

# DAM-BREAK FLOOD RISK MANAGEMENT. AN INTEGRATED PROJECT

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**ABSTRACT:** Contemporary dam safety regulations include risk assessment at downstream flood plains and consideration of potential damages due to dam rupture, regardless of the expected probability of occurrence of such event. The aim of these kind of procedures is to increase the safety level along the valley against abnormal floods caused by dam accidents.

Emergency plans for downstream flood plains, including zoning, warning and evacuation plans, are being developed as special risk mitigation procedures. In modern open societies these plans should include public information and training. All these valley actions will be justified in order that the global safety level be increased, not only in objective terms by increasing the survival probability, but also in subjective terms. In fact, public risk perception is a very important dimension in any risk management methodology. For dam and valley safety policy, public participation and perception becomes more and more a very important issue.

Among the different complex aspects of this topic, the ethical questions related to risk assessment and management as well as with the risk communication need to be considered. Risk public perception is one of the variables that must to be introduced in the emergency planning.

To study, develop and improve an integrated methodology for dams and valley risk management in Portugal, a special project is under development, since 1994. This project is sponsored by NATO, through its Science for Stability Program.

The main objectives of the project were the following ones:

- to improve the computational capacity to simulate dam-break floods (one and two-dimensional models), including validation procedures based on physical and experimental models;
- to improve the portuguese dam safety legislation in what concerns downstream valleys;
- to introduce the applied social sciences in risk management methodologies, specially in what concerns risk public risk perception and information and the land-use management during dam lifetime;
- to develop new decision tools to aid dam and valley risk management based on advanced computer technologies (SIG and multimedia databases);
- to develop a guideline for valley emergency plans and a full scale exercise.

The project was organized in five sub-projects that were being working in order to reach the objectives. The work was based on a theoretical and applied works for a case study, including valley with two dams: Arade valley at Algarve, in the south of Portugal, where two dams are in operation upstream two cities.

The paper will briefly describe the main concepts and developments achieved by this NATO project including the conclusions and the practical consequences and measures that are being implemented in Portugal.

## 1 PROJECT CONTEXT

Effective dam risk management and mitigation have become a high priority of organizations concerned with valley safety as well as with civil protection procedures against floods. For this particular type of risk, dam structural safety has been the focus of almost all mitigation actions. However, most of the potential damages and losses will occur along the downstream valleys. Past events show this evidence and recent dam safety legislation includes some procedures related to the downstream effects of a dam failure.

An effective mitigation of possible hazards due to a dam accident or incident clearly imposes an integrated risk management including both the dam or internal risk control and the valley or external protection.

- The success of such an integrated methodology is based on a set of methods and techniques:

- Computational modelling of dam breaches and dam-break floods;
- Damage analysis based on inundation mapping and socio-economic land-use as well as on public risk perception and response;
- Emergency planning including evacuation planning and public information and training;
- Information management based on the new information technologies (e.g. GIS and database for decision support).

As a result of the importance of this problem in Portugal a proposal for a development project on this topic was presented by two portuguese research institutions, in 1992, to NATO "Science for Stability" Program. The project was selected and partially funded by this organization. The five year project began in 1994. The research institutions are the "Laboratório Nacional de Engenharia Civil" (LNEC) and the "Instituto Superior Técnico" (IST) of Lisbon, Portugal. The project is also supported by three portuguese organizations strongly related to dam safety and civil protection:

- "Instituto da Água" (INAG), the portuguese dam safety authority;
- "Electricidade de Portugal" (EDP), the main portuguese electricity utility and dam owner;
- "Serviço Nacional de Protecção Civil" (SNPC), the portuguese authority and organization of civil protection.

The aim of this NATO project was to develop some new integrated methodologies in order to improve in Portugal the dam-break flood simulation and inundation risk zoning, the emergency response, the land-use planning and the knowledge of risk social perception. The final report was approved by NATO in September 2002.

## 2 SAFETY OF VALLEYS WITH DAMS

### 2.1 *Integrated Safety and Risk Concept*

The concentrated water (and energy) behind each dam can be considered as a major risk factor to downstream valley especially in what concerns potential abnormal and catastrophic floods induced by a dam accident. Meanwhile, millions of people live along valleys with dams, often with a very dense land occupation. Valley safety, in this context, can not be completely dependent on dam structural and operational reliability. In fact, valley safety need to be considered as an integrated concept closely involving both dams and reservoirs as well as the downstream valley system comprise the people, the land and the economic occupancy.

A shared risk need to be negotiated and implemented: the valley risk management process need to include the human feelings and values in order to understand potential conflicts and to find equity between individual interest and public good.

Protection against natural or controlled floods needs also to be considered in the integrated safety and risk concept. Flood risk should be a factor to be taken in consideration by land-use and urban planning as well as insurance policies and the valley risk management should be an active and dynamic tool not only for crisis situation but also for regional and local decision-makers.

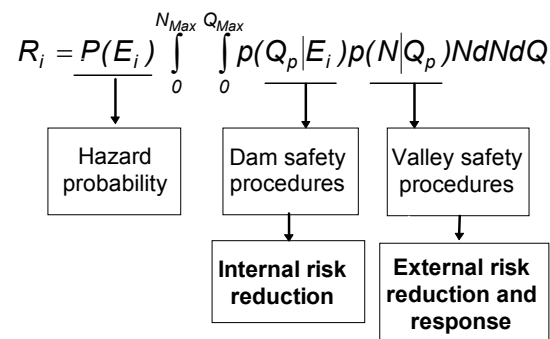
### 2.2 *Conceptual framework*

For each potential event or hazard  $E_i$  acting on the dam system, the formal mathematical risk,  $R_i$ , can be considered split in two kinds of risk: the internal dam risk and the external or

downstream valley risk. In Figure 1 this formal risk concept is presented, where  $P(E_i)$  = hazard occurrence probability,  $P(Q_p | E_i)$  = conditional probability of occurrence of an abnormal flood with maximum peak discharge  $Q_p$  induced by the dam response to hazard  $E_i$  and  $P(N | Q_p)$  = conditional probability of  $N$  losses along the valley due to the induced dam-break flood.

Dam-safety procedures will contribute directly to the **internal risk reduction** and the valley safety procedures will contribute directly to the **external risk reduction**.

The main objective of this integrated management is to improve the real safety of people and ecosystems along the valleys and its implementation should reduce the valley vulnerability. That can be achieved by a consistent dam-valley risk mitigation system.



**Figure 1** - Formal mathematical dam risk concept due to an hazard  $E_i$ .

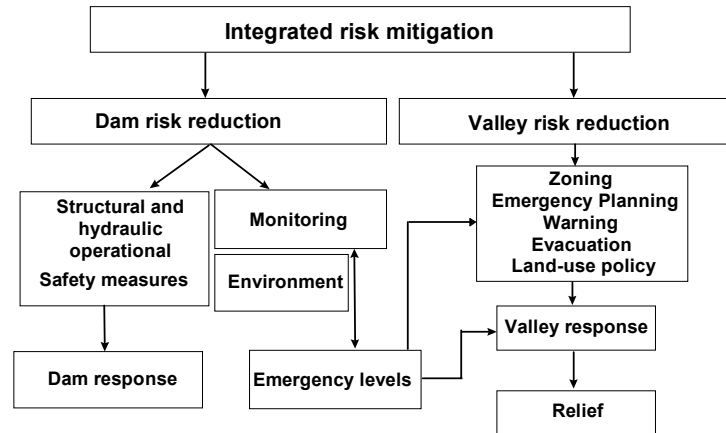
In this context an integrated dam-valley risk management system can be conceptually composed by two parts: *the risk assessment process*, in which an approximate quantitative risk estimation and evaluation is made for dangerous situations; it includes the hazard identification and characterisation as well as the dam risk analysis; and *the risk mitigation process*, in which actions to reduce the risk will be identified and implemented. In the risk assessment process we need to consider the hazard determination and the risk analysis. Both tasks are at the core of the process. They should identify the dangerous events and damages that can occur and to assign a probability for each event and consequence.

The risk assessment implies some form of action in of uncertainty and provides a basis for making decisions concerning the need for risk control measures. These actions will be based in a certain level of acceptance of potential catastrophic events. These arise an ethical component to the process. In the risk mitigation process two main set of actions can also be considered (Figure 2):

Risk control and reduction, including the actions to be taken, in different operational phases and situations of the dam-valley systems, in order to reduce the response probability functions referred in Figure 1. These actions include the operational safety of each dam during all its lifetime especially in what concerns the routine monitoring and inspection procedures and the safety procedures during an emergency situation, it also includes the actions to face a potential accident (early warning systems, emergency action plans, preparedness training and land-use restrictions or risk zoning).

Risk response, including the actions to be taken in order to develop and implement the crisis valley response plan should a disaster occur, caused by a dam incident or failure; it includes the

civil protection actions for short-term assistance, evacuation and survival planning for both emergency and post-emergency phases.



**Figure 2** - Integrated dam-valley risk mitigation.

So in this aspect of floodplain safety and risk management we need to consider the following strategies:

- The principle of **preventing accidents**, in what concerns the **internal risk** reduction management (in dam operation).
- The principle of **minimizing damage**, in what concerns the **external risk** reduction management (in valley management).

### 2.3 Ethical constraints

The valley risk assessment and management, as well as the public information and participation in the risk decision process, had a strong ethical component that should be clarified. The ethical problems can be important when a new dam is to be built in a valley and when a risk assessment and management are considered in a valley with one or more dams already in operation. In the first case the question of potential risk will included in a very general environmental risk assessment and impact study. In the second case the main problem will be the dam and valley safety. In what concerns the risk assessment and risk management processes the following questions can be selected:

- Why we should do it?
- How to do it?
- What are their consequences?

In these three aspects, ethical constraints or implications can be identified. Risk assessment can be justified as a moral duty for the dam experts (engineers and dam safety officials) because absolute dam safety is neither attainable nor affordable. In this context it will be a duty to evaluate the degree of risk induced by a dam in order to be possible to judge if it is “acceptable” or not. Engineers and safety officials can be legally responsible and be sued individually, even when acting according to dam safety guidelines, should an accident occur and the risk be considered as being not acceptable by the society and the proof of negligence can be not essential to impose liability.

It can be concluded that the obligations of dam engineers or dam experts and dam safety officials is to be ethically responsible with regard to risk and they must protect the public from unacceptable risks. Engineering codes strongly require engineers to hold paramount the safety, health and welfare of the public ethics. Uncertainty and potential human losses and balancing the protection of individuals along a valley against the promotion of the public welfare (e.g. water or electricity from the dam) poses ethical problems to the decision-makers.

#### *2.4 Ethics and risk communication*

Public participation and information implies a reflection on ethics related to risk communication and effects. Some dam experts and safety officials have the opinion that risk information may frighten so much the population that can induce a problem greater than the one we want to solve or mitigate. However, there are other opinions about this subject: the valley risk mitigation can not be possible without the public participation and information and the participation of local authorities. Viewing engineering as an experiment on a societal scale the **principle of informed consent** focuses on the human beings potentially affected by technology. This principle is against the traditional concept that engineering activity is by principle good for the society and the public and the participation of laymen is negative.

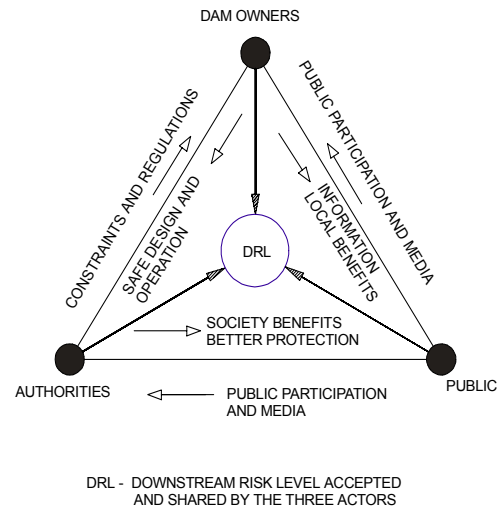
- The concept of a downstream risk level accepted and shared by the three actors in dam safety and acceptance decision process includes the principle of informed consent as a general basis. However, when the participation and the discussion leaves the field of experts and dam safety authorities, strong emotions can perturbate the process as fear and panic.

#### *2.5 Public perception and participation*

Rare events with very low yearly probabilities are difficult to be accepted or understood. In fact, risk perception involves people's beliefs, attitudes, judgements and feelings, as well as the wider social or cultural values and dispositions people adopt toward dam hazards and benefits. Engineers are well trained to work with the physical truth or objective safety evaluation based on a quantitative analysis and on, as much as possible, "neutral" and rational decisions. However, in open and democratic societies, the public and the media are now a part of the decision process on what concerns dam impacts and flood mitigation. Typically, the individual doesn't easily accept a new uncertain risk or threat imposed to him and family by others. In order to conciliate the individuals and the groups of people under potential threat as a whole, social psychology and sociology are two social sciences that should be introduced in the interdisciplinary set of specialists involved in dam safety and valley risk assessment and management. The consideration of both subjective (human response) and objective factors (inundation maps and evacuation plans), can improve the emergency response and also the real survival capability under limit or critical conditions. The integrated valley safety and risk management should also include abnormal floods and dam outflows. Another very important category of difficulties, against a full integrated dam-valley safety and risk management, is the institutional one and especially the rigid separation between traditional roles in safety, civil protection and land-use policies. The integrated dam-valley risk management has a definitive complementary role to the restricted dam safety concept only based on procedures related to dam works and operation.

A shared risk responsibility (Figure 3) should be developed between dam owners, safety authorities and public, due to a better consideration and characterization of the dam benefits and

risks as well as a mitigation or control action to protect the valley according to an accepted societal risk level.



**Figure 3** – Dam risk sharing between dam owners, public and authorities.

## 2.6 Project Structure

The NATO PO-FLOODRISK Project for Dam Risk Management at Downstream Valleys is organized in five sub-projects:

- Sub-project 1 - Hydraulic Analysis and Computational Simulation;
- Sub-project 2 - Dam and Reservoir Safety Analysis;
- Sub-project 3 - Social Impact of Dam Break Risk;
- Sub-project 4 - Computer Aided Decision Support System;
- Sub-project 5 - Integrated Emergency and Training System.

Each sub-project is composed of several tasks with precise objectives. The methodologies developed by the NATO project are being applied to a case study in Arade river valley in South of Portugal. In this valley there are two dams: 1) Funcho Dam, a concrete arch dam, built in 1991, with a height of 49 m and crest length of 165 m. The reservoir has a gross capacity of 43.4 hm<sup>3</sup>; 2) Arade Dam, an earthfill dam, built in 1955, with a height of 5.0 m and a crest length of 246 m. The reservoir has a gross capacity of 28 hm<sup>3</sup>. Two urban areas are placed downstream the dams: Silves and Portimão.

## 3 PROJECT DEVELOPMENTS

### 3.1 Sub-project 1

A good characterization of the floods induced by dam breaks is a fundamental requisite for the valley risk management. According to the project program the following tools were developed:

- computational flood simulation with fixed bed models (1-D and 2-D) for irregular valleys, based on a numerical technique with the capability to deal with flow discontinuities or shock waves (MacCormack - TVD technique);

- experiments in a special canal with different boundary conditions in order to validate the computational models. This canal was also used for CADAM tests;
- a physical model (scale 1/150) reproducing a reach of the Arade river 4 500 m long for model validation under real irregular conditions.

Dam-break floods, in real conditions, induce two-phase (solid-liquid) flows: the sediments in the reservoir are forced to move with the outflow and the downstream river bed will suffer erosions and strong modifications due to this kind of abnormal flood. The NATO project also have promoted studies on this topic including analytical analysis and the coupled and non-coupled modeling of solid-liquid mixtures and experimental studies on a laboratory flume. At 1998 CADAM Munich Meeting some results were presented. In what concerns the Arade case study it was concluded that inundation maps based on 1-D and 2-D computational models presented very relevant differences both in what concerns the inundation area affected by the flood and in maximum flow depth and flood time arrival.

### 3.2 *Sub-project 2*

In this sub-project the dam safety legislation was discussed as well as the conditions to follow in dam-break flood studies as by example:

- dam failure scenarios for single and compound breaks (cascade dams along a river valley);
- hydrological conditions to consider in dam-break flood studies;
- outflow hydrographs due to a dam breach according to dam type and accident cause.

Another topic considered was the criteria for flood risk characterization based on the inundation maps obtained by computer simulations. The flood impact on human life's and on buildings will depend on the hydrodynamic characteristics of the flow: maximum depth and flow velocity, depth gradient with time, time of flood arrival and flooding duration, among others. The flood severity characteristics should be the basis for a first or preliminary risk zoning.

### 3.3 *Sub-project 3*

#### 3.3.1 *Social perception research*

The NATO project made the first field inquiries in Portugal about dam risk social perception along the Arade valley. Downstream the two dams the valley has a length of about 14 km to the Atlantic Ocean and 8 200 inhabitants as population at risk (PAR), both in rural areas and urban areas (Silves town, 7 km downstream the Arade dam and Portimão town, 13 km downstream this dam). The analysis covered the following aspects:

- subjective probability and awareness of negative consequences of a dam failure disaster;
- perceived risk of flood and dam failure;
- perceived benefits and perceived safety of dams;
- association of perceived risk with other social beliefs.

Residents near the dam perceive dam-break risks as more dread than people living far away. The accidents living near the dam have a great awareness of the consequences to their site in case of dam disaster, but those living near the coast don't.

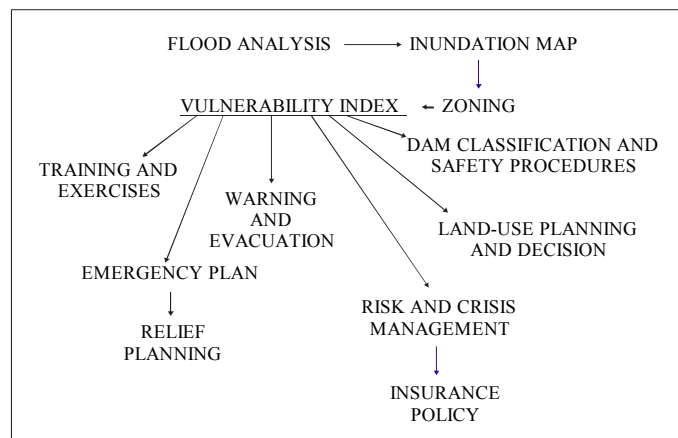
Arade dam (earth fill dam) is perceived as safer than Funcho dam (concrete arch dam), specially by the residents near the dams. Judgments of dam safety are based on confidence in

dam engineering and characteristics of the dam. Older dams are considered as more trustable than younger ones, because they have already proved to be safe. These results present some challenges in terms of risk communication strategy which need to be sensitive to the characteristics and feelings of the population at risk along the valley.

The low frequency of accidents of this kind, or the low probability of occurrence associated with the high catastrophic potential have a strong influence on risk public perception. These aspects need to be considered when defining the risk communication strategy to be adopted in each case (Sub-project 5). This strategy is intended to dissipate feelings of apathy and public passivity and to motivate the community to prevention and supervising. The aim is also to avoid the triggering of overreactions of risk amplification conditioned by feelings like fear, anxiety or stress deriving from the consciousness of the catastrophic potential of the event. The results of this particular case study have also shown that people at risk have self-efficacy and control illusions (positive illusions) and need them for their well being when faced with dam failure risk day to day. For more details see “Dams and Safety Management at Downstream Valleys” (1997).

### 3.3.2 Valley vulnerability

Valley socio-economic vulnerability towards each potential hazard is a major factor to be considered in risk management. Vulnerability reflects the potential weakness to react to, or recover from, a hazard impact as a dam-break flood. This concept pretend to characterise the socio-economic, especially the human, tolerance to valley hazards in general, and to floods in this particular case. For operational efficiency, a methodology for quantitative description of the valley vulnerability should be developed, like a vulnerability index. This would allow an approximate measure of the risk levels along each valley and between different valleys. This vulnerability index should be considered in risk management and emergency planning as an integrated concept combining both physical and tangible factors as well as social and intangible factors. It can be a reference for the actions to be taken in valley risk and land-use management (Figure 4): the vulnerability index should not increase with the time. This index can also be a basis for insurance policies in floodplains.



**Figure 4** - Vulnerability index as a reference for valley risk management actions.

### 3.3.3 Land-use control

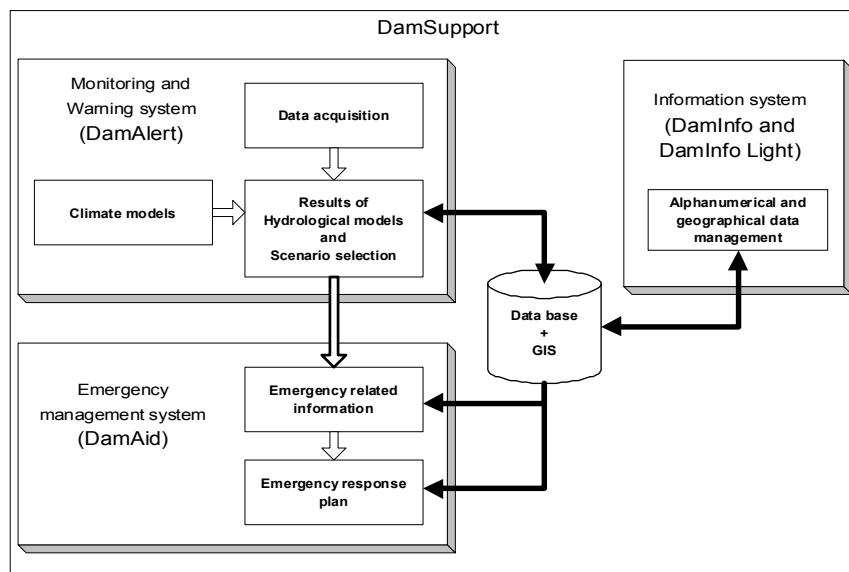
The valley vulnerability will be closely linked to the probability of a certain number of human losses or other damages should a dam-break flood with special characteristics propagate along the valley. Preventive procedures to be considered within an integrated valley risk management should include the land-use control according to high risk zoning. This control should avoid very vulnerable or strategic infra-structures or permanent people concentrations in areas prone to flooding. This information is now easily considered and up-to-dated in a GIS interconnected through a special network (Sub-project 4).

### 3.4 Sub-project 4

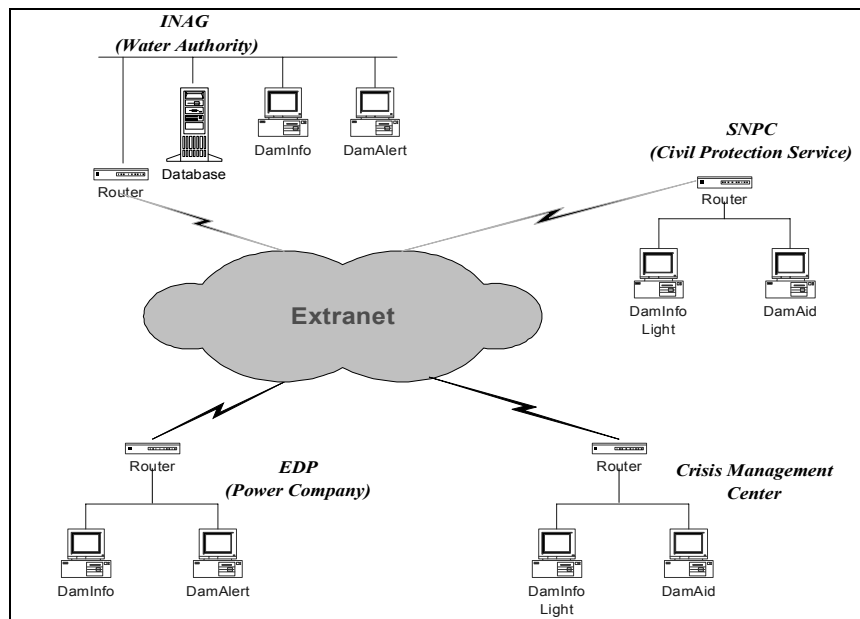
The research group of the NATO project developed the Decision Support System (DSS) for the project team and also for future users (Dam Support). Basically, the following products were developed (Figure 5):

- a multimedia database oriented for dam safety as an inventory of all relevant information related to design, construction and exploration of each portuguese dam;
- Geographical Information System (ARCINF) linked to computational models and database by special interfaces;
- a database for crisis decision support including the valley emergency planning procedures (Dam Info and Dam Info Light);
- a monitoring and warning system (Dam Alert);
- and an emergency management support system including the emergency response plan (Dam Aid).

The DSS will be interconnected between the Water and Dam Safety Authority (INAG), the Civil Protection Service (SNPC), the EDP Power Company and a Crisis Management Center to be implemented at the end of the project (Figure 6).



**Figure 5 - Dam Support System (NATO project).**



**Figure 6 - DSS interconnection between end-users.**

### 3.5 Sub-project 5

At the end of the project the main goal is to have contributed for an effective improvement of valley safety and risk management in Portugal. This general objective is being obtained through the case study (Arade valley) where the developed methodologies and techniques are being applied. This work is composed by five stages including aspects like: flood computational simulations, inundation mappings, risk zoning, socio-economic characterization, regional and local hydrologic study (flood analysis), dam reservoir exploitation and land-use planning criteria.

Emergency and risk management must act on four different stages: to understand the phenomena that may induce a failure and reduce its impact (mitigation); to prepare for effects of the hazard (preparedness); to respond in an effective way to the event, may it occur (response); to restore the systems to normal situation (recovery).

According to the conceptual risk framework already presented, two types of plans were considered:

- the Internal Emergency Plan, that refers to the actions concerning the dam safety and operation; and;
- the External Emergency Plan, that should mainly be concerned with the actions in the valley.

The Internal Emergency Plans should include: 1) the characterisation of the water control infrastructure; 2) the identification of potential dangerous situations for the dam; 3) the definition of the safety levels in dam operation; 4) the methodology for hazard detection and decision-making; 5) the notification of dam safety and local authorities; 6) the notification and mobilisation of civil protection services. The External Emergency Plan should include:

- 1) the characterisation of the downstream valley (population, infrastructures and equipment, routes and communication systems, military and paramilitary forces, medical care, economic activity);
- 2) the implementation of a the means of public warning and notification system;
- 3) the identification of the safety agents and their responsibilities;
- 4) a definition of the decision-making hierarchy;
- 5) the allocation of human and material resources;
- 6) the definition of shelter areas and the access routes (including alternate routes);
- 7) the identification of transportation material;
- 8) the identification of the communication systems.

As a prototype for Portugal, an emergency plan, including evacuation procedures and a warning system were developed by the NATO project in cooperation with the support institutions (INAG, EDP and SNPC). This system will include normal floods and dam discharges. The DSS is being extended to a national level including an emergency or crisis center. The results of the project are now being implemented in the new Alqueva dam, one of the largest reservoirs of Europe.

#### 4 CONCLUDING REMARKS

Dam safety legislation in several countries are now taking in consideration the potential effects or damages at downstream valleys should a dam-break occur regardless the probability of the event. These procedures introduce several problems to all organisations involved in dam exploitation as well as in dam and valley safety and, civil protection. An integrated dam-valley safety and risk management is proposed in this work.

Dam owners faces a responsibility towards society in what concerns the internal dam procedures that will avoid a dam-break or diminish the probability of a dam-break flood should an abnormal event or action occur (e.g. an extreme hydrological event or flood). Insurance premium related to dam failure consequences will also be in the future a serious factor to be considered by dam owners.

Civil protection authorities or valley safety authorities faces a responsibility to diminish the probability of human and economic losses should a dam-break event occur. To mitigate the risk along the valley, non-structural procedures should be implemented as land-use control according to flood risk zoning and emergency planning.

Emergency planning and effective warning systems are now mandatory by the portuguese dam safety regulation and all modern dam safety regulations. However, these procedures need to be implemented with the support of local authorities and with an adequate public information and participation according to the risk perception level of the population at risk. The emergency planning should also include the normal floods as another integration dimension. Evacuation planning need to be well prepared and trained and in almost all real cases the alarm need to be switch on as soon as a failure is predicted: before the failure inception time and the failure time, in order to be possible to evacuate a large number of inhabitants. This condition implies:

- advanced monitoring systems will real time capability to predict with more accuracy a dam failure scenario and the dam breach characteristics;
- good coordination between dam owners, dam safety authorities and civil protection authorities in order to be sure that emergency and evacuation planning's are effective;
- good public information in order to guarantee a good response to flood crisis.

The formal risk concept can be differently perceived by the specialists and laymen. A new index was developed based on valley vulnerability, as it is presented in this work.

The results of the multidisciplinary research project funded, by NATO Science for Stability Program, developed in Portugal and concerning the integrated dam-valley risk management is now being implemented. The project developed new methodologies for dam risk management in Portugal based on a cross-fertilisation between different engineering and social sciences techniques. The dam design practice and safety legislation can be improved as a result of the innovative proposals related to the accuracy of computational models and to an integrated land-use management, dam risk public perception and zoning as well as to decision support systems. These methodologies were applied to a real valley (Arade valley in Portugal), where the first social field research about dam risk perception was made in Portugal.

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