering the large amount of parameters that must be simultaneously integrated into the modeling process. The last few years have witnessed a growing use of these tools in this specific field.

The methods mapping fire risks through the use of GIS to store, manage, process and render geographic information are numerous. GIS can file, analyze and manage a large amount of data. They enable us to rationalize the collection and processing of spatially referenced data (data acquisition remains a problem to be addressed), and to develop logical and topological relationships among these data.

Regardless of the purpose, fire risk analysis is focused on a geographic area that reflects the economic and social history of the place. There can be found a certain number of natural and anthropogenic elements that are linked together by a complex system of interactions:

– high gradients: altitudinal terracing of the vegetation, distance to the sea;
– more or less hierarchical networks: transportation links, trail networks, railway roads;
– obstacles or ease of connection, related to high-level terrain or to large forest area;
– neighborhoods: they generate exchanges and flux.

Spatial analysis allows us to decompose this geographic area so as to describe the places according to their location and characteristic attributes.

6.2.2.1. Towards a risk analysis approach

We propose to implement an approach (see Figure 6.4) taking into account the nature of the requirement. The specific requirement under consideration is schematically analyzed to be decomposed into elements of risk; each element of risk is evaluated after having chosen a form of representation involving a certain number of parameters, which were themselves obtained from available data.
6.2.2.1. Elements of risk

Within the field of natural risks, it is generally agreed we should consider the hazard and vulnerability as risk components. With respect to forest fires, it has become common to consider both aspects of the hazard:

– the natural aspect: the hazard, as for any other natural hazard, is the combination between the probability of fire and fire intensity (also sometimes called suffered hazard),

– the technological aspect: as for other industrial accidents, the hazard results from anthropogenic activities. With regard to forest fires, this aspect consists of the combination between the outbreak probability and the threatened surface area (called induced hazard).

The probability of fire is the probability of a fire spreading all over a given place (wherever the fire might originate). Sometimes we use the term propagation risk, which refers to a rather fuzzy notion, varying between authors, including fire intensity, propagation speed, fighting effect, etc.

Fire intensity refers to the fire front power, that is, the amount of energy released by the fire in a given time (in kilowatt per meter of fire front). The notion of intensity enables us to assess the fire behavior. However, in the specific field of forest fires, this notion is not really taken into account, whereas it is frequently used in the study of other natural phenomena. Closely linked to the vegetation, it is thus highly variable over time, depending on the stage of development of the combustible, on past events and on the answers implemented (works aiming at reducing the biomass).
Contrary to the other natural phenomena, fires can theoretically break out at any point in space (within vegetated sites). The outbreak probability refers to the probability of a fire starting in a given place. This essentially depends on the flammability of plant material and on the presence of a spark (mainly due to anthropogenic action).

A threatened area is an area that could potentially be hit by a fire that would have started in specific conditions (baseline conditions). Reduced to the point of breaking-out, this should not, theoretically, consider the protection measures (especially the fighting actions). It refers to a notion of intensity, which is used to measure the potential danger of a fire ignition.

Vulnerability depends on three elements: the elements at stake, the damage and the protection measures (prevention or fighting devices).

The elements at stake consist of all the assets exposed and susceptible to being affected by a natural phenomenon. The stakes can be with or without monetary value. In the latter situation, a correspondence system should be established between the various types of stakes.

Damage, and more precisely the rate of damage, is the proportion of an element exposed (stakes) that a phenomenon of a given intensity destroys. It corresponds to the impact of the phenomenon on the stakes, that is to say, the potential damage.

The answers are the means of prevention, equipment and fighting. Among these measures, active answers (intervention of human means) must be differentiated from passive answers (DFCI means: trails, water points). Both types of answers aim at mitigating damage resulting from disasters. Human-induced fires also require answers, addressing the prevention of outbreak through direct actions on the hazard.

This is how interwoven elements appear (see Table 6.1).

Then, each element of risk is modeled. Various forms of modeling are possible:
– probabilistic: a modeling essentially based on historical and statistical data,
– semi-probabilistic: a modeling based on historical data, but also on expertise and experimentation,
– deterministic: a modeling based on the knowledge of the physico-chemical mechanics of fire.
RISK

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occurrence</td>
<td>Stakes</td>
</tr>
<tr>
<td>Intensity</td>
<td>Damage</td>
</tr>
<tr>
<td>Probability of outbreak</td>
<td>Fire intensity</td>
</tr>
<tr>
<td>Probability of fire threatened</td>
<td>Surface threatened</td>
</tr>
</tbody>
</table>

Table 6.1. Elements of risk

6.2.2.1.2. Components and parameters: data sources

Let us call parameters the natural habitat and anthropogenic factors that influence fire outbreak, propagation and intensity, as well as its progress (aspects related to the fighting). For instance, slope and exposition are the main topographic parameters used in hazard studies. The elements exposed to the forest fire phenomenon are also part of the parameters considered in risk assessment.

Numerical ranges refer to the values taken by the parameter, when they are gathered into ranges to ease hazard or vulnerability calculations. Here, we talk about information layers to describe an information plan characterizing a parameter.

Families of parameters are called components. The latter relates to the natural habitat and anthropogenic factors that influence fire outbreak, propagation and intensity, as well as its progression (aspects related to the fighting). There are five components. You will find below the detailed data relevant to each component, but their impact on fire ignition and propagation are not discussed (see section 6.3):

– vegetation: characterizing vegetation represents a major difficulty in hazard assessment, because the necessary data are not always available. However, throughout France, it is possible to have access to data on vegetation at a scale of 1:25,000 from the national forest inventory (IFN), and from CORINE land cover (1:100,000, at the European level). It is also possible to determine vegetation types using aerial photographs or satellite images (SPOT, Landsat, etc.). Some specific studies dealing with vegetation can also be available in the form of paper or digital maps, resulting from ground surveys or expert evaluation. Drought is evaluated directly in the field, or through satellite images (with caution), or even from meteorological data analyses (models taking into account temperature, pluviometry and relative humidity);

– topography: topography is obtained from 1:25,000 maps and digital elevation models, both produced by the IGN. Digital elevation models can also be generated from satellite images, or through the scanning of paper-based maps (contour lines).
Data relating to insolation are acquired by weather stations (independent, Météo-France) or by satellite images;

– meteorological parameters: the parameters considered (wind, temperature, relative humidity, etc.) are assessed through statistical studies or physical simulations (scale model of the research area in a hydraulic tunnel) or digital simulations (mathematical model). Data are provided by Météo-France (wind data or use of compass rose), or by other weather stations belonging to other organizations (INRA, county councils, etc.);

– human activities: this component is threefold: ignition sources, stakes (people, property, infrastructures) and fighting means. Available data can be found on documents such as the BD Carto® of the IGN. SPOT images (land use) and aerial photographs are other data sources relating to housing and roadways;

– historical data: statistical data relating to past fires provide information on priority fire ignition zones, fire causes, surfaces hit (Promethée files for the 15 South-East French Departments, departmental and communal documents). This approach provides much information, but must be carried out rigorously and carefully. Indeed, being based on past events, the study must take into account the evolution of the current resources and conditions.

Risk assessment builds on databases, often computerized, which provide a representation of reality. This representation varies according to the objectives, in close conjunction with the data entry scale. For instance, a detached house, which may cause a fire, can be perceived as a punctual element at the scale of a forest massif, but has to be processed as a surface if we consider brush clearing distances, at the scale of land use planning.

Building the database is the foundation of the GIS project (60% to 80% of the total cost). However, data acquisition and management represent major concerns in the use of a GIS. Several problems must be tackled successively:

– graphic data acquisition: data can be drawn from available paper maps (in this case they are digitized directly on a graph pad, or scanned and then vectorized and finally geo-referenced). Already digitized data can also be integrated in the GIS (the only limit is the cost). Remote sensing data require an image-processing application as well as an oriented interpretation (e.g. locating DFCI trails with a GPS). In the Provence-Alpes-Côte d’Azur region, there is now a geographic information regional committee (CRIGE) which implements a digital data exchange platform;

– graphic data structuring: graphic data captured this way must be structured in a format adapted to ulterior processing (creation of the topology in vector format, rasterization);
-- data storage: a distinction must be made between the data used for computing and that used to display the results. Moreover, storing digital data requires an efficient organization of the workplace, and large storage capacities;
-- computing times are sometimes a limiting factor affecting the assessment of some intermediary parameters necessary to calculate the risk index.

On the other hand, digital data are particularly relevant with respect to updating fire risk maps. Land use is in constant evolution: urbanization phenomenon, land use change, natural dynamics of vegetation. Updating one of the risk factors means updating the risk map. However, it is necessary to keep a trace of the constitution mode of the risk index. This is why the notion of metadata is very important, that is to say the data about data, such as, for instance, data entry accuracy, or the initial scale of a map. These indications provide the final user with specifics on how he can use the map, to avoid any mistake relative to the accuracy of the spatial representation provided.

On the basis of the data, spatial analysis tools provide the parameters and the elements of risk. Various tools enable us to participate successively in the qualification of a single parameter or element (see section 6.2). Initial information is transformed according to targeted objectives and to our own perception of space. However the existing tools need to be complemented with the use of models to better understand the complexity of the phenomenon.

6.2.2.2. Implementing traditional spatial analysis tools to assess forest fire risks

Spatial analysis techniques are numerous and common software programs offer more and more functions. Four major families of techniques are frequently used in risk mapping:
-- information extraction,
-- classical statistical analysis,
-- data layer combination,
-- spatial interactions.

6.2.2.2.1. Information extraction

Raw information is often very detailed. It has to be summarized to make it usable for the characterization of a parameter or an element of risk.

This simplification has two approaches:
-- class grouping, weighting: too many classes descriptive of an area might inhibit the comprehension of it with respect to the targeted objective. The grouping of certain classes is necessary to facilitate their understanding in regard to the studied phenomenon. For instance, the forest stands of the National Forest Inventory
can be grouped into a few classes to describe the combustibility parameter. The setting up of these groupings is based on the advice of experts from the research field, and on references from the literature;

- remote sensing image processing: remote sensing data provide valuable information on the characteristics of a geographic area. There are various approaches to process remote sensing images, especially satellite images when they consist of several channels (multispectral images, as opposed to panchromatic). Supervised classification is one approach, which is used to group image reflectance values that are related to a specific land use classification.

6.2.2.2.2. Classical statistical analysis

This technique achieves synthesis through the use of descriptive, multivariate statistics, etc. The same object (for instance the object defined by the contours of the local authorities) is described by several parameters. Analyses are carried out on this object. They can be simple algebraic operations, a typology to divide the situations into classes, a multivariate regression, etc. These analyses do not necessarily require a GIS to make the calculation, but the results can be easily spatialized.

This category includes the methods used to compute the annual average risk (average percentage of the combustible surface burnt each year) or the annual average pressure (number of fire outbreaks per unit area).

Data layer combinations use analytic geometry tools such as combination operators between spatial objects. This is the case for superimposition, intersection or union enabling us to quantify these relationships. Each parameter is described in one separated data layer.

![Combination of parameters and Final risk map](image.png)

**Figure 6.5. Combination of data layers**

This combination can be achieved through the cross-checking of the parameters:
- either empirically: by involving experts (weighting, tabulations, etc.);
– or using deterministic mathematical relationships between the parameters, usually drawn from literature (e.g. slope effect, fire surface area, etc.).

Most of these models require a GIS if the output variables need to be spatialized, but the result might remain punctual. The final result can characterize surface areas different from those described for each parameter (in vector format). The methods using a classical combination of various factors are included in this category: the raster format is the most commonly used here. All the pixels that geographically match are then combined (see Figure 6.5).

6.2.2.2.3. Spatial interactions

These consist of a topological analysis that presents objects (vector or raster) in a spatial structure to correlate them. They use the following notions:

– adjacency: this relates to the definition of a zone of influence on either side of an element. For instance, a 50 m zone can be drawn on both sides of a road to display the fire outbreak probability (see Figure 6.6);

– proximity, distance: this type of tool can be used to determine the response times to deliver emergency aid, the evacuation time for people at risk, etc.;

– neighborhood: for example filters, smoothing, interpolation.

A square or rectangular filter can be applied to a map and a new value (average, maximum) is computed and then assigned to the center of the cell in a new map (see Figure 6.7). More complex filters can be used (e.g. Laplacian filter).
Sometimes, data are obtained punctually, as, for instance, meteorological data that are provided by each weather station. In order to obtain spatialized information on the research area, data interpolation models are used to assign values to each point in space on the basis of known values.

![Raw risk index](image1)  ![Smoothed risk index](image2)

**Figure 6.7. Application of filters**

### 6.2.2.3. Coupling to models

GISs do not integrate the dynamic aspects of natural phenomena [CRA 97]. Therefore, some additional tools are used to improve the efficiency of GIS: knowledge and simulation models. Integrating these different tools generate a decision-support system, which provides spatialized information and simulation methods.

Simulating environmental processes (outbreak, propagation, meteorology, vegetation drought, etc.), for whatever purpose, requires taking into account numerous phenomena simultaneously. Data variability, the diversity of habitats and the complexity of physical mechanisms related to fire growth entails a large number of parameters that are often difficult to measure. Classical modeling (mathematical, statistical methods, probability calculations, system dynamics, etc.) can provide accurate simulations of some phenomena [GUA 97], but is inappropriate for some others that require the use of expert insights, such as the identification of wind regimes at the local level. In both cases, the basic process consists of incorporating knowledge of phenomena with a spatial extension. Therefore, there are many models within a single system, more or less perfect or complete, enabling us to shed full or at least partial light on the research reality. An example of spatial simulation of phenomena is given hereafter.
6.2.2.3.1. Fire propagation

Fire prediction systems are simulation tools that predict fire edges for a given time, establishing the propagation speed at some of the points of the perimeter. Fire ignitions can be simulated to see where and how the fire grows. These tools make it possible to change some parameters or to simulate the effects resulting from the development of new installations. In order to predict fire behavior over time, it is necessary to have at least:

– input data: maps of vegetation, relief, wind;
– a local model to determine fire propagation or behavior.

These tools provide, at a given point of the fire front, the rate and direction of the fire progression, as well as its strength depending on some local vegetation conditions (type, water status, density, height), on the relief and on the atmosphere (air temperature and moisture content, wind direction and speed). Most commonly used models are semi-empirical: they are based on experimental or real fire observations, or on laboratory experiments, and on the partial consideration of the physical and chemical representation of fire behavior. These models predict some aspects of the phenomenon and are simple enough to be integrated into prediction systems. They take some account of the relief in the extension of the fire.

Fire edge is determined through the use of a contamination algorithm (see Figure 6.8). One or several fires can be simulated within the risk basin. Examples of simulators: Farsite (using the Behave model [ROT 73]), Geofeu, Cardin, and the simulator developed by the Ecole des Mines de Paris.

Figure 6.8. Examples of fire simulations
6.2.2.3.2. Wind simulation

Wind direction and speed can be simulated in a digital wind tunnel (see Figure 6.9), if the relief characteristics (e.g. a digital elevation model) and vegetation roughness (vegetation height and cover) are known.

![Image of simulation arrows with North marker](image)

**Figure 6.9. Examples of modeling applied to the Massif des Maures**  
*(source: Cemagref Grenoble/ETGR)*

In section 6.3, examples of possible applications of GIS use in forest fire prevention will be given. The first application relates to fire zoning at the scale of the Massif des Maures. The second application emphasizes the relevance of coupling a GIS with a simulation model, a process which is, for instance, at the origin of WILFRIED, a system used to support forest fire fighting.

6.3. Using GIS to map forest fire risks

In this third section, you will find two concrete examples of GIS use in supporting fire risk management: the development of a raster GIS tool to achieve risk zoning in forest areas, and the notion of a system of fire fighting support models.
6.3.1. Forest fire risk assessment and mapping in the Massif des Maures (Department of Var): raster GIS

The needs expressed with respect to town planning, in terms of fire risks, bring to the fore the necessity for a preliminary zoning at the departmental scale, to establish priorities in future natural risk prevention plans.

With this in mind, a study has been carried out by the Cemagref [JAP 97] in the Massif des Maures (Var) to assess the ignition and propagation hazard over the whole forest area (a total of 13,000 hectares).

6.3.1.1. Analytical approach: the example of fire propagation hazard

The method consisted of an analytical approach: forest fire hazard was decomposed into various factors, each factor being mapped and integrated in raster mode. Finally, the factors were combined into a global index dividing the hazard into three different levels.

6.3.1.1.1. Choosing the factors, developing the database

The different risk factors are organized as shown in Figure 6.10. Considerable efforts were expanded on the development of the database, and particularly with respect to the knowledge and mapping of the wind factor.

In order to analyze the wind-relief interaction, a simulation of atmospheric flows was carried out in a hydraulic tunnel by the National Meteorological Research Center (CNRM) in Toulouse. The characteristics of low-level atmospheric flows are simulated by flowing water on a scale model of the Massif des Maures. This is a particularly appropriate method for strong and turbulent winds.

A 1:10,000 scale model was built with the use of a digital elevation model, and the relief was modeled on a 30-by-30 m grid with a vertical resolution of 1m. The integration of the landscape roughness was achieved through the reproduction on the scale model of three vegetation height classes: trees > 5 m, low vegetation < 5 m, sea and water bodies.

The hydraulic tunnel (see Figure 6.11) consists of a 30 m long and 1.6 m deep canal. Some devices enable us to set speed and density vertical gradients.
Visualization techniques and punctual flow measurements are implemented to reflect the atmospheric behavior as accurately as possible. A general direction of
300° was simulated, which is the mistral orientation; the prevailing wind all over the Massif des Maures, which also corresponds to a high frequency of fire ignitions.

The flow data appear on a 500-by-500 m mesh grid that provides an overall view of wind behavior: direction, speed (see Figure 6.12) and turbulence. This grid is directly imported into the raster GIS.

![Figure 6.12. Wind speed classes](image)

6.3.1.1.2. Index calculations

Next, GIS functions were used to combine the different information layers. Intermediary indexes have thus been determined to report on the interactions of some factors. For instance, wind-exposed areas, which are more vulnerable to fire propagation, have been separated from sheltered areas and from intermediary situations (see Figure 6.13). A different mark was assigned to each of these three areas.

Similarly, a mark was assigned to each modality of the various factors participating in the propagation of the event: combustibility index, wind-relief combination, wind speed. The final index (see Figure 6.14) combines all these factors previously analyzed.
6.3.1.2. Towards a global approach: characterization of interfaces with the use of remote sensing

The same analytical approach can be applied to determine an ignition hazard index. However, nowadays, research focuses on a more global approach, which allows us to characterize housing/forest interface areas and to develop an ignition hazard assessment model.

On the basis of remote sensing data (see Figure 6.15), it is possible to individualize automatically some types of housing/forest contacts. Several image processing methods have been tested [FOL 00], either through supervised classification on pre-processed or raw channels or through manual thresholding of the radiometric values.

This methodology is based on the analysis of the radiometric properties of pixels, regardless of their location. It characterizes residential areas in contact with natural habitats (see section 6.3.1.2). The results obtained from this digital image processing chain are imported into a raster GIS (with a middle phase consisting of the vectorization of contour lines) for the future modeling of fire outbreak risk.

The emergence of new sources of ultra high resolution of satellite data [BOU 99] gives rise to new perspectives to recognize and identify interfaces.
Figure 6.14. Map displaying the three levels of propagation risks on the Massif des Maures

Figure 6.15. Land use image (source: Landsat 1999)
6.3.2. WILFRIED – fire fighting support (coupling GIS and model)

With respect to forest fire fighting, we have selected the model system concept to grasp the complexity of fires, on the one hand through the organization of knowledge, and on the other hand through the exploitation of this knowledge with respect to the intended objectives.

6.3.2.1. Model systems and knowledge-based systems for the processing of knowledge

The use of model systems to study the forest fire phenomenon is designed to serve three purposes:

– implementing a more synthetic approach that would recognize the dynamic interaction properties between the elements of a group, conferring upon it a character of completeness;

– developing a methodology to mobilize and organize knowledge for a more effective use of resources with respect to the intended objectives;

– promoting a unitary language on which the articulation and integration of models spread out in many different disciplines.

To achieve such objectives, it is necessary to test the various models constituting the model system, by varying the conditions and multiplying hypotheses on many case studies for purpose of validation. The repetitive application of these models systematically faces problems with their integration in a high-performance operating platform capable of managing them and making them cooperate with the intention of solving complex problems.

Among all the models and tools dedicated to artificial intelligence, we have selected a knowledge-based systems approach that proposes knowledge representation formalisms and knowledge inference mechanisms.

Today, further efforts can be made to foster the formalization and integration of knowledge. The various forms of modeling, characterizing a model system, can now be associated, through a knowledge-based system approach, so as to work together to solve complex problems.

The advances achieved by knowledge-based systems for the last 15 years reveal that it is now possible to gather different forms of modeling within a single research project. Consequently, the reasons that justified the choice of a specific approach to the detriment of another one, even though they still prevail, are now key elements to be considered. They enable us to integrate models of different types, within computer tools capable of solving problems that have long been thought to be unsolvable. These are called problem solving environments (PSE).
The notion of a problem solving environment appeared in the 1960s. Today, even though few advances has been made with regard to *intelligent information systems*, this field has become very active, particularly through improvements in IT over the last 15 years. In order to define the concept of PSE, we will use the definition given in [BUI 90].

An intelligent information system is a knowledge-based system aimed at helping a specialist in a specific field by providing him with all the tools he might use by their integration into a methodology.

6.3.2.2. WILFRIED, a PSE dedicated to forest fire prevention

Modeling the behavior of a fire not only requires knowing the fire, but also the interactions it has with other phenomena (natural or anthropogenic), which are also very complex. The “forest fire prevention” system (see Figure 6.16) has to be studied as a whole linked to an environment, but also as an element of a larger structure the other constituents of which compose its environment. Building a model of such a system implies defining:

- the element composing the system,
- the system boundaries,
- the interaction rules between the elements of the system,
- the elements characterizing the different stages reached by the system during its evolution,
- the interactions the system develops with its environment.

![Figure 6.16. The “forest fire prevention” system](image-url)
These considerations result in the development of a “forest fire prevention” model system (see Figure 6.17).

By applying a relevant reduction of reality, this model system improves our perception of the processes going on, and thus provides decision-makers with essential elements (information, knowledge, models) to support informed decisions. Therefore, the process consists of specifying a function made of several scientific constructs (models) to find or even to imagine relationships that they could form to contribute in resolving a given problem.

This model system integrates the knowledge and models related to the meteorology component [GUA 95], and to forest fire risk and propagation. Integrating all these models (throwing light on some aspects of the research issue, aspects that are generated by different formalized languages) is a partial breakthrough in the field of forest fire prevention, since to date no decision-support tools in this specific field do consider all these components in this format. This model system takes into account the needs in terms of decision support, and scientific expertise knowledge. All this knowledge clarifies the relationships between the observation scales of the phenomenon, the decision and action scales with respect to prevention, and forecast scales tackled by scientific researchers.

Henceforth, the “forest fire prevention” model system (see Figure 6.17) is formalized according to the computer language chosen, that is, the language applied to knowledge-based systems.
All the data, knowledge and models selected to tackle our issue are represented by structured objects that are grouped into classes and described in a list of attributes. This second effort to formalize knowledge does not challenge the structure of our model system. The shift to computer tools, which might appear rigid (classes, properties, instances) and with a tendency to dramatically simplify the complexity of the research phenomenon, actually consolidates the meaning and richness of the model system proposed. This formalization of knowledge, achieved through a declarative formalism, gives us the possibility to upgrade our model system without challenging the knowledge base structure.

In order to best optimize the management of spatially referenced data, two geographic information system software programs were chosen: Geoconcept for vectorial information and Grassland for raster information.

These data relates to:
– past events (fire start and edges location, etc.),
– protection equipment (fire breaks, water points, trails, etc.),
– networks and infrastructures,
– topography,
– vegetation, etc.

A man/machine interface was also designed and developed. It provides access to all the data, knowledge and models managed by the WILFRIED PSE (see Figure 6.18).

Figure 6.18. Man/machine interface of the WILFRIED PSE
6.3.2.3. Partial conclusion

This work enabled us to:

– highlight some general principles for the identification and representation of models, whatever their formalized language, within knowledge-based systems, by the determination of three levels: hypotheses (on the phenomena to be considered so as to represent the whole process), the models appropriate to represent one or more phenomena, and the methods (or sets of equations) necessary to implement the models;

– to express in knowledge bases how the models work, as well as their respective characteristics (input, output, cost, expected accuracy of the results, field of application, physical phenomenon involved) in order to enable assisted or automated assembly. Most models being associated with specific spatial divisions, the different necessary divisions have to be developed in parallel to the model assembly, and also revised with the models when required.

However, the potential perspectives of such an approach are still numerous. The validation issue for a specific model remains to be clarified, and particularly more so for a model system. The arrangement of various forms of modeling is difficult and raises many questions about the relevancy, the legitimacy or simply about the efficiency of such a combination. The simple fact that a prediction error can be compensated for or increased by another error must be overcome, and a more accurate analysis of the interactions existing between the assembled models must be carried out, for instance on the basis of a typology that remains to be developed.

6.4. Conclusion

The combination of GIS and models enables us to better understand the phenomenon, and therefore the risks. However, the notion of risk is essentially related to human activities and assets. Consequently, this specific hazard must be associated with the elements at stake in the research area. To do so, research on this phenomenon must be carried out, especially in the field of forest fires, in which studies on ignition and propagation still remain qualitative. It would be interesting to take into account and to integrate into risk analyses the results produced by physical propagation models, developed by the National Institute for Agricultural Research (INRA) and the University Institute of Industrial Thermal Systems (IUSTI). Additional information relating to knowledge of the hazard, and particularly to the fire front power, would improve our knowledge of fire-related damage. The latter consists of people and property for which it is necessary to mitigate exposure to the phenomenon, that is, the vulnerability.
With regards to this objective, fire management is inseparable from the implementation of a prevention policy, which is in the hands of the public authorities in charge of ensuring people and property safety. Yet, developing a prevention plan requires us to know the risk. This is why public authorities need scientists and experts from this specific field to implement mechanisms for risk assessment and mapping.

Then, these authorities have to face the juridical translation of fire risk, that is, the transfer of scientific data from “technical” mapping to the production of norms aiming at maintaining some sort of stability in social relationships. This aspect relates to decision-making and consultation with respect to risk prevention. However, risk analyses must not be limited to technical aspects versus socio-economic aspects. Efficient risk management implies iterative learning processes between decision-makers and scientists, in other words, a series of transactions between power and knowledge [STE 96].

As such, geographic information could be presented as a tool with limited accuracy to produce technical information, but also as a communication tool, being an integral part of the public debate. According to the National Committee on Geographic Information (CNIG), the purpose would be to use GIS to generate the technical documents, which will be easy to use with regard to consultation and decision support.

6.5. Bibliography


This page intentionally left blank
Chapter 7

Spatial Decision Support and Multi-Agent Systems: Application to Forest Fire Prevention and Control

7.1. Introduction

We are facing today an ever-increasing demand for spatial decision support systems (SDSS) dedicated to natural hazard prevention. Many systems are now available to managers. They offer a large variety of information and services in various fields and business lines (early detection, monitoring, response action management, communication, diagnostic services, databases, etc.). When considered separately, these SDSS give ample satisfaction to the users. However, parallel requirements emerge and evolve with respect to information exchange and services between dedicated SDSS, for it appears that combining these tools provides a means to resolve ever more complex problems.

Making SDSS cooperate with one another is not an easy task, since these systems were developed in different contexts. The computer scientist in charge of this task will have to tackle issues ranging from the nature and content of SDSS to the knowledge of the possibilities offered by these systems (services, data, ergonomics, etc.). Despite the important advances in programming languages, deficiencies still remain in terms of integration, management of interactions and cooperation between software, regardless of the application domain. The current

Chapter written by Franck GUARNIERI, Alain JABER and Jean-Luc WYBO.
solutions are far from satisfactory to address the difficulties and the complexity of the problems to be solved. A line of research has emerged and is based on the concept of an intelligent software agent. A model was thus developed and implemented (tested) in the field of forest fires.¹

7.2. Natural risk prevention support and the need for cooperation between the software programs

7.2.1. The cooperation issue between the information systems

The extreme complexity of natural risk prevention consists of two inseparable aspects. One is related to the phenomena by which the risk situation is generated (floods, forest fires, avalanches, etc.). The second results from the organization in charge of the prevention and management of this event and of its effects. An organization is a dynamic structure consisting of a group of specialized stakeholders. At any time, a stakeholder can come in and join the organization or, on the contrary, can leave the organization.

In response to this double complexity, it is generally acknowledged that the essential components of prevention and efficient risk management should be based on:

– the capacity to gather and diffuse the relevant information within an acceptable period of time;
– the need, with a specific view to predict and anticipate, to model the evolution of the threatening phenomenon;
– the need to facilitate information exchanges and cooperation within a group and between the groups of stakeholders in charge of the situation.

Risk prevention and management are achieved through the cooperation of a group of stakeholders specialized in the field of forest fires (firemen, foresters, local authorities, prefectures, etc.), in which each one has a different knowledge and experience. Prevention-related knowledge is distributed among the different stakeholders ensuring risk management, who are themselves geographically spread out in a given area, and who, in crisis situations, must cooperate and collaborate. The double distribution (knowledge distribution and the geographic distribution of the stakeholders) and the implementation of an efficient cooperation raise questions on the following relationships:

¹. We would like to thank the European Commission (DG XIII, Telematics for Environment) and the 11 partners (in France, Italy, Spain, Germany and Greece) for the European project DEDICS (Distributed Environmental Disaster Information and Control System) [WYB 96].
– communication and cooperation between stakeholders,
– communication and cooperation between the stakeholders and the information systems,
– communication and cooperation between information systems.

Our study focuses on the question of integration and cooperation between the existing spatial decision-support systems. The difficulties of cooperation between stakeholders who have to work together to solve complex problems is not considered here. The question of cooperation between the stakeholders and the information systems is not addressed either.

7.2.2. The various approaches aiming at facilitating this type of cooperation

Cooperation between SDSS, initially dedicated to a specific type of task and “self-contained” (there are non-communicating systems, that is to say they do not have any information exchange nor service function, and even less ability to collaborate with other SDSS) is achieved through providing each system with communication facilities to enable the exchange of information and services. To make a group of SDSS cooperate, it is thus necessary to develop and implement computer-based methods and models to enable the exchange of information and services between existing SDSS, within a heterogenous environment (PC, MAC, working stations, C++, Pascal, Lisp, Fortran, etc.).

It is also required that we design and develop a communication layer between existing SDSS that would go beyond mere data exchange. This layer must especially be used as a cooperation tool between the SDSS: request for services, opinion exchange, and interaction between them. Each message (information) sent must be understood by the receiver. Consequently, the communication must be built on semantics recognized by the receiving SDSS.

Defining a communication language between the SDSS is accordingly essential, even though it is not sufficient to implement cooperation. It does not describe the relationships between SDSS or decide upon what a SDSS should do, when and who with. SDSS thus require methods of cooperation to be capable of analyzing the relevance of the information, of the results or of the data they process, in comparison with all the other SDSS.

In order to formalize this cooperation between SDSS, there are three potential approaches [GEN 94a]:

– to rewrite existing SDSS software programs and transform them into communicating and cooperative entities. The advantage of this approach is that it
improves the quality of existing SDSS. The drawback is that the expenses related to “redesigning” and developing quickly add up;

– to undertake changes within existing SDSS to make them cooperate. This method is extremely delicate compared to others, for it is very complicated to achieve and it requires a deep understanding of each software program (which, for instance, when software are designed by different organizations and in different countries is almost impossible);

– to create a layer above each existing SDSS. This layer, associated with an existing SDSS, sets up and manages cooperation and communication mechanisms with the other SDSS. This is the approach we have chosen for our study.

The advantage of this approach is that it does not require specific knowledge with respect to existing SDSS modeling and implementation methods (contrary to the second approach). All that matters are the services provided by each SDSS to the other SDSS.

7.3. Towards an intelligent software agent model to satisfy the cooperation between the decision-support systems dedicated to natural risk prevention

7.3.1. The multi-agent paradigm

Traditionally, approaches to artificial intelligence have shown their limits in the design and development of complex applications: expertise, know-how, skills and knowledge are owned by different people. These people act, communicate, exchange their point of view and collaborate to reach a common goal, within a group, even if with regard to work sharing, each person has a goal of his own.

Distributed artificial intelligence (DAI) arose from the need to find solutions to these difficulties. Contrary to artificial intelligence, DAI is based on the principle that solving complex problems requires us to distribute control, knowledge, information, etc., between the entities that make up the system. This is how DAI enables cooperation between different entities. DAI consists of the three following research fields [NWA 96]: distributed solving of problems, parallel artificial intelligence and multi-agent systems (MAS).

There is no common formal definition of the notion of an agent. It is often defined in broad terms such as a physical or abstract entity able to act upon itself and on the environment, that has only a partial representation of this environment, that can communicate with other agents, that has a goal of its own, and the behavior of which results from its observations, knowledge, skills and the interactions it might have with other agents and the environment [FER 95].
The agent, in the broadest sense of the term, is characterized as a physical or virtual entity [FER 95]:

– able to act within an environment,
– able to communicate directly with other agents,
– driven by a number of different trends (under the form of individual objectives or a function of satisfaction and survival, which the agent seeks to optimize),
– has its own pool of resources,
– has only a partial representation of this environment (and sometimes none),
– has skills and provides services,
– that might reproduce,
– the behavior of which aims at satisfying its objectives, taking into account its own resources and skills, as well as the perception, representations and information it receives.

The agent is an autonomous entity that operates without the intervention of human beings or other agents, and has some control over its actions according to its internal state, and environment [COH 95]. Its skills range from mere calculations to various reasoning processes. It can have different behaviors: procedural (stimuli-answers) and cognitive (based on knowledge).

7.3.2. Intelligent software agents

Among the various research lines related to agents, there is one that has broadened its scope to include intelligent software agents (also called heterogeneous agents) [NWA 96], and which provides effective and efficient answers to the problem of platform cooperation [GEN 94b]. An intelligent software agent (ISA) can be a simple process or, more often, a more elaborate entity (a set of tasks within a single program, several processes within a single computer or several processes on different computers) [MAY 95].

J. Mayfield et al. [MAY 95] define ISA as software programs able to communicate with one another through the use of a performative language. They work together in a cooperative manner to solve complex problems; they are autonomous entities able to take initiatives. They handle local information and knowledge to manage resources and answer the queries issued by other agents.

According to these authors, intelligent software agent languages fall into two categories:

– agent implementation language, that is, any language used to describe an agent;
– languages allowing communication between two or more agents. They are based on the principles of human communication and on the theories of languages. They are implemented through communication protocols between software programs.

Intelligent software agents are considered as such if, and only if, they communicate correctly in an agent communication language (ACL) [GEN 94b]. In other words, these entities must be able to read and write ACL messages and meet the implicit constraints associated with the messages:

– truth constraint (an agent must always tell the truth),
– autonomy constraint (an agent cannot require any service from another agent as long as the latter agent has not stated that it agreed to provide the said service),
– commitment constraint (if an agent states that it can provide a service, it is then compelled to provide the said service if another agent asks for it).

Therefore, the principle of multi-agent approach is based on sharing and distributing with other agents all the knowledge and reasoning faculties possessed by an intelligent system. In practical terms, the intelligent software agent is in charge of activating the services and functions of the existing SDSS necessary to the cooperation and resolving of a given problem. It also ensures the reception and transmission of information to the other SDSS.

All ISA are designed with the same structure, and on the same “model”. Each ISA is associated with a specific SDSS (see Figure 7.1). Cooperation between SDSS is obviously impossible without at least two SDSS communicating together. Therefore, the objective is to design an intelligent software agent system consisting of equal numbers of elements and connected SDSS (see Figure 7.2).

Achieving this model requires we consider and propose solutions not only regarding the language and protocol for communication, but also the mechanisms assisting the effective implementation of a cooperation process between the software programs.

![Figure 7.1. Association between an ISA and its SDSS](image-url)
7.3.3. A proposed intelligent software agent model

An ISA consists of two parts (see Figure 7.3):

- an intelligent part, provided with social knowledge of the other ISA and reasoning faculties that allow effective cooperation;
- a part specialized in a given field and able to achieve certain tasks related to this field (the services and functions of the associated SDSS).

The ISA model is unique, which means that all ISAs have an identical structure, and that the only difference relates to the services offered by the SDSS. This identical structure characterizing all ISAs subsequently enhances the multi-agent system. Any improvement to the model is automatically replicated to all the ISAs of the multi-agent system, and does not challenge the relationships between the ISAs. Consequently, designing a multi-agent system only requires the design of a single ISA. The general ISA model consists of four parts (see Figure 7.4).

The communication layer is in charge of the sending, the receiving and the interpretation of the messages transmitted by the other ISA. This layer is responsible for interfacing between the ISA and its acquaintances (the other ISA of the system).
The public layer consists of the elements (functions and data) necessary to the cooperation and the exchange of information with the other ISA. It is available to the other ISA, which can consult it to learn about the skills and ongoing activities this ISA can complete.

The private layer, or associated SDSS, contains the algorithms and codes of all the services and functions of SDSS used by the ISA to complete the tasks it is responsible for.

The user interface is an interface between the operator handling the crisis and the different modules of the ISA (the communication layer and the public layer).

![Diagram](image)

**Figure 7.3. The ISA “global” model**

### 7.4. Experiment in the field of forest fire prevention and control

#### 7.4.1. Context of the experiment

The purpose is to demonstrate the validity of the ISA system supporting the communication and cooperation between SDSS dedicated to forest fire prevention. In this particular field, many SDSS are available to managers to support them in their mission. They offer multiple functions and services [VAS 95]:

- early detection of fire with video cameras fixed into a lookout tower,
- weather monitoring with automatic sensors on the ground,
- positioning ground control means with GPS,
- communication and telecommunication networks,
- forecasting tools (risk level, calculation of the potential propagation zones, etc.).
Table 7.1. Summary of the services provided by SDSS

An experiment was carried out over five days. One day (detailed below) was used to test some of the functions of the ISA system in fire conditions. Four days were dedicated to monitoring and analyzing common situations (weather monitoring and risk analysis). Table 7.1 summarizes the characteristics and services of each system that had been selected for the “experiment”.

![Image of the human-computer interaction of the WILFRIED SDSS]
7.4.2. The experiment scenario

A twofold scenario [GUA 99] was designed and implemented on the site of Sophia-Antipolis, in collaboration with the departmental fire and rescue services (SDIS) of the Alpes Maritimes. Three operational stakeholders were involved in this experiment (see Figure 7.5):

- the operational command center (COC) provided with three SDSS (WILFRIED, METEO and MCI);
- an intervention vehicle equipped with a GPS and a radio and satellite communication system (FLORINUS);
- a lookout tower in which a system to automatically detect fire ignitions (BODQUE) is directly linked to the operational command center.

![Figure 7.5. The different stakeholders involved in the experiment](image)

7.4.3. First part of the scenario

This first part of the scenario deals with the monitoring of a “normal” situation (see Figure 7.6):

- 9:00: the METEO system queries all the weather stations of the department of the Alpes Maritimes. All of the parameter values (wind direction and speed, temperature, pluviometry and air moisture) are stored in its database management subsystem. At the end of this stage, the ISA of the METEO system notifies WILFRIED of the arrival of new meteorological data;
- 9:30: the WILFRIED system receives the meteorological data from the METEO system. On the request of its intelligent software agent, WILFRIED starts the interpolation process of each meteorological parameter, and then computes the various maps necessary to operational management (ignition risk, propagation risk). The information provided by WILFRIED is also used to support the deployment of intervention and control resources. The ISA of WILFRIED transmits the different risk maps (computed by WILFRIED) to the FLORINUS system. The ISA of the
FLORINUS system, in charge of the deployment on the ground of the various firefighting groups, uses the risk maps provided by WILFRIED to identify the risk areas (the high-risk fire ignition/propagation areas are monitored in priority);

– 9:37: the operational command center first analyzes the different risk maps provided by WILFRIED, and then asks the field patrollers to transmit their GPS position. The teams involved on the ground automatically send this information to the stationary unit via the FLORINUS mobile unit;

– 10:00: the operational command center decides to anticipate and analyze the evolution of the situation if the weather conditions are to change in the next three hours. They generate their own meteorological scenario. They consider an extreme situation where the mistral is rising in the area and the winds reach 60 km per hour in some places. WILFRIED computes all the data necessary to evaluate the hypothetical situation.

Figure 7.6. Sub-scenario corresponding to risk monitoring and analysis

7.4.4. Second part of the scenario

This second part of the scenario (see Figure 7.7) demonstrates the efficiency of the agent system in a degraded situation (fire outbreak).

11:00: a fire is detected and located by the BOSQUE system, which then informs the MCI, WILFRIED, METEO and FLORINUS systems. From the moment a fire is
detected, we are no longer in a mere monitoring situation; the cooperation between the SDSS must support the hazard management and monitoring.

The intelligent agent managing the MCI system takes the decision to send the information to its MCI system, which results in the creation of a new folder associated with this fire within the MCI database. It requests its MCI to store in this new folder all the information exchanged between the firemen at work on the ground and the operational command center.

**Figure 7.7. Crisis management sub-scenario of fire outbreak**

In the MCI basis, the folder/fire is a comprehensive knowledge base that new responders can consult to be informed of all the actions that have been carried out on the ground before their arrival.

The ISA in charge of the WILFRIED system assists the decision-makers in analyzing risk and in implementing a control strategy based on the fire propagation simulation generated by WILFRIED.

The fire propagation simulation is a service provided by WILFRIED, but its implementation requires additional information held by other SDSS (points of origin of fires provided by BOSQUE, weather data, etc.).
To enable WILFRIED to complete its assisting tasks by producing a simulation of fire propagation, its ISA generates the “PropagationAct” activity. This activity consists of the following elements:

- **Name**: fire propagation activity (name of the activity);
- **Type-pb**: problem of the fire propagation simulation (type of problem processed by the activity);
- **Group-actions**: all the actions related to the activity;
- **WeatherInfo**: action to inform oneself about the meteorological status;
- **InterpolateWeather**: action to interpolate the different meteorological parameters (wind, moisture, etc.);
- **RiskMap**: action to produce the fire propagation map from these information;
- **BroadcastRiskMap**: action to provide the local users and the different groups on the ground with the result;
- **Body**: propagation (name of the function that starts the activity).

Before starting the “PropagationAct” activity, the ISA control unit of WILFRIED checks if the set of actions necessary to this activity are feasible through the cooperative system. In this case, it consults the actions related to the “PropagationAct” activity and it concludes that the three actions InterpolateWeather, RiskMap and BroadcastRiskMap can be completed locally by WILFRIED (according to the List-ISA field), but the WeatherInfo action cannot be completed locally. After having analyzed the structure of this latter action, the control unit deduces that the WeatherInfo action can only be carried out by the METEO system (Nb-ISA = 1 and Ag-name = METEO system) and that this action is already being processed by the METEO system (parameter info-agent) and moreover WILFRIED is Ethernet linked to the METEO system (high-speed connection).

Furthermore, the various information related to the actions of the “PropagationAct” activity are dynamically generated (deduced) by the reasoning module of the ISA of WILFRIED from the knowledge it possesses both of and via the associated systems. This knowledge changes dynamically according to the overall situation of the cooperative system.

Indeed, the ISA of the METEO system was informed (just as the ISA of WILFRIED) of the fire outbreak by the ISA of the BOSQUE system. Following this information, it launched the meteorological data collection in its METEO system and notified all the other ISA of the cooperative system that the METEO data collection activity was “in process”, which enabled the ISA of WILFRIED to know that the WeatherInfo action was being carried out in the METEO system. Now, the
ISA of WILFRIED only has to inform the ISA of the METEO system that it needs the result to complete its “PropagationAct” activity.

The ISA of FLORINUS is in charge of the communication between the operational command center and the groups of firemen involved on the ground. It takes the “decision” to inform the operational center of the situation on the ground: status of the fire front, location of the trucks, fire-damaged bridges, water points, etc.

The FLORINUS human-computer interaction enables the operational center to transmit their orders to the people involved on the ground in a graphic format. For instance, if they decide to direct a truck on the ground from a point X to a point Y, they will draw the course between the point X and Y on the screen of the FLORINUS stationary unit (in the operational center) and will send the message to the truck concerned. The latter truck will receive the order (in a graphic form) on the screen of the FLORINUS mobile unit (within the truck).

By analyzing the information messages received from the others, the ISA of the FLORINUS system understands that WILFRIED is working on simulating fire propagation. Therefore, its control unit asks its communication layer to inform the ISA of WILFRIED that the FLORINUS system needs the result of the “PropagationAct” activity. Then, the FLORINUS system stationary unit disseminates the result of the fire propagation simulation produced by WILFRIED to the mobile units of the firemen involved on the ground.

After it has detected the fire, the BOSQUE system keeps on monitoring its evolution, and communicates the images related to the progress of the fire front to FLORINUS and WILFRIED.

11:10: patrollers arrive on the fire site. They draw the real edges of the fire via the graphical interface of the FLORINUS system mobile unit, and transmit them the FLORINUS system stationary unit at the operational center. The ISA of FLORINUS (from the stationary unit) sends the real edges of the fire to the ISA of WILFRIED, which in turn asks WILFRIED to reactivate the fire propagation activity on the basis of the real edges.

11:20: the operational center makes a query on the METEO system to display the meteorological data in order to analyze again the risk indexes. WILFRIED determines the location of water resources (lakes, tanks, etc.) that are the closest to the fire front, and then it starts to interpolate the meteorological data to generate a new fire propagation map.

11:30: new reinforcements arrive at the operational center; they consult the folder/fire via the MCI system interface.
7.4.5. An example of problem solving

We will define here the different decision-making levels used by the ISA of WILFRIED with respect to the problem of fire propagation [JAB 99]. The problem given to the ISA of WILFRIED is as follows: “Where will the fire front be located in 1 hr 30?” (see Figure 7.8).

The first decision-making level for the ISA of WILFRIED is: “Am I able to coordinate the process of solving the propagation problem?” Its answer is “Yes”, because it expressed its will to support the others in solving the problem, by using the following act of language: “involvement if requested”. That is, it stated that it was available to solve the problem if it was requested to do so.

The second decision-making level is: “Can it solve the problem alone (with WILFRIED) or does it have to cooperate with the other ISA?” It cannot solve the problem locally with WILFRIED without cooperating with the others, because the actions that must be completed in WILFRIED require data held by other systems.

The third decision-making level is: it must find the ISA that will provide it with the data necessary to achieve local actions. The data it needs are: (1) the last position of the fire front, which can be provided by the ISA of the FLORINUS system, and (2) the most recent meteorological conditions, which can be transmitted by the ISA of the METEO system.

The fourth decision-making level is: the choice for cooperation is made, and then the cooperation process is to be activated. It asks for the last location of the fire front
to the ISA of FLORINUS and the last meteorological conditions to the ISA of the METEО system.

As soon as it receives the meteorological data, the ISA launches (locally) in WILFRIED the interpolation of the different meteorological parameters (wind, temperature, etc.); then, it calculates the vegetation water status. Finally, it activates the fire propagation simulation in WILFRIED by forwarding to the latter the parameters of the last location of the fire front provided by the ISA of FLORINUS and the interpolated values generated from the meteorological parameters.

7.4.6. Conclusion of the scenario

This simple scenario of exchange and cooperation between the various SDSS through the use of an intelligent software agent model emphasizes the potential of such a cooperative system to support analysis and crisis management. The cooperation between SDSS enables all the stakeholders (on the ground and in the command center) to share the same information and the same view of the hazard. This is how exchanging information between the ground and the command center via the cooperative system is far more reliable than traditional radio exchanges (it avoids human inaccuracies), such as: the locations and resources on the ground (automatic GPS detection and transmission from the FLORINUS mobile unit to the other SDSS in the operational center), the fire edges (drawn on the DFCI map of the FLORINUS mobile unit and transmission to the operation center) and the fire front (automatic transmission of the visible image from the BOSQUE system to WILFRIED and FLORINUS).

7.5. Conclusions and perspectives

This chapter has presented an ISA model dedicated to the solving of integration and cooperation problems between existing forest fire management software programs. This model enables cooperation between software designed and developed by many different bodies in varied contexts. Intelligent software agents have been designed to propose an efficient interoperability between them. They allow the integration of existing software and provide an extensive platform that facilitates future improvements.

The case study, in the field of forest fire risk management, partially validated the model proposed. The fire and emergency services saw it as a potential solution for the future. Indeed, to date their concerns are essentially twofold: the implementation of geographic information covering the Alpes-Maritimes department and the replacement of their radio communication system.
The current ISA model is designed on the following basis: an ISA for the management and integration of a single SDSS management in the cooperative system. It would be interesting to study the possibility of integrating several SDSS with one ISA and to analyze the advantages and limits of such an approach. The interest can be measured through communication: decrease in the number of ISA in the cooperative system, which minimizes the number of messages to be exchanged between the ISA. On the contrary, centralizing several skills within a single ISA (the various capabilities of the SDSS it manages) can entail a slow-down of the overall process of solving problems, for the ISA has to manage even more important tasks.

7.6. Bibliography


[CRI 96] CRIADO A., CARDONA A., Interface WILFRIED-BOSCQUE, Deliverable number D06.3 Version 1.0, Internal reference WP06.DL.03.01, November 1996.


Chapter 81

Flood Monitoring Systems

8.1. Introduction

Of all natural hazards, floods cause the largest loss of life and the most damage.

When exceptional events occur, they are always characterized as “unprecedented”. Yet, there are many significant disasters with traces and testimonies in history. These reactions are often expressed straight after the event by victims completely traumatized by what they had just experienced.

We can find in old testimonies (several centuries ago) many descriptions of events that took place in all the large French watersheds and that are similar to the major floods that have occurred during the last 150 years; the risings of the Garonne in 1875, of the Seine in 1910, of the Tarn in 1030, etc. There are also many testimonies with regard to smaller watersheds.

In his book, Maurice Champion relates [CHAP 62, p.17] the Ouvèze river flood of 1617 in Vaison-La-Romaine thus: “[…] at six o’clock in the evening, the Roman bridge of Vaison is covered by water and its parapets are swept away, several houses are washed down.” There are numerous testimonies.

Such information is known by a limited number of specialists, historians, hydrologists or people with a passion for the history of their region, but these data are of little use for they are rarely objective and often in the form of a socio-

Chapter written by Jean-Jacques VIDAL and Noël WATRIN.
economic narrative. However, they provide a human-scale view of these disasters. We are also led to wonder about the evolution of modern hydrology, which through operating measurement networks, moved towards statistical analysis techniques using drainage flow data, that is to say small samples (often based on a maximum of 50 years of observation).

These approaches made indisputable and even essential contributions to many fields of study, and yet they conceal the past, focusing attention on the accurate quantification of the rare or exceptional flow without any connection to the past.

Do we still need statements proclaiming that a certain flood is centennial, that it will recur every 200 or 300 years, knowing that most of the time the difference is only a few tens of centimeters? What really matters is that these floods are at the origin of disasters of similar magnitudes.

This notion of the exceptional flood is more and more common and postulates that the extreme events that have been observed during the last 100 to 150 years are usually representative of the catastrophic events that have marked the history of the river. Risk prevention policy relies on this paradigm before implementing most actions (land-planning, protection, regulatory mapping, etc.).

With respect to flood monitoring, the approach is very different. All floods, whatever their magnitude, represent a risk and must be detected with the purpose to provide the accurate observed level of a river so as to launch measures to secure people and certain property (animals, small furniture, etc.).

8.2. Flood monitoring and warning

In France, flood warning services on large rivers (Seine, Loire, Garonne, etc.) were implemented at the end of the 19\textsuperscript{th} century. According to its current definition (Joint Ministerial Decision of February, 1984), a flood warning is usually based on the detection and warning of any breach of the threshold level determined for each monitored river. The government, although not compelled by law, has undertaken the monitoring of some segments of rivers, in order to be able to warn local authorities in charge of protecting people and property, that is, the mayor, of potential risks. This mission is carried out under the authority of the \textit{prefet} of the department and defined in a document entitled “Departmental regulation on flood warning”.

This mission required the implementation of technical resources and the development of cooperation, especially with Météo-France.
The technical choices and the resources mobilized vary according to the watersheds and the French regions covered by our study.

### 8.3. Situation diversity

Due to its meteorological situation, topography and littoral length, the French territory experiences extremely diverse hydrological events. Rivers react proportionally to the size of their respective watersheds, and this reaction may vary from a few hours to a few days. Flood magnitude also depends on rain intensity, watershed topography and morphology, etc. This is the reason why in watersheds of similar size, the magnitude of the floods observed can be very different.

**Figure 8.1. Flow assessment of outstanding floods on the French territory**

The speed of the water level in some rivers is only a few centimeters or tens of centimeters a day, as is the case for the Seine or the Loire in its lower course, but in some other rivers in the south of France (the Gardon river in the Gard area, the
Ardèche river, the Tarn river and its tributaries in the Garonne basin, etc.) this speed can reach over 1 m (sometimes 2 m) per hour.

The exceptional flood that occurred on July 7, 1977 in the Lannemezan basins illustrates these extreme events observed in the Southern basins. Nearly 200 mm of rain fell in 16 hours. A large part of the Pyrenean Piedmont was affected by this precipitation. The water levels in all the rivers of the Lannemezan area rose very quickly, over 1 m per hour being generally observed.

![Figure 8.2.Flooding of the Gers river in Auch and Lectoure, July 8-9, 1977](image)

![Figure 8.3. Flooding of the Save river in Grenade, July 8-9, 1977](image)

The scale of these events and the specific characteristics behind them, particularly meteorological information, make it very difficult and even impossible to forecast such floods. Moreover, water usually recedes quickly, leaving behind devastated valleys.

Watersheds with larger response times are easier to monitor, making flood warnings more reliable.
The slow rising of water levels is characteristic of the floods observed in the large basins. The specific problems resulting from such situations are very different, but also delicate to handle for the emergency and psychological support teams. Indeed, having one’s house and all property under a meter of water, or more, for several weeks is an unbearable situation.

Flood risk threatens every region in France.

8.3.1. Spatial information for a better understanding of the phenomenon

Flash flood monitoring and warning, when possible, require adapted techniques and specific means. Detection and knowledge of these phenomena require a spatial view of the area affected.

Local measures can do no more than record an increase in water levels. They have no means of prevention.

Floods are often named after the town corresponding to the populated or industrialized areas affected, but the origin of the disaster results from a combination of meteorological and hydrological events spread all around the surface of the watershed. Therefore, spatial views are key elements to monitoring, understanding and explaining the situation, especially in small watersheds where floods are due to precipitation. The distribution of rainfall over the watershed, the position of the intense core, among others, must be known to establish a diagnosis, or even a prediction.

The same type of rainfall occurring downstream or upstream of the watershed can provide a very different answer at the outlet of the basin.

To the above should also be added the influence of topography, the degree of soil saturation, the vegetation cover, etc. The relief, for instance, has a strong impact on rain intensity. 50 mm are often observed over the Pyrenean Piedmont, and it can reach 100-150 mm over the reliefs. All of these elements have a complex spatial influence that is always difficult to measure and to take into account.

Most of the time, the circumstances are highly diverse and do not allow us to reason by analogy alone on the basis of the floods observed in the past.

In down-valley areas, which are called plain zones, the issue is less complex due to the fact that the measures carried out up the mainstream and on the upstream tributaries are good indicators.
Floods occurring above large watersheds are due to water running off all the basins upstream.

In this case, the floods observed upstream create waves moving downstream following the principles of wave propagation (reduction, distribution, etc.) and they combine with one another to form the main part of the flood in the plain zone.

Forecast uncertainties are especially related to the importance of non-point source inputs, that is to say the runoff or tributaries that are not taken into account, between the upstream observation points and the point monitored downstream. Approximations issued from models working on the upstream flood-wave propagation phenomenon are also a source of mistakes.

Undoubtedly, the diagnostic quality, along with the anticipation or forecasting processes, will depend on an optimal allocation of upstream measurement points. Establishing an upstream research station will contribute to finding a compromise between the time allocated to forecasting and the expected accuracy. The longer the forecasting period, the higher the uncertainty over the results.

8.3.2. Spatial information for flood impact assessment

Assessing the impact of a flood requires information on its development in space. Measuring a flood at a warning station enables us to provide a constant reference, to assess the significance of the event, or even to statistically quantify the flood-receding phase, but this measurement does not predict the impact of the flood on the disaster area. Knowing the scope of a flood is key to assessing the risk, to identifying the affected areas and determining emergency response. Today, real-time monitoring of flood areas is very difficult to achieve, whether because real-time models require too much information, especially topographical information, and entail computation times incompatible with the rapidity of propagation for such events (particularly on small basins), or because satellite monitoring technology, for instance, is still inappropriate.

On the other hand, developing atlases, as initiated by the risk prevention policy in 1994, provides maps of the areas vulnerable to flooding near a large number of rivers. For example, in the Midi-Pyrénées region, an informative mapping of the areas vulnerable to three types of flooding (very frequent flooding or annual flooding, frequent flooding necessitating a 10 year-period to restore the environment to its original state, and exceptional flooding) was achieved under the planning contract between the national and regional governments, over 7,000 km of rivers. This type of information, even though it is static, constitutes a valuable tool for decision-making processes in crisis management.
When floods occur successively, the knowledge of flood areas progressively grows; this type of mapping could thus evolve in real time through simple interpolation.

8.4. Technical answers

Observation and decision support systems must be exploited in real time. Indeed, in the south of France, and more particularly for the monitoring of small basins, the notion of real time takes on its full meaning. There are many areas where a diagnosis must be rendered and decisions made in about half an hour. During the development of the monitoring systems, these characteristics influence the technical choices, the observation means, the types of processing, the organization, etc.

The reliability, availability, interchangeability, computation times, capability of state-management over most elements of the system are important criteria to take into account.

8.4.1. Hydrological observing networks

The basic element of flood monitoring systems is the hydrological observing network. It generally consists of hydrometric and precipitation stations spread all over the basin. More complete stations are sometimes established in mountain areas to take into account the snowpack. These stations are connected to a central data collection hub via a transmission system. Choosing the transmission medium is a crucial step, for it must be suited to the type of event to be monitored.

In general, the development of these observing networks prioritizes to technical solutions aimed at mitigating incidents in times of crisis. On plain basins, the telephone is usually the transmission system chosen.

In short-response time basins, radios are frequently used as the main communication medium. Radio is very flexible and offers complete autonomy; the user does not depend on a service provider. The structure of the radio transmission chain is designed to face crisis situations. Therefore, the redundancies are identified and used as emergency connections to maintain transmission with the measurement stations. Other equipment has, for the most part, an emergency power generator enabling it to maintain transmission for several days.

This choice requires skill development for a team of technicians within the operating service. Radio also allows fast-paced data collection, which is fundamental for efficient monitoring. Collections are carried out every hour, sometimes every 30 minutes, on all these systems. For services in charge of
monitoring large basins, such collections consist of huge volumes of data that need to be processed in real time and in a short period of time. When the first teletransmission measurement networks were established in the large basins, at the beginning of the 1980s, the first difficulty was the design of the structure and the operation of the transmitting radio stations. The second difficulty encountered by the managers was the exploitation, in real time, of large amounts of data.

For example, the flood monitoring network of the Garonne river, which consists today of 109 measurement stations, sends every hour nearly 200 pieces of hydrological data, plus the maintenance parameters of each set of equipment. The amounts of data soon raised difficulties for the forecasting officers who often had to make quick decisions at any hour of the day or night. Consequently, managers acquired the necessary experience, with respect to automatic network management, to design computer-based decision support tools.

In parallel, at the beginning of the 1990s, complementary observation devices became available and were implemented. The METEOTEL system, developed by Météo-France, is a receiving platform for radar and satellite imagery that provides global and ongoing information on some specific parameters, and particularly on the precipitation surge.

8.4.2. Data processing

In association with the collection networks, information processing was also implemented. The first computer-based applications were developed in the 1980s through the improvement of the human-computer interaction usability. Intuitive access to information, synthetic representations of data in dynamic synoptic forms, curve charts to visualize the variations in time of the different hydrological data, all these have found their respective uses.

Ground-based measurement networks, and especially those dedicated to rain, only provide a short overview of this parameter. The density of the measurement networks is inadequate to give a representative picture of a rain event distribution. Measuring rain at a specific point with a precipitation gauge is very accurate, but the result can be very different some kilometers away. This observation is particularly relevant with respect to the monitoring of basins in mountainous areas where the relief greatly influences rain events.

The combination of ground-based data with the information issued from the METEOTEL system enables us to carry out qualitative analyses of an ongoing event and, even though anticipation is a delicate process, this combination provides the operator – along with his expertise – with an insight into the evolution of the event.
The need for quantitative projections led the emergency services to develop flood forecasting models. These methods, based on the propagation of flood waves in plain areas, are relatively easy to develop and implement. On small basins, forecasting depends on pluviometric information and is achieved through rain-flow relationships, which only give an approximate representation of the drainage conditions. Flood formation conditions in small basins are linked to a large number of characteristics all over the basin.

The complete modeling of such a system is still at the research stage. At the present time, several simple and robust models are used but they do not cover every possible situation. Consequently, operational systems using multi-model processes are implemented, so as to automatically manage several models tailored to different situations.

The performance of the models also depends on the knowledge of the precipitation. The amount of work related to the management of the measurement networks, to their performances and reliability with regard to real-time exploitation limit the expansion of the measurement points. Therefore, the pluviometric information produced by the ground-based measurement networks is not always representative of a whole rain event. This data, which is integrated into the rain-flow models, contributes to the degradation of the system performances, and thus caution must be used when exploiting the results.

In order to address this inadequacy, meteorological radars are used to assess the precipitation surge. However, rain assessment through radar imagery requires some processing and calibrations.

The use of radar as a \textit{hydrological sensor} is essentially based on measurement of the intensity (or power) of the echo signals, and interpreting this in terms of precipitation intensity.

Radar measurements, although flawed, provide encouraging results for rain assessment. This method is yet more delicate to implement in high-orography regions where echo signals meet with interference. Ground clutter returns, masking areas, and strong rain heterogenity are, among others, conditions affecting measurements. The presence of the 0°C isotherm within the radar beam is also a source of error.

Work is underway in various basins to automatically introduce radar data in the hydrological models. Experimental chains working in real time are currently being tested.
It is clear that the ability to forecast flood elevation depends very much on the basin and on the type of weather disturbance. In large basins, it is possible to anticipate a variation of some tens of centimeters in the water level 24 to 48 hours in advance; whereas in small basins, forecasts issued 2 to 4 hours in advance are often not very accurate.

Therefore, the structure of the systems developed and the organization of the services can be very different depending on the basins they are responsible for. The implementation of hydrological and technical stand-by systems is particularly essential in rapid response basins.

8.4.3. The integration of acquired knowledge in the natural hazard prevention policy

Risk prevention policy especially aims at developing knowledge of natural hazards. The production of atlases of areas vulnerable to flooding, systematic mapping after a major flooding, identification of sensitive areas along a valley, implementation of post crisis management, etc., represent data that must be progressively integrated into the monitoring systems so as to improve expertise and hydrological analysis capabilities.

Such an increase of knowledge should lead to improved and timely forecasts and ultimately towards spatial forecasting. Cartographic materials dealing with areas vulnerable to flooding and, in certain situations, with hydraulic models for the assessment of flood-sensitive areas must be integrated into monitoring systems.

This spatial information, processed in real-time, requires a more comprehensive reflection on the size of the processing computer units, and on how to exploit them in times of crisis.

8.5. Conclusion

Most flood monitoring systems were implemented in the 1980s. After over 15 years, an upgrade phase has been launched.

The technical advances will lead to the development of more efficient systems. For example, the networks collecting data in 15 or 20 minutes will probably reduce this time to five minutes, and today’s processing capabilities are beyond comparison with former systems. The integration of cartographic information is unavoidable and standard computer capabilities are appropriate to this type of processing. This also applies to the implementation and generalization of forecasting models within multi-
model environments. Moreover, experimenting with adaptive systems is to be further explored, for it could provide an alternative or complementary solution.

When possible, short-term precipitation forecasts (three to five hours) for small areas (100 to 1,000 km²) will be a significant advancement for hydrological forecasting on small basins.

Satellite observation is also a potential solution to be explored.

As was already the case at the end of the 1980s, one difficulty remains: the operator still has to exploit a huge and varied array of data. Information fusion is a major issue for systems now being designed. How can we organize and display a large amount of data, the spatial vision of which is fundamental for an event characterized by dynamic evolution in time? How can we go from timely information to spatial information? How can we support the operator in finding the relevant data at the right time, so he can prioritize actions? How can we combine information to improve expertise and provide forecasts, or anticipate situations as early as possible with more accurate results?

Future flood monitoring systems will have to answer all these questions.

8.6. Bibliography


This page intentionally left blank
Chapter 9

Geography Applied to Mapping Flood-Sensitive Areas: A Methodological Approach

9.1. Introduction

Flooding is a dynamic and more or less paroxysmal phenomenon, limited in time and space, and which can be defined as an overflow of water submerging a part or all of a plain liable-to-flooding, defined as a functional alluvial plain. Such events affect space, leaving new and contemporary geomorphological traces, readily identified, or older ones, more or less altered and sometimes difficult to reshape. Flooding also leaves psychological scars in the collective memory, due to the more or less disastrous impact of each event on which variable amounts of data were collected (flood marks, cartographic or photographic record, water data archive). Today’s morphogenic dynamics have turned flood-sensitive plains into specific geographic spaces, where some of the dynamics shape the relief, the landscape of the plain; and where interactions are constantly evolving between flood dynamics and strong socio-economical activities. Government land-planners characterize liable-to-flooding areas as risk areas, because hazards (flooding) meet key vulnerabilities (social infrastructures). These two parameters define flood risk.

The geographic understanding of flood risk is associated with the analysis of the flood hazard, closely related to the analysis of the area on which it spreads out, that is, the floodplain.

Chapter written by Christophe PRUNET and Jean-Jacques VIDAL.
9.2. A geographic analysis of flooding

As a geographic phenomenon evolving both in space (floodplain lands) and time (duration of submergence, flood-receding period), floods can be analyzed considering three indissociable parameters: the intensity, frequency and extension of the phenomenon.

9.2.1. Intensity

Intensity corresponds to the power of the flood and can be assessed by measuring the flow rate (Q) or the height (H). Today, many hydrometric stations provide such data in real time, for many rivers in France. Flood height is particularly interesting for space management – the reasons are threefold:

– the flow rates are derived values depending on the reliability of the rating curve, and all the more so since flood flow rates are most of the time extrapolated values beyond the limits of the diagram displaying the relationship between height and rating curves. Conversely, the maximum instantaneous height is a raw value, concretely measured and immediately available and at scale on the limnigraph. Flow rates are thus primary geographic data, extremely reliable with respect to the heights measured with a limnigraph, and highly reliable when the heights are read with concern and skill;

– flood heights, whatever the location, are concrete values, understandable to anyone. Much more concrete than flow rates, heights are usually taken into account in studies preliminary to risk prevention plans (the French plans de prevention des risques – PPR). Moreover, they depend on the geomorphology with regard to the low-water bed and to the alluvial plain at the measurement station point, therefore they inform on flood dynamics.

Exploring flood height enables us to emphasize historical flood marks of the old flood warning stations, where events are registered, sometimes as far back as 200 years ago for large rivers. After validating the data, it is thus possible to create very rich samples, available for stochastic study, and thus to take into account data related to very old disastrous floods, which, although disputable quantitatively, provide information on the frequency of exceptional events.

9.2.2. Frequency

Frequency is a piece of data pertaining to the field of geography applied to natural hazard prevention. Analyzing rainfall record enables us to register all the notable floods of the follow-up period, to which are added the potential historical
floods that occurred before the same follow-up period. Some statistical adjustments support the correlation of the height of the event and its apparent frequency.

Figure 9.1 refers to the statistical adjustment of a sample consisting of the 306 floods higher than the Garonne river by 2 m, registered at the Toulon-Pont-Neuf station between 1875 and 1998, 124 years of non-stop hydrometric monitoring; a document developed in semi-logarithmic coordinates.

![Image of Figure 9.1](image)

**Figure 9.1. Height-frequency correlation**

The image produced consists of circles illustrating a progressive and rectilinear evolution of the frequency according to the height. The regression segment drawn as a solid line clearly emphasizes this evolution. The figure shows that a height of 2.5 m corresponds to the annual frequency (f = 1), that the decennial flood (f = 0.1) reaches 3.6 m, flooding occurring every 50 years reaches (f = 0.02) 4.7 m, and flooding occurring every century reaches (f = 0.001) 5.00 m.

In the figure above, the position of the flood that occurred on June 23, 1875 is irrational compared to the overall evolution of the flood sample, for it reaches a height (8.32 m) that clearly stands out above all the others on the linear regression plot, which requires consideration. Indeed, if this flood does not follow the evolution of the large floods within the timeframe, it is probably because the dynamic
conditions of the flood at the site measurement were different for the 1875 flood than for the other events.

The measurement of this flood height at Pont Neuf was exacerbated by an ice jam, which had been caused by the local authority of Toulouse and the bridge itself. This was confirmed by studying the hydrological records of the town of Toulouse and of the flood warning service, and it also explains the peculiar position of the mark on the regression plot (see Figure 9.1).

Adding the large historical floods sheds light on the phenomenon. Since 1770, nine floods exceeding 3.5 m have been recorded. If we set apart the floods reaching 3.5 m and above from the research sample, 3.5 m being a critical submersion level with respect to embankments (readily visible, for there is a plateau in the rectilinear evolution of the points on the graph), and if we add these nine historical floods, then we have a sample consisting of the large inundating floods for the period 1770-1998, that is, 229 years. The calculation of the apparent frequency is achieved within this specific period of time, to produce an image (squares) where the 1875 flood has a homogenous position compared to the big floods suffered by the town of Toulouse. This new image displays a double-evolution with regard to the floods of the Garonne river at Toulouse: (1) events below 4 m satisfying the same law governing the correlation between height and frequency, and with regular intra-riverbank flood dynamics; (2) inundating floods exceeding 4 m forming a sample on the regression plot that suddenly raises up (heights rising more rapidly) and emphasizes the impact of the ice jam or other obstacles to the water flow, and which also makes a visible difference between inundating flood dynamics, less common, and “ordinary” floods (below 4 m). As a result, the centennial flood assessed at 5-5.5 m with the first sample now rises to 6.5-7 m with the second sample.

This exercise reveals the very significant uncertainty with respect to the assessment of the flood return periods and the direct relation to the quality of the sample. Even though discharge volumes correspond to variables that are more appropriate to the application of statistical laws, the uncertainty characterizing the assessment of large flood discharges or major and exceptional flood discharges can cause serious errors when estimating the frequency of a flood. There are many examples; a 10% error on an extreme flow (minor error) can change the estimate of the return period by several centuries.

In the case of the station in Toulouse-Pont Neuf, taking the historical floods into account is key to understanding the large flood dynamics above the town of Toulouse.
9.2.3. Extension

This stochastic inundating of flood estimations, vital to flood prevention, would be incomplete without any spatial study of the flood, which consists of the geomorphological analysis of the functional alluvial plain. This essential data of the triptych intensity-frequency-expansion is the third and final step. Here the question is asked, a fundamental question for the geographer, dealing with the transition from information that is regular in time and space (such flood level, at such date and at such place) to spatial information, covering all the flood-sensitive areas (a particular portion of space suffering a flood at a particular frequency).

The best tools dedicated to geographic analysis and enabling us to study systematically flood-sensitive areas are the IGN flying missions at a scale close to mapping (for instance, 1:20,000 to produce a 1:25,000 informative map).

Aerial photographs, which are a systematic and primary information source (covering the whole French territory), enable us to achieve the transition from timely information to spatial information through decoding the geomorphological and geographic information they contain. The stereoscopic analysis of these photographs provides five types of crucial information.

9.2.3.1. Extension of the flood-sensitive alluvial plain

The extension of the flood-sensitive alluvial plain, historically flooded, that is to say the limits of the embankment in which lies the liable-to-flooding valley floor, the functional alluvial plain. This is an easy task when the embankment is steep, with a sharp contact (transition from a liable-to-flooding plain to a rectilinear slope or dead fluvial cliff), but it is a more delicate work when the contact is gradational, when a gentle slope characterizes the transition from the liable-to-flooding floor to a lopsided slope, which is actually not so steep. This determination is all the more difficult when farm work standardizes land use, levels the relief, and erases the break-in-slopes existing between the slope and the plain. Field trips complete the analysis of the photographs in order to carry out the necessary check and validate the mapping.

9.2.3.2. An accurate analysis of the fluvial landform development

A fine analysis of the fluvial landform development, caused by the last major flood and a cause of future flooding, can only be achieved through a stereoscopic analysis of aerial photographs. This type of analysis provides a satisfactory distinction (except for dense urban areas), and sometimes an excellent distinction between:
– very frequently flooded areas, seasonally. Floods submerge these sectors each hydrological winter, and sometimes several times per winter. They correspond to frequent floods exceeding 1, occurring about 100 times per century;

– frequently flooded areas, with a return period of 5 to 15 years. They occur about 10 times in a century (this is the reason why their return period is said to be decennial) and shape their own floodplain. Initial accelerations are frequent in these areas, and load transfers result in complex morphogenic dynamics leaving geomorphological traces that require interpretation. In large alluvial plains, the inner parts (on the river side) of this area can suffer more floods (less than 5 years), which characterizes them as transition zones between seasonally-flooded areas and decennially-flooded areas. They are easily noticeable on aerial photographs because of their landform (a mix of flood channels and folds in the ground), their tree distribution and their agricultural land use (pastures, meadows and hayfields);

– areas suffering exceptional floods, which cover the whole space up to the embankments. Only very large floods reach these areas, forming a usually thin water surge, less than a meter thick, and where the fundamental and dominant process consists of the deposition of fine-grained sand, silt and clay, initial acceleration being rare in these zones. These specific areas are particularly flat, and their boundaries are difficult to define.

All of these three areas form the floodplain, inundated by the biggest historical floods, known or otherwise.

9.2.3.3. Locating water projects

Far superior to IGN maps, a stereoscopic analysis of aerial photographs allows us to locate water projects at the valley bottom. These water projects both organize and disturb flood dynamics, whether they consist of agricultural, road and railway embankments, or of submersible or insubmersible dikes. The space between the piers of bridges, riverbank developments (groynes, rock-fill dams) and hydraulic structures on the low-water bed can also be identified and provide further information.

9.2.3.4. How does society use space?

Aerial photographs also provide a major piece of information regarding the connection between the areas liable to suffer highly frequent, frequent or exceptional floods, and public use of these liable-to-flooding areas, since they consist of many different soils with many different potentialities and possible uses. A key indicator is assuredly rural land use. This is how seasonally flooded areas are identified because farm operators use them as pastures, timber, or sometimes as permanent meadows, or even for low-investment cereal cropping. The less frequently flooded lands (f < 0.1), fertile and easy to till, are used for more awkward crops requiring major capital investments (spring cereals, fruit and vegetable crop production, etc.). Land use,
with respect to housing and other buildings, is another indicator useful to determine flood risks: in big valleys, farming villages and townships would develop away from liable-to-flooding areas, but as close as possible to loam soils: that is to say at the edge of floodplains, or on natural or built mounds, overlooking the liable-to-flooding areas. However, today, intense urban expansion results in the development of housing and areas of human activities in floodplains, whether in large valleys, or in small ones suffering severe floods that are all the more disastrous because the valley bottom and the lopsided slopes are densely urbanized.

9.2.3.5. Extension of liable-to-flooding riverside areas lacking hydrological monitoring

Small rivers and minor tributaries, with no limnigraph station, with few or no hydrometric records, also suffer floods, which are sometimes severe and devastating, generated by intense rainfall over small-sized watersheds. A stereoscopic and geomorphological analysis can provide a cartographic, geographic solution to the problem of inundating floods affecting these watercourses. If the bottom of these valleys is flat all along the banks of the waterbodies, it geomorphologically means that these bottoms are covered with an alluvial layer formed by the local historical floods. Only a systematic stereoscopic analysis of the aerial photographs could detect and map these flat bottoms liable to be submerged by floods. These watersheds being of small size, located above the main rivers, the longitudinal profile of their main drain is steeper; consequently, floods are swift and brief, and have different dynamics. This is why the identification of distinct areas based on recurring floods is very complex. However, the stereoscopic analysis will enable us to define the external limits of the liable-to-flooding areas, ending at the embankments. This constitutes a fundamental piece of information to map flood risk.

Nevertheless, a certain number of unknowns remain to be determined, with respect to concrete situations and more particularly to the current situation in 2001, because all the parameters studied from aerial photographs evolve over time. The status of the low-water bed, riverbanks, dikes and embankments are data that greatly change from one hydrological winter to another, whereas mapping is based on flying missions used for stereoscopic analysis, and on the topographic map used as the basis for the mapping of liable-to-flooding areas. These documents are updated every 10 years, which is not appropriate to provide a representative picture of the low-water bed and its banks.

As we have clearly explained above, a stereoscopic analysis of aerial photographs is very rewarding and essential for our research work, yet it does not provide all necessary information. It absolutely requires astute and reasoned ground observations, with sometimes many accurate details depending on the scale used (1:25,000 or 1:10,000):
– observations previous to the stereoscopic analysis, so as to determine the proper questions to be addressed and avoid false leads. Exploring the research area enables us to memorize landmarks that are very useful to analyze in photographs;

– subsequent observations to check the accuracy of the findings, or to clarify certain ambiguities. This checking process is twofold since the stereoscopic analysis points out where to go on the field to obtain information and what complementary observations must be carried out.

The importance of a geomorphological analysis based on aerial photographs to map flood-sensitive areas justified an accurate presentation of this systematic analysis tool. Flood understanding being assessed on the basis of a threefold relationship – intensity-frequency-expansion – the map rendering parameters must be defined in detailed specifications to obtain a homogenous final document for any research area. The priority is to produce a single map, easy to distribute and reproduce, as well as clear and concise for non-specialist users. Figure 9.2 presents a summarized profile of an alluvial valley to provide a synthesis of the mappable geomorphological units that are contained or that predominate in the functional alluvial plain, and which govern the dynamics of inundating floods, regardless of their respective frequencies.

The original aspect of the approach presented in this chapter is that it explores the complementarity between the geomorphological approach, ground observations and the hydrological analysis. The historical research and the statistical analysis of the water data particularly allow cross-referencing and control through successive comparisons of, for instance, the boundaries of the liable-to-flooding areas drawn by the stereoscopic analysis and the flood marks compiled in the field. For example, the demarcation of an area suffering a frequent flood (decennial), in an area where the boundaries are indistinct, can be fixed or confirmed by a flood mark that has been characterized by statistical analysis to have a 10-year return period.

There are many examples of this kind, which show how fruitful the complementarity of each technique can be. This approach was applied in Midi-Pyrénées to map 7,000 km of rivers.

9.3. A concrete example

We will present here an example of the dynamics of an inundating flood above a large alluvial valley.

Figure 9.2 summarizes the main hydrological and geomorphological phases of the dynamics of flooding above Verdun-sur-Garonne, a town in the Middle Garonne Region, located 35 km below Toulouse.
This section of the valley, situated downstream of a 13,000 km² watershed, faces the Garonne de Piémont, which develops into large and free meanders, with a slope a little less than 1%, and lying in an alluvial trough, the bottom of which is liable to flooding and 2-4 km wide. The low-water bed has a piedmont slope with fast runoff. The large alluvial bottom is totally submerged when the Garonne river suffers major floods coming from the Pyrenees and the Gascon region. Therefore, this section of the Middle Garonne has been identified as a sensitive area since 1896, thanks to the flood warning station of Verdun-sur-Garonne. The hydrological regime of the Garonne river in the Toulouse region belongs to the pluvionival oceanic type, with high water levels in winters and hydrological springs. Flood risk is greatest from December to June.

Of course, the Garonne river is no longer free to spread its flood waters and to cross its meanders. Since the middle of the 20th century, society has taken more and more action on the riverbeds of the Garonne, and particularly in the high-water beds, where increasing farm investments and urban pressure led to developments in the exceptional floodplain, and sometimes even the decennial floodplain.

This description of the research area will facilitate the understanding of Figure 9.2, which presents the six main hydrological phases of a mega-flood above Verdun-sur-Garonne, registered upstream of the morphogenetic flow, when the flood becomes an inundating flood. In the left column, you will find the longitudinal profiles of the valley above the station, where only the heights are at the right scale. In the right column, you will find the water line profiles at the different phases of the flood, and relevant elements of the hydraulic dynamics.

During the first four phases, the flood keeps on rising, inflow at the station being higher than outflow, the water level is thus higher than the low-water bed, and waters submerge the right bank of the plain. Phases 2, 3 and 4 represent the three flood categories that were mapped in Midi-Pyrénées (very frequent, frequent and exceptional flood). Phase 5 corresponds to slack waters: outflow equals inflow. Finally, phase 6 is the fall: outflow is higher than inflow. The flood flow reaches the plain drains (flood channels) and the low-water bed.

This document is a clear illustration of the close complementarity between the hydro-geomorphological approach (spatial and cartographic) to flooding and the historical analysis (statistical and site) of flood heights and their return periods. It shows the relationship between a given event, in terms of height and frequency, and its impact, in terms of expansion.

It also shows the efficiency of the two-fold approach, historical and geographic, of flood-sensitive area mapping, one validating the other and vice versa.
Figure 9.2. Dynamics of flooding in Verdun-sur-Garonne

9.4. Bibliography


This page intentionally left blank
Chapter 10

Information Systems and Diked Areas: Examples at the National, Regional and Local Levels

10.1. Context

There are several thousand kilometers of dammed waterways in France for flood protection. Compared to other natural hazards, flooding is characterized by being largely dependent on the behavior of dikes in a crisis situation. To the “natural” flood hazard, resulting in the overflowing of a river, is added a “technological” hazard of the breaching of dikes built to control flooding: this further complicates flood study and prevention. In parallel, protected (up to a point) by these dike systems, social issues have dramatically increased in the last few decades, due to a more or less controlled urban development.

Since the 19th century, the large French rivers had not suffered any major flooding (1846, 1856 and 1866 in the Mid-Loire river, 1856 in the Rhône river), and this remained so until the 1990s. Becoming complacent, people had progressively forgotten the notion of flood risk due to dike breaching. However, the recent disastrous floods, abroad (Mississippi River in 1993, Rhine river in the Netherlands in 1995, Oder and Vistule rivers in Poland in 1997) and in France (Rhône river in Camargue in 1993 and 1994, Var river in 1994, Meuse river in 1995, Aude and Agly

Chapter written by Pierre MAUREL, Rémy TOURMENT and William HALBECQ.
rivers in 1999) have increased awareness of the key role of dikes with respect to safety.

Dealing with flooding requires us to understand the behavioral mechanisms of dikes when dry or during periods of flood, and particularly those causing breaching, so as to assess these mechanisms when dikes are “dry” (that is, outside flood periods), and to be able to carry out on-site monitoring, maintenance and to strengthen dikes, taking into account the environment in protected areas. This brings us to the issue of implementing information systems and therefore of tailoring computer, human and organizational resources to exploit these systems.

A number of initiatives have been taken to ensure dike security since the middle of the 1990s.

In 1996, the Mid-Loire Plan Multidisciplinary Team (EPPLGN) launched a historical study of the causes of levee breaching along the Loire river during the 19th century floods [HAL 96].

Also in 1996, this team commissioned Cemagref, associated with the engineering consultancy firm ISL, a comprehensive methodological work to develop an operational process to diagnose and monitor dikes [CEM 97].

In 1997, at the request of the ministry of land and environment management, a temporary special committee of the General Council for Roads and Bridges and of the General Council for Rural Engineering, Water and Forests was set up to draft a summary of several missions that had been implemented after the French floods of 1993 and 1995. This request was part of the interministerial circular dated 17 August 1994, which instructed “inventory of all the flood protection works” and to conduct a technical audit of these works. In compliance with this circular, the commission eventually supported a national survey to draw a list of all dikes, of their respective managers and of everything they protect. The ministry entrusted Cemagref with the creation of a questionnaire and the monitoring of a computer application development on a database management system (DIGUE software) to carry out this inventory and exploit the results [CEM 99, ROY 98]. The survey was started in mid-1999 at departmental level, and the first answers were received in 2000. To complement this inventory, the ministry also urged Cemagref to develop a guide for the monitoring, maintenance and diagnosis of flood protection dikes [MER 01].

As early as 1998, Cemagref wished to answer the need for software and database tools to diagnose dikes, and thus started to analyze and design a geographic information system to support stakeholders involved with flood risk in diked areas to coordinate their actions for an integrated management of these areas [CEM 00].
The context of the document being set, we would like now to detail the information systems dedicated to diked areas by making a fourfold presentation:

– in order to provide a reference framework for this document, we will use the results of a study conducted by Cemagref in 1998 with the aim of identifying the stakeholders involved with diked area management, their tasks as well as their level of intervention;

– then, we will study the importance of the spatial dimension relating to the general issue of diked area management;

– we will describe the three information systems that were developed during the studies mentioned above;

– finally, we will conclude with a synthesis of these various experiences so as to suggest approaches to develop multi-stakeholder and multiscale GIS that could contribute to a more integrated management of diked areas.

10.2. Analysis of the current situation for the management of diked areas

The results presented here were obtained at the end of the first step, that is, at the end of the strategic diagnosis of the process carried out by Cemagref to analyze and tailor GIS to diked areas [BEL 99].

This step revealed that the stakeholders involved with the management of diked areas, even though extremely numerous in France, could be grouped into four categories:

– the central administration of the Ministry of Land and Environment Management (MATE): Directorate for Water, Directorate the Prevention of Pollution and Risks;

– regional coordination structures, acting as an organ of reflection and decision-making with respect to land use planning near dammed rivers and involving several dike managers: departments and regions, regional Directorates for the Environment (DIREN), basin authorities and more specific structures such as EPPLGN for the Loire river;

– departmental services carrying out activities falling under the missions of the central government (water policy, implementation of risk prevention plans, etc.), or providing contracting authorities with technical assistance for dike work: prefecture, Departmental Directorate for Equipment (DDE), Departmental Directorate for Agriculture and Forests (AFDD, technical services of the department);

– local managers in charge of the monitoring and maintenance of dikes and protected area (called val in the Loire region): local authorities, labor organizations, inter-municipal trade unions, government departmental services such as the DDE;
organizations such as the Public Works Regional Engineering Offices (CETE), Cemagref, the CETMEF (formerly the Central Technical Service for Seaports and Navigable Waterways) and also consultants, who provide technical and scientific support to the stakeholders listed above.

On the basis of interviews conducted among stakeholders from different categories, a two-way typology was set-up in the management system presented in Table 10.1. The upper entries in the columns refer to major systems (dike and riverbed management, diked area management, crisis management), and the row headings refer to three levels of intervention (at a scale of 1:25,000 for all the dikes along a river or a part of a river, at scales from 1:5,000 to 1:10,000 for a dike or a long section of a dike, at a scale of 1:500 for a small section of a dike). Each cross-section “management system x level of intervention” corresponds to processes and management operations that are based on automated or non-automated information systems.

<table>
<thead>
<tr>
<th>Prevention/Land use planning</th>
<th>Crisis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dike and riverbed management</td>
<td>Liable-to-flooding areas land planning and management</td>
</tr>
<tr>
<td>Planning work and interviews</td>
<td>Displaying the hazard and negotiating protection objectives</td>
</tr>
<tr>
<td>1:25,000</td>
<td>1:10,000</td>
</tr>
<tr>
<td>Dike diagnoses, vegetation maintenance</td>
<td>Regulation on the comprehensive development area map (POS)</td>
</tr>
<tr>
<td>1:500</td>
<td>Topography and visual inspection of dikes, work achievements</td>
</tr>
</tbody>
</table>

Table 10.1. Processes and management operations in diked areas according to the management system and the level of accuracy

The study revealed that the level of information was extremely heterogenous, with on one side highly sophisticated warning flood systems and on the other side a
management with scarcely any knowledge of the data on dikes. The situation also varied a lot from one diked area to another.

10.3. Spatial dimension and integrated management of diked areas

A real integrated management of fluvial diked areas would require, from a spatial point of view:

– having a comprehensive knowledge of all the dikes associated with a single river system, in order to understand the upstream/downstream interactions and right/left bank during the course of a flood;
– comparing information on dikes with information on the protected area and on the dammed riverbed. This would enable us, for instance, to identify dike sections in contact with the river, or to locate high-stake areas lying behind impaired dikes;
– the ability to aggregate information at various geographic levels according to the managers’ tasks.

To date, there are several spatial constraints obstructing this integrated approach. These constraints can be grouped into two broad categories: the first is that documents are scattered and heterogenous; the second is related to spatial positioning systems.

Usually, when information on dikes is available, their spatial representation is executed by draftspersons (provided with or without CAD software programs) on very large scale plans (typically 1:500) or on basemaps (e.g. enlargements of IGN maps at a scale of 1:25,000) which, in this case, constitutes a limit to the amount of information represented, as well as to accuracy. Sometimes, these documents are preliminary project documents that have not been updated to take into account the modifications that occurred during the execution of the work. Paper-based documents limit the potential for data storing, exchange and exploitation. Documents are often disparate, and thus only provide heterogenous information on dikes. Finally, the multiplicity of managers in charge of the dikes along the same waterway leads to an ongoing compartmentalization of information, redundancies, and sometimes even to incoherencies.

Most of the time, dike-related information is displayed in a specific linear system as kilometer points (pk), reference points (pr), etc.; see the linear reference system of the dammed waterway. When dikes are provided with reference systems, they often consist of markers facilitating the positioning of information observed in the field. For instance, when a road passes over a dike, markers correspond to the kilometer posts. On the other hand, the geometric template matching of such information with that relating to the protected area or to the dammed riverbed is still a difficult
process, as these data are not detected in the same systems. Finally, there is no unified marking system with kilometer and reference points for dikes across France, contrary to rivers that have benefited from standardization work carried out by the French Data Reference Center for Water (SANDRE) and water agencies. Consequently, each manager responsible for a specific section of a dike often uses his own marking system without considering the types of systems used upstream or downstream.

All these observations emphasize, on the one hand, the importance of a spatialized digital approach for diked area management and, on the other hand, the challenges to be overcome to achieve its successful implementation.

10.4. Examples of information systems dedicated to diked areas

We will now describe three different experiences relating to information systems tailored to diked areas that have been carried out over the past few years and mentioned above. Table 10.2 sums up the main characteristics of these three projects.

<table>
<thead>
<tr>
<th></th>
<th>National inventory</th>
<th>Breaching risks in the Mid-Loire river</th>
<th>Dike GIS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project objectives</strong></td>
<td>Inventory of the dikes, managers and stakes</td>
<td>Understanding of failure mechanisms and inventory of current risks, scheduling work</td>
<td>Diked area integrated management</td>
</tr>
<tr>
<td><strong>Information system user</strong></td>
<td>MATE Regional and departmental managers</td>
<td>EPPLGN</td>
<td>Local managers. In the end, aggregation at upper levels</td>
</tr>
<tr>
<td><strong>Geographic extent</strong></td>
<td>National territory</td>
<td>Mid-Loire river</td>
<td>Diked area</td>
</tr>
<tr>
<td><strong>Spatial unit of information aggregation</strong></td>
<td>Single-manager dike section (varying in length)</td>
<td>500-meter dike section</td>
<td>Point or dike section (no min. limit)</td>
</tr>
<tr>
<td><strong>Software</strong></td>
<td>DBMS</td>
<td>GIS</td>
<td>DBMS and GIS</td>
</tr>
<tr>
<td><strong>Duration of the use of the IS</strong></td>
<td>Study duration and then updates</td>
<td>Study duration</td>
<td>Durable management tool</td>
</tr>
<tr>
<td><strong>Stage of development</strong></td>
<td>V1 operational/ V2 is being developed</td>
<td>Operational</td>
<td>Demonstration</td>
</tr>
</tbody>
</table>

Table 10.2. Characteristics of the three IS projects for dikes
10.4.1. An information system at the national level for dike inventory

In 1997, on the request of MATE, Cemagref created a paper-based questionnaire that was first tested in 1998 on six pilot departments, which represented a total of 170 worksheets. This experience enabled Cemagref to write a requirement document that led to the development of a computer-based application as a runtime version of the DBMS Access. Data were captured under three major headings:

- “work”: this heading describes a dike section, individualized as an occurrence in the database according to two criteria: one and only one manager is in charge of the dike section, who might be unknown, the section impacts one and only one protected area. The section length varies from a few hectometers to some kilometers, depending on the situation;

- “manager”: this heading describes the structure managing a dike, and which is also responsible for its monitoring and maintenance. Managers are identified by name and the questionnaire inquires about their legal status, their jurisdiction, their staff and financial resources, the quality of both maintenance and monitoring performed on the works;

- “area”: this heading describes the geographic unit protected by a dike (or a dike system), that is, all of the area lying below the dike crest elevation, and which would be flooded in case of breaching or submersion of the infrastructure. This heading emphasizes the extent and nature of human activity in the area (permanent housing, concentrated or disseminated, major lines of communication, activity and service zones, farm businesses) and the sizes of the surface areas concerned.

Considering the objectives of this inventory, the questionnaire was limited to essential questions (45 mandatory fields were to be completed). With this survey, MATE aims at identifying the protection works that, like dams, could join the “public security related” category, which then involves mandatory monitoring and maintenance procedures. These works are very important and protect vulnerable areas, that is, areas that would be submerged under at least a meter of water in case of dike breaching, and which are densely housed areas, with activity zones (urban and natural zones of Land Use Plans), campsites, numerous sensitive agricultural infrastructures (greenhouses, tobacco, vineyards supported by the designation of origin, seed crops, vegetable cropping). Identifying dikes that are not related to public security is possible but optional.

The ongoing survey is carried out at the departmental level by the Water Inter-Services Missions (MISE) associated with river associations if necessary, or with any other organizations with good knowledge of waterways and flood-protection works. The results are then aggregated at the regional level by the Directorates for the Environment before being forwarded to the Directorate for Water of MATE.
The database operating module performs two main functions:
– aggregation of local data at the departmental level, of departmental data at the regional level, and of regional data at the national level;
– at the three levels: exploitation analysis, entry-by-entry analysis (work, manager, protected area) and cross-analysis of information using predefined queries.

This tool will regularly update the database.

To date, this tool is not provided with a module to map dikes and related information; however, several fields enable us to locate for any dike: 1) zones of implantation (district name and INSEE code), 2) Lambert III coordinates at the two extremes of the dike, 3) the river name, 4) the bank affected (right or left) and 5) the 1:25,000 IGN maps number, which is optional.

Small-scale cartographic exploitation is thus possible through the use of a GIS. Then, the basic cartographic unit can be the district, or the dike itself represented by a straight line between both its extremities.

This national inventory is the first of its kind and as a key step to enhancing our overall knowledge of dikes could be used as a basis for scientific research and to develop scientific regulations (designated as “public security related”, relations to risk mapping and town planning regulations, etc.). This was only the first version of the database, with regard to the structure, the software applications and its user interface. A second version was developed and was made available in 2002. The database structure remained substantially the same, but the interface and the software functions were modified (sorting, exporting, exploiting, etc.). Moreover, data was made available on an intranet hosted by the French Ministry for the Environment (Ministry, DIREN, Ministries of Civil Engineering and Agriculture, Cemegref), which has facilitated updates and prevented multiple and redundant data capture, and thus ensured data consistency. The national inventory is currently nearing completion and the database is starting to be updated on a regular basis.

10.4.2. An information system at the regional level to analyze dike failure risks in the Mid-Loire region

One of the objectives of the Plan Loire Grandeur Nature (Loire development and environment management plan) is to protect people in the Mid-Loire region from flooding and therefore from dike failure risks. In order to better understand the risks, the EPPLGN wished to simulate various scenarios of floods and developments, which requires a better knowledge of the following elements:
– current conditions of dikes in terms of structural soundness;
– the impact of dike strengthening works;
– the relevance of the scheduled works and those to be scheduled;
– the impact of evolving water flow on the strength of protection works;
– the impact of the riverbed morphology.

In 1996, the EPPLGN started historical study of the causes of failure on the Loire levees during the 19th century floods [HAL 96]. The analysis, based on physical, hydraulic and geomorphological parameters, highlighted triggers (reduction of the dammed riverbed width, the toe of the dike is built in or is in contact with the mean-water bed) and aggravating factors (curves in the riverbed, junction zones between dikes with different outer coverings) for dike breaching. The results revealed that 90% of the failures occurred in narrow sections of the riverbed, and 50% in the areas where the levees were in direct contact with the mean-water bed. The analysis of the causes of dike breaches in Camargue in 1993, and along the Aude river in 1999, confirms the importance of these factors.

On the basis of this historical study, which demonstrated the benefit of combining spatially different parameters relating to dikes and the riverbed, the EPPLGN obviously decided to use a GIS to achieve a second study aiming at understanding current dike failure risks [HAL 1998]. This second study included all of the 515 km of dikes along the Mid-Loire river, spreading out in the departments of Cher, Loiret, Loir-et-Cher, Indre-et-Loire and Maine-et-Loire. Considering that the results were to be delivered at the local level (dike section) and at more general levels (valley or department), the 1:25,000 scale was chosen because of the quantity and quality of the data to be processed. Dikes were homogenously segmented, that is, divided into sections between two strong anchorage points (natural terrain, bridge, crossroads), and again each section was divided into 500 m portions for the dike body and 100 m portions for the retaining walls (this length of 100 m is justified because of the significant number of accesses to the dikes, and thus of apertures in the retaining walls).

The dike portions were then described with the following parameters (the geotechnical aspect was voluntarily omitted):

– morphometrical parameters:
  - width of the dammed riverbed upstream of the dike portion,
  - distance between the toe of the levee and the mean-water bed,
  - shortening rate of the dammed riverbed upstream of the section,
  - presence of an erosion mark or an entry point,

1. A retaining wall is a raising block over the dike body, consisting of an earthwork (sometimes a low masonry wall) protecting it from the river lapping. A raising block over a spillway, consisting of an earthwork that is theoretically fusible when flooded.
- distance between the upstream and downstream anchorage points of the levee, or between strong fixing points;

  - hydraulic parameters:
    - available safety margin,
    - possible modifications of the river,
    - available alluvial storage;

  - constitutive parameters of the levee:
    - presence of a protection on the Loire,
    - presence of a protection at the level of the toe,
    - condition of the levee on the Loire side
    - presence or absence of dense vegetation,
    - presence of a downstream protection (e.g. toe drain),
    - condition of the levee on the valley side,
    - presence of old breaches,
    - presence of pipes, works, apertures in the dike body,
    - other parameters such as the presence of subsidence, houses with a potential cellar in the body of the work;

  - parameters relating to retaining walls:
    - size, condition of the retaining wall,
    - nature of the work,
    - conception (lying on the levee, fixed in the body, etc.),
    - wear caused by floods and possible water height.

In the end, about 120,000 pieces of data were captured in the GIS.

Then, these data were grouped into three categories, according to the failure hazard: due to an overflow, due to erosion at the toe of the dike, due to a hydraulic leak. Within each risk category, and then for the three risks combined together, data are weighted and cross-tabulated to group dike portions into three levels of risk (low, mean, high). This classification is based on the results of the historical study and on expert opinion. However, this type of approach will continue to evolve and improve along with scientific understandings of dike failure mechanisms.

The results of the research revealed that out of the 515 km of levee involved in the study, 118 km were assigned an average risk of erosion at the toe, 12 km a high risk, 40 km were assigned an average risk of overflow and 4 km a high risk of hydraulic leak.

This study emphasized that, in the future, efforts should be focused on dike toe protections, and particularly for the portions at risk that protect highly populated areas with numerous infrastructures.
10.4.3. An information system at local level for the integrated management of diked areas

Following the strategic diagnosis carried out in 1998 (see section 10.2), Cemagref expressed to MATE a willingness to develop a GIS specifically for the local dike managers.

Since this is a new approach, and since every dike-related situation is very different from any other in France, Cemagref have chosen, in the first instance, to develop a generic model of the GIS, in order to provide a promotion and demonstration tool for stakeholders on the ground.

Relating to the analysis of the strategic diagnosis, the following orientations have been adopted:

– to prioritize the analysis of a GIS dedicated to dikes and dammed fluvial beds with a level of accuracy tailored for local managers;
– to integrate the aspects related to the regulations of liable-to-flooding areas and to pre-crisis monitoring at the management level;
– to identify the interactions between the bed, the dike and the protected area, particularly through comparing the results of flood hydraulic models with or without dike failure.

Considering the aims of this category of managers, the type of information to collect in situ and to map, we have chosen an in-field positional accuracy of 5-10 m, that is to say map scales ranging from 1:5,000 to 1:10,000.

Due to data availability, the research area corresponds to the Val de Cisse, in Mid-Loire, between Blois and Tours, on the right bank of the river.

The first step was to meet the field stakeholders to study their work procedures, inventory the information processed and identify their expectations relating to the GIS.

10.4.3.1. Functional analysis of the diked system

A functional division of the dike (crosswise and lengthwise) and of the management zone led to the identification of major divisions in the future system. The management zone was divided into three main entities, two of which have surface representations (the bed and the protected area) and a third which has a linear representation (the dike). In order to be compatible with the national survey of MATE, each dike corresponds to a distinctive manager and a distinctive protected area.
The dike was divided both crosswise and lengthwise. Crosswise, the dike was divided into five entities (see Figure 10.1), which are described with specific attributes.

![Figure 10.1. Functional break down of a dike – crosswise](image)

Relating to the lengthwise division of the five entities described, we have chosen an approach called *dynamic segmentation*, which is adapted to linear elements. It uses referencing signs such as PK and enables us to divide a single linear entity (here, the dike body, or one of the two embankments, or the crest, or lastly the retaining wall) into basic portions, with different lengths depending on the values assigned to an attribute (or several attributes) along this linear entity. For instance, a dike can be divided into sub-portions structurally homogenous in terms of height, with respect to the retaining wall, or of nature of the protection cover on the embankment on the river side. This technique also enables us to locate punctual elements on linear entities, such as openings, crossing pipes, access ramps, and hedges.

Finally, it allows managers to set the aggregation level of the information captured. Therefore, they can have access to a very detailed informative content relating to a part of a dike of interest, and to a less detailed content regarding another part. Another advantage of dynamic segmentation is that there is no need to modify the topological and graphical coding of the linear entity after each update. The graphical part is defined once and for all; changes only affect the attribute tables where are stored, for each observed attribute, the values assigned to this attribute and the PK from start to end for each observed value. There is a single PK for punctual observations, such as an opening or crossing pipe.

10.4.3.2. *Conceptual modeling and prototyping*

The next step consisted of conducting conceptual modeling of the information system and physical developments of the demonstration model (using the DBMS Access coupled with the GIS Arc/View) and in collecting opinions from about 60
stakeholders (project partners and dike managers) [CHR 00]. We have used a tool specifically designed for modeling spatio-temporal databases, CASE tool Perceptory (computer-assisted software engineering), developed at Laval University – Quebec [BED 99]. This CASE tool is based on an object-oriented approach and uses the formalism of the UML language. It also enables us to automatically generate the object class and report dictionaries.

The database has been divided into four major UML packages (see Figure 10.2): bed and structure management, floodplain management and planning, crisis management, managers. The first three correspond to the different management systems that had been identified during the strategic diagnosis. Each package is then divided into sub-packages, which in turn are broken down into classes.

Figure 10.2. General structure of the database demonstration model

This structure makes the understanding of the conceptual model easier for the stakeholders working in the field, and will subsequently enable us to quickly tailor the generic model to specific dammed valleys. It also allows easy extractions of views fitting the different professions using this type of application (dike managers, chief vigilance officers, protected area planners, etc.).

It should be stressed that each package, or group of packages, can correspond to a separate information system, some of which might even already exist in certain dammed areas studied.
The bed and structures management package is the most detailed one, as per the recommendations issued from the strategic diagnosis. It consists of several sub-packages:

– description of the dike: this sub-package contains all of the structural elements of the dike. For mapping purposes, the linear elements are characterized by a start Loire kilometer point (PKL) and an end PKL, and the punctual elements are characterized by a single PKL to indicate their location;

– diagnosis: the observations of the dike are related here (particularly alterations);

– document: this sub-package gathers the description, positioning and the document references of the large-scale elements related to the dike (longitudinal profiles, cross-sectional profiles, etc.);

– description of the bed: information on the riverbed and islands.

In the crisis management package, the vigilance plans, historical data and results of the hydraulic processings were modelled:

– historical floods: the purpose here is to keep record of past floods through capturing available information (hydraulical readings, damage, archival materials, evidence, etc.);

– hydraulic modeling: the purpose was not to integrate the hydraulic models into the demonstration model of the GIS (or in any future operational version), but to define a data model so as to structure and document the graphical and alphanumeric results of the hydraulic modelings (with and without dike failure) performed by specialized services. The objective is to keep track of the modeling efforts (as well as of their validity range), and of the historical observations, to help planners to control the protected areas;

– vigilance plan: this sub-package compiles all the monitoring stations, their related staff, their actions, their equipment and a list of people to call on in a crisis situation.

With respect to the floodplain management and planning package, our objective was not to develop a detailed conceptual model of the vulnerability and control of protected areas, but to focus on a database structure sufficient to illustrate the existing or desirable interactions, between the dikes and the bed. This package was divided into three sub-packages:

– description of the management areas: this is the core of this package. The management area consists of the dammed mean-water bed, the dike and the protected area;
– regulation: even though this part was very little developed in the current version of the demonstration model, it was important to mention it because of the strong interactions between the dikes and the bed;

– vulnerability: as for the regulation sub-package, this part was only little tackled, but its presence is essential in a GIS generic model for dikes. The vulnerability of the protected area must be taken into account to determine the priorities relating to the maintenance and strengthening of dikes. On the contrary, the characteristics and conditions of dikes should be considered before taking actions that might alter the vulnerability of the protected valley.

Management, tracking, monitoring and intervention are often entrusted to distinctive organisms, and vary according to the research diked areas. The managers package gathers all of the people involved at the level of the dike and of its appurtenant structures (owners, managers, stakeholders) and describes their relationships.

Presented in Figure 10.3, the description of the dike sub-package consists of:

The dike (digue) class (within the definition of the national survey carried out by the ministry) is a linear entity split longitudinally into portions (tronçon_gestion) that correspond to management units: a portion depends on one manager only (gestionnaire).

All these elements are divided in the linear element subclass (element_linéaire) characterized by a start PKL (PKL_Départ) and an end PKL (PKL_Arrivée), or in the punctual element subclass (élément_ponctuel) characterized by a single PKL.

The homogenous element superclass (élément-homogène) has temporal and attribute proprieties that will be inherited by all the sub-classes and their respective sub-classes:

– when changes only affect a part of a given sub-portion, this old sub-portion is removed and replaced by a new generation of two or more basic and homogenous sub-portions (characterized by new start PK and end PK). The pictogram ☐ that is part of the homogenous element class means that records must be kept (start and end dates of each sub-portion);

– each piece of information will be provided with a reference assigned by the PK system (Système_PK) to locate that piece of information on the dike, as well as with the date of last observation (date_dernière_observation) and date of next observation (date_prochaine_observation). This information might also be completed with a commentary.
The *linear element* class (*element_linéaire*) divides into several subclasses, which are characterized by the attributes inherited from the parent-classes and by their own respective attributes:

- *corps_digue* (*dike-body*): characterized by its constitutive materials (earth with variable granulometry, concrete, etc.), its nature (e.g. stream sediments), its permeability;

- *crête* (*crest*): characterized, for a given homogenous potion, by its minimal and maximal height, its average width and by the presence or absence of a commuter lane and its width;

- *talus* (*embankment*): characterized by its side (river or valley), its height, its slope inclination, condition and nature of the protection coating (rip-rap, gabion, etc.), the width of the segonal;

- *banquette* (*retaining wall*): characterized by its condition, its nature (earth, masonry, concrete, prefabricated, etc.), its height;
– ouvr_linéaires (*linear works*): characterized by its type (weir, spillway, reinforcement), the side of dike on which it lies, the presence or absence of a fusible raising block.

The *punctual element* superclass (*element_ponctuel*) specializes in several sub-classes, which in turn are characterized by the attributes inherited from their parent-classes, and by their own attributes:

– *ouvr_ponctuel* (*punctual work*): all the punctual works on a dike (access ramp to the river, limnimetric scale, stairs, door, crossing pipes, openings, flood mark and line, etc.). Some of these elements can weaken the dike. Some punctual works have openings that can be blocked up in case of rising water. This class is characterized by the type and condition of the work;

– *bouchure* (*blocking up*): this is a sub-class of the punctual work class, and it corresponds to all punctual works that can be blocked up. It is characterized by the dimension of the work (opening width and height, depth and thickness of the grooves, nature of what is used to block up that is to say wood or metal, the number of elements, their thickness, their condition, the certainty of these observations, their storing place);

– *ouverture* (*aperture*): this is a sub-class of the punctual work class, and it corresponds to the punctual works that have apertures, but not provided with elements to block them up.

### 10.4.3.3. Examples of results

Here are three results from the tests performed on the demonstration model, for illustration purposes.

Figure 10.4 is an example of mapping information on the dike satisfying the principle of dynamic segmentation (here, the height of the retaining wall, then the nature of the protective covering of the embankment located on the riverside).

Figure 10.5 illustrates the results of a topological study seeking to identify sensitive buildings (hospitals, elementary and secondary schools) recorded in the IGN BD Topo® database and located less than 200 m from the portions of the dike in contact with the bed of the Loire river.
Figure 10.4. Map of the structural elements of the dike

Figure 10.5. Examples of results from a topological query (in dark gray: the areas where the river is in contact with the dike)
Figure 10.6. Two flood scenarios are compared and then related to vulnerability.
Figure 10.6 reveals the importance of technical hazards related to dike breaching in flood risk. The two upper maps represent the heights of water modelled by the Cemagref in the case of an eddy flood without any dike failure (T = 100 years) and in the case of a flood including a dike failure resulting from a leak (T = 100 years). The valley is almost spared in the first case, whereas it is completely submerged with water in the second case. The last map is a zoom on a highly vulnerable area: the BD CARTO® from the IGN confirms the presence of numerous residential and commercial buildings. Water height values, in the case of a breach due to a leak, were obtained for all the grids of the Cemagref model within this specific area, and their analysis provides a mean value of about 0.6 m and a maximum value of about 1.5 m.

10.5. Recent progress and perspectives

These three examples of information systems dedicated to dikes were developed after the 1990s floods that occurred in France.

Each of these systems satisfies a category of stakeholders and meets specific needs. In the case of the GIS developed for local managers, the demonstration model has been most favorably reviewed on a technical point of view. However, there have been many reservations relating to the real chances of adoption of such a tool, essentially because of the cost and of the lack of available staff to collect data and manage the GIS. Actually, the economic and social aspects of this tool can be justified when comparing the implementation and operating costs with the costs of the works and the benefits achieved, whether direct or indirect (and thus difficult to quantify): improved efficiency at work and in planning works, coherent management of a wealth of data and knowledge for future generations, reduction of dike failure hazard (and possibly of vulnerability), which would consequently result in less major damage (including losses of lives) and remediation costs, improved risk communication, etc. However, developing such GIS will become systematic only with the raising of political awareness for the indivisible relationship between sustainable management of dikes and sustainable management of the information relating to these structures.

The ideal solution would be that the implementation of such a tool among the different stakeholders could be reasoned at the level of the whole fluvial system, or even at the national level to ensure a coherence in terms of upstream/downstream, and especially in terms of right bank/left bank. In this case, the information collected in the local GIS could be aggregated at the regional and national levels with the use of relevant indicators, which would make it possible to meet the objectives of the first two IS presented in this document. In the short term, these IS are more likely to continue developing in a relatively independent way, and local GIS will probably
first emerge from more or less coordinated or concurrent local initiatives, but could become models. Since the human, political and organizational context varies from one diked situation to another, each attempt to implement a GIS will remain, from now on, a particular case.

In the case of the GIS dike project, two levee managers joined the project partnership in 2000-2002: the SYMADRE M in Carmargue for the levees of the Rhône river (“Syndicat Mixte inter régional d’AMénagement des Digues du delta du Rhône et de la Mer”, Arles) and the AD-IDR for the levee of the Isère river (“Association Isère-Drac-Romanche”, Grenoble). They decided to fund the final GIS application development. During the next two years, after a call for tenders in order to choose the developer, the application was coded. The development ended in July 2004 and the deployment at the levee managers’ sites started almost at the same time. The system is currently used in an operational way by these two managers and a third manager joined the group in 2007: the Regional Environmental Office in charge of 600 km of levees along the Loire’s middle course. Cemagref is still playing the role of technical and methodological adviser for all these users.

10.6. Bibliography


Chapter 11

Geomatics and Urban Risk Management: Expected Advances

11.1. Towns, risks and geomatics

11.1.1. An overview

For the past 20 years, a large number of towns throughout the world have been trying to make use of computer science advances to improve knowledge, management and availability of relevant information relating to their territories. Most of the time, these efforts were initiated by people working in technical services, who primarily aimed at facilitating their tasks, particularly with respect to roads and networks. It was not until the progressive popularization of the initial computer tools, particularly modern GISs, that the expected advances in territorial data management and their associated experiences and knowledge arrived.

This popularization, along with the expectation it aroused, was very beneficial. The intensive marketing that surrounded the GIS product greatly contributed to the process. However, in the meantime, many deviations or abusive interpretations arose among users who were bewitched by the availability of new solutions that facilitated their tasks, but who had not adequately considered the hidden pitfalls associated with them. This behavior is nothing new but a very old social phenomenon!

Data cross-referencing and the combination of layered information, for summing or sorting, can be extremely useful. Yet, some wrong conclusions have often

Chapter written by Jean-Pierre ASTÉ.
resulted from these processes, particularly in the specific field of urban risk prevention mapping, which is the subject of this last chapter. Therefore, it is key to define the fundamental aspects of the relating issue, before addressing the expected advances in this area of study.

11.1.2. City: a much sought after security area

A city is a very old organized area, but which is now taking new, varying and flexible forms in space and time. From the oversized megalopolis to the village perched on a rocky headland, or the borough that becomes a winter resort for several weeks a year, there is very little in common, apart from the fact that the concentration of a vulnerable population in all these areas increases the harmful consequences of dangerous events that might occur, consequences that are usually termed as risks involved.

Moreover, the second half of the 20th century witnessed a rapid and diversified growth in urban population. It resulted in even more complex urban infrastructures, despite the development of new technical solutions to meet basic, structural or functional needs, such as energy and water systems or the building of infrastructures.

It is in cities that society develops the most complex levels of organization. Consequently, it is the place where people expect the highest levels of security. Whether in the most modern or pleasant western towns or in the mega-cities of the developing countries where urban growth is difficult to control, town dwellers expect protection and maximum comfort from their host social structure.

This is how elected representatives are often entrusted with more responsibilities to take into account these social basic needs. Yet, even though this accountability is justified, it unfortunately also entails an extremely harmful shift away from individual responsibilities: attempts are made to transfer to public authority the responsibility of events that cannot be controlled individually, but the limits of this transfer are discarded.

Finally, if the identification, understanding and then the prevention of risks require many short-term efforts, their progressive annihilation can only be considered in the long-term. However, engaging society in long-term projects is very difficult: it requires a political courage difficult to maintain through time and successive mandates.

Therefore, it is necessary to use patience in developing the most efficient means possible first to identify and prevent risks, and then to generate a progressive change
of the way they are perceived and considered by the society concerned. We will see later on how geomatics could help in doing so.

11.1.3. Risk: a poorly understood notion

The notion of risk has aroused much confusion for the last 30 years, during which it has been increasingly referred to all around the world. The principal source of confusion lies in the excessive use of the term itself. Indeed, risk is a vague concept since it refers to what is unknown, to what we can only imagine, with much subjectivity, and depending on our own sensitivity or vulnerability.

Therefore, although familiar, the term risk should not be used thoughtlessly, without making every effort to identify and analyze the elements that precede risk formation, that is, the conceivable potential phenomena and the conditions required for their occurrence and appearance, as well as the fragility and vulnerability of elements (people, societies, activities, public or private functions and properties) that are at risk in areas likely to be impacted by such phenomena.

11.1.4. Geomatics as a data structuring and management tool

At first glance, geomatics can be defined as the application of computer technologies to earth sciences, a concept that will be explored below.

Computer science has emerged as a very efficient tool for performing complex data management tasks, especially since it has been widely popularized. It not only allows us to structure existing data, but it also carries out algorithmic or logical analyses or processing of these data. The relatively new development of spatial referencing methods has increased these already valuable potentialities, and consequently aroused enthusiasm among the stakeholders and researchers involved in land planning and environmental issues.

However, there is a difference between enthusiasm and efficiency, and this is what we will try to demonstrate in this chapter, first through analyzing the needs and the current state of the resources so as to discern prospects for progress.
11.2. Prevention stakeholders: their responsibilities, their current resources and expectations

11.2.1. Ordinary state or emergency state

It is important to stress the fact that an ordinary situation and an emergency situation or post-emergency situations are radically different. The motivation that inspires us to achieve what we would have wished to have had in an emergency situation rapidly wears off, and with it, so does the memory of the event. The capacity to forget is essential to avoid excessive pessimism, but it is also an obstacle to carry out what is necessary.

Key players are the same in both situations, but their involvement varies considerably. They fall into five main categories.

11.2.2. Government and institutional stakeholders

There stakeholders primarily work in state services and mainly in the French ministries concerned, such as the Ministry for the Environment for prevention and the Home Ministry for emergency organization. The Ministry of Equipment also plays an important role in considering risks with respect to land planning and road route management. In the 1980s, the Ministry of Agriculture legitimately demanded to be given a specific responsibility with respect to the management of certain mountain territories.

The Ministry of Industry is essentially involved in the area of technological risks, and those related to mines and quarries. The Ministry of Health tackles pollution, air quality and noise pollution issues.

At the beginning of the 1980s, the Government launched a policy of solidarity, focusing on risks, and initiated a certain number of procedures ranging from the inventory of sensitive areas to repair works through processes involving insurance companies. This policy generated a certain number of trials and errors that have led the French Government, since the 1990s, to limit its own responsibility to collecting and sending information to concerned local authorities and to the public, while continuing to play a controlling and incentivizing role in the orientation of actions and conduct of procedures.

At the end of the 1990s, the Ministry for the Environment and its Directorate for Risk and Pollution Prevention (DPPR) started multi-year programs to carry out risk prevention plans (PPR) through financing related studies. Departmental risk reports and atlases are produced prior to or in parallel with these programs, and local
authorities were provided with district summary documents (dossiers communaux de synthèse – DSC). In turn, these documents should enable mayors to organize a first information session with their fellow citizens based on the community information of major risks (dossiers d’information communaux sur les risques majeurs – DICRIM).

All of these various steps are difficult to organize, control and finance. Although undisputedly useful, their short-term efficiency is very difficult to assess, which is absolutely normal given that prevention is only effective in the mid- and long-term. However, the very complexity of this group of tasks would require us to carry out their scheduling, implementation methodologies, control and management through the use of modern resources, and particularly of networking resources. Unfortunately, we are still wide of the mark, even if the Ministry for the Environment has created a website to provide information on natural hazard prevention (www.prim.net).

11.2.3. Municipal stakeholders and the populations they represent

After all, and whatever the support they might expect to receive, the district and its elected representative are those accountable for risk prevention. Therefore, it is at this level that the most efficient prevention strategies should be developed. It took a very long time and many mistakes to understand that risk assessment and prevention were personal issues rather than societal issues.

The expression risk appropriation has become very popular in recent years. It runs directly counter to security and the search for responsibility at all costs, which is a social and economical nonsense, but it does not free society at all from the utmost obligation to reduce known hazards.

The first results that were obtained from the DCS and DICRIM programs are quite deceiving. Created with a very low budget, DCS are often content-poor and seem to be the result of some copy-and-paste of existing documents rather than a real formal communication. As far as DICRIM are concerned, these documents are well structured for large cities, but at the municipal levels, the copy-and-paste aspect still prevails.

Finally, the administration does not have the means to review the consistency and quality of the documents produced. Consequently, their expected outcomes in terms of prevention are very limited. We will see further in this chapter the benefits, for this specific research area, that could be drawn from a system such as SAPhIR, which was introduced in Isère by the departmental interministerial task force on natural hazards.
For all these stakeholders, assuming political responsibilities and working whether at the governmental, regional or municipal level, there is so much work to be done to achieve more than the few successful experiments that have been carried out over the last 20 years. The French experience is an often-cited example abroad. Therefore, it has become urgent to consolidate it, and to develop the methods and tools necessary to do so, through the use of computer-based resources, which must first be tailored and dedicated to the corresponding professions and processes.

### 11.2.4. Operational and technical stakeholders

Beyond the aspects mentioned above, which are mainly administrative and legal in nature, the key role with respect to prevention is played by the operational and technical stakeholders. We will define here the influence of municipal technical services, as well as the public or private logistical resources they can mobilize.

Apart from a few specific situations, some of which will be mentioned further on, there is, in middle-sized towns, very little structure within municipal technical services to ensure risk appropriation. These include the towns of the Rhône-Alpine network, which are all aware of the various risks threatening their respective portions of territory, but which have only implemented very flimsy structures serving primarily a monitoring and information role rather than taking actions.

On the contrary, small-sized towns are more intimately aware of certain types of risk, such as large winter sports resorts for instance, so they can develop much more active strategies (see below).

However, in most cases, only a few things are being done today in the cause of prevention. Therefore, there is a huge need for data acquisition and structuring, for defining tasks, monitoring, preparedness to handle emergency situations, and finally for equipment and training.

### 11.2.5. Insurance agents

Insurance companies have had a key role to play and, especially since the July 1982 Law, in the repair of the damage, they have benefited from supporting risk prevention. Yet, to manage any action in this field, they need the corresponding means and resources. One of the pillars of insurance is the best assessment possible of the conceivable potential loss so as to control the repair economy. The core requirements for insurance companies are similar to those of the other risk stakeholders, that is, analyses of past events and forecasting capacities. However,
just like other players, they have no resources to deal with the issues we have presented here.

They are often blamed for not financing all or a part of the development programs necessary to solve these problems, but this reproach is only partially justified, for it is the responsibility of the whole company, and particularly of the state services representing it, to make the decisions relative to the implementation of these programs and to their financial support and monitoring.

Moreover, the overall repair cost for the damage, harm and malfunctions is mostly generated by some events of disastrous proportion. The events impacting only a small number of people, even though they might have disastrous consequences for these people, cause little economic loss and thus are of little interest here.

It is noteworthy to emphasize that the major French insurance or mutual companies have since 2000 started a common comprehensive review of natural hazards (MRN); hopefully the contribution of this analysis will be as fruitful as possible [NUS 00].

11.2.6. Scientific stakeholders

Scientists have a huge responsibility with respect to risk prevention since the onus is on them to “know, understand, anticipate, forecast and detect”. Actually, there is an enormous gap between this responsibility that society has placed on them and the resources it provides them with. Moreover, and this must be emphasized, there is a deep gap between the highly compartmentalized way research teams work, and the complex reality of risk-generating events.

Several interdisciplinary research programs, termed as cross-cutting programs, have been initiated over the last 20 years with little success, especially when they involved collaboration between naturalists, engineers and humanists. In addition, there has been much redundancy in these research programs, both at the European and French levels. Indeed, within large bodies, for instance, the priority is more often to ensure full employment and the continuity of the existing teams rather than promoting new ideas and assuming the risks of failure. As far as small teams or societies are concerned, all those who tried to propose innovating programs are ineligible, so they must self-finance their research and development and, even when they achieve their research goals and provide interesting results, they do not have leverage to translate their results into usable information and effective decision.
All this probably explains a large part of the rigidity that has been observed for too many years.

The advent of geomatics and GISs gave rise to a very large number of programs aiming at building specific and georeferenced databases. However, there were many failures, because many of these programs were sidetracked and bewitched by the wonderful opportunities offered by these new tools.

Nonetheless, it is through scientific understanding, monitoring, modeling and forecasting that the greatest improvements are expected to arise, but this will take some structure, responsibility and discipline in the new programs to be developed.

The arcane scientific language is another challenge, particularly when it comes to communication and training. Here again, the current computer technology is very promising.

11.2.7. Compelled to live with an identified risk

Maps that inventory potential hazards are developing all around the world, and provide easy-to-grasp information to help appreciate and share with others the large number of risk regions. In some countries, over 50% of the total surface area is threatened by flooding or landslides (Bangladesh, Ecuador, Calabria, etc.), and this is without considering earthquakes. Some winter sports resorts and access roads are vulnerable all year round to these same hazards and to avalanches as well. Some other areas are threatened by nuclear generating stations, some valleys by dam failures and some floodplains by dike failures. Risk is also present in every industrial region.

Therefore, we must learn to live with risk but not attempt to endure it! There have been many examples throughout history of populations devastated by earthquakes but refusing to leave their apartment buildings in danger of falling so as no to be cut off from their roots. Very large cities were built on volcanoes from which they derive their wealth. Recently, in Brittany, many communities have decided, with much courage, to organize their own defense against repetitive floods.

All this means that if long-term preparedness is possible and necessary to avoid any development in areas that are known to be vulnerable, it should not entail intolerable prohibitions of large portions of the territory (which is too often the case on hazard maps, the hidden purpose of which is to shun responsibilities), and it should not lead to resignation regarding the inevitable risks in areas where there are life and infrastructures without any action for short-time beneficial effects.
With respect to hazard maps, the first case involves, if there is much at stake, going through the necessary thinking process to make informed decisions. However, the administrative and legal services have not assigned any stakeholders or resources to this specific task. Indeed, the wealthiest or best organized local authorities will invest in such studies or approaches to recover or save all or a part of their properties, but with regard to the poorer ones, their conditions will simply worsen.

The second case implies investing in monitoring and preparedness tools for temporary evacuations.

Both cases require a new economic and social approach that at least in Western societies, no-one seems inclined to pursue. In Japan, which is greatly affected by many different disasters in a cramped living area, this is a long-understood principle!

11.3. Today’s methods and tools: strengths and weaknesses

11.3.1. Urban reference systems and the expected connection with the digitizing of cadastral maps

For 20 years now, many towns have installed urban reference systems based on some of the conventional GISs that we will not cite here. These systems have almost always been developed for internal use to meet the needs of the technical services, especially in terms of roads and networks, and are essentially dedicated to planimetry and mapping.

Most of them were not available for public use, and paradoxically, even the user services could only obtain paper-based documents on the structured information of the system for many years. Of course, today these solutions are obsolete and, despite the major investments that have been made in the past, some new and huge modernization efforts are still to be made.

The main obstacle is that, in many cases, computer services do not lightly give up the prerogatives they have enjoyed for the last quarter of a century, but usually hamper the initiatives that are possible today so as to address their own needs more efficiently, particularly with respect to prevention.

The popularization of GIS, combined with the huge commercialization efforts related to it, has led many local authorities to install systems more or less tailored to their needs. They benefited from significant savings in time and money compared to large cities that played a very expensive pioneering role. Here again, as is often the case in commercial systems, the priority is given to short-term technical or
administrative interests rather than to more complex and interesting uses that local authorities could gain at the end of their investments.

Another reason behind the popularization of urban geographic information is the digitization of cadastral maps, which is facilitated by the fiscal services. Unfortunately, in most cases, digitization is financed at the lowest rate possible, processed by poorly-trained staff and with low-performance tools. As a result, many defects appear at the end of the process (duplication of the contours of plots of lands, wrong reference system). Moreover, it is upon this cadastral base map that databases are built up, the content of which is determined by the fiscal administration. Although these databases might be relevant to this specific administration, their content is inappropriate to other fields such as risk management. However, through some engagement processes and additional investments extremely interesting elements could be derived.

In a recent application dedicated to the evacuation of people threatened by avalanches, we were given access to the cadastral database. There were highly accurate findings on a very extensive series of mundane information. One of the major issues dealt with the accommodation capacity of the apartment buildings. The number of bedrooms available in each apartment was thoroughly detailed, but there was no way to establish a link between the owner, the apartment building where his apartment was located in and the location of that building in the detailed survey of the district! We might reasonably expect some quick improvements in this field that would facilitate the development of new and more efficient systems of analysis.

11.3.2. Managing experience

In order to understand phenomena and their consequences, we need to keep in mind details of their past occurrences so as to provide all those willing to become involved in this issue with a maximum of structured and validated data.

It is also essential to carry out analyses as accurately as possible each time a damaging event occurs. Fortunately, this is increasingly the case with commissions of experts, and particularly when the need for repair necessitates some judicial link or support from insurance companies. However, the efficiency of these commissions is limited, mainly due to a lack of resources, which partly explains why their results are often withheld. However, it is absolutely natural that these resources are dedicated to repair in support of the victims, rather than to long-term cognitive investments. This is the case today in El Salvador and India for instance, as a result of the 2001 earthquakes.
No country throughout the world has any infrastructure dedicated to the memorization of damaging events, even though it was one of the objectives announced by the International Decade for Natural Disaster Reduction organized by the UNDRO (United Nations Disasters Relief Organization) between 1990 and 2000. Indeed, a few isolated initiatives were made by some towns, or for some specific phenomena such as volcanic eruptions, earthquakes or tropical cyclones, but these initiatives are too few and poorly constructed to distribute and exchange relevant information.

Today, the development of new technologies enables us to have access to the information provided by some centers. Two days after the disaster that struck western India, and a week after the earthquake that occurred in El Salvador, both in January 2001, pictures, press clippings and seismological data were available on the Internet, but these data are of little or no use at all for operational purposes such as analysis addressing the way the crisis was handled.

Less deadly phenomena, such as floods, get plenty of media coverage, but generate no interest for understanding and prevention. The helicopters dedicated to observation and relief efforts could additionally provide sequential shooting and more efficient monitoring and interpretation of the progressive spreading of the flood waters over time.

Again, nearly no investment is ever (or not satisfactorily enough) directed to the research of the causes of major slope movements. Even at Séchilienne or at La Clapière, in France, despite the efforts involved, the level of knowledge or the validity of the explanations remain questionable. However, many problems of this type can be found in most cities around the globe. Even in mountain areas, where the Mountain Land Restoration services (RTM) have 100 years of high-quality archives, they received few resources to make the most of there records.

As far as technological risks are concerned, the BARPI (Office for risk and industrial pollution analysis or Bureau d’analyse des risques et pollutions industrielles), from the Ministry for the Environment, launched a program aiming at structuring a system to memorize past events. Major development and communication efforts are still awaited, along with the modernization of the corresponding computer tools and methods. This also applies to the services of underground pits and leading mining companies.

The current efforts made by the Ministry for the Environment focus on the feasibility of a system that could analyze economic and legal aspects resulting from past experiences, but local authorities still do not have many structured elements apart from oral and journalistic traditions.
Consequently, it is extremely difficult to structure an epidemiological approach to catastrophic events, and even more so to mere damaging events. The author can cite many examples of cases where he had intervened 15 to 25 years ago in small and middle-sized districts, and the reports made at the time are totally unknown from technical services today.

11.3.3. Knowledge and modeling of phenomena

We are now moving on to the scientific arena. It should be stressed that despite many programs carried out over the past 20 years, there are no significant advances. At the French level, and at the European and global levels as well, progress has been made in understanding the mechanisms controlling the natural phenomena generating risks, but not as much as had been expected at the beginning of the 1980s, and scientists are accountable for it.

The self-containment of disciplines that should cooperate to achieve improvements, magnified by the fact that they compete with each other to obtain financial support, is probably the leading reason for failure in this sphere.

The poor performance of most models that simulate phenomena, and especially in the fields of mechanics and hydraulics, rarely reflects reality, because the 3D or multidimensional and the temporal aspect of natural phenomena is often poorly processed by these models, which also applies to the integration of the social or economic consequences.

This poor performance is manifest even from a purely phenomenological point of view, except in the field of seismology where the severity of the consequences enabled to generate the resources needed to make significant advances, if not in prevention, at least in understanding what is called local seismic hazard. What is being taught in universities has not really changed over the past 30 years, both in terms of ground movements and surface hydraulics.

A particular and common aspect of both types of phenomena is that they are 3D. However, most modeling methods are 2D, since the third dimension requires much more information and very complex processing algorithms. This was a huge obstacle 10 years ago. Today, some solutions are emerging.

Water, a key element in flooding events, is also often determinant with respect to slope instability. Weather forecasts are still only reliable at small scales. General tendencies can be determined over the Rhône river, but it is more difficult to do so over a specific watershed, and even more over a specific slope within this
watershed. Faced with such a challenge, much promising research was dropped: today, it is resumed, so we can be very hopeful for the future.

11.3.4. Monitoring phenomena

Efficient monitoring requires thorough understanding, and vice versa. The problem with all instrumental monitoring methods is that they are still based on technologies that are too diversified and not standardized. Monitoring processes are therefore much too expensive compared to the traditional tools and resources used by local authorities.

However, significant improvements and popularization are being achieved with regard to technology, data acquisition and data pre-processing. If the appropriate tools and measurement networks could benefit from some standardization at the European level, a new attractive market would certainly open up for designers and developers of systems dedicated to the monitoring of various relevant factors for risk prevention.

We are at a standstill for now. With respect to noise pollution or air quality, which are particularly sensitive issues in urban areas, the amount of measuring equipment is desperately low. This situation is even worse regarding river and groundwater monitoring, and still worse for slope instability and landslide monitoring.

Moreover, apart from these instrumental deficiencies, it should be stressed that local authorities’ staff, and particularly administration engineers, are increasingly involved in supervision and control tasks and thus miss first-hand experiences of the territories they are accountable for. This is how the experience related to observation and local control of vulnerable areas has progressively been lost.

11.3.5. Reducing vulnerability

The assessment of the interaction between the phenomenon and the exposed elements is referred to as vulnerability. This vulnerability is characterized by many different economic aspects (which are the best understood), but also by structural, social, cultural aspects, etc.

Many researchers have particularly insisted on one of those aspects. If we focus exclusively on the modern urban environment, and more specifically on events that have been encountered, we are forced to admit that the research carried out on vulnerability is still at an early stage, except in the field of seismology. Indeed, after
seismic disasters, many expert taskforces are always sent out to emergency sites to try to understand behavioral differences related to structures, properties and society.

Less is known about the vulnerability of other phenomena, such as flooding, ground movements or the transportation of dangerous goods, whether they result from natural or anthropogenic causes. With respect to flooding, even though this phenomenon is very easy to characterize in terms of vulnerability, no methodology is yet available. In the field of ground movements and avalanches, very little has been achieved to date, with the exception of a few works [AST 94, LEO 96].

Reducing the vulnerability of equipment and facilities to be built is much easier than reducing what already exists. Moreover, a city corresponds fundamentally to an environment that has been structured over a very long period of time, the spatial organization of which is impossible to change quickly, except during the rehabilitation of some neighborhoods.

Just like any other complex issue, reducing vulnerability is a task requiring both persistency and patience, and a complete knowledge of the social and economic aspects, along with the technical specifications. This means plenty of time and effort, but also no hesitation in initiating processes.

The capabilities of modern geomatics offer faster data acquisition, structuring and exploitation times, which is necessary for the implementation of solutions. They also enable us to obtain a continuous and informed insight on the populations concerned, and thus to facilitate the development of consensual solutions over long periods of time: 20 to 30 years, maybe even more.

11.3.6. Risk assessment

Based on a conventional belief coming from the USA (Varnes), it has often been stated that risk was the product of hazard and vulnerability. This simple formula has an attractive simplicity, but is also very dangerous and has caused much difficulty. Actually, risk is a very complex notion, the assessment of which cannot possibly reflect such an abrupt expression. Consequently, we will choose to talk about loss, damage, injury or potential disfunctions susceptible to be directly or indirectly generated by a predicted phenomenon. This is much harder to express, but it is also much more accurate.

Another comment should be made with respect to semantics, and is related to the word hazard. In this chapter, this term refers to the definition mentioned above, that is to say: a predicted natural phenomenon, a presumption that can be more or less
vague as regards to the characteristics of the phenomenon and the conditions in which it occurs (starting or acceleration, rhythm, extension, etc.).

The real purpose of risk assessment is to identify potential losses. On the basis of this assessment, the societies concerned and the persons to whom they entrusted decision-making power will be the only ones with the proper qualifications to decide which course of action is to be adopted. These persons are elected to make a decision between preventive investments regarding risks that are only potential in nature and standard investments meeting the common needs of the local authority concerned.

Naturally – and fortunately – society knows and must develop intermediate solutions. This aspect reflects the importance that experts must give, on top of their scientific or technical responsibilities, to the development of clear explanations and justifications in their diagnoses and forecasts of “risks”.

However, for the last 20 years, in France as abroad, and apart from some very specific cases, the production of hazard maps with little or no detail has significantly increased. In some cases, especially during the 1980s, some believed they could translate these hazard maps into risk maps as provided in the 1982 Act. The results were far beyond expectations! The potentialities related to the intersection or overlay of layers provided by GISs were often at the origin of these limits. Therefore, tomorrow’s geomatics will have to solve these problems.

11.3.7. Macro and microeconomic approach

In order to solve all these problems considerable investment will have to be made in equipment and facilities, as well as in the social restructuring of areas concerned.

Therefore, there is no need to wait for the completion of technical solutions to discover that they are expensive, but on the contrary, time should be taken to gather all the micro and macroeconomic elements that are to be considered, and their possible evolution over the long period of time required to progressively implement security.

In this field, little has been achieved, even though, despite the obligation to abide by the Computing and Freedom Law, helpful analyses could be carried out to assess the value of properties, activities and people at risk. Here the word value is used in its broad sense, not just its economic meaning. You will find below how these values or potential losses can be assessed through the use of relatively simple systems to produce a specific risk scenario.
11.3.8. *The means of exchange of experiences, skills and knowledge*

From the perspective of potential loss assessment and preventive measures, it is key to share both experience and knowledge. Yet, most of the time this is done through traditional and obsolete processes, that is, seminars and congresses. This is all the more unfortunate since very interesting events occur all around the world in contexts and societies that are different but which might yet offer attractive solutions.

A particularly noteworthy point is that the greatest and most painful experience in terms of natural or technological damage is to be found in cities in developing countries. Therefore, and contrary to conventional wisdom, it is from these cities that knowledge should be transferred towards well-off cities. Japan is well aware of this and systematically sends out teams of experts anywhere a disaster occurs!

In 1993, the La Josefina disaster, in Ecuador, could have been an extraordinary source of information for the French specialists concerned with La Clapière and Séchilienne. The author spent considerable time and money to try to establish an exchange program with the Ecuadorian specialists who managed the crisis remarkably well.

It is very important to create think-tanks based on these exchanges of experience through the use of modern remote communication tools, and to stop or limit inadequate conferences and seminars. The various instances and institutions that developed here and there to provide training or information on risks and their prevention should instead become involved in such solutions and remain vigilant so as not to be outstripped in their own field in terms of competence and experience.

11.3.9. *Consultation, public information, training and culture*

We have insisted enough in the above upon what should be done between the moment the assumption that a damaging natural or technological phenomenon might occur is expressed, and efficient and justifiable decision-making chosen by society and its representatives.

This led to a new concept in recent years, which is referred to as risk appropriation, for prevention cannot be addressed without proper risk appropriation by the societies concerned.

There is a long way to go from a map filled with different colors on which we try desperately to locate the elements we own or are responsible for, and future
prevention support systems offering a plethora of explanations, guidelines and processes to take action.

If we take the example of building a PPR or a PEP, when the technician presents the first drafts of the maps to the local authorities, an intense negotiation begins since these maps will immediately result in major appreciations and depreciations in land value. These negotiations, although irritating for the technician, are necessary and even helpful. Moreover, it clearly appears that the owners concerned often present resonant and much better grounded arguments than the technician, who usually has no resources to develop a solid argument, owing to the fact that his task is only limited to rough preliminary operations.

Indeed, each map or plan should clearly display not only the absolute facts that were inventoried during the technical survey but also their interpretation. A program enabling us to refine this interpretation should also be mentioned or recommended. Finally, the modern hypercommunication techniques should allow easy access to anyone interested in a specific portion of territory upon the reading of these facts, arguments and recommendations.

This can easily be achieved, and yet the only progress made to date is the production of maps on which the outline of the various “risk areas”, or equivalent, is digitized. However, the outgoing format differs considerably according to the computer resources of the administrative services that are in charge of these processes. This is nothing more than geomatics reduced to cartographic drawing, which far from fulfills the existing potentialities.

As far as public training and information is concerned, we will have to await the end of the DICRIM programs, for it is premature to judge the results. However, after having read the first documents available, there is cause for concern. Instead of using modern office technology, and particularly hyperdocumentation, new documents are created with the copy-and-paste of existing documents. This entails a further waste of time and money.

A last and very important element must be emphasized in the field of urban policy. One of the most eminent and noble roles of politicians is to take responsibility for making decisions when all the resources of science, technology and consultation are exhausted. All elected officials know about this big black hole, in front of which they are left alone with the power and duty to decide, which may result in mid-term penalization if the consequences are not those expected. Therefore, the various stakeholders who support the decision-maker have to organize their knowledge and arguments explicitly in order to, on the one hand, make sure that the final decision will be as informed as possible and, on the other
hand, enable the decision maker to easily prove if needed, the quality and transparency of the support he was provided with.

11.4. New potentialities using geomatic methods and tools

11.4.1. Geomatics

Geomatics really developed with the popularization of the first geographic information system (GIS), to such a point that this discipline is often reduced to the use of these systems, whereas it actually encompasses all the contributions of computer science to the earth sciences and the associated professions.

These professions are complex and go beyond basic geographic applications, dealing particularly with land planning and environmental issues. Lying at the basis of these issues is the natural need to know about the spatial distribution of a certain number of relevant elements, which is performed using GISs. Nevertheless, this knowledge can be useful only if we know what to do with it and if we make the necessary efforts to do it! Many users, when they discover GISs, are fascinated by the most basic functions without wondering whether these functions fit their needs, or if they only excite their curiosity.

Geomatics should not be reduced to the purchase of a software program, no matter how efficient. Geomatics requires a deep humility and a thorough analysis of what we do and how we do it, that is to say a comprehensive knowledge of the professions that could greatly benefit from it.

This is the reason why this discipline has to be quickly relayed by the skills of the various categories of specialists or stakeholders involved in the corresponding professions. They are the only ones able to clearly define the data they need, to validate, structure and prepare it to be used in such a way that will allow them, later on, to justify the use of these data, as well as the conclusions and recommendations they are responsible for providing.

From the specific perspective of risk prevention, it is important to emphasize some of the main functions offered by computer tools for achieving these responsibilities? We think particularly of the acquisition and structuring of spatial and temporal data, of the modeling of phenomena and behaviors, of task analysis and the available support to complete and control tasks, and finally of knowledge and experience management.
11.4.2. Acquiring and structuring spatial and temporal data

11.4.2.1. Data for territories

The most traditional mode of description is the map with its standard, topographical, planimetric and thematic components.

Topography, although thoroughly outlined in the French territory thanks to the works carried out by the National Geographic Institute (IGN), is still unsuitable to risk analysis and management issues detailed above. In urban environments, the vision of the morphology of the area observed is hidden by all the changes brought about by man, and only very little remains of the original natural landscape. This is a huge obstacle to understanding not only natural but also anthropogenic phenomena. Therefore, there is a need to rediscover and structure the data relating to the primitive shapes of the relief of urbanized areas.

Planimetry is inherently evolutionary. The current systems and methods, even in the best equipped cities, do not allow an efficient updating of land use and especially of the accurate characteristics of infrastructures, properties and activities developed in urban areas, although it is possible to implement such updating processes in near-real time.

Finally, with regard to the main thematic components, apart from the land use plans (or natural risk prevention plans), geomatics offers many wonderful possibilities for bringing some order into rarely used data representation and management methods. Although perfectly understood with respect to networks, this has not been the case for many other themes such as, for instance, knowledge of the subsoil, from geology and hydrology to underground infrastructure management, via green spaces or management of industrial sites on polluted soils.

11.4.2.2. Data of phenomena

The traditional method used to describe what may conveniently be referred to as natural hazards consists of building and then overlaying (the well-known intersection) a certain number of maps. These maps translate what we know, or think we know about the spatial distribution and variations of certain predisposing factors for the occurrence of certain types of phenomena. Far away from reality, these mechanisms reduce these phenomena to a too simplistic cartographic expression. We have already mentioned the impact in terms of responsibility with respect to decision making, and now we will define the impact with regard to modeling.
It is important to be aware that we map what we see, but mapping would be improved if it was based on a topographic (and thus morphological) model reflecting the reality of the territory concerned.

Urban databases do not contain much, if any information of this type. A quarter of a century ago, an attempt to build geotechnical interpretative maps failed due to the inappropriate resources of the time. It would be worthwhile to reconsider this attempt with modern subsoil knowledge and management capabilities in urban environments.

Usually, the topography is known from the road and network surveys, but its accuracy is very poor in built-up areas, and it is very difficult to check all the plans made before and during new developments.

However, all the resources required to complete these tasks are available today. If an effort could be made towards specification and standardization then local authorities could be provided with modern methods to manage the knowledge of their soil and subsoil. Unfortunately, once again, the solutions offered are obsolete: we try to apply existing software programs that do not fit the real problems at stake, instead of favoring coordination and sound reflection among the teams with a proven capacity for opening new paths, which would be extremely beneficial.

Besides, in conjunction with the predisposing factors for the occurrence of certain types of phenomena, it is necessary to focus on the aggravating or triggering factors. Most noteworthy of these are the natural factors (weather conditions, seismic or volcanic events) and anthropogenic factors (uncontrolled earthworks, waterproofing of certain surfaces, over-stressed habitats, accidental pollutions).

The models that are detailed below must throw light on the respective roles of these different parameters. Still, permanent factors must be regionalized and the changes of aggravating factors must be monitored.

With regard to regionalization, today’s computer science resources enable us to envisage, through the use of more or less complex models, a more efficient way to identify the sectors where predisposing elements are concentrated. As far as the surveillance and monitoring of changes are concerned, we have already explained what could be expected from the standardization of the measurement systems and of the acquisition and interpretation processes.

11.4.2.3. Data related to exposed elements

On the basis of the above, we could expect urban databases to be better structured with regards to exposed properties, activities and people. Unfortunately, this is not the case, and we will explain it using examples of systems dedicated to
the safety of people exposed to avalanches. As we have already mentioned, urban databases as well as most of the GISs to which they are integrated are, in their present condition, not designed for this purpose.

Many actions must be developed to specify and then conceive the methods and tools necessary to fulfil these objectives. Moreover, better structured data would certainly prove to be extremely interesting for many other urban management applications.

11.4.3. Modeling phenomena and behaviors

In order to understand and forecast phenomena, we need to refer to models of mobility and vulnerability of exposed elements, but also to social or economic models revealing the behavior of exposed people.

11.4.3.1. Modeling phenomena

Perfect modeling is of course impossible, but this is no excuse for not attempting to develop and systematically question the best models possible. In addition, the best models are not the most complex ones. There is much to develop and exploit between the extremely complex theoretical model and the simple model based on some common-sense principles.

In regard to flooding, most of the models used are those based on longitudinal profiles, while compartment models are more rarely used. These models are not very helpful for forecasting flood extension, particularly in urban areas. A valuable resource would be low-altitude aerial photographs of the flooded areas after each significant episode, which would be adjusted according to an accurate topography and the localization of specific infrastructures (see section 11.5.1 dealing with the GERICO project).

In mountain areas, the building of most rock-fall control structures is based on singular profile studies, which is nonsense considering the importance of 3D relief on which the blocks roll around. Unfortunately, many other criticisms could be made.

Another criticism could be brought against the models used in urban environments. Indeed, they are rigid and ineffective in terms of critical analysis, maintenance and fits. Thus, for instance, the identification of avalanche-exposed areas is essentially based on the memory of past events rather than on modeling, for lack of data and resources. Actually, the problem is always the same, that is to say a poor appropriation of understanding, measurement and interpretation.
To conclude on a more optimistic note, many projects are currently in active development, the results of which are expected to be promising, given that the local authorities concerned will immerse themselves in efficient overall procedures of acquisition, modeling and surveillance. However, and as mentioned above, the trap must be avoided of administrative bureaucracy. Indeed, the officers entrusted with the corresponding tasks must be technicians before being prime contractors or process supervisors. This is once again a problem related to the appropriation of the approach.

11.4.3.2. Vulnerability assessment

Although extremely important, only a very few vulnerability analyses have been conducted, except in the fields of seismology and hydrogeology. Developing such analyses with respect to flooding, ground movements and avalanches would be extremely valuable.

In 1996, Frédéric Léone published an original work on ground movements. His research has not been followed up by other subsequent studies. In Lyon (France), for instance, many recorded real events of this type are available, and could be used to identify a pathology. This has been done in certain countries in South America, particularly in Venezuela.

Even though vulnerability seems much easier to assess with regard to flooding, no vulnerability data or methods are available in this specific field.

Therefore, on the basis of similar methods of analysis, of characterization and spatialization of data and real events, the guidelines proposed in this chapter could be very helpful in achieving highly productive advances in this field.

11.4.3.3. Understanding social and economic behavior

Socio-economic characteristics, although long-neglected, are key to risk prevention. On the contrary, since attempts have been made to shed light on this issue, sociologists have written many papers on this subject. Unfortunately, excepting that the basic principles do converge, there is no real core coherence in their views. Moreover, all the attempts that have been made to initiate collaborations between sociologists and physical environment specialists have had limited success. Each is much too influenced by their own research sphere and the reasoning processes that are bound to it, blinkering them to the potential contributions of the others. However, Latin America have achieved some successes.

Current resources in terms of structuring of knowledge, process analysis, hyperdocumentation and communication hold the promise that things might improve [ASR 99]. The incentives for public authorities to federate multidisciplinary teams
should be stronger. The solution could and should come from urban communities. Finally, there is the economic and political area, the importance of which is undeniable.

11.4.4. Task analysis and support to complete and control them

Functional analysis-type approaches, or similar ones, must provide essential information for prevention. They are already largely used for developing emergency plans, as by definition such plans assign a precise role to each stakeholder during a crisis.

They are, above all, an extremely effective thinking tool with respect to what can and what should be done, as well as to the tools and methods necessary to achieve that goal. This is not about returning to the old fantasy of expert systems nourished during the 1980s, but rather to guide all logical and algorithmic processes and to provide the best support possible for their quick and reliable completion, through allowing stakeholders to focus on the essential priorities, that is, on interpreting results and making decisions.

Most prevention-oriented tasks can be analyzed this way, from technical or scientific tasks, through operational tasks and to administrative and legal tasks. We will see, later on, how task analysis was first applied to the management of avalanche crisis, or the monitoring, in Lyon, of small stream-related flood risk. Other applications of this type have been carried out on certain specific actions, for instance, the development of a guide providing instructions and help for the design of drainage structures on slopes or, more generally, providing methods to control mountain slope instability.

All this only constitutes an introduction, paving the way to extremely fruitful and promising prospects as regards the potential contributions of computer science to prevention management support.

It was with such a view that in Isère, the MIRNAT (departmental interministerial task force on natural hazards), the IRMA (the Institute for major risks), the DDE (Departmental Directorate for Equipment) and the consulting company GIPEA proposed developing a tool distributed freely to all “producers” of DCS and DICRIM to provide them with basic georeferencing functions and a comprehensive hyperdocument database containing everything you need to know about prevention. The facilities offered by such a tool would enable instructors to focus their efforts on producing the best analysis possible of the territory they control and of the events that might occur there.
11.4.5. Managing experience and knowledge

Preventing a risk requires us to understand the potential origins of this risk, that is to say to refer to the experience of all the situations that in the past generated damage and losses, and to try to grasp its evolution, mechanisms and consequences. This, in turn, enables us to carry out the epidemiological actions we have already mentioned above.

Unfortunately, there is insufficient reliable data on these past events, but we have already emphasized this issue at the beginning of the present chapter. Indeed, many databases on various specific hazards have existed for some years now, but most of the time, they were built up by teams who were not fully aware of the real potentialities of modern computer tools, nor committed enough to real conceptual thinking with regard to the database’s architecture and functions. There is little use in building up databases if you do not know the extent to which you can use all these data together, and if you have not checked their quality and relevance.

Actually, one of the major difficulties encountered when using databases is that their structure is not open and their content is limited. Such limitations are no obstacle if the data to be saved are very structured and repetitive. They are more of a problem when it comes to risk analysis, because it involves keeping all available information since they might be useful some days.

This is why a simultaneous development of knowledge and modeling, in the broad sense, and of archiving systems as flexible and effective as possible is so important. Again, it is necessary to separate the basic facts or data for which standard and simple georeferenced database structures seem to be appropriate, from the data resulting from interpretations for which more open techniques based on hyperdocumentation are required.

These systems must also be open and controlled. They must be open so that all stakeholders could have access to the data available to use them, but also to criticize them or enrich them. There is the continuing problem of data ownership added to the one of confidentiality.

They must be controlled to find a solution to the double problem we have just outlined, and also, obviously, to validate new data, motivate their acquisition and structuring, to avoid redundancies and solve many other problems such as that associated with the direction of relevant research programs.

Finally, these systems must enable efficient exchanges between all the specialists involved at the town level, but also at the departmental, regional, national and international levels. This requires the structuring of exchange systems that are based
on the use of new information technologies, as well as the hosting of regular forums on fundamental issues of common interest. This is one of the objectives of the CŒUR project that we will discuss later.

11.4.6. *Quantified and hierarchical appreciation of the risks involved*

Among all these prevention methods, the potential losses involved are scarcely expressed in a clear, quantified and hierarchical manner. To do so, thoroughly defined phenomenological and event scenarios along with efficient vulnerability assessment systems are necessary, but constitute a whole that quickly becomes difficult to manage.

This difficulty, not fully understood at the beginning of the 1980s, explains the numerous confusions between hazard and risk maps and the famous and pernicious Varnes’ formula, unfortunately repeated many a time and according to which risk is the product of hazard and vulnerability!

Today, the various geomatics-based approaches greatly facilitate spatial and temporal representations of phenomena and of the regionalization of their impacts, although much remains to be accomplished.

More intelligent development and use of urban databases would help to more accurately define the distribution of people, of activities and properties at risk within areas where various types of phenomena could occur.

Then, in turn, the multifaceted interaction between phenomena and elements must be defined, and can be referred to as vulnerability. All this appears to be possible today, even if it involves major efforts to identify potential damaging, disfunction or prejudice functions. We will see further below how, for instance, these processes are carried out with respect to avalanches. This perspective can be presented at different levels.

At the regional level of PPR, for instance, the simple notion of lack of protection, often mentioned, was recently formalized in a paper published in Switzerland.

At the community level, a geomatics-based application (EVINOND) of the acceptability of the likelihood of flooding (Cemagref Lyon, 1997) was carried out by GIPEA to facilitate its implementation. It enables us, on a given territory where land cover or use have been analyzed, to ask each stakeholder to express his/her own perception of what is acceptable in terms of flooding by means of four criteria: the season, the submersion time, submersion height, water velocity and pressure, and finally the receding phase of the phenomenon. When a specialist forecasts a flood
with given characteristics, the system identifies the areas where the event is or is not acceptable, which provides key information when conducting a consensual search for the best possible prevention solution.

At the local level, GIPEA has developed EVARISK, which enables us to forecast potential losses, expressed in terms of monetary values and non-monetary values (patrimonial, social, aesthetic, cultural, etc.). Once again, the system can identify, area by area, the nature and components of the value of the elements exposed. The damaging functions take into account the way the phenomenon occurs and the vulnerability of the elements exposed, which are in turn integrated into the system to be progressively developed and improved. Then, the system provides a forecast of potential losses for each phenomenological scenario proposed.

11.5. Some ongoing initiatives since the beginning of 2001

We will present here some ongoing actions that started at the beginning of 2001. The list is only a sample; it is not intended to be exhaustive. Some of the experiences cited are not localized so as not to affect their achievement. Some others are only scientific thinking processes and are not operational yet.

11.5.1. Examples from Lyon: the information system of the service of Balmes and the GERICO project

In Lyon, like in many other cities, there are natural and technological risks. There are dangers resulting from very heavy industrial concentrations such as the chemistry corridor downstream from Lyon, but also road, rail or river transport-related risks. There are nuclear risks, with nearby centers, and also, though less known, large dam-related risks such as in Vouglans – Jura region. We will focus here on the natural risks.

With respect to ground movements, the Lyonese hills and more particularly the slopes of the famous Balmes\(^1\) have experienced numerous accidents. As early as the 1930s (Fourvière and the Aristide Briand walk disasters that caused several tens of victims), the local authority established a commission of experts with the purpose of expressing relevant opinions and recommendations related to any projects impacting these balmes. This commission, whose actions were almost at a standstill, was reactivated and structured with a specialized branch at the heart of the technical services of the city of Lyon during the accident that occurred on the Herbouville

---

1. In Lyon, the Balmes refers to the hill slopes (of the Croix Rousse and Fourvière especially) that consist of sandy-gravelly or clayey glacial deposits that molds an old granitic bedrock. Many controlled or uncontrolled springs contribute to the instability of the lands.
walkway in 1978 (3 victims after the firemen succeeded in evacuating several dozens people from a building that was falling down). For several years now, this service has used a records and response management system structured on the basis of Mapinfo, and which seems to meet all its initial targets, even though it is a complex system to use because it is an application of a commercial system and not the result of a project specifically developed for the commission. This is a difficulty often encountered!

The success of the Balmes commission was such that a geotechnical commission for Greater Lyon was created in parallel for the 50 districts concerned. Both commissions only have a consultative role, although they are difficult to escape!

In regard to flooding, and putting aside the major problems generated by the Rhône and Saône rivers, particular attention was paid to the 30 or so streams that drain the whole territory of Greater Lyon, and which have already often caused, at least some of them, damaging torrential floods. No-one is in charge of these streams except the residents, which is confusing. Various reports were generated by the communities concerned to detail the conditions of these streams, but the data collected remained disparate and scattered, although it was clear that, from the point of view of both data management, communication and consultation, an efficient validation, structuring and exchange system was necessary. This has been achieved by GIPEA under the auspices of the Ecology and Environment group of the Greater Lyon with the GERICO project (flood risk management for the Lyon urban community streams).

This project was developed independently from all standard commercial software, but with the proper interfaces to ensure the necessary exchanges, and offers the following functions:

- access, stream by stream, to the drainage basin orthophoto, then localized zoom-in on this orthophoto, with the overlaying of the areas liable to flooding;
- access to the land use plan and the related specific regulations;
- access to the plots and constructions extracted from the APIC database of the urban information system of the city of Lyon;
- access to the specific information and testimony provided by owners who freely agreed to do so;
- selective display of all the hydraulic structures, the operations of which have been diagnosed and forecast as exceptional during some analyses;
- localization and access to photographs that were taken during inspections of the ground and revealing quality or disfunctions;
- saving and updating the inspectors’ comments each time they return from their tours.
The system, which was initially designed to be available on the Internet or on an intranet, was finally distributed on a CD to all the local authorities concerned, who now want this system to be adapted to all the other risks! This is how the CŒUR project was initiated, but we will detail it further below.

11.5.2. An Alpine concern: avalanche risk management

Winter sports resorts, in France and all around the globe, have developed in avalanche-prone areas. In such areas, it is impossible today to control snow accumulation through artificial triggering, because its immediate consequences could dramatically affect constructions, and no-one is willing to accept such a responsibility.

The only short-term solution is to try, with the support of weather forecasts and snow and avalanche specialists, to predict some hours in advance the appearance of conditions favorable to the development of dangerous avalanches, and to control the emergency actions with respect to the population who might need to be temporarily evacuated or confined for their security. Such processes are already implemented in certain territories or countries facing cyclone warnings.

One of the biggest resorts in the Alps undertook, with the help of the French Ministry for the Environment, the development of a system supporting the organization and control of evacuations of this type.

The system offers the following functions:
– spatial and temporal identification of the different types of built land cover and the best possible enumeration of the persons exposed and of their respective characteristics;
– identification, building by building, of the vulnerability to various avalanche scenarios and of the specific emergency safety procedures;
– selection of dangerous areas according to nivological and meteorological criteria;
– real-time control of logistics and of the order of procedures.

This system enables us to consider a large range of possible scenarios, to prepare responses and to identify the limits between what is possible and what is not. It will certainly lead to prevention methods requiring the tourist populations’ approval and a soft communication and information strategy to guide them towards risk appropriation.
Contrary to what might have been expected, this consensual policy appears to be an additional bonus to the quality of the resort. The tourists feel closer to their hosts!

11.5.3. Risk management and natural or man-made subterranean caverns, mines and quarries

Many towns are affected by this type of risk, which is most of the time of anthropogenic origin, such as the subterranean caverns famous in Paris, or more or less abandoned mining sites such as those in Saint-Etienne or Auboué. However, natural cave-in risks also generate significant damage such as in Jura or Var and in many other regions with limestone or gypseous bedrock. Less known, because they are less common in France, are the subsidence phenomena that greatly affect Venice as well as many towns on the Pacific coastline.

Paradoxically, anthropogenic cave-in risks are not the easiest to control, whether because the exploitation processes were disorganized, as was the case for the Parisian subterranean quarries (for which an inspection body was created), or because the plans are still in the hands of the former owners, who are often not willing to communicate them.

Regardless, true 3D georeferencing and 3D modeling resources must provide significant advances in this field.

11.5.4. The RADIUS project of the international decade for natural disaster reduction (Décennie internationale pour la prevention des catastrophes naturelles (DIPCN))

RADIUS (Risk Assessment tools for Diagnosis of Urban areas against Seismic disasters) aims at promoting prevention measures for urban area earthquakes, particularly in developing countries. The objective is to design tools: a manual to develop damaging scenarios, a graphic software program to facilitate the application of the terms of the manual, case studies, a guide book to carry out the basic assessment of buildings and houses, and documentary films.

The program, with a €1.5 million cost estimate, was carried out from 1997 to 2000. Although fewer than 10 cities benefited from it throughout the world, the real consequences are still to be defined, but they should be very positive if the efforts are maintained. Yet, we might wonder if this program will have the necessary impact among the decision-makers of developing countries compared to the scope of the phenomena concerned and of their economic impact.
It is always easier to teach others how to do things properly rather than doing them ourselves. There is an urgent need to prove the efficiency of prevention methods in places where the resources should be available to implement them, particularly in the large cities of developed countries!

### 11.5.5. Bogotá and its risk and crisis information system (SIRE)

Bogotá is a megalopolis with over six million inhabitants exposed to the whole range of natural hazards: earthquakes, landslides, flooding, but also to technological and social risks.

Considerable efforts have already been made to identify the most dangerous sectors in risk areas. A remarkable seismic risk and vulnerability study was accomplished by the Colombians themselves after they had learnt, with international support, from the Papayan disaster (several hundred deaths) at the end of the 1980s.

A program named SIRE was created between 1997 and 1998 by the Colombian geological service (INGEOMINAS) and the risk prevention office of the Colombian capital (UPES), with the support of GIPEA.

This system started in 2000. Further information can be found at the following website: http://www.fopae.gov.co.

### 11.5.6. The CŒUR project in preparation between the Rhône-Alpine and Mediterranean cities

GIPEAN developed, on the principles of SIRE, the CŒUR project (control of urban environment and risks), but with a wider scope of objectives with the Greater Lyon and the network of Rhône-Alpine cities. This project is currently being developed with large European and Mediterranean cities. Looking for continual improvements, CŒUR wishes to offer the best possible synthesis of all the projects already mentioned, but also and especially to reach the necessary critical level to become an efficient exchange and reference system for urban risk management.

Its main objectives are:
- to create a space for permanent collaboration and exchanges on the management of the urban environment and risks, building upon the knowledge acquired in all the previous projects already mentioned;
- to foster the development of measurement technologies (measurement transmission and processing), which would be economical and well distributed (with
sufficient quantity), to provide relevant and efficient monitoring elements with respect to the understanding of phenomena and to decision making;

– to progressively develop a European code and regulations for urban environment monitoring.

This is how we will move from a disordered situation in which everybody does their best while repeating the same mistakes with the same technological, scientific and economic inadequacies, to clearer prospects with:

– a power and efficiency boost in terms of measurement technologies (an important European market will automatically result in a significant reduction of cost, with clear specifications and standards);

– significant improvements in sharing knowledge and experiences.

11.5.7. The Base-In project of recording Grenoble’s historical floods

This project, jointly developed by the Cemagref (Lyon flood division) and the ACTHYS and GIPEA companies, consisted of an inventory of historical elements related to the flood events that occurred in Grenoble during the 19th century, and also of a similar piece of research in the Ardèche department.

This project showed how, on the basis of a careful analysis of municipal archives, exploitation of old engravings and as accurate a reconstruction as possible of land cover at that period, we could understand how the exceptional phenomenon that struck the town in 1859 had been generated, and draw hypotheses on what would be the hydrogeological impacts of such a scenario today, considering the physical transformations of the territory and of the land cover. This project prefigures how profitable such approaches could be to urban risk management, and makes it possible to reassess historians’ contribution to prevention.

11.6. Assessment and outlook: fundamental elements of future systems

In the previous sections, we have tried to shed some light on the notion of risk, to rapidly analyze the stakeholders’ expectations, to show how modern computer tools, on the condition they are well understood and efficiently used by these stakeholders, can support them in undertaking their duties, and finally to show the current trends through some examples.

To conclude, we would like to define what might be the main elements to be considered in the general specifications of future systems meeting these needs and using the resources of the most advanced geomatics methods and tools [LAU 01]. These elements are essentially: the territory, the phenomena and the stakeholders.
11.6.1. Territory

As far as the territory is concerned, it is necessary to improve the knowledge of its physical characteristics, and of its land cover and land use. It is a huge step forward from traditional maps and the possibilities offered by georeferenced databases and the success of GISs is only the beginning of it.

Nevertheless, making the most of this progress especially requires the implementation of true data sharing policies, but also of acquisition, validation and structuring policies dedicated to relevant applications. However necessary this approach is, it cannot be thoroughly enforced. Everyone must have the opportunity to contribute and to gain some scientific, technical or socio-economic benefits.

It is not easy to strike the proper balance between too many standards and too much freedom, but new information and communication technologies will greatly help in that matter.

11.6.2. Phenomena

If most phenomena liable to generate risks in urban environment are known, still very little is being done to detect the preliminary signs, to enhance the value of experience and to control the impacts.

Most scientific or technical stakeholders have to reinvent, each time, solutions for which a body of knowledge and experience is available, but is accessible to only a few.

Moreover, in terms of monitoring the phenomena, there is a huge gap relating to both specifications and technologies. A minimum of European consultation and standardization would significantly improve efficiency and realism.

Finally, the extreme confusion that is still prevailing between risk and vulnerability hinders decision-makers really appreciating, and then clarifying what is at stake. Major advances are expected in terms of vulnerability assessment, from analyzing the origin and the creation of damage. In order to carry out this type of analysis, new methods must be developed, and research teams must work together and no longer confine themselves to either solely technical or social aspects, as they have been doing for too long.
11.6.3. Stakeholders

Although the stakeholders, along with their respective needs, are clearly identified, it is still very difficult to make them work together between crisis situations, that is to say, in moments when they can have the calm and objectivity necessary to organize prevention, but in those moments they simply forget all that had been said during the crisis about what should be done.

Social debates on risk and its appropriation should be instigated, particularly in Western countries. Finally, there is a need to educate the public, and especially young people, because solutions can only emerge from long-term programs.

In the end, what urban risk management does really demand of geomatics is the development of systems that would allow anyone interested to have access to all available data, which represents a considerable shortcut to raise awareness of the complexity of the issue at stake, and which facilitates the creation of modern information networks, of a genuine exchange, consultation and discussion forum.

11.7. Bibliography


http://www.gipea.fr: GIPEA site, with illustrations of GERICO, EVINOND.

http://www.fopae.gov.co: site for the Columbian project SIRE
Paola ALLEGRA  
Istituto di Ricerca per la Protezione Idrogeologica nel Bacino Padano  
Turin, Italy

Jean-Pierre ASTÉ  
GIPEA  
Caluire, France

Frédéric BERGER  
Cemagref  
Grenoble, France

Raphaëlle BLANCHI  
Ecole des Mines de Paris  
Sophia-Antipolis, France

Philippe BOLO  
Aqualis  
Beaucouzé, France

Christophe BRACHET  
Aqualis  
Beaucouzé, France

Gérard BRUGNOT  
Cemagref  
Grenoble, France

Bertrand DE BRUYN  
SOGREAH and LTHE  
Grenoble, France

Catherine FREISSINET  
SOGREAH  
Grenoble, France

Franck GUARNIERI  
Ecole des Mines de Paris  
Sophia-Antipolis, France

William HALBECQ  
Consultant  
Mainvillers  
France

Alain JABER  
Ecole des Mines de Paris  
Sophia-Antipolis, France

Marielle JAPPIOT  
Cemagref  
Aix-en-Provence, France

Jérôme LIÉVOIS  
RTM  
Annecy, France
Index

A
aerial photographs, 47, 54–57, 75–77, 93, 130–131, 185–188, 235
aggradation, 78, 80–82
air quality, 218, 227
analysis
geomorphological, 74, 181, 185–189, 201
stereoscopic, 185–188
area
diked area, 193–198, 203, 207
atlas of flood-risk areas, 174, 178
atrazine, 28–29, 32, 34–35
avalanche, 79–81, 87–106, 112–113, 228, 235–237, 239, 242
C, D
cadastre, 55, 57, 223–224
CLPA, 92–97, 101
combustibility, 118, 123, 133, 140
cooperation between software programs, 151, 158, 162, 165–167
decision support, 2, 4, 9, 135, 145, 148, 151–160, 166–167, 175–176
DFCI, 3–5, 7, 9, 10–12, 16, 21, 124–125, 129, 131, 166
dike breaching, 193, 199, 201, 212
distributed artificial intelligence, 154
E
earthquake, 115, 222–225, 243–244
evacuation, 2–3, 134, 223–224, 242
experiment, 100, 129, 136, 158–160, 177, 179, 220
F
fertilizer, 39–40
firemen, 2–3, 5, 19, 152, 162, 164
flood
flash flood, 71, 173
warning, 170, 172, 174, 179, 182, 184, 189, 196
forecasting, 3–4, 17–18, 23, 73, 220–222, 226, 229, 235, 239–242,
forest fires, 2–6, 8, 12, 15, 18, 21, 115–117, 119, 121–124, 126–149, 151–152, 158, 166, 168
forest playing a protective role, 87–113
frequency, 9, 59, 73, 85, 93–94, 109, 116, 140, 182–185, 188–189,
fuzzy arithmetic, 23–37
G, H
Garonne, 169–170, 172, 176, 179, 183–184, 188–191
geographic information
preventive, 123, 125–126
geomatics
and urban risks, 215, 217, 222, 228–233, 239, 245, 247
ground movement, 226, 228, 236, 240
history, 123, 127, 169–170, 222
hydraulic structure, 186, 241
hydro-geomorphological approach, 189
hypodermic runoff, 51
I-L
ignition probability, 118, 121–122
index of controlling hazards, 102–103
indicator, 24, 27–31, 37, 65, 173, 186–187, 212
infiltration, 41
insurance, 126, 218, 220–221, 224
intelligent software agent, 152–167
inventory of dikes, 199
landslides, 71–73, 77, 79–82, 88–89, 115, 222, 227, 244

M
managers, 194–200, 203–207, 212–213
management
  crisis management, 2, 4, 7, 13, 15, 18, 78, 85, 123, 162, 166, 174, 178, 196, 205–206
  integrated management of diked areas, 196, 198
map of socio-economic issues
  hazard map, 108–110, 222–223, 229
  map giving the likely position of avalanches, 92–93
  natural hazard map, 102, 104, 126
  forest map, 102
maximum instantaneous height, 182
measurement station, 175–176, 182
meteorological radars, 177
Mid-Loire river, 193–195, 198, 200–201, 203, 213
moisture, 117–118, 122, 136, 159–160, 163
modeling
  conceptual, 204
mountain, 71–76, 84, 87–113, 175–176, 218, 225, 235–237
multi-stakeholder and multiscale GIS, 195

N-P
natural factors, 71, 119, 234
natural hazard zoning, 87
non-point source pollution, 39–69
  Perceptrory, 205
pesticides, 39–40, 42, 58–60, 68, 70
  phytosanitary products, 23–28, 32–33
Piedmont, 74–75, 172–173
pollution, 39–70, 218, 225, 227, 234
population growth, 122, 216
precipitations, 25, 79, 172–179
problem solving, 165
problem solving environments, 143–144
propagation, 118–119, 122, 128, 130, 135–136, 138, 140, 142, 145, 147, 159–166, 174, 177

R
real time, 2, 7, 12, 17–20, 174–178, 182, 242
regionalization, 234, 239
research, 221, 225, 227, 236, 238, 246
rescue means, 2–3, 8–9, 11, 15–17, 160
risk
  propagation risk, 118, 128, 142, 160
  technological risk, 6, 218, 225, 240
  urban risk, 215–247
risk appropriation, 219–220, 230, 242
risk prevention plan, 106, 111, 125, 138, 182, 195, 218, 233
rock fall, 73, 75, 79–80, 88–90, 94–95, 108, 235
road, 3, 12, 15–17, 54, 59, 71–85, 134, 215, 218, 222–223
road and network surveys, 234

S, T
saturation (degree of), 51, 173
scale, 48–49
security
  road security, 73–76
situation of crisis, 152, 175, 193, 206, 247
slope instability, 73, 226–227, 237
spatial decision support systems, 51–53, 167
start zone, 89, 92–97, 101–104
statistics, 67–68, 71, 98, 133, 159
subterranean caverns, 243
surface runoff, 41, 51
temperature, 117–118, 122, 130–131, 136, 159–160, 166
territory diagnosis, 40
transportation of dangerous goods, 12, 228

U, V, W
underground water
  surface water, 23–26, 28, 33, 41, 51–59, 64, 67–70
urban policy, 231
use of space, 187
vegetation cover, 24–25, 30–31, 173
water resources, 23, 39, 56, 68, 159, 164
weather conditions, 12, 161, 234
wind, 88, 97, 100, 117–118, 122, 135–140, 159–166