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ORIGINAL ARTICLE

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Decision-support systems for groundwater protection: innovative tools for resource management

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Abstract Governmental authorities are forced by law to make decisions within the framework of European, national and regional directives in the fields of spatial planning, groundwater and environmental protection. These tasks can be supported by a decision-support system, which integrates data from various sources and helps to make decision processes more effective and transparent. Basic work for such a decision support system has been done in a transnational and interdisciplinary project (Interreg II C: KATER), including metadata definition, metadata system, cartographic tools and GIS tools. The direct integration of these tools and information in the decision process will be implemented in the next few years (project KATER II).

Keywords Water management · Decision support systems · Metadata · GIS

Water management issues: problems and measures

Water management is a central issue in the twenty-first century, because water is rapidly becoming a scarce resource. The focus in dealing with water resources on a global scale thus has to shift from a water development perspective to one of water management (World Bank 1998). Water plays a vital role in human development, as the necessary basis for nutrition, a central factor for health and a resource in agricultural and industrial development.

The issues involved seem at first sight to differ quite strongly between developing countries and industrialised countries. In the developing countries studies in the last few years usually agreed on the main issues (Lee and Bastemeijer 1991). Nevertheless, they still apply in many respects to industrialised countries as well:

Need to address water source protection more systematically

Although water related environmental problems have received much attention in the last few years, because of their central importance for sustainable development in many sectors, there is still the need for a more systematical identification and analysis of source problems.

Lack of reliable information

Due to the complex interactions between natural environment and human action, which determine the quantity and the quality of water resources, the knowledge about water resources and their (possible) contaminations is often very low. This is especially true for karstic aquifers, because of their hydrogeological complexities, and presents an increasing problem, as currently karstic aquifers contribute 25% of world-wide water supply, which is supposed to rise to almost 50% in the near future (H. Trimmel, personal communication).

Legislation not enforced

Environmental legislation and water laws often concern only large watersheds and so do not provide adequate protection for smaller water resources. The enforcement of laws and regulations is often hampered by a lack of awareness of drinking water problems and the interactions between the environment and human action.

Lack of awareness

A general lack of awareness of the environmental issues can be attributed to planners and decision-makers and sometimes even to water users. Short-term needs are often given higher priority than long-term protection of water resources. More attention should also be given to training of local staff and users, to increase awareness and to allow them to play a more active role in water resource protection.

The Interreg IIc project KATER was set up to provide solutions to some of the problems named above—especially the information gap and the systematical treatment of water issues. In the project period 1999–2001, information systems were developed to allow a comprehensive and integrative view of water measurements and their environmental conditions. KATER II—which was started in April 2003—will concentrate on the knowledge base of decision making and on tools for technical support of the decision-making process. KATER II thus provides an information base and a knowledge-network which is in line with the current developments of the "World Water Portal", which also focuses on water information sharing and cooperation. KATER II and the "World Water Portal" share the following objectives (see also: United Nations: World Water Development Report 2003):

- Using common structures, protocols, and standards to provide seamless access to a wide body of water information;
- Provide technical support (metadata assistance/standards, "good practice" guidance, search and database integration software, development of processes for data acquisition, etc.);
- Capacity-building in the area of information management (education and training for both managers and technicians);
- Facilitation of working partnerships via a physical and virtual network, the use of reliable information, and the improvement of integrated water resource management decisions;
- Providing a water information source for use by decision-makers, resource managers, researchers, students and the public at large.

The legislative framework

On the European level, the base of legislation is the water framework directive. This directive has to be transformed into national legislation by all EU member states by the end of 2003. It is also part of the general provisions of becoming member states of the accession countries.

The key objectives of the directive at European level are generally protection of the aquatic ecology, specific protection of unique and valuable habitats, protection of drinking water resources, and protection of bathing water. All these objectives must be integrated for each river basin. It is clear that the last three—special habitats, drinking water areas and bathing water—apply only to specific bodies of water (those supporting special wetlands; those identified for drinking water abstraction; those generally used as bathing areas). In contrast, ecological protection should apply to all waters; the central requirement of the Treaty is that the environment be protected to a high level in its entirety.

On the source side, it requires that as part of the basic measures to be taken in the river basin, all existing technology-driven source-based controls must be implemented as a first step. But over and above this, it also sets out a framework for developing further such controls. The framework comprises the development of a list of priority substances for action at EU level, prioritised on the basis of risk; and then the design of the most cost-effective set of measures to achieve load reduction of those substances, taking into account product and process sources.

On the effects side, it co-ordinates all the environmental objectives in existing legislation, and provides a new overall objective of good status for all waters, and requires that where the measures taken on the source side are insufficient to achieve these objectives, additional ones are required (see: European water framework directive:http://www.europa.eu.int/comm/environment/water/water-framework/overview.html).

All the elements of this analysis must be set out in a plan for the river basin.

The framework also addresses the need of public participation and informing the public as well as the problem of pricing. This includes the principle of recovery of the costs of water services, including environmental and resource costs.

In addition, the European Spatial Development Perspective (ESDP) explicitly aims at a linkage between groundwater protection and spatial development policy.

Decision problems in water management

The basic tasks of water management can be divided into

- Administration,
- Crisis management and
- Planning activities.

A more detailed task list for the roles of "water supply" and "water protection" can be defined as follows (Fig. 1).

A detailed analysis of tasks shows that the nature of decision making and the time scale of decisions is clearly different between task categories. Planning needs long-term decisions under conditions of low time-pressure, whereas administration and, above all, crisis management need immediate decisions. The support of decisions in water management must take into account the differing information needs and tailor the decision-support system (including the structuring of data access, the manner of data presentation and the system functionality) according to user needs.

Supporting decisions: information needs (KATER I)

Regarding the objectives of the KATER and KATER II projects, the main goal is the development of a decision-support system to handle the main tasks of water management: administration, crisis management and planning. However, before starting the actual application development process, it was necessary to collect details about the actual workflow of users and their information needs. A detailed analysis of the workflow gives, on the one hand, the possibility for optimisation of the workflow (avoiding duplicate work, etc.), and on the other hand, it is the basis for the conception of any support by tools like GIS. To satisfy the information needs of user groups the following steps were taken in KATER I:

Data collection and integration in GIS database

The first step was to integrate data sources of various disciplines. These include geology, hydrogeology, meteorology, vegetation mapping, pedology, remote sensing, surveying, etc. The data was transformed into one consistent system of spatial reference, including the activities of assessment of data quality and plausibility. The systematic integration of direct spatial information, like geological or hydrogeological maps could easily be used within GIS. It proved to be more difficult to integrate the measurement data of various measurement

Fig. 1 Task lists for "water supplier" and "water protection"

Task category	Water supplier	Water protection
Administration	• monitoring of discharge and outlet (water quantity and water quality) • regulation of used amount of water	• Property Management • Monitoring of Land Use Activities • Monitoring of Natural Environment
Crisis management	• technical accidents • water contamination	• Elementary Natural Accident • Global Contamination • Local Contamination
Planning	• maintenance work • forecast of quantity and quality • analyses supply versus demand	Analyses concerning possible changes in interdependences: • Land Use with Water Balance • Natural environment with Water Balance

campaigns and monitoring stations into the same system of reference. The objective of integrating the measurement data is to have online access via the information system to the measurement stations. This is especially important for the tasks of crisis management and also administration (Fig. 2).

Data documentation via metadata

Metadata are regarded as the main key for successful and lasting multidisciplinary work (e.g. Streit and Bluhm 1998). They present users with information about data availability and—even more important—about the possible use and usage restrictions of this data. This includes basic information about data (projections, attributes, paths and so on) but also information about data quality, which determines the possible level of detail of analysis and the depth of results of analysis. Thus, the development of metadata has become an important step in most integrative research projects in the last years.

From the point of data quality, a main task in realising quality management is building up a consequent *metadata organisation*. These metadatasets, which describe the content of the 'normal' datasets, are the basis for further data processing and analysis.

As the basis of the metadata definition, the internationally well known Federal Geographic Data Committee (FGDC: defined a widely accepted and adopted standard for spatial metadata) standard was choosen and a database application built. This tool serves as the metadata management tool for all partners involved in the project (Fig. 3).

System development

The development of the information system concentrated on the following objectives (Fig. 4):

- Adaptability to the needs of different user groups, above all water suppliers, spatial planners, environmentalists and scientists.
- Conformity with the provisions of the European Water Framework Directive in respect to maps, plans and GIS usage.
- Ease-of-use for non-expert users.
- Integration of map data and its attributes with measurement data and statistical data in a variety of presentation forms.
- Analytical and modelling capabilities.
- Possibility for model implementation on the basis of the available information sets.
- Cartography and reporting.

Supporting decisions: decision-support systems (KATER II)

Basically, decision-support systems are computer-based systems, which help decision makers to make "optimal" decisions in uncertain decision environments.

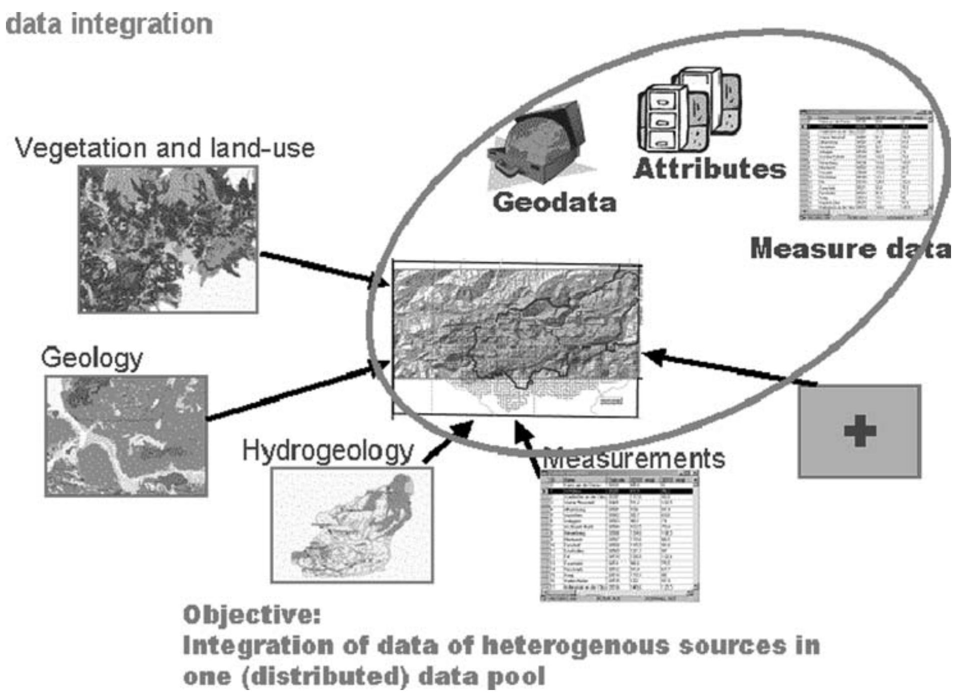


Fig. 2 Data integration

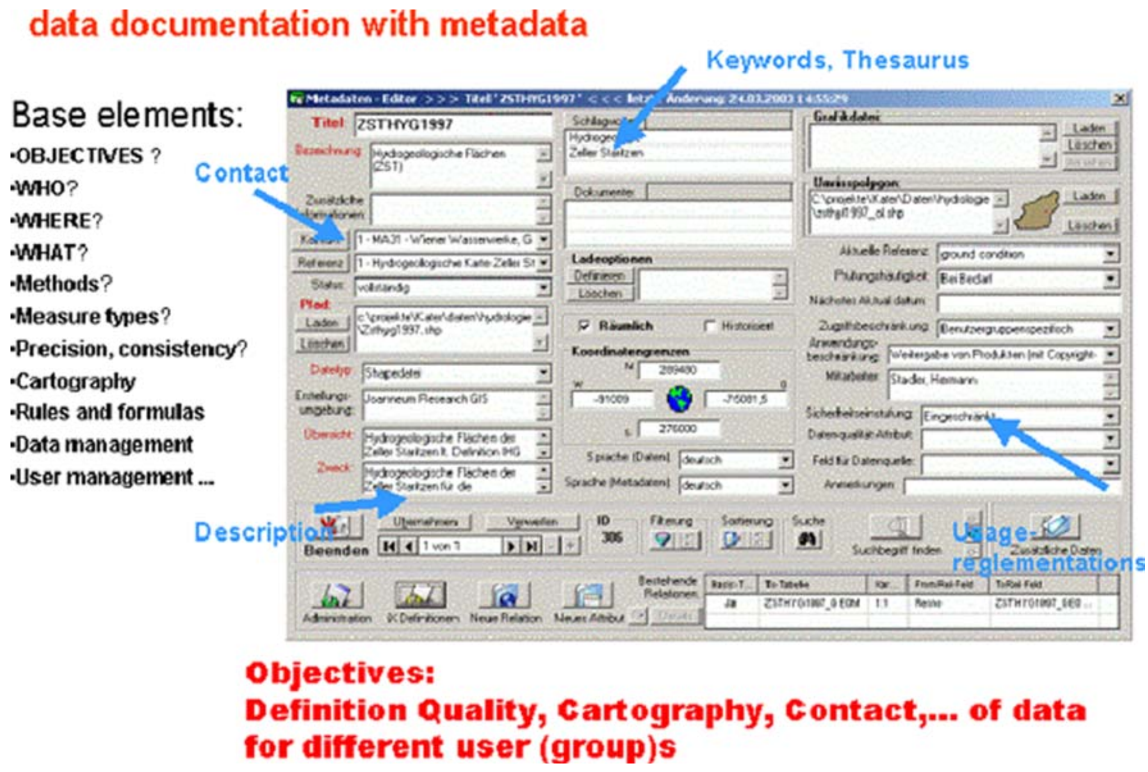
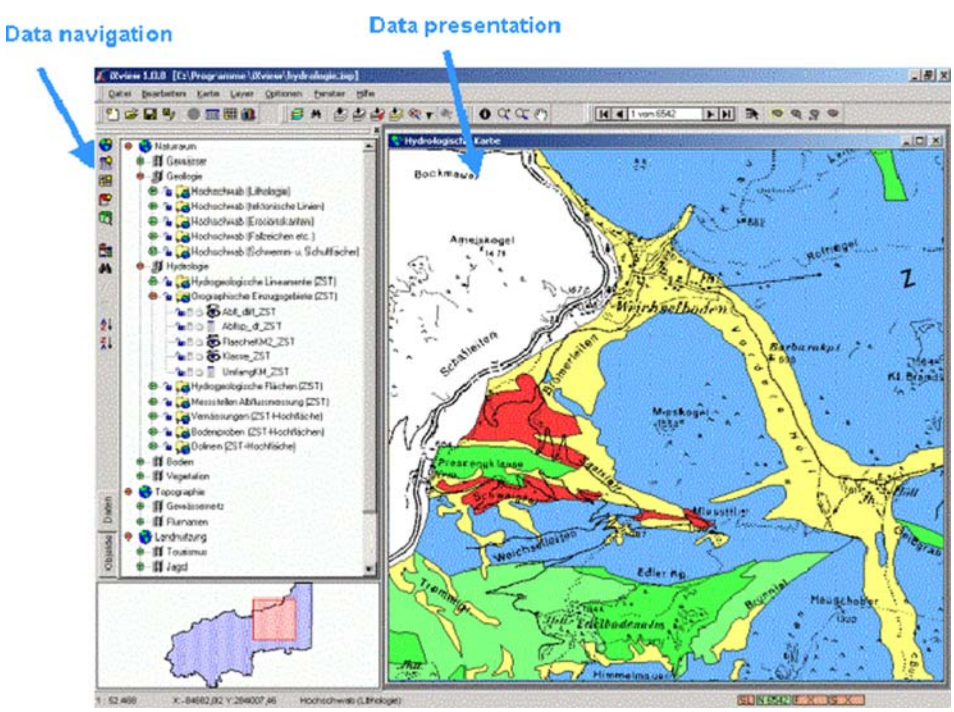


Fig. 3 Metadata example

Fig. 4 User interface system



They become a necessity when some of the following problems arise:

- Uncertain evaluation: lack of information, complexity of system,
- Number of criteria: conflicting objectives and interests,
- Heterogeneous solution possibilities,
- Trans-disciplinary and complex problem situation, which cannot be managed by single person or single group of persons,
- Fast decisions for complex problems.

Most of these problems are existing in the case of water management and can thus be supported by implementation of decision-support system.

The methodological basis for organising the decision process starts with the definition of basic functional roles in the decision-making process and the corresponding methodological, data and application requirements:

- Decision-maker,
- Analyst (“intermediary”, “translator”),
- Decision support system (DSS) builder (uses a DSS generator),
- Technical supporter (for the definition and integration of new elements into the system),
- Tool-smith (developer of the underlying technology).

These roles are not necessarily identical with persons—many persons may fill one role, one person may fill more than one role—but clearly show the organisation of functions and use of a DSS. The technological phases of the DSS may be defined as:

- Basic tools,
- DSS generator,
- Specific DSS (used by decision maker and/or analyst).

The development of the DSS will be based on the following steps:

- Definition of formal methods for the decision-making process, including multi-criteria decision-making and techniques of fuzzy evaluation;
- Formalisation of rules and guidelines which describe the complex interactions between land-use and water and environmental protection (knowledge-base);
- The system architecture of the decision-support system includes the following basic components:
  - Database and data models (DBMS)
  - Models for data retrieval, rules usage and analysis (EXPERT SYSTEM)
  - Evaluation methods (EVALUATION)
  - Presentation module with cartography and report generator (DISPLAY)
  - User interface;
- Reference will be made to sources of additional external data relevant to the decision-making process (natural disaster information systems, online early warning systems, etc.);
- System development for the defined user groups with attention paid to the following basic principles:
  - Use and support of (thematically and technically) relevant national and international standards
  - End-user friendliness

Fig. 5 Decision scheme

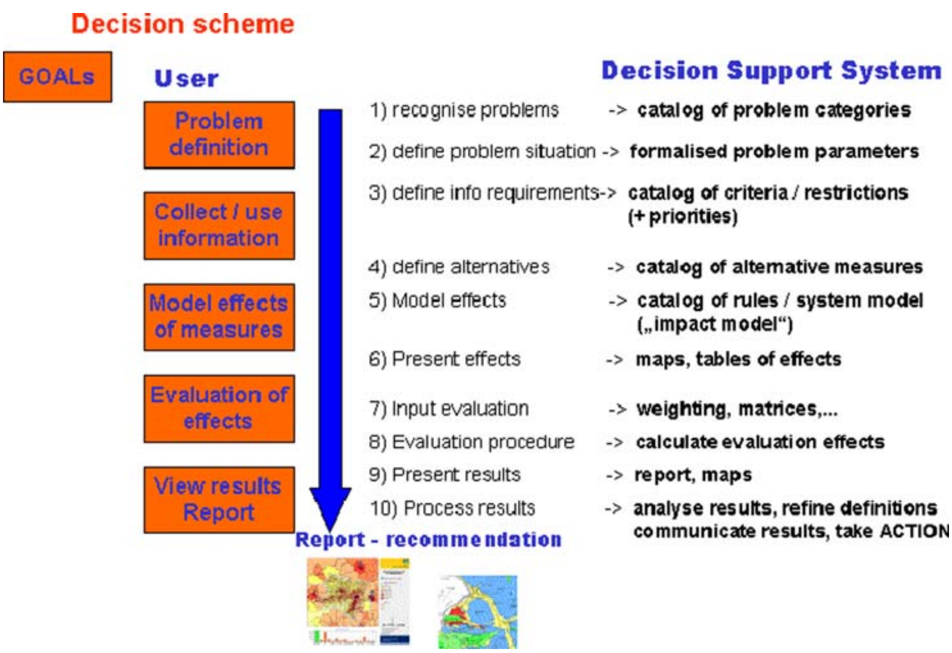


Fig. 6 Basic categories for evaluating land-use effects

Basic influence	Physical	Bacterio-logical	Chemical	Radiological
Intermediate	Vulnerability			
Target categories of effects	water quality + water quantity			

– Presentation and direct use of expert system (rules)
– Use of specifically adapted methods to define evaluation measures (fuzzy evaluation, ...)
– Extendable and easily deployable system development (component technology, web-based services, XML standard, etc.).

The following figure shows the basic scheme of a decision-making process and the possible use of a decision-support system on various stages of this process. It shows that support may be helpful not only when the actual decisions are taken but also in the previous stages of problem definition and information collection (Fig. 5).

Weighing factors: the example of land use activities

Starting with the results of efforts to enhance the scientific basis of water management and planning in the catchment areas of the Vienna waterworks [which includes data collection campaigns on vegetation (Grabherr et al. 1999) and on hydrology (Stadler and Strobl 1997)] additional detailed data about land-use turned out to be of importance.

The basic steps for the integration of land-use effects are:

- Evaluation of effects with regard to their influence on the water system and its vulnerability;

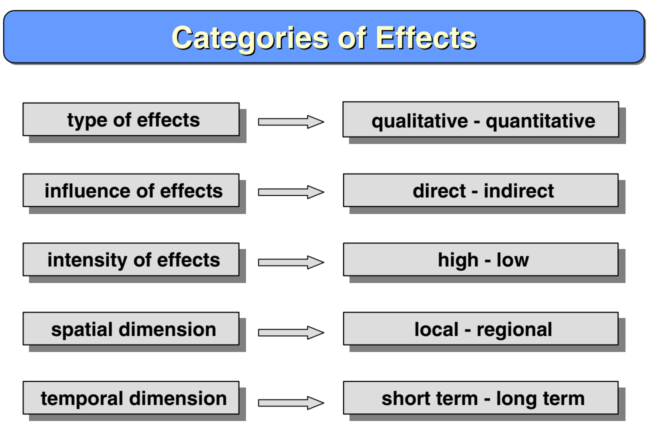


Fig. 7 Categories of effects

- An identification of possibilities/necessities for an implementation of land-use information in vulnerability models.

Vulnerability as a basic concept may be defined dependent/independent of the kind of contaminant/human activity (general vulnerability vs. specific vulnerability).

The objectives of including land-use data are to

- Identify potential influences (dangers) and to
- Gain additional control possibilities (Fig. 6).

When using this basic categorization as a starting point, it can be further differentiated between *direct influences* (e.g. contamination in bacteriological terms due to pasture) and *indirect influences* (increase of vulnerability due to soil changes/vegetation changes as effect of skiing). For the different land-use categories (or its subcategories, its up to the user to refine this categorization) thus the effects on the different levels can be identified and weighed (high/low weight; local/regional effect; short/medium/long-term effect) (Fig. 7): In more detail the effects of a certain land-use category can be demonstrated. The matrix form of presentation provides a valuable starting point for evaluation and analysis (Fig. 8).

This simple example shows how much thematic knowledge is necessary before formal procedures may be applied in the decision process. The definition of this knowledge base was actually started in the early 1990s and will be enhanced and formalised in the course of KATER II.

The formal methods applied for the decision-making process include multi-criteria decision-making and techniques of fuzzy evaluation. They are used to define a system of rules describing the concrete forms of impact of land-use activities (derived from an activity impact model) on the natural environment, as described in vulnerability models. This system of rules—the formalised knowledge base is the core of the decision-support system, which will help to make decisions and their potential impacts transparent as well integrative—bridging the gap between different institutions and experts involved in groundwater protection.

Fig. 8 Land-use effects: example of skiing

Effects in Land Use - Skiing

Categorization of Effects - Example

Land Use skiing	physical effects	chemical effects	bacteriological effects	(radiological effects)
skiing free	vegetation destruction	ski wax	faeces	
skiing lift	vegetation destruction soil erosion	ski wax	faeces	
slope preparation	vegetation destruction soil densification soil erosion	snow stabilisation chemicals fertilizer fuel and oil exhaust fumes		
lift infrastructure	vegetation destruction soil densification soil erosion reduction in slope stability	fuel and oil painting chemicals		
hotel and restaurant infrastructure	vegetation destruction soil sealing reduction in slope stability	endangering refuse cleaning chemicals painting chemicals	faeces grey water	

Outlook

The discussion above and the experiences of many transnational and international projects allow the definition of a list of basic steps on how to proceed in the development of a water management system. This list is by no means complete and it has to be considered that it still includes desiderata, which have not yet been delivered by the scientific community.

(a) A common language, to integrate the views on water issues of the diverse actors in the water management process, including scientific disciplines (e.g. hydrology), water authorities, planners and economists as well as people from technological disciplines (information processing...).
(b) Metadata have been proven to be of highest priority to make the results of any project and data collection process usable. The metadata issue is in many respects directly related to point (a).
(c) A multi-disciplinary approach has to be taken, to integrate the heterogeneous problem views of scientists, authorities, technicians and users.
(d) Decision-support systems have to be simple in use but allow the integration of a wide range of data (of very heterogeneous data quality) and presentation facilities with well developed functions.

The steps shown above do fulfil some of the tasks which are necessary in water supply and water protection. However, for more detailed analyses and an in-depth understanding of the underlying processes further steps will be taken:

- Spring monitoring concept;
- Further measurement campaigns to collect additional information about certain contaminants, like bacteriological contaminants;
- Measurement database with online-integration in the software application;
- Vulnerability model of karstic aquifers; for this purpose a flow-chart model will be developed, which allows for easy parameterisation of the model and easy extension of the model with new/enhanced datasets and model functions. The models available and used differ by country in Europe and include EPIK (Switzerland; Gogu et al. 1996; Stadler 2000) and Sintacs (Italy; Civita and De Maio 1997). The existing models provide starting points for decision support (in the modelling stage) and will be directly used and/or enhanced by some of the project partners. The adaptation of these models to specific problem situations will be facilitated by the developed tools.

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