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A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge

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ABSTRACT

This study reports the development of a new spatial multi-criteria decision analysis (SMCDA) software tool for selecting suitable sites for Managed Aquifer Recharge (MAR) systems. The new SMCDA software tool functions based on the combination of existing multi-criteria evaluation methods with modern decision analysis techniques. More specifically, non-compensatory screening, criteria standardization and weighting, and Analytical Hierarchy Process (AHP) have been combined with Weighted Linear Combination (WLC) and Ordered Weighted Averaging (OWA). This SMCDA tool may be implemented with a wide range of decision maker's preferences. The tool's user-friendly interface helps guide the decision maker through the sequential steps for site selection, those steps namely being constraint mapping, criteria hierarchy, criteria standardization and weighting, and criteria overlay. The tool offers some predetermined default criteria and standard methods to increase the trade-off between ease-of-use and efficiency. Integrated into ArcGIS, the tool has the advantage of using GIS tools for spatial analysis, and herein data may be processed and displayed. The tool is non-site specific, adaptive, and comprehensive, and may be applied to any type of site-selection problem. For demonstrating the robustness of the new tool, a case study was planned and executed at Algarve Region, Portugal. The efficiency of the SMCDA tool in the decision making process for selecting suitable sites for MAR was also demonstrated. Specific aspects of the tool such as built-in default criteria, explicit decision steps, and flexibility in choosing different options were key features, which benefited the study. The new SMCDA tool can be augmented by groundwater flow and transport modeling so as to achieve a more comprehensive approach to the selection process for the best locations of the MAR infiltration basins, as well as the locations of recovery wells and areas of groundwater protection. The new spatial multicriteria analysis tool has already been implemented within the GIS based Gabardine decision support system as an innovative MAR planning tool.

1. Introduction

In the field of Water Resources Planning and Management, managed aquifer recharge (MAR) is becoming an important solution for mitigating water scarcity related problems in arid and semi-arid areas. MAR has been practiced throughout the world for the recovery of groundwater levels, improvement of groundwater quality, storage of surface water in the sub-surface, and as a barrier to salinity intrusion. Depending on the water source, water quality, geology, surface conditions, soils, and hydrogeology, a variety of methods have been developed to recharge groundwater (Bouwer, 2002). The spreading basin technique (infiltration) is widely practiced and is useful in areas with high land availability, highly permeable soil, and where the hydrogeology allows for infiltration to an unconfined aquifer (Ghayoumian et al., 2005). Other MAR techniques employing injection wells require less area but a better quality of source water due to the fact that the water is directly injected into the aquifer without taking advantage of natural attenuation processes within the vadose zone. The interdependency of the water quality,

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MAR location, and technology makes project planning multifaceted and complex.

Many factors need to be considered during the site selection process for MAR projects. Complex regional characteristics, heterogeneities in surface and/or subsurface characteristics, and variable groundwater qualities make site selection for MAR difficult (Anbazhagan et al., 2005). Apart from these hydrogeological considerations, other factors such as political and social factors are important in the decision-making process. National and international water policies, natural conservation regulations, environmental impact assessments, and socio-economic considerations make the site selection procedure complex. Complexity increases when MAR project managers are from different disciplinary backgrounds; this may often lead to disagreements concerning which criteria to give more weight in the decision-making process. These conflicts always need to be dealt before the MAR project is implemented. GIS and the traditional Decision Support Systems (DSS) alone do not effectively facilitate the implementation of MAR project parameters, which are equally based on complex decision criteria and spatial information (Jun, 2000). GIS based analysis methods are poor in dealing with uncertainty, risks, and potential conflicts; therefore, there is a large possibility of losing important information, which in turn may lead to a poor decision (Bailey et al., 2003). Multi-Criteria Decision Analysis (MCDA) integrated into GIS (SMCDA) provide adequate solution procedures to this problem because the analysis of potential MAR projects may be done more comprehensively and at a lower cost. Variable project sites, risks, MAR techniques, policies, and limits in geological as well as social, environmental, and political realms can easily be considered by the Spatial Multi-Criteria Decision Analysis (SMCDA) approach (Calijuri et al., 2004).

MCDA is helpful in identifying priorities for a given MAR project (Gomes and Lins, 2002). The integration of MCDA techniques with GIS has considerably advanced the traditional map overlay approaches for site suitability analysis (e.g. Malczewski, 1996; Eastman, 1997). MCDA procedures utilize geographical data, consider the user's preferences, manipulate data, and set preferences according to specified decision rules (Malczewski, 2004). The advantage of integrating GIS with MCDA has been elaborated by many authors (e.g. Malczewski, 1996; Jun, 2000; Gomes and Lins, 2002; Sharifi and Retsios, 2004). According to Malczewski (2004), the two critical considerations for SMCDA are: (i) the GIS capabilities of data acquisition, storage, retrieval, manipulation, and analysis; and (ii) the MCDA capabilities for combining the geographical data and the manager's preference into unidimensional values of alternative decisions. A number of methodologies have already been developed for SMCDA in different fields of science and engineering to select the best alternatives from a set of competing options (e.g. Sharifi et al., 2006; Zucca et al., 2007).

The overlay MCDA plays an important role in many GIS applications. Boolean logic and Weighted Linear Combination (WLC) are the most popular decision rules in GIS (e.g. Eastman, 1997; Malczewski and Rinner, 2005) and both can be generalized within the scope of Ordered Weighted Averaging (OWA) (e.g. Malczewski and Rinner, 2005; Malczewski, 2006). In OWA, a number of decision strategy maps can be generated by changing the ordered weights. Several OWA applications have been implemented already (e.g. Rinner and Malczewski, 2002; Calijuri et al., 2004; Malczewski et al., 2003; Malczewski, 2006). The Analytical Hierarchy Process (AHP), proposed by Saaty (1980), is another well-known procedure. This procedure is important for spatial decision problems with a large number of criteria (Eastman et al., 1993). AHP can be used to combine the priorities for all levels of a "criteria tree," including the level representing criteria. In this case, a relatively small number of criteria can be evaluated (Jankowski and Richard, 1994; Boroushaki and Malczewski, 2008). The combination of AHP with WLC and/or OWA can provide a more effective and robust MCDA tool for spatial decision problems. Boroushaki and Malczewski (2008) implemented AHP-OWA operators using fuzzy linguistic quantifiers in the GIS environment, which has been proven to be effective.

An intensive review of the respective literature has indicated that the modern and updated analysis techniques as GIS and MCDA have not been well investigated and compiled in the field of MAR site selection (see the following section for details). In this respect, a structured, non-site specific and flexible decision analysis tool has been developed. In this study, a methodology has been settled up to support the identification of suitable sites by combining modern spatial multi-criteria analysis techniques with decision analysis methods. As consequence, a new tool has been developed to offer the following:

- A comprehensive framework consisting of AHP, WLC, and OWA analysis techniques for spatial multi criteria analysis for MAR site selection.
- A wide range of flexibility and preferences for criteria selection, standardization, and weighting.
- An interactive user interface, which offers the standard techniques and leads the user systematically to complete the site selection process.

This paper includes a review on MAR site selection techniques and may be read at any time as needed for reference purposes (section 2). Section 3 is a description of SMCDA for site suitability analysis and also information on how AHP, suitability mapping, and weighting are involved in the analysis. A brief description on possible sensitivity analysis is done the presentation of a *GIS Based Site Suitability Analysis Tool in* Section 4. This section together with Section 3 provides distinctive information to MAR site selection. The two sections together are considered to embody the core objective of this paper, which is to explain the development and functionality of a new SMCDA tool for MAR site selection. Section 5 presents the concepts described in Sections 3 and 4 as applied in the field. The case study presented in Section 5 refers to a MAR site selection. It has been developed on the Querenca-Silves aquifer system in Portugal. Section 6 provides a summary of conclusions and recommendations in the scope of future applications and further developments.

2. The state-of-the-art: MAR site selection techniques

Only very few studies exist which focus on site selection procedures for Managed Aquifer Recharge (MAR). Respectively, the following three sections differentiate data types (section 2.1), present data processing via GIS (section 2.2), and give reference to the steps involved in site suitability analysis methods (section 2.3) for example, screening of sites, criteria hierarchy and standardization, criteria weighting, overlay, and sensitivity analysis. The three parts of this chapter are intended to serve as a reference for the basic methods which have been integrated into the SMCDA tool for site suitability analysis of MAR.

2.1. Data types

For MAR site selection, different types of data are required. Considerations for data type selection derive from data availability and the objective of the analysis as dependent on each data type. Geological maps, geomorphologic maps, lineament maps (e.g. Saraf and Choudhury, 1998; Jothiprakash et al., 2003; Reddy and Pratap, 2006), slope, infiltration rate (e.g. Ghayoumian et al., 2005; Werz et al., 2009), lineament density, structure, fluvial and denudational geomorphology (e.g. Anbazhagan et al., 2005; Shankar and Mohan, 2005; Chowdhury et al., 2010,), soil texture (e.g. Kalantari et al., 2010; Jothiprakash et al., 2003), and land use (e.g. Brown et al., 2008; Reddy and Pratap, 2006; Ghayoumian et al., 2007) have been used to provide detailed quantification of surface characteristics. Infiltration rate, transmissivity (e.g. Ghayoumian et al., 2005; Brown et al., 2008), borehole recharge capacity, borehole abstraction capacity, and recharge retention time (Anderson et al., 2005), have been used to quantify subsurface characteristics. Groundwater quality data is usually not paid any attention as being important for site selection (Brown et al., 2008; Ghayoumian et al., 2007; Chowdhury et al., 2010), although it should be due to the nature of MAR as being often involved with water storage and recovery. In addition to surface and sub-surface characteristics, Brown et al. (2008) considered ecological status, road density, power lines, proximity to a water source, and groundwater pollution among other parameters. Wood (1980) considered the possibility of aquifer plugging. Legal aspects together with cost-benefit analyses should also rank among important considerations (O'Hare, 1986). A comprehensive combination of all of these input considerations, however, is absent from the literature of MAR project site characterization.

2.2. Data processing

The quantity of spatial data needed to collect, integrate and analyze for MAR project site evaluation is very large and the application of traditional data processing methods for site selection can be very complex and tedious (Anbazhagan et al., 2005). In groundwater management studies, land use suitability mapping and other geographical research, GIS and remote sensing technology have been used separately or in combination to process, integrate, and analyze spatial data (e.g. Krishnamurthy et al., 1996). Use of GIS and remote sensing is also commonly used for MAR site selection studies (e.g. Saraf and Choudhury, 1998; Brown et al., 2008; Ghayoumian et al., 2007; Werz et al., 2009). Anderson et al. (2005) used the mathematical functions implemented in GIS together with spatial analysis operations to calculate retention time and recharge capacity of an aquifer over a wide spatial distribution.

2.3. Site suitability analysis methods

In general, the site suitability analysis follows the path: screening of feasible areas → classification of thematic layers → weighting of the criteria → overlaying.

Only few studies have concentrated on screening-out the areas where MAR is actually non-feasible (e.g. Anane et al., 2008; Brown et al., 2008; Ghayoumian et al., 2007). Boolean logic is usually used to demarcate feasible and non-feasible areas. Studies mostly concentrate on classifying maps according to relative importance. Each thematic map is classified according to importance of the respectively represented parameters. Linguistic classifiers, such as *very good*, *good*, *suitable*, etc. (e.g. Jothiprakash et al., 2003; Ghayoumian et al., 2005) and value type classifiers such as class 1 to class 4 are implemented in these studies (e.g. Ghayoumian et al., 2007). Step-wise functions are used in different studies in order to standardize thematic maps for aggregation. Ghayoumian et al. (2007) uses membership functions for map standardization. No linear or piece-wise linear function is used in any study for MAR site selection.

Weighting of each criterion is an important factor for spatial multi-criteria analysis. Direct weighting after consultation with experts has mostly been used (e.g. Saraf and Choudhury, 1998; Brown et al., 2008). The Analytical Hierarchy Process (AHP), introduced by Saaty (1980), has been recently used by Chowdhury et al. (2010). The advantage of AHP in site selection or spatial multi-criteria analysis is well established (e.g. Jun, 2000; Sharifi et al., 2006) and is therefore implemented in the new tool presented in this report (see section 3.3 B).

The most important step for site selection is map overlay. Conventional overlay methods (e.g. Weighted Linear Combination (WLC)) have been practiced in most of the studies for MAR site selection (e.g. Saraf and Choudhury, 1998). Kallali et al. (2007) used Boolean logic for combining maps. Normal successive intersection of the thematic maps has been used, too (e.g. Jothiprakash et al., 2003). The Ordered Weighted Averaging (OWA) method has not been implemented in any study. It is important to note that combination of AHP-WLC or AHP-OWA has yet to be implemented and is thus presented for the first time in this report (see Chapter 3). Ghayoumian et al. (2005) briefly mentioned the integration of DSS and GIS for MAR site selection, but no special considerations for DSS decision rules or technological descriptions were provided. A spatial knowledge-based decision analysis system for pond site selection has been reported by Shrier et al. (2008). The authors coupled spreadsheet software that facilitates rule processing, with GIS to display spatial data.

Site suitability analysis for MAR is like most other site suitability analyses, but the methods which are best applied are being applied in a unique combination. The advantage of SMCDA has not been properly and fully utilized in this field. This report presents all the data types and data processing techniques needed for MAR site assessment as well as the familiar yet unique procedure to do so. Also, MAR is a developing field but also has a long and fragmented history. This report is a breakthrough for the field of MAR in the respect that state-of-the art analysis techniques are being compiled and applied in this field and finally more work is being done to ensure the continued implementation of MAR with decreased uncertainty, as demonstrated in the entirety of this paper. This report presents for the first time an interactive non-site specific decision tool for MAR site selection.

3. The spatial multi-criteria decision support method for site suitability analysis

The overall methodology of the new site selection tool is shown in Fig. 1. This flowchart shows the main decision steps which are implemented for spatial analysis. In general, the entire process involves three main steps: (a) constraint mapping, (b) suitability mapping, and (c) sensitivity analysis. After preparing the constraint map, AHP is combined with WLC and OWA for the suitability mapping, which is based on standardized subcriteria. The function of AHP is threefold: (1) developing the hierarchy after the selection of criteria (2) doing a pair-wise comparison to assess criteria importance and (3) undergoing construction of the overall composite weight (global weight). Afterward, WLC or OWA operators are used for the final suitability map. These steps, following the MAR problem statement, are described in greater depth below:

3.1. Problem statement

In water resources management, MAR has proven to be an effective response to water scarcity problems. MAR is helpful for the recovery of groundwater levels, the improvement of groundwater quality, and for storage of water and as a barrier against salinity intrusion. The selection of suitable locations for MAR

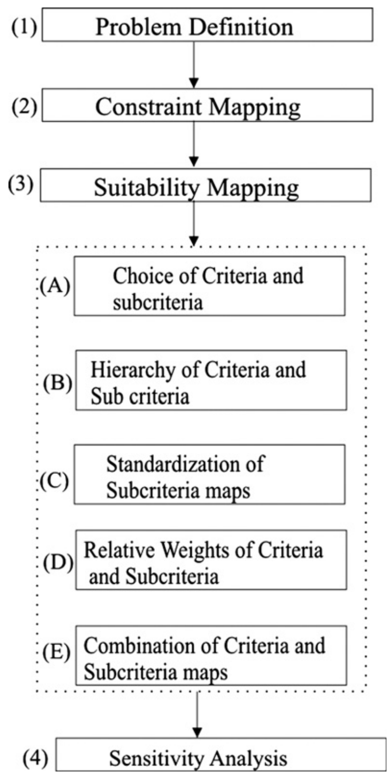

Fig. 1. The procedure for MAR site suitability mapping.

implementation based on proper technologies is one of the primary requirements.

3.2. Constraint mapping

The main objective of constraint mapping is to screen out a large number of alternatives which have been deemed as being non-feasible. This step helps the user to avoid conflicts in decision-making. The sites which are of prime interest to other planning projects or which are simply not available or completely non-feasible for MAR implementation are screened out in this step. A conjunctive screening approach was chosen for constraint mapping. Under conjunctive screening, an alternative is accepted if it meets specified thresholds for all evaluation criteria. Fig. 2 shows the general procedure for constraint mapping. The developed constraint map serves as a mask for suitability mapping.

3.3. Suitability mapping

(A) Choice of criteria and sub-criteria

In this step, all relevant surface, subsurface, and regional characteristics are selected. Each characteristic is defined as a sub-criterion. The sub-criteria are grouped under the main criteria. The combined main criteria are the “suitability map,” which is the goal of the SMCDA.

(B) Hierarchy of criteria and sub-criteria

The role of AHP begins at this step. This step involves the decomposition of the ultimate goal into a three-level hierarchy

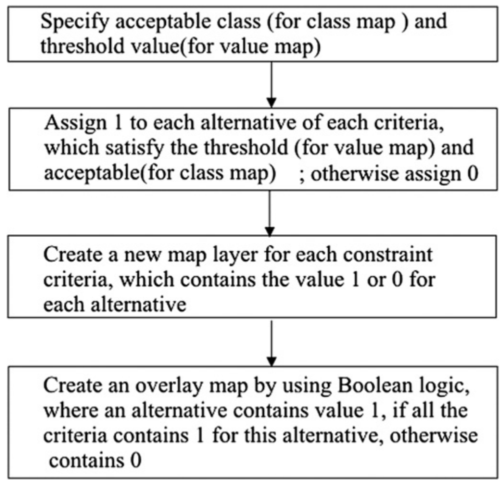

Fig. 2. Flow chart for constraint mapping.

consisting of sub-criteria of the goal. The top of the hierarchy is the goal of the analysis/problem. The middle level contains more specific criteria with regards to the objective and the bottom level refers to the most specific criteria. The sub-criteria in the lowest level are related to the main criteria in the middle level, while the top level relates to the “suitability map” (see Fig. 12). The sub-criteria are represented by thematic maps or attributes. The tool’s user-interface allows the user to construct the hierarchy or “criteria tree.”

(C) Standardization of sub-criteria maps

Each sub-criterion in the criteria tree is represented by a map of different types such as a classified map (e.g. land use) or a value map (e.g. slope, infiltration). For decision analysis, the values and classes of all the maps should be converted to a common scale to reduce the dimensionality. Such conversion is called standardization (Sharifi and Retsios, 2004). Different standardization methods may be applied to different maps. This model offers linear, piecewise linear, and step functions for standardization. The outcome of the function is always a value between 0 and 1. The function is chosen in such a way that cells in a map that are highly suitable for achieving the goal obtain high standardized values and less suitable grids obtain low values.

(D) Relative weights of criteria and sub-criteria

The next step in the site selection procedure is assigning values of importance for all criteria and sub-criteria, which is done by assigning a weight to each criterion. Different weighting methods are available. Pair-wise comparison and direct weighting are used here. The sub-criteria under each main criterion are compared amongst themselves and a weight is assigned to each one. The main criteria are also evaluated in this way.

(E) Combination of criteria and sub-criteria maps

After standardization and weighting, the next step is to obtain the overall suitability index of each alternative. The index value is given to the cells of the map. Overlay methods available are WLC and OWA with fuzzy linguistic quantifiers. WLC is the most simple and the most commonly used aggregation method in spatial analysis (Eastman et al., 1993).

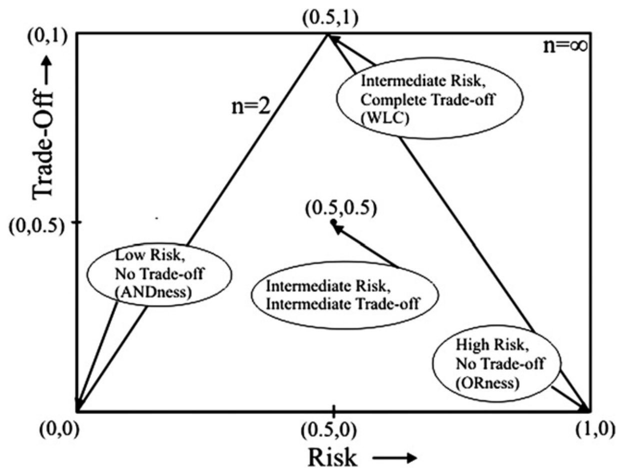

Fig. 3. The decision strategy space showing relation between trade-off and risk, n is the number of criteria (modified after Eastman, 2000; Malczewski, 2006).

$$\text{WLC,} \quad S(x_i) = \sum w_i \cdot s_i(x_i) \tag{1}$$

w_i = normalised weight; $\Sigma w_i = 1$; s_i (x_i) = standardized criteria function/map.

OWA is a class of multicriteria combination operators, involving two sets of criteria weights, which are "criteria importance weight" and "ordered weight" (Yager, 1988). The concept of fuzzy linguistic quantifiers, introduced by Zadeh (1983), allows the conversion of natural language statements into proper mathematical formulation (Munda, 1995). In this study, the regular increasing monotone quantifier class was considered. Given the criteria weights, w_i, the quantifier-guided OWA can be defined as follows (Boroushaki and Malczewski, 2008):

$$\text{OWA}_{(i)} = \sum_{j=1}^{n} \left(\left(\sum_{k=1}^{j} u_k \right)^{\alpha} - \left(\sum_{k=1}^{j-1} u_k \right)^{\alpha} \right) z_{ij} \tag{2}$$

z_{ij} = weighted attribute value; α = parameter for linguistic quantifier; u_k = criteria weight reordered according to z_{ij}; j = number of criteria.

OWA allows for a high degree of input variability and for the trade-off of importance among input variables (Fig. 3). When $\alpha = 0$ (linguistic quantifier categorized as "*at least one criterion satisfies*"), the result yields no trade-off and full ORness; when $\alpha = \infty$ (linguistic quantifier categorized as "*all criteria satisfy*"), the result yields no trade-off and full ANDness. Using α value between 0 to ∞, yields a range of MCE operators in the decision strategy space. When $\alpha = 1$ (linguistic quantifier is categorized as "*half of the criteria satisfy*"), the results yields the full trade-off (WLC) (Fig. 3).

The detailed description of AHP combination with OWA is given by Boroushaki and Malczewski (2008).

3.4. Sensitivity analysis

A sensitivity analysis may be undertaken by the user in order to study the robustness of the suitability map with respect to the linguistic quantifier (α). The new SMCDA tool also permits assessment of site suitability as respective to the influence of the application of different weighting schemes and standardization. In this respect, sensitivity analyses are useful where uncertainty exists in the construction of hierarchy and in the assignment of relative importance (Store and Kangas, 2001).

4. GIS based site suitability analysis tool

4.1. Overall system framework

The site suitability analysis tool extension is tightly integrated in the ArcMap environment. This instrument is developed as an ArcMap extension, using ArcObjects and VB.Net. ArcObjects is a developer kit for ArcGIS based on Component Object Model (COM). This solution considerably extends the functionalities of ArcMap by implementing the MCDA within the GIS environment by allowing the developer to combine the advantages given by the user interface controls available in the .Net framework with the GIS functionality included with ArcGIS (ESRI). The advantages of customized components by using a COM-Compliant environment such as Visual Studio 2005 are: (1) a wider range of functionalities can be integrated into customization, (2) codes are not accessible by the user, (3) all aspects of ArcGIS application can be used further, extended, and customized, (4) the customization can be easily supplied to the client machines (ESRI, 2004; Boroushaki and Malczewski, 2008). Fig. 4 shows the overall system development.

The model has been incorporated into the table of contents of ArcGIS as the "Site Selection" option. By activating the tab, the user can access the main steps of the site selection instruments: "Constraint Mapping," "Site Suitability Mapping," and "Site Ranking." Further options related to each main step (Fig. 5) derive from this one.

The supporting database structure is an ArcGIS Personal Geodatabase (ESRI). The geodatabase can store, beside the geographical data, data behavior rules such as domains, relationship classes, and custom behavior. The geodatabase management module is composed of two sections: (i) Data Input/Output and (ii) Spatial/Time dependent query and visualization. The geodatabase management module focuses on designing the user screens, so these match the different sections of the data model. This component includes the following subcomponents:

- Data access subcomponent, which contains functions for database connection, data reading, and database update.
- Data model objects, which are used for storing the data in memory while the application is running. These data model

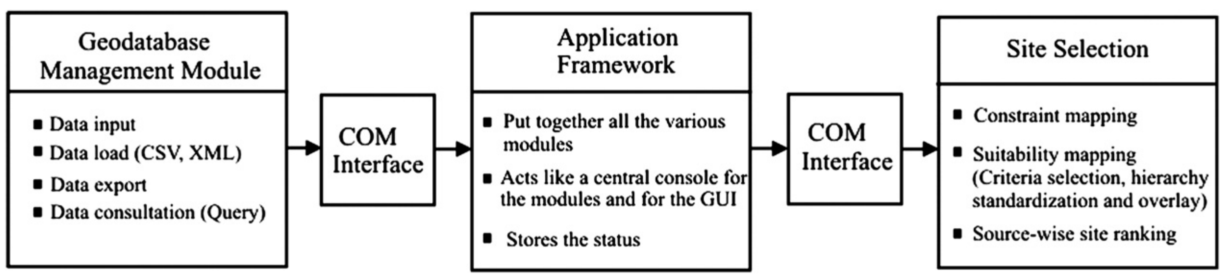

Fig. 4. Structure of the site selection tool developed in the ArcGIS environment.

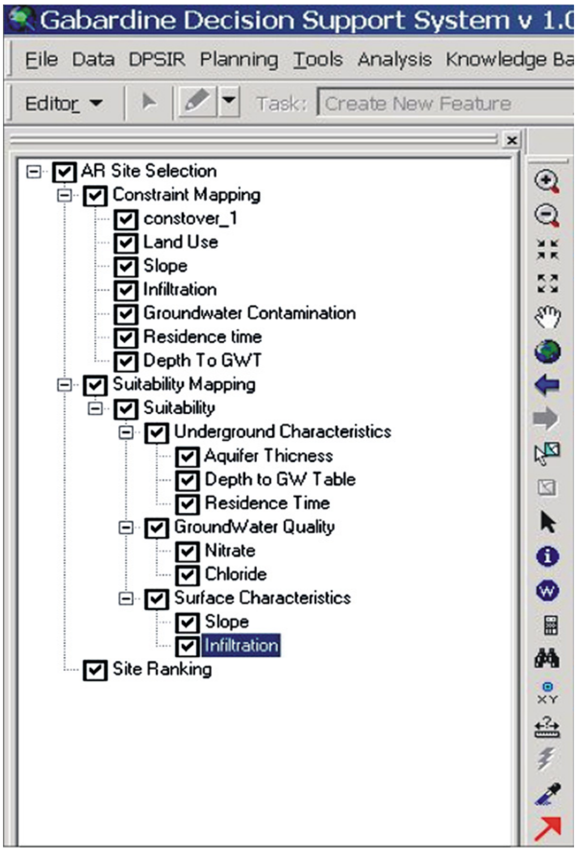

Fig. 5. Exemplary table of contents in ArcGIS Display for the site suitability analysis, incorporated to Gabardine DSS.

objects abstract the feature classes and the tables in the geodatabase and mimic the relationships between them.

- Interface components, which include the user screens that provide user access to the data stored in the data model objects. The user can input data through a list of standard user interface controls, such as text boxes, combo boxes, data grids, etc.

The personal geodatabase format was considered suitable for the scale of the current application; however, the format can be easily upgraded for further developments to an ArcSDE (ESRI) geodatabase. The ArcSDE allows connecting ArcGIS and the Site Suitability Analysis Tool interface to future database versions developed using other Spatial Relational Database Management System (RDBMS) software like Oracle, SQLServer, IBM-DB2, and others.

4.2. Site suitability mapping

This first step offers default criteria for choosing and selecting the corresponding raster map to generate a constraint map. The default constraint criteria have been selected after a close discussion within a consortium consisting of a number of international experts from different organisations (e.g. LNEC – National Laboratory for Civil Engineering, Portugal; University of Liege, Belgium; EWRE – Environmental & Water Resources Engineering Limited, Israel; University of Nottingham, UK; PHG – Palestine Hydrology Group, Palestine; GeohidroConsult, Romania; University of Goettingen, Germany, etc.). Moreover, new constraint criteria may be added by the user (Fig. 6). Both value type and class type map can be handled by the system. The user defines the threshold value for value type criteria and to each class of the class type map; the user may assign a zero for a non-potential area or a one for a potential area. The system then creates a constraint map of each sub-criteria separately. Afterwards, the maps may be overlain and one constraint map may be prepared with Boolean logic. The constraint maps are added to the ArcGIS document and can be used for further analysis.

Site suitability mapping starts with the preparation of a hierarchical structure, which is performed by selecting criteria and sub-criteria for each level. The user selects the criteria from the default list. The default criteria are prepared, considering all relevant characteristics that should be included for the spatial analysis. Special care has been given to avoid any duplication of the criteria/sub-criteria. New criteria or sub-criteria can also be easily added via the user-interface. The user can visualize the hierarchical structure and edit for presentation and reporting purposes. The standardization process follows the building of hierarchy. The user selects the criteria, the constraint map, the threshold values, and the preferred standardization function. For a better visualization, the converted function is drawn graphically in the interface (Fig. 7). The overlay command of the criteria tree proceeds to the step of weighting and overlay. The system offers the pair-wise comparison and the direct weighting methods. The weights of each criterion in each level can be given directly or can be generated by the pair-wise comparison

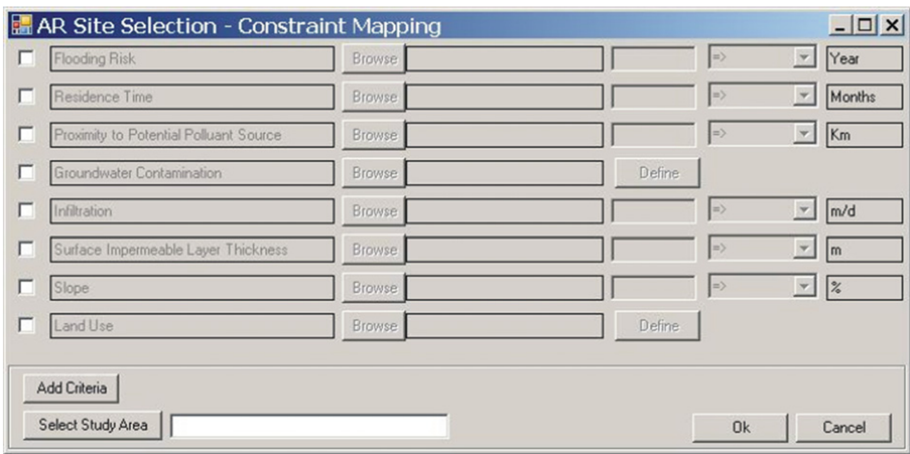

Fig. 6. Interface to select constraint criteria and assign the threshold value.

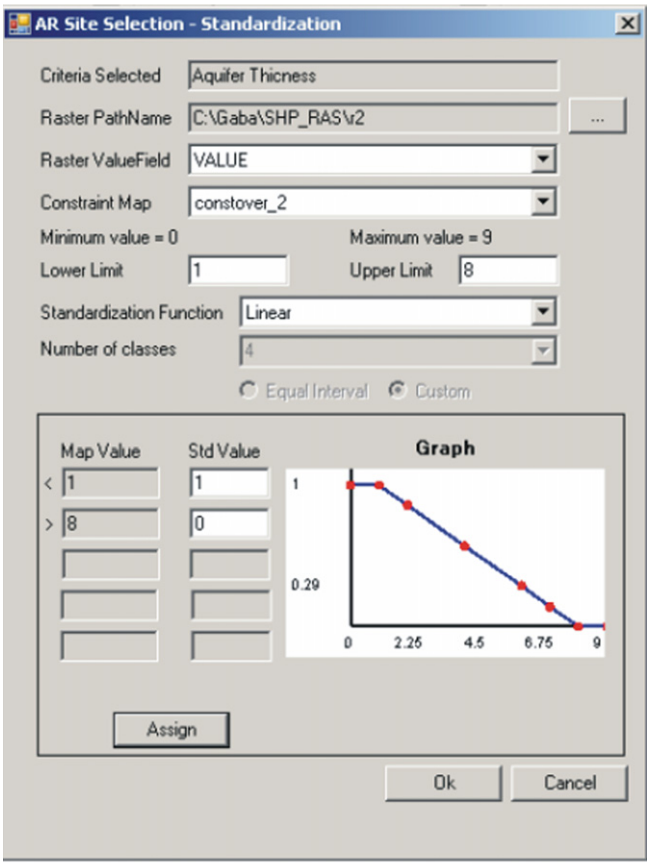

Fig. 7. Standardization procedure.

method. In the pair-wise comparison method, the user can input preferred values using a scale bar. The weights are generated using the specified formula by Saaty (1980).

After finishing the weighting procedure, the user reaches the final steps of the site suitability mapping (Fig. 8). The user chooses an overlay procedure, either WLC or OWA. In the OWA procedure, the linguistic quantifiers are assigned to each level of overlay. The resulting map is then created and shown in ArcGIS format. The role of the AHP function is the construction of a criteria tree as well as to calculate the relative weights of the criteria and of the sub-criteria by pair-wise comparison. After applying the AHP, the WLC or OWA are used. WLC computes the overall suitability for each alternative or cells using the standardized map, weights, and constraint map. OWA produces the suitability maps by specifying the linguistic quantifier (a set of ordered weights are generated, which are related to α; the generated values for each alternative are combined).

By changing the weights of each overlay method and of the linguistic quantifier associated with the objectives and attributes for OWA, a wide range of decision scenarios can be generated and the corresponding map layers are added to the map document. This helps to check the sensitivity of the system with changing weights and linguistic quantifiers.

Areas on the suitability map can be classified as very good, good, moderate, poor, and bad. The system offers five different colours for the five classes (Fig. 8), taking into account the colour code for ecological status classification proposed by the Water Framework Directive (WFD) (Water Framework Directive, 2003). The user has the opportunity to change the range of class manually.

The third step is a spatial analysis of the optimal MAR locations with respect to water source locations. In a user-defined buffer zone spatial query, the most favorable MAR locations based on proximity to water source are chosen. The result is a raster map, which shows the optimal MAR locations that satisfy the user chosen distance to proximal potential sources of water.

5. A case study

5.1. Problem description

Due to the geographical location, the Algarve region in southern Portugal is prone for experiencing droughts, and the region has been affected by many droughts over the last few decades. The hydrological year of 2004/2005 was extremely dry in the entire Portuguese mainland and especially in the Algarve region. The drought caused severe problems, considering the availability of water resources. Surface water reservoirs reached volumes that were below acceptable levels, and the Querença-Silves aquifer system was over-exploited (Fig. 9). The Querença -Silves aquifer system was a major source of drinking water to the urban areas within the Algarve region, during the 90's. Today the Funcho Dam is

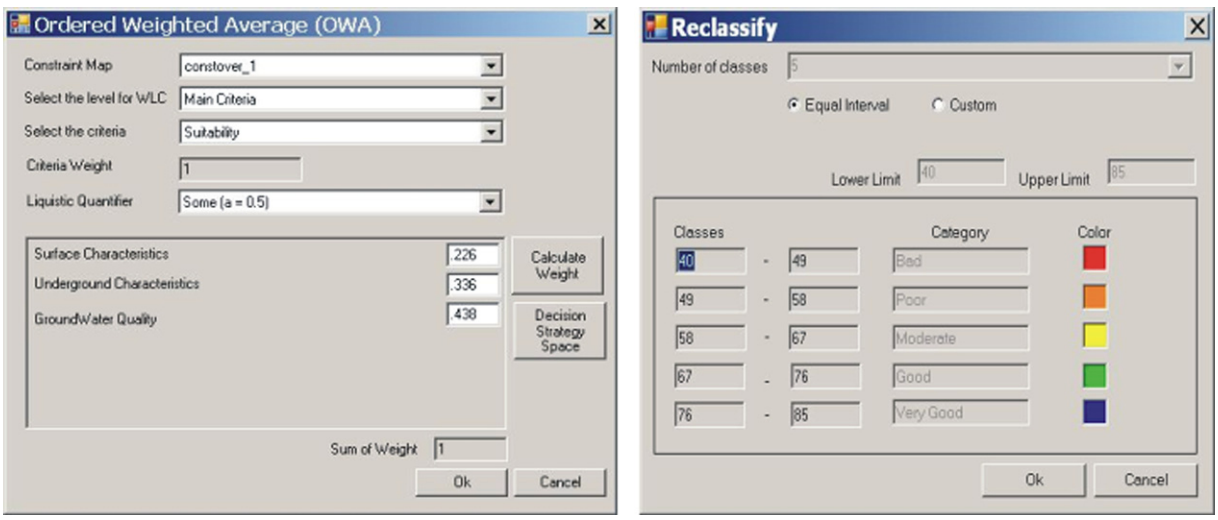

Fig. 8. The overlay for the suitability analysis (left) and the reclassification step of the suitability map (right).

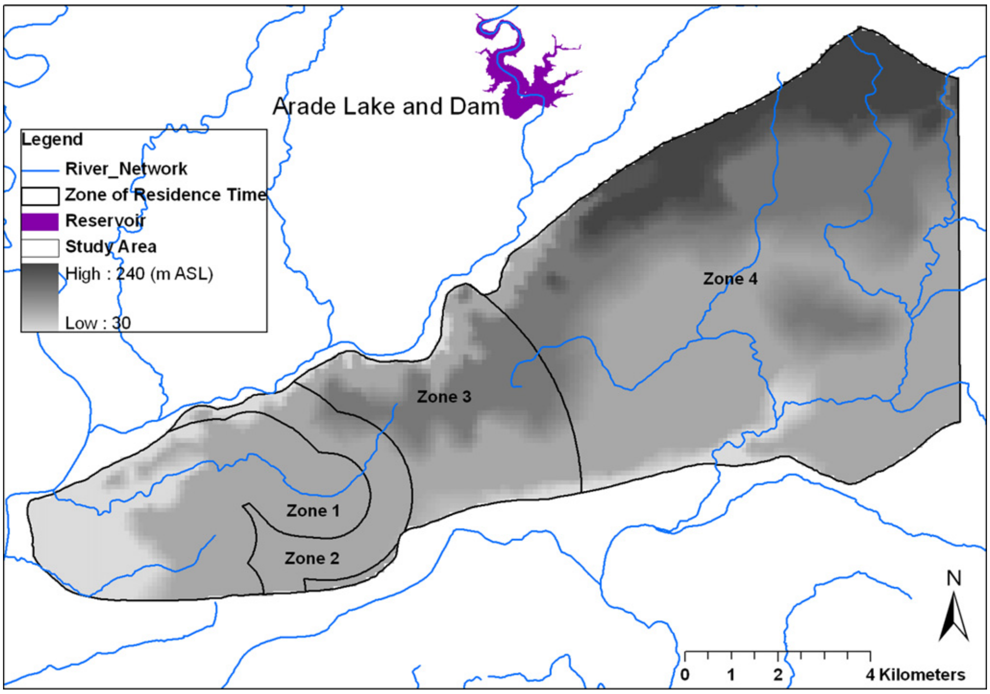

Fig. 9. Study area (Querença-Silves Aquifer) map showing the elevation (in m ASL).

considered to be the most important drinking water source in the western part of the Algarve. Another dam, the Arade Dam is located downstream of Funcho Dam in the Arade river. More than 50 hm^3 of river water was lost to the sea during the wet hydrological year of 2000/2001, and in dry hydrological year of 2004/2005 there was an equivalent shortage of water resources (54 hm^3). (Lobo-Ferreira and Oliveira, 2007). MAR is considered as a potential strategy to store water during the wet years and use it during dry years. The overall planning and management of MAR consists of: selection of water source, location of infiltration basin, and location for recovery of the infiltrated water. This study focuses on suitability mapping for the implementation of infiltration ponds for aquifer recharge.

5.2. General characteristics of the test site

The Querença-Silves Aquifer System is a 318 km^2 aquifer system, the largest of the Algarve, located in the municipalities of Silves, Loulé, Lagoa and Albufeira (Central Algarve). The aquifer is mainly composed by karstified Lower Jurassic (Lias-Dogger) dolomite structures. The southwestern part of the aquifer is mainly unconfined. The general groundwater flow direction is from Northeast to Southwest. According to the characterization of the Querença-Silves aquifer system (Almeida et al., 2000), the hydraulic parameters are heterogeneous and aquifer productivity values are high. The transmissivity values range between 83 and 30,000 m^2/day and the storage coefficient ranges from 5×10^{-3} to 3×10^{-2}. INAG (2001) presents the recharge value as being 220 ± 54 mm/year. This represents a percentage of precipitation of around $40 \pm 10\%$. Monteiro (2005) obtained an average recharge of 292.5 mm/year. These are average values using the average precipitation values in the area, therefore when the precipitation is much smaller (e.g. the hydrological year of 2004/2005, when precipitation was more than half the average) the recharge is also much lower.

Analyzing 69 wells of the aquifer for the year 2002, a withdrawal rate of 19.5 mm/year was computed as being possible to meet the water demand of Silves, Lagoa, Albufeira and Loulé. This value was higher during the drought years of 2004–2005.

In this study, only the southwestern part of the Querença-Silves Aquifer is being taken into account due to geology and aquifer properties. The groundwater catchment area is 114 km^2. For analysis purposes, the study area has been divided into four zones (Fig. 9), according to the residence time of groundwater in the aquifer. These are: Zone I (residence time is less than 6 months), Zone II (residence time is 6 months to 1 year), Zone III (residence time is 1 year to 3 years) and Zone IV (residence time is greater than 3 years). These zones are overlain in each constraint and suitability map so as to assess suitable MAR sites according to the residence time zonation. Results of GIS analysis and of groundwater modeling have been used as spatial input information for MAR site selection procedure.

5.3. Selection of criteria for spatial analysis

After discussion with local and international experts and institutions and under the prevailing site characteristics and study objectives, two different sets of criteria were selected: a) criteria for constraint mapping and b) criteria for suitability mapping. Some important criteria were selected for both cases after analyzing their importance and relevance. Table 1 lists the selected criteria for constraint and suitability mapping, showing the relevance and the usefulness of each criterion for MAR site suitability mapping.

5.4. Constraint mapping

In order to screen out the non-feasible areas, constraint mapping was undertaken at an early stage. Table 2 shows the list of criteria and their threshold values for screening. For the land use map, land class feasibility was defined separately (Table 3). The threshold values for each constraint criteria are chosen so that criteria values or classes should satisfy the minimum requirement of MAR implementation such as the infiltration basin

Table 1
List of criteria chosen for constraint mapping and suitability mapping and their relevance to MAR site selection.

Criteria	In the model, used for	Description
Land use	Constraint mapping	The existing land use provides information about the land availability for MAR. For example, areas that are under commercial and industrial use, are non-feasible areas for MAR implementation.
Slope (topography)	Constraint mapping and Suitability mapping	Steeper slopes do not permit the implementation of infiltration basins. Furthermore, water runoff is directly related to slope angle. Flat areas allow high infiltration rates and is suitable for aquifer recharge. The lower the value, the higher the priority.
Infiltration rate (soil)	Constraint mapping and suitability mapping	Infiltration rate of soil controls the penetration of surface water into an aquifer system. Soils with high infiltration capacity are more suitable than those of low infiltration capacity.
Sub-surface impermeable layer thickness	Constraint mapping and suitability mapping	The thickness of impermeable layer should not be high, otherwise the excavation costs would be high. The lower the value, the more suitable the place.
Groundwater depth	Constraint mapping and suitability mapping	In terms of water quality improvement by natural attenuation processes, considerable unsaturated zone thickness is preferred. A deeper groundwater level benefits of the natural attenuation capacity at the studied location.
Distance to groundwater pollution source	Constraint mapping	The place of MAR should have a sufficient distance from groundwater pollution sources.
Aquifer thickness	Suitability mapping	Suitable sites should have high thickness values. Transmissivity and aquifer storage volume depends on the aquifer thickness. The higher the value, the higher the priority.
GW quality (chloride and nitrate)	Suitability mapping	The groundwater quality should be adequate at the place of recharge, except the objective of the MAR is to improve the groundwater quality. The parameter has to be considered function of the groundwater quality of the area.
Residence time	Constraint mapping and suitability mapping	The residence time of the infiltrated water in the aquifer should be sufficient to be able to use the aquifer as water transfer and recovery system.

construction, the water quality improvement by using unsaturated zone, the aquifer storage capacity and others. For example, the used threshold value for the residence time of 6 months, as mentioned by most of the international standard guidelines for MAR (CDPH, 2008; NRMMC, EPHC, NHMRC, 2009) suggest to keep the water in the aquifer at least 6 months for water quality improvement.

After defining the threshold values for each criterion, the thematic map of each constraint criterion has been converted to a constraint map. Fig. 10 shows the thematic map of slope and the converted constraint map. All the converted thematic maps were overlain by conjunctive screening to achieve the final constraint map (Fig. 11). This constraint map was used later as a mask for suitability mapping.

5.5. Suitability mapping

After analyzing all available data and site characteristics, sub-criteria were selected according to their characteristics, and the main hierarchical structure was prepared (Fig. 12). The sub-criteria, or thematic layers, were standardized. Three value functions, such as linear, piece-wise linear, and step-wise linear functions were used for this approach (Fig. 13).

The importance of each sub-criterion has been calculated using pair-wise comparisons and this is shown in Fig. 12. Infiltration rate of the soil, residence time of groundwater, and depth to groundwater were given highest priority in the analysis. Groundwater quality was a low priority criterion because of low variability of groundwater quality over the entire area. The weighted criteria were then overlaid by two state-of-the-art overlay procedures: WLC and OWA.

Fig. 15 shows the suitable sites for MAR in the region using the WLC method. Fig. 16 shows suitability maps using the OWA procedure. The map shows the suitable places under the following decision condition: “half” of the important criteria are satisfied by an acceptable alternative. According to the definition of the OWA, when $\alpha = 1$, the output should comply with the WLC output.

5.6. Sensitivity analysis

A sensitivity analysis was done which indicates a significant change in site suitability based on changes in risk acceptance of

Table 2
Defined threshold values (discarding conditions) of the selected criteria for MAR constraint mapping.

Criteria name	Threshold value	Explanation
Land use	–	See Table 3.
Infiltration rate (soil)	25 cm/day	The areas where infiltration rate is greater than 25 cm/day are considered as potential area.
Groundwater depth	5 m	The places where groundwater depth is greater than 5 m are considered as potential sites.
GW pollution sources	500 m	The places which are within the radius of 500 m of groundwater pollution sources are rejected.
Residence time	6 months	A residence time of at least 6 months should be guaranteed.
Slope (topography)	5%	MAR is feasible for areas with less than 5% slope.

Table 3
Categorization of the land use types at the study area for MAR constraint mapping.

Land use type	Threshold
Agricultural systems, agricultural areas outside irrigation perimeters, irrigated areas, quarries/stone pits, marshy places, salt-pits, isolated urban areas	Non-feasible (value is 0)
Permanent crops, orchards, poor pastures/grasslands, natural vegetation, underwood, rivers (water in lines to build check dams, and infiltrate)	Feasible (value is 1)

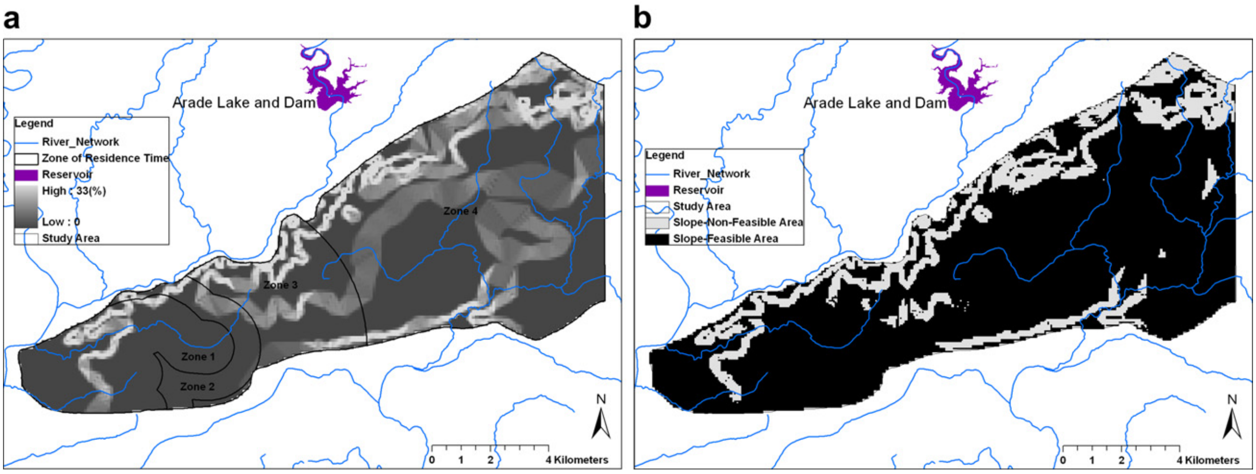

Fig. 10. Thematic map of slope (left) and it's converted constraint map (right).

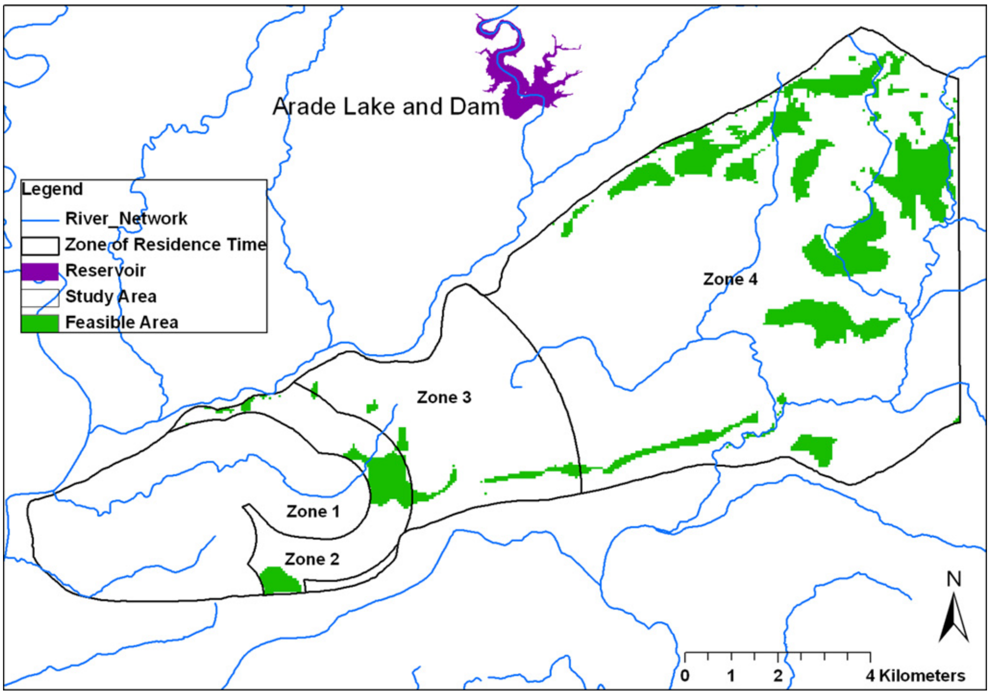

Fig. 11. Constraint map for suitability mapping.

the decision maker (see details in Fig. 3). In this way, different decision maker's attitudes may be simulated and considered in the MAR planning process, contributing to the integrated management of water resources. A sensitivity analysis has been performed to demonstrate the effect of the decision rules on the site selection procedure. Given the standardized map and corresponding criterion weight, we have chosen four fuzzy linguistic quantifiers: at least a few ($\alpha = 0.1$), a few ($\alpha = 0.5$), most ($\alpha = 2$)

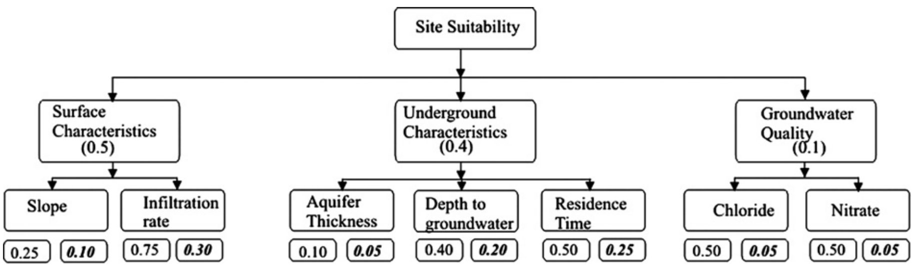

Fig. 12. Criteria for suitability mapping and hierarchical structure (in brackets the local and global weights are given).

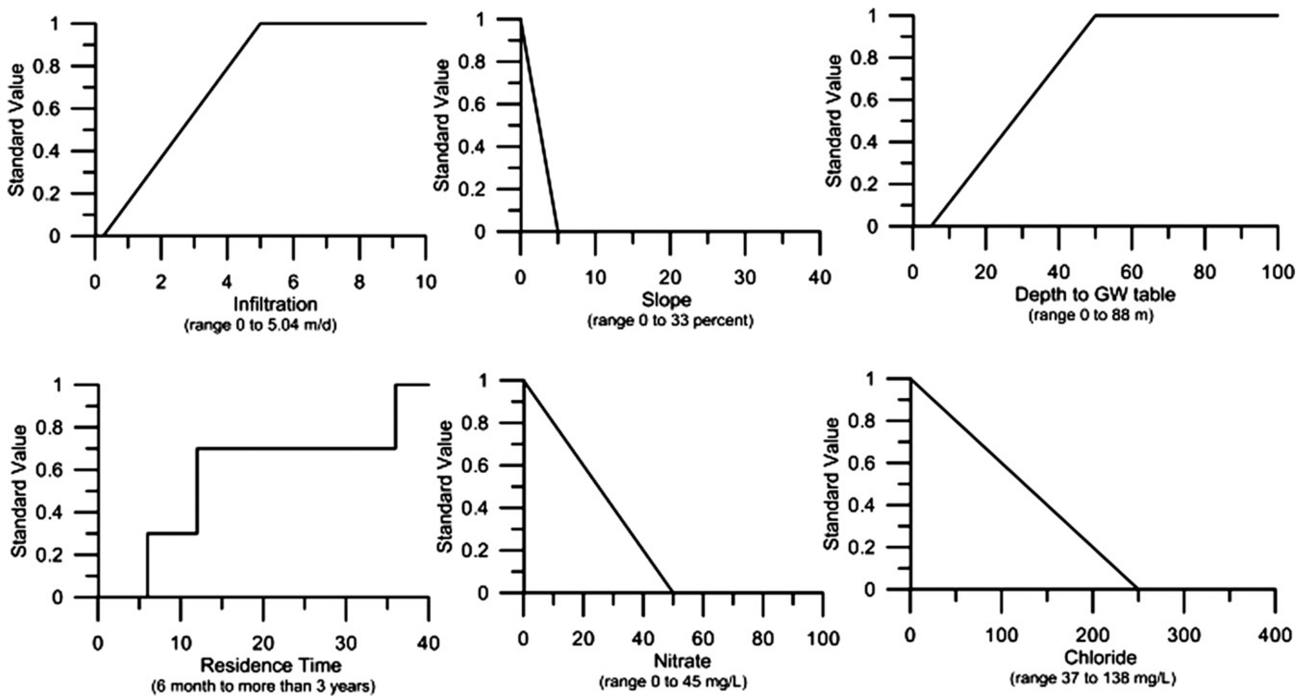

Fig. 13. Procedure for criteria standardization used in this study (range indicates the limit of the criteria value present in the study area).

and almost all ($\alpha = 10$). The corresponding OWA maps are shown in Fig. 17.

5.7. Results and discussion

The constraint map (Fig. 11) generated by the Boolean logic overlay method shows that only 11.2% of the total study area is feasible for construction of infiltration ponds to recharge groundwater. Land use and infiltration capacity of the soil are the main constraints for the potential site selection. Most of the potential sites are located in Zone 4, which is characterized by a higher groundwater residence time. The overall suitability map shows the relative ranking of the potential sites, generated by constraint mapping, according to the criteria importance. The suitability scores indicate the relative site ranking alternative to construct an infiltration basin. High suitability scores indicate the site is highly suitable for MAR. It is evident from the suitability analysis (Fig. 14) that considering only surface characteristics, the study area offers just few adequate locations for the implementation of infiltration basins. In contrast to that, the study shows good suitability for aquifer recharge with regards to the generally feasible areas, considering the prevailing underground characteristics. According to the overall suitability score (Figs. 15 and 16) 1% of the total aquifer is very good (suitability score 80–100), 3.2% is good (suitability score 60–80), 6.4% is moderate (suitability score 40–60), and 0.6% is poor for MAR. The rest 88.8% of the aquifer surface is not suitable at all due to the constraints of MAR implementation. The most suitable areas are situated on agricultural land which have high infiltration capacity soil (infiltration rate ranges between 2.7m/d and 5m/d) with very flat topography (slope is about 0%), and which do not require additional excavation efforts. The groundwater table under the agricultural land is at about 70 m below the land surface, which provides a sufficient unsaturated zone thickness to assure the

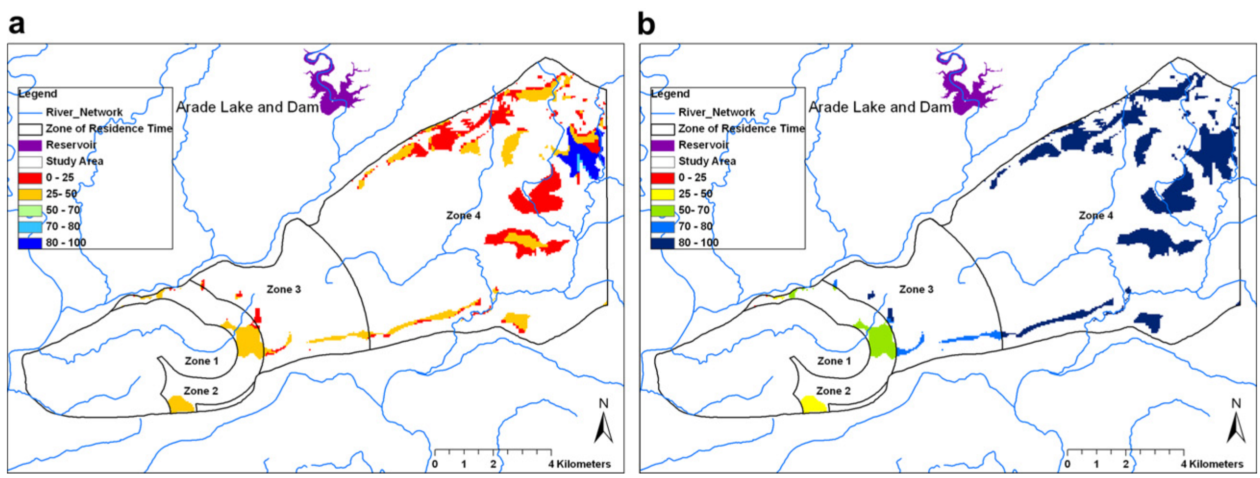

Fig. 14. Weighted Linear Combination map for considering surface characteristics (left) and underground characteristics (right).

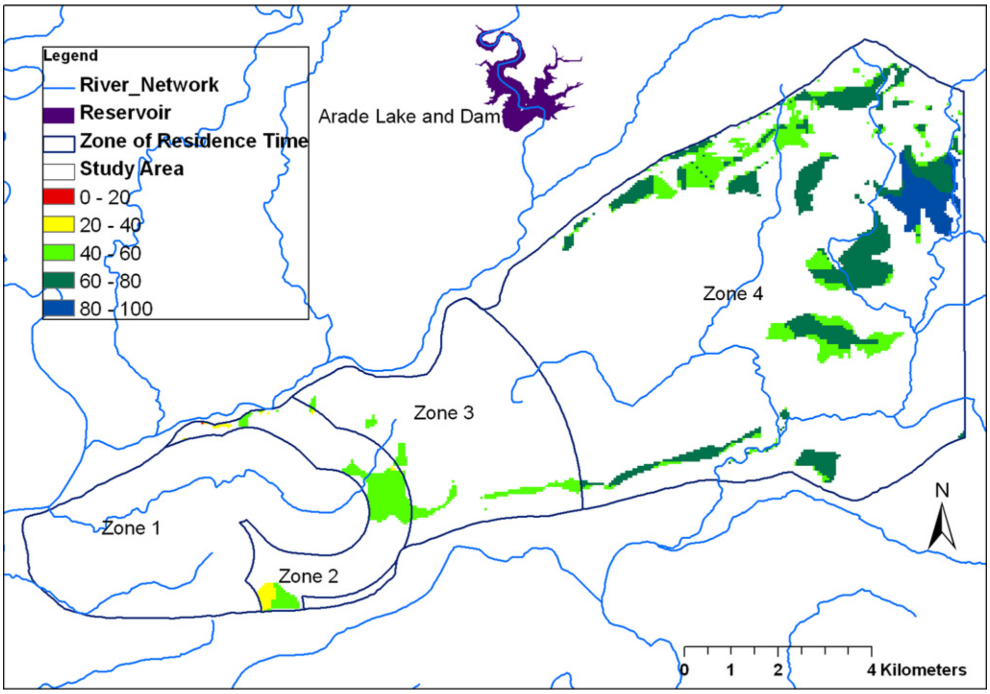

Fig. 15. Site suitability for MAR based on Weighted Linear Combination (WLC).

water quality improvement. The groundwater quality is moderate at the high suitability scores places. Since the regional groundwater flow direction is northeast to southwest, the infiltrated water may be easily transferred downstream from the highly suitable area to the northeastern part of the study area by using the natural groundwater flow. The water may then be pumped in Zones 1 and 2 where drinking water pumping wells are already installed. The distance to the Arade Dam, the potential water source for MAR, is at about 8.5 km distance from the highly suitable areas. This distance may incur extra water transportation costs. An approximately 27 ha area is categorized as “Good” which is at only 3 km distance from the Arade Dam. The groundwater is at about 60 m depth and its quality is moderate. In this location the infiltration rate is relatively low. In this area a comparative study and a pilot experiment is desirable in order to make the final decision of using an infiltration basin.

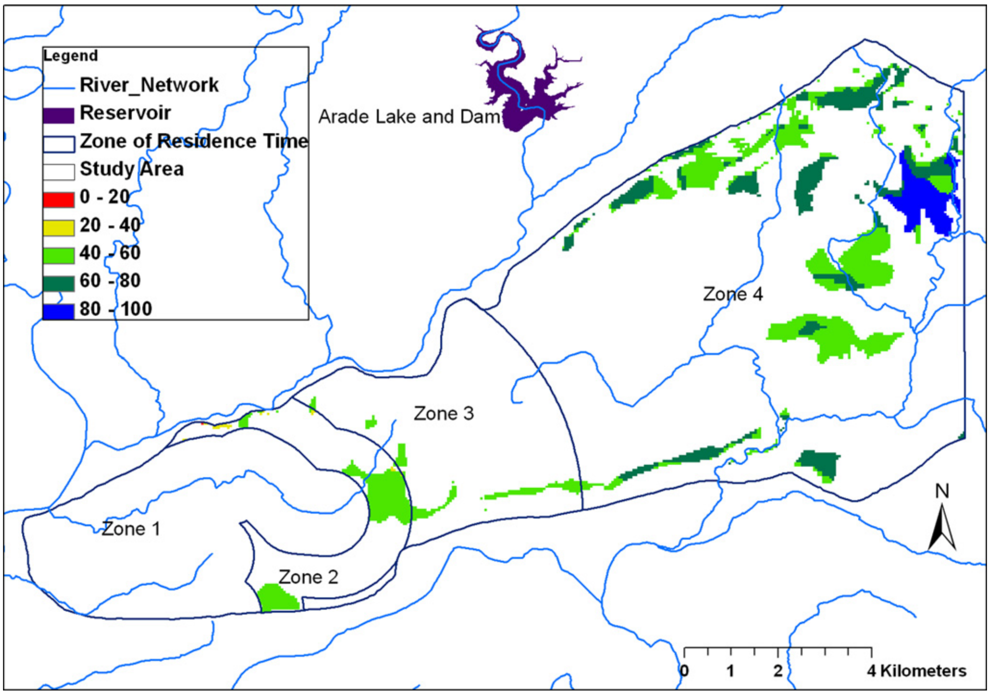

Fig. 16. Site suitability map using Ordered Weighting Average (OWA) method, $\alpha = 1$ decision rule. The assigned α value corresponds to each level of the hierarchy.

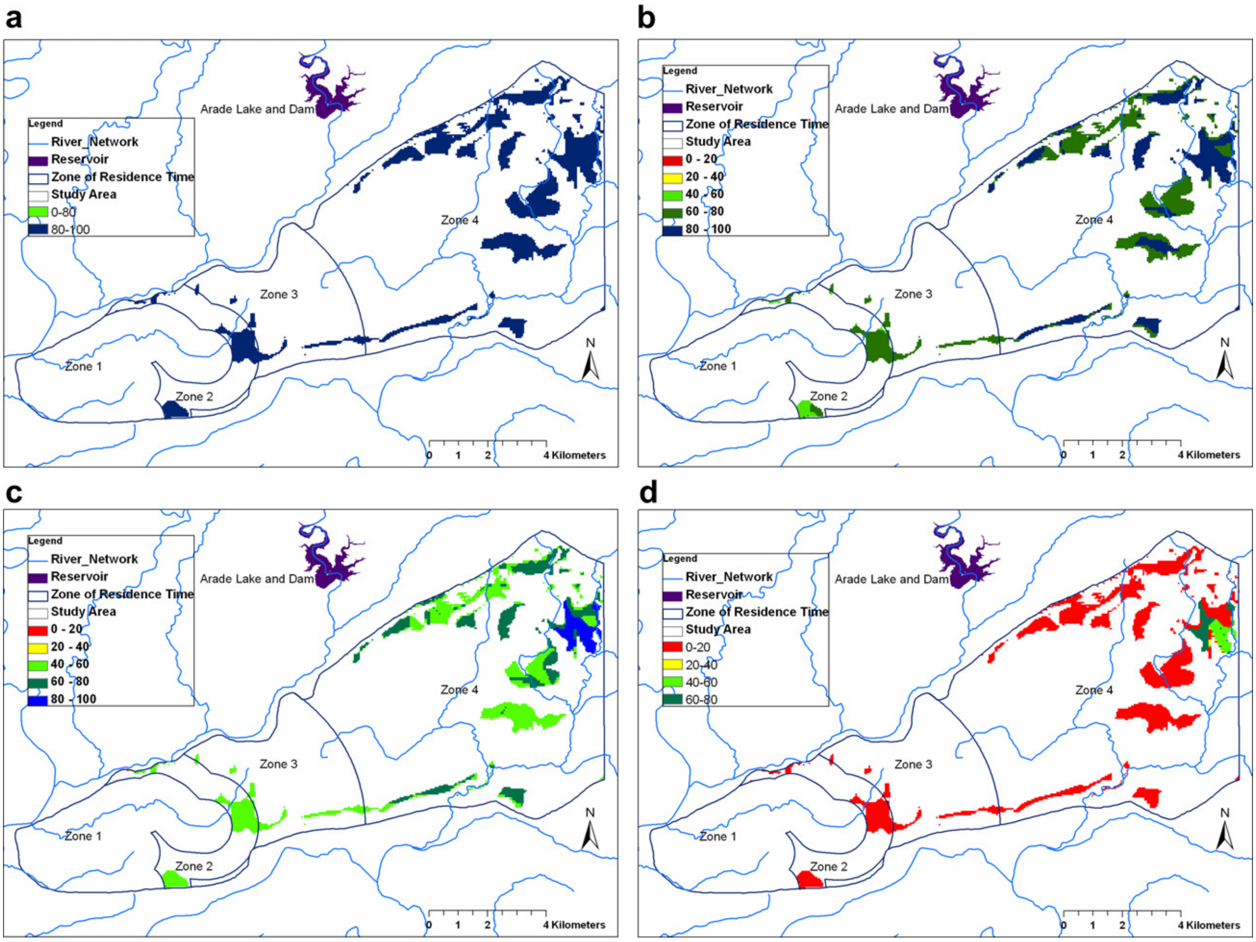

Fig. 17. Sensitivity analysis showing the change of site suitability according to the change of decision rule; the assigned α value corresponds to each level of the hierarchy for each performed analysis. (a. upper left) $\alpha = 0.1$; (b. upper right) $\alpha = 0.5$; (c. lower left) $\alpha = 2$; (d. lower right) $\alpha = 10$.

The sensitivity analysis indicates a change in site suitability due to varying risk acceptance of the decision maker (Fig. 3). In this way, different decision makers' attitudes have been simulated and may be considered in the MAR planning process. This unique capability of the new SMCDA tool contributes to its better integration in various water resources management activities The sensitivity analysis (Fig. 17) indicates also the significant impact of the decision rules on site suitability mapping. The first map of Fig. 17(a) indicates the best solution of site suitability. This represent the most optimistic decision strategy (*at least a few criteria should satisfy*) of the decision maker. In this case, almost the entire feasible area (10.8% of the total area) falls into the category "very good." When increasing the value of α (or reducing the risk), the number of suitable areas which are categorized as "very good" is reduced. The last map (Fig. 17d) shows the worst-case scenario when the decision rules are considered. In this case (*almost all criteria should satisfy*), no place is categorized as being "very good," but 9.7% of the total area is categorized as being "bad." From the four alternative maps presented in Fig. 17 together with the map presented in Fig. 16, one may notice that the fuzzy quantifier based on OWA approach is able to simulate a wide range of decision maker's preferences regarding MAR implementation.

6. Conclusions and recommendations

This paper mainly demonstrates the new suggested GIS based spatial multi-criteria decision analysis software tool for the site ranking to implement MAR projects. Site selection analysis involves a number of criteria, alternatives and decision factors, resulting in a complex decision environment. With this new tool, the decision steps are explicitly given to the user according to the overall analysis procedure in order to tackle an unstructured problem. Standard criteria and decision rules are offered to the user in order to reduce the analysis efforts and the risk of ignoring relevant decision criteria. The considered hierarchical framework of AHP promotes clear thinking and better understanding of the problem together with reducing errors in importance judgment. Pair-wise comparison permits the checking of consistency to the user's input weight. Decision makers are able to obtain a wide range of decision strategies and scenarios by changing linguistic quantifiers, in the incorporated OWA method (Yager, 1988). In order to show the efficiency of the tool, a case study has been performed in Querença Silves Aquifer, Portugal. Provided default criteria, explicit decision steps, and flexibility in varying criteria standardization and overlay, are found to be very beneficial.

According to the analysis results from the case study, there are just few areas, 11.2% of the total aquifer, where the implementation of infiltration ponds would be feasible. Non-adequate surface characteristics cause further restrictions for MAR implementation. On the contrary, the underground characteristics, studied for the feasible areas, are adequate for the MAR implementation by means of infiltration technologies. The overall suitability maps, in both methods, suggest installing the infiltration ponds in Zone 4. The high suitability areas are characterized by adequate unsaturated zone thickness, which is very important for water quality improvement. The groundwater quality is also moderate. In order to obtain more locations for infiltration ponds, better analysis of restrictions with regards to land use and soil type is recommended. Decisions with regards to the selection of optimal locations for the installation of water recovery wells and groundwater protection should be supported by groundwater flow and transport modeling, while checking the actual flow path of the infiltrated water and the impact of water pollution sources. Besides this, some other in-situ parameters, such as soil salinity, organic carbon content, and sediment chemistry can be studied further in order to rank the alternatives according to the potential of further water quality improvement. Some socio-economic criteria, recharge and recovery water transportation cost, cost of excavation, etc. can be taken into consideration for further study. Above all, the local agency can verify the analysis result while implementing MAR on the test site.

The SMCDA tool can be further developed to support more decision analysis techniques for the end user. In the future, a number of standardization functions (e.g., concave, convex, sigmoidal functions etc), weighting methods (such as ranking method, rating method etc.), and overlay methods (e.g., fuzzy additive weighting method, composite programming etc,), will be added to the existing SMCDA tool. The new spatial multi-criteria analysis tool, due to its non-site specific, adaptive and comprehensive concept may serve as a complementary element for any GIS based Water Resources Management support system. By altering the input criteria and using the relevant dataset and decision rules, this spatial multicriteria analysis tool can be applied to a wide range of disciplines, such as groundwater vulnerability assessment, land use planning, site selection for waste disposal etc. Multi-objective decision analysis techniques can be added to this tool easily. The tool has been already implemented in the Gabardine DSS, a comprehensive GIS based decision support tool for MAR planning and management (Rusteberg et al., 2008).

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ORIGINAL ARTICLE

The use of GIS-based 3D geological tools to improve hydrogeological models of sedimentary media in an urban environment

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Abstract A software platform was developed to facilitate the development of 3D geological models of sedimentary media for hydrogeological modelling, especially for urban environments. It is composed by a geospatial database and a set of tools that enable the user to perform an accurate stratigraphic analysis. The geospatial database is used for the management of a large amount of different data types coming from different sources (geophysical logs, borehole logs, hydraulic tests, etc.). Its structure allows us to store accurate and very detailed geological borehole-log description that can be straightforwardly generalized and further upscaled. The set of stratigraphic analysis instruments, working within a Geographical Information System (GIS) environment, has been set up to facilitate the geological data interpretation. Detailed stratigraphic columns of the selected boreholes can be generated using customized queries. Creating automatically a geological profile is further possible by displaying the boreholes lithological columns and the geophysical and geotechnical field-tests' results together with the defined stratigraphic units. Based on an interactive analysis environment is created, where the user is able to analyze and to define the possible existing correlation surfaces, units, and faults. The obtained information represented by the geological units/subunits can be then converted within a 3D environment. The resulted 3D features could be used within the same GIS environment or by external software packages for further stochastic analysis or to build up 3D geological and hydrogeological models. Starting from an accurate and very detailed geological description, the software allows us to represent in three dimensions (3D) the heterogeneity of the sedimentary media and their spatial distribution. Thus, it shows how connectivity implemented into hydrogeological models among the different sedimentary bodies plays an important role. Results are shown consisting in a case study located in the Besòs River Delta, in the metropolitan area of Barcelona, on the Mediterranean coast in NE Spain.

Keywords Geospatial database · GIS · Stratigraphic analysis · 3D geological model · Hydrogeological model

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Introduction

Sedimentary media (alluvial sediments, deltas, etc.) constitute important aquifers because of their high permeability, storage capacity, and interaction with surface water. In an urban environment, there is a considerable impact of human activity in terms of quality and quantity on groundwater (due to the sewerage system, the water supply network, etc.). Moreover, groundwater poses a problem for the development of infrastructure such as tunnels, basement crossings of large buildings, underground parking lots, etc. (Vázquez-Suñé et al. 2005; Pujades et al. 2011).

Groundwater models constitute an essential tool for a reliable water management in urban sedimentary media (Pokrajac 1999; Vázquez-Suñé et al. 2006; Carneiro and Carvalho 2010). These models allow us to conceptualize, identify, and quantify the hydrogeological processes. They enable us to simulate various scenarios such as droughts, water resource exploitation, water quality evolution, and interaction with civil works in terms of hydraulic and geomechanical behaviour of the ground.

Hydrogeological modelling simulates the aforementioned processes provided that (1) the geometry and connectivity of the different sedimentary bodies are known (thus the distribution of the hydraulic conductivity, porosity, and other hydraulic relevant properties will be correctly characterized), (2) the petrophysics and hydraulic parameters of the sedimentary media are correctly estimated, and (3) the geometry and properties are adequately implemented into hydrogeological model.

The first two points focus mainly on the geological modelling as a first step in hydrogeological analysis. The last point highlights the need for reliable tools to implement the geological model and its properties into the hydrogeological model.

In the absence of a detailed stratigraphic interpretation, the geological modelling of the heterogeneous sedimentary media will be incomplete or will fail. A detailed stratigraphic analysis can be performed only if sufficient data are available.

Thus, the first step in geological modelling is to collect, sort, and then select usable geological data (Kaufmann and Martin 2008).

Traditional geological data such as two-dimensional (2D) maps (geological maps, profiles, and contour maps) are used to help geologists address practical problems. However, geological information essentially exists in three dimensions (Ming et al. 2010). The integration of original geological data and the reconstruction of their 3D shape in a 3D model will provide a reliable spatial representation of the geological variability, thus improving the hydrogeological models. This aspect has been emphasized by many authors such as Robins et al. (2005), Ross et al. (2005), Wycisk et al. (2009), and Velasco et al. (2012).

In many subsurface modelling studies, especially those concerning urban areas, some specific issues focusing on the gathering and the management of usable geological data should be addressed:

1. Outcrops are often infrequent and available subsurface data come from different sources (building foundations, roads, underground infrastructures, research campaigns, etc.) and are normally very heterogeneous (Rienzo et al. 2008) in both format (borehole logs, records of drilling parameters, etc.) and description (depending on the knowledge of the professional, the accuracy of the instruments, etc.)
2. Despite the limited information because of continuing urbanization, there is usually a vast legacy of available geological information (Culshaw and Price 2011) including previous geological interpretations and older raw data. Interpretations of geological observations depend not only on the observer and work scale but also on geological knowledge at the time of interpretation. Therefore, reinterpretation may be needed to use this information (Kaufmann and Martin 2008). To this end, a suitable system of data storage, management and validation is essential.

Once the geological model is constructed, further hydrogeological information constituted by a large amount of different data (chemical and heads measurements, hydrogeological tests results, etc.) must be integrated to complete the hydrogeological conceptual model.

This large pool of diverse subsurface data cannot be easily handled and analyzed without a unified database and software that allows interactive display and visual correlation. Geographic Information System (GIS)-based software is one of the solutions for the management and analysis of geological and hydrogeological data since most of these data refer to locations on the Earth and such spatial complexity can be well accommodated in GIS (Chang and Park 2004; Wu et al. 2008; Chaaban et al. 2012).

This paper presents a software platform that integrates a spatial database and a set of tools and methodologies developed in a GIS environment with the aim of facilitating the development of 3D geological models of sedimentary media for hydrogeological modelling, especially in urban environments.

This set of tools and methodologies allow the user to (1) edit and visualize 3D data, (2) use the inherent query and retrieval facilities offered by GIS software, and (3) employ the resulting geological model in support of the hydraulic parameterization for hydrogeological modelling.

These technologies were applied to some studies in urbanized areas such as Barcelona, Spain (for further information see Escorcia 2010; Riera 2011; Velasco et al. 2012) and Bucharest, Romania (for further information see Gogu et al. 2011). Here, a study case located in a part of the Besòs Delta in the metropolitan area of Barcelona (Spain) is discussed to illustrate an application of the presented tools and methodologies.

Software instruments and spatial database concepts for geological analysis

Commercial and research instruments that assist the creation of 3D geological models are found in different software packages. These tools may be classified based on their background philosophy as Computer-Aided Design (CAD) packages and Geographical Information System (GIS) software. Geological analysis tools have been developed inside both software families. As a result, there is a marked difference between different software packages in accordance with their origin. A reliable geological modelling software platform should include both GIS and CAD instruments. This should be based on the spatial data storage, query, and retrieval facilities offered by GIS software and on the abilities of 3D data editing and visualization provided by CAD. Both software families (CAD and GIS) are currently expanding their functionalities. Particular CAD abilities are implemented in GIS software and database management facilities are implemented in CAD-based products. CAD software was not designed to handle spatial data structures needed to provide reliable and accurate geological description (which is one of the main advantages of using GIS instead CAD) and GIS packages are still deficient in complex data editing and 3D analysis and visualization. A short review of some of these packages underlines the need for the work to be performed. This begins by reviewing some professional stand-alone CAD-based software packages, paying particular attention to GIS-based software in the second part of this section. Software like Earthvision (2012), Vulcan (2012), 3D Geomodeller (2008), EVS and MVS (2012) as well as other powerful packages can be added. Nevertheless, this review is not intended to be exhaustive.

- GOCAD (2011) is a large and complex geological modelling software package based on CAD technology. Its main module is focused on structural modelling, allowing geological cross sections and map generation. The basic module offers an analysis platform for seismic data tests. Additional modules support specific tasks such as 2D or 3D grid construction and time-to-depth conversions by modelling the entire geologic column, or merging seismic interpretation with structural modelling, or constructing pillar-based stratigraphic grids for geostatistic and flow simulation.
- Leapfrog software (Leapfrog3D 2012) has been developed for 3D modelling of drill-hole data and for the construction of 3D geological models. Leapfrog generates wireframe models of lithology, alteration, and mineralization, which can be exported to other mining software packages. Existing maps and cross sections can also be viewed in its 3D environment. The Leapfrog 3D models can be exported to a variety of CAD software formats as for example dxf, Vulcan, or GOCAD. In addition, Leapfrog 3D can import pre-selected structures from interpreted seismic images or any of the common GIS output formats.
- Rockworks (2012) software offers a specialized modelling method that allows a lithology model interpolation. Its algorithms can be used to interpolate continuous stratigraphic surfaces, which when stacked, form a 3D stratigraphic model. Other functions enable the user to create individual logs or multi-logs cross sections, fence-diagrams, and maps in 2D and 3D. Furthermore, it provides some GIS processing tools as well as import/export capabilities in various formats.
- HydroGeo Analyst (2011), developed by Schlumberger Water Services, is designed for groundwater and environmental data management. It uses the SQL server as its database and the construction of plots entails the use of one program to generate and execute a SQL statement and then a second program for data mapping. It enables us to display borehole logs, and permits the interpretation of cross sections. The software supports some steps of data pre-processing in modelling 3D groundwater flow and contaminant transport by defining hydrological layers interpreted from borehole logs. Its map manager allows us to exchange geographical information and uses GIS mapping technology.

Thus, any complicated 3D model can be constructed in principle using the aforementioned editing tools by employing CAD-based package software. However, GIS-based tools developed for geological analyses are especially suited for managing spatial data in terms of information query and retrieval. The need for querying tools emerged as a way of visually sorting and grouping the data to find areas that have certain characteristics and yield insights from their locations and distribution (McCarthy and Graniero 2006). This is systematically applied to working hypotheses regarding geological processes by outlining the relative values, frequencies, or distributions of some attributes across different lithologies or formations. In this regard, some of GIS-based software packages for geological analysis are reviewed below.

GIS-based software packages for geological analysis

GIS-based packages for geological analysis depend on the spatial database structure on which they are based. There are several concepts and developments of structuring geological spatial information for hydrogeological studies (Barazzuoli et al. 1999; Gogu et al. 2001; de Dreuzy et al. 2006; Carrera-Hernández and Gaskin 2008; Comunian and

Renard 2009; Wojda et al. 2010, Chesnaux et al. 2011). However, there are few spatial data structures that allow a very detailed stratigraphic analysis and most of them do not have the necessary tools to exploit the information. Two examples of efforts in structuring stratigraphic data were considered significant and they are discussed in the following paragraphs:

1. The Subcommission on Stratigraphic Information System forms part of the International Commission on Stratigraphy (ICS) (2012), which is a organization concerned with stratigraphy on a global scale. This commission organizes the stratigraphic information in a number of ways: Geological and biological events and Earth history, Facies stratigraphy, Paleostratigraphic and Paleoclimatic maps (continental and marine ecosystems), and Iconographic Atlases (Index fossils species and Biostratigraphy in thin-sections). It also organizes the Geological Time Scale Information and Stratigraphic standards and Lexicons.
2. The other example is the coal-related Stratigraphic database developed by the Coal Section of the Illinois State Geological Survey (2012). The database is designed to store drill-hole log data and the description of outcrops and of mine exposures. Various stratigraphic characteristics are represented within the database: outcrop descriptions, cores, geophysical logs, driller logs, and mine exposures. Multiple descriptions of the same exposure or drill hole are possible.

Some commercial software packages discussed below are examples of tools developed to exploit the geological information in a GIS environment to construct geological models.

- Target for ArcGIS 3.5 (2011) was produced to allow visualization and analysis of borehole-log data within the GIS environment. It has several functionalities that allow surface and borehole mapping that regroups a subsurface 3D viewer and tools to carry out borehole plans, cross sections, surface mapping and professional map production.

While this system contains many powerful features for performing geological analysis, it has not been based in a comprehensive predefined geodatabase to facilitate the integration and representation of detailed stratigraphic data with hydrogeological data.

- Part of the EQuIS (EQuIS 2012) software platform produced by EarthSoft is EQuIS 3D Geology. The platform is fairly complex and allows us to view the lithology data in 2D or 3D. The ArcGIS (ESRI) software module adds modules and utilities to enhance the capabilities of ArcMap and ArcScene applications. The GIS functionalities therefore create, query, map, analyze, and report from the EQuIS project databases. Visualization of borehole logs is done by querying the database on the GIS platform and using gINT (Gint-software 2011) software. 2D cross sections are performed using a RockWorks package or by creating a duty cross section in gINT software package. In the ArcGIS (ESRI) module, Arc Scene, the users can visualize the output from RockWorks 3D fence diagrams, which EQuIS transfers to either shapefile or a personal geodatabase (ESRI) format. For advanced 3D visualization, EQuIS for ArcGIS is integrated with EVS software packages (CTech's 3D). Results from spatial queries and lithology information for boreholes are exported to EVS compatible format and thumbnails of various visualizing scenarios can be carried out. Because of the well-defined integration within ArcGIS, it can use its geostatistic and spatial analysis modules.
- RockWare GIS link 2 (2012) imports the borehole location into ArcMap and enables us to generate cross sections, fence-diagrams, logs, isopach and contour maps using ArcMap and Rockworks.

Although these software packages may be very useful for developing three-dimensional geological models, the use of third party software to perform a detailed stratigraphic analysis complicates the procedure and increase the cost of the product.

- The British Geological survey concept "Geological Surveying and Investigation in 3 dimensions" (GSI3D) involves a methodology and an associated software tool for 3D geological modelling (Kessler et al. 2009). The software is written in Java and data are stored in extensible mark-up language XML. GSI3D uses a digital elevation model, surface geological linework, and borehole data to enable the geologist to construct cross sections by correlating boreholes and outcrops. Mathematical interpolation between the nodes along the drawn sections and the limits of the units produces a solid model comprising a stack of triangulated objects, each corresponding to one of the geological units present. The user can construct cross sections automatically where it is possible to perform borehole correlations.

Other research tools have been developed in a similar vein. Some of them are discussed in the following paragraph:

McCarthy and Graniero (2006) developed a tool (BoreIS) to aid in the management, visualization, querying and analysis of borehole data building in ESRI's established ArcScene software. Creation and visualization of cross section for its further interpretation was not possible.

Whiteaker et al. (2012) recently develop a GIS data model and tools for creating and working with a 2D cross section. The data model and tools create a framework that can be applied using ESRI's ArcGIS software. In addition, the 2D cross sections are converted to 3D fence-diagrams and displayed in ArcScene. This system is complete and powerful since it integrates this set of tools with other features related to site characterization in the GIS (using ArcHydro Groundwater data model). However, it does not contain specific tools to develop a detailed sedimentary media stratigraphic analysis. For instance, the geological cross sections do not show some stratigraphic details that are useful in performing accurate stratigraphic correlations.

GIS-based platform for 3D geological analysis

Design goals

The main difficulty for geologists has been to depict a three-dimensional system through a two-dimensional media, traditionally on paper, and in recent years with GISs.

The creation of two-dimensional profiles constructed from well log data resolves the problem of showing 3D objects in 2D and constitutes an optimum framework for performing geological interpretations by borehole correlation.

The correlation of borehole data entails a combination of subjective and objective examinations of processes based on stratigraphic analysis, interpretations and assumptions that can lead to a geological model with some uncertainties (Borgomano et al. 2008).

Furthermore, the geological interpretation derived from 2D cross sections can be transferred to 3D by aligning profiles along different cross sections, thus creating a 3D view of the entire model.

It should be pointed out that the accuracy of the correlation depends on the quantity and the quality of the available well log data and on the geological interpretation.

To make the evaluation of the data more realistic, it is also important to be able to integrate and compare different types of data related to the geology of a site. For instance, when reading and interpreting geophysical logs it is possible to corroborate these data with other data from lithological boreholes or available samples.

Accordingly, an accurate stratigraphic interpretation of a site demands (1) the availability of sufficient data; (2) tools that facilitate homogenization, integration, and query of these data; and (3) the availability of suitable tools and methodologies to interpret these data in a 3D environment.

In the light of the foregoing discussion, a software platform that brings together the tools and methodologies to facilitate an accurate stratigraphic analysis for the subsequent development of 3D geological model was developed. These tools, which were developed within a GIS environment, enable us to construct a geological model with several techniques and allow us to implement this information into flow and transport models. To this end, the following technical requirements should be fulfilled:

1. Management and storage of spatial features and time-dependent data on a geospatial database.
2. Stratigraphic interpretation and analysis of geological data using:
   - Typical queries and visualization of data in a GIS environment.
   - Specific instruments to perform accurate stratigraphic analysis: visualization of stratigraphic columns and generation of cross section.
   - Different geostatistics tools.
   - Typical capabilities of GIS for interaction with other features and creation of thematic maps.
3. Creation of 3D geological models using:
   - Different modelling approaches (deterministic or stochastic).
   - Tools to generate 3D surfaces of isopachs and isobaths maps in a GIS environment.
   - Tools to generate fence-diagrams in a GIS environment.
4. Hydraulic parameterization based on the petrophysical distribution of the geological units using tools that enable us to:
   - Calculate hydraulic properties from the stored data.
   - Import/export hydraulic parameters.
5. Facility of interaction with external software such as:
   - Geostatistic software such as SGEMS (Remy et al. 2009) or GSLIB (Deutch and Journal 1998).
   - Groundwater modelling packages such as TRANSIN (Medina and Carrera 2003).
   - Pre-processor package to generate 3D finite element mesh such as GID (2012).
6. Post-processing using:
   - Maps, diagrams, or queries in a GIS environment.

Analysis software platform

The 3D analysis platform for groundwater modelling is composed of a hydrogeological geospatial database and several sets of instruments that enable us to perform an accurate stratigraphic analysis. These instruments were

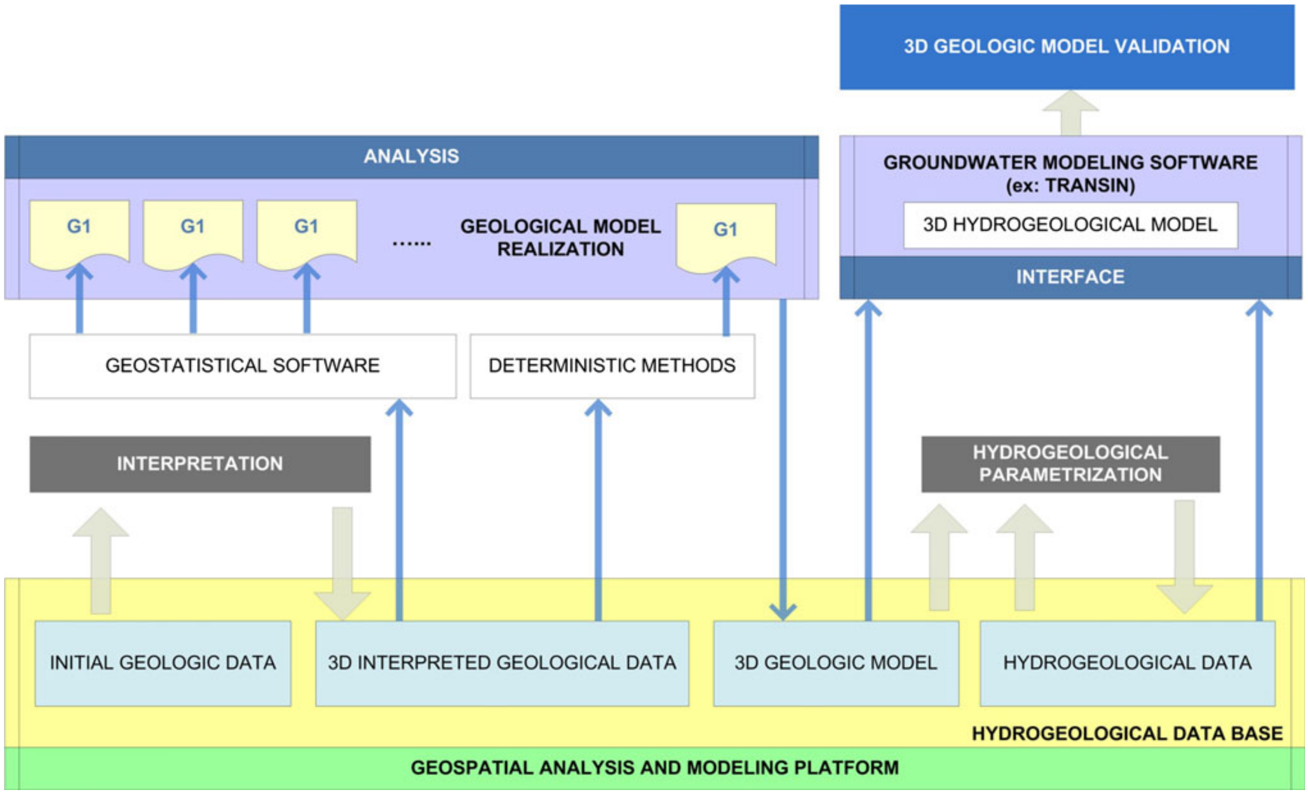


Fig. 1 General scheme of the GIS-based 3D geological analysis platform for groundwater modelling

developed as an extension to the ESRI's ArcMap environment, which is part of the ArcGIS version 9.3 software package. They were created with ArcObjects, which is a developer kit for ArcGIS based on Component Object Model (COM) and they were programmed in a Visual Basic of Visual Studio (Microsoft) environment.

The analysis software platform was developed according to the following guidelines (See work-flow diagram; Fig. 1):

1. Collection of geological data in a hydrogeological database. This database follows the geodatabase structure provided by the ArcGIS (ESRI) concept for representing geospatial information. It stores geological and groundwater information about the sedimentary media.
2. Interpretation of geological data and construction of a 3D geological model using a set of instruments that use the database spatial information termed *Lithological and Stratigraphic analysis tools* to perform stratigraphic analysis. Its main components, which will be described in this section, are the *Borehole diagram instruments* and the *Stratigraphic cross-sections correlation tool*.
3. These tools together with the deterministic methods and the import/export procedures to the Geostatistic software are shown in the work-flow diagram as being part of the *Interpretation* module.
4. Parameterization of the geological model. This is mainly performed by another set of instruments termed *Tools for the hydraulic conductivity initial estimation*, which enables us to estimate the hydraulic conductivity of each lithological interval defined in the borehole and of the user-defined stratigraphic units. In Fig. 1, these tools are represented by the *Hydrogeological parameterization* module and its interactions with the hydrogeological geospatial database.
5. Exportation of all these data to an external modelling platform. The results of the aforementioned model can be exported to another external platform.

Hydrogeological geospatial database

The geospatial database design has an object-oriented approach and is easily extensible. An important step in the development of the database process was the creation of a conceptual model of the required information. A wide range of data was identified: geography, geology, hydrology, hydrogeology, meteorology, water engineering, land management, and others. Existing projects and data models

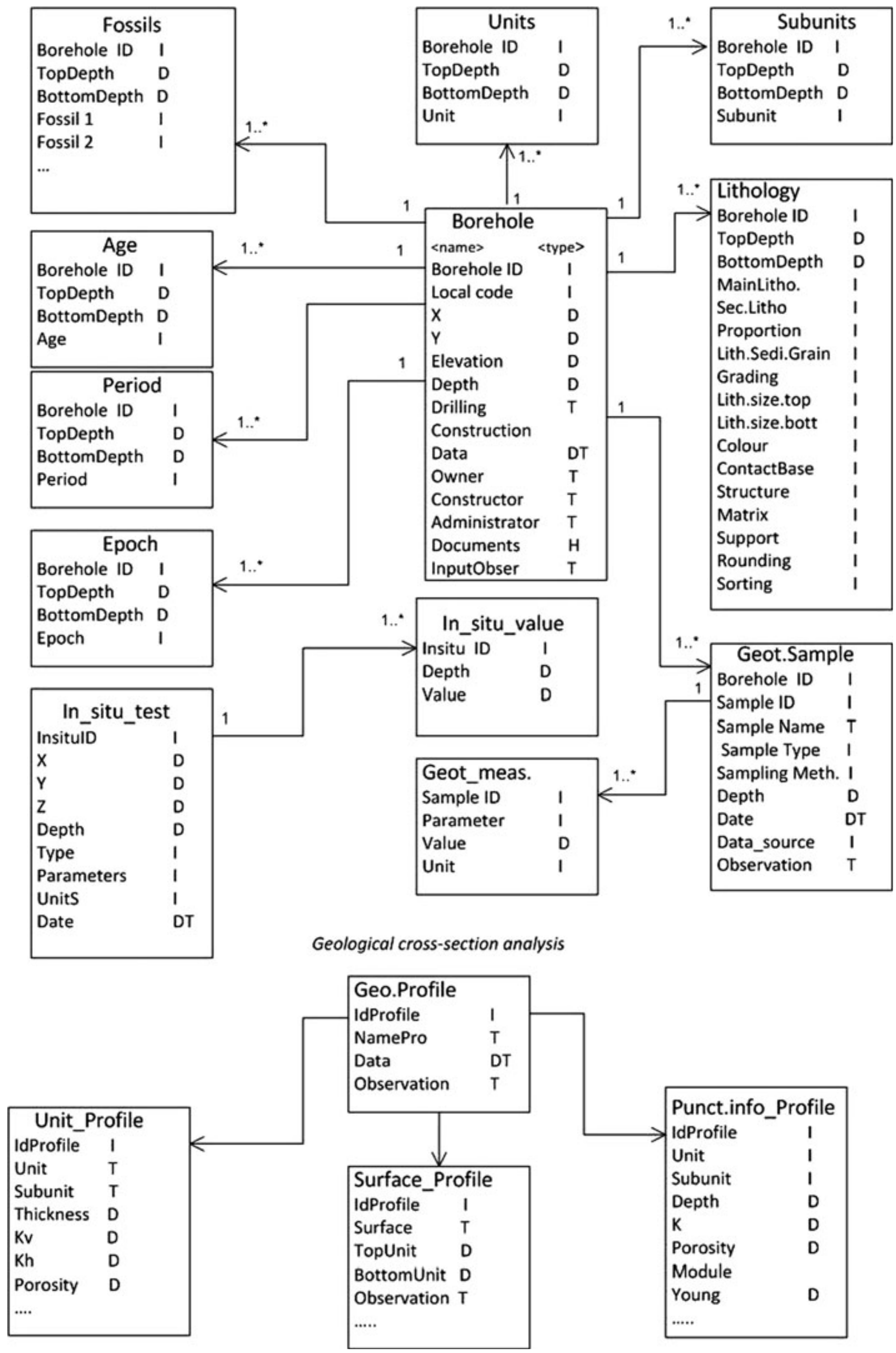


Fig. 2 Simplified conceptual diagram representing the main geological contents of the hydrogeological geospatial database. The *1* and *1..** represent the cardinality of the relationship between tables and *I* Integer, *D* double, *DT* date, *T* text

were also explored to identify possible interactions and contributions.

The architecture of the hydrogeological database is in accordance with international standards concerning geospatial data encoding and transfer. This is reflected in its object-oriented approach supported by the Open Geospatial Consortium (OGC) and the International Organization for Standardization (ISO).

Several existing patterns or data models were explored and are listed below:

- The Australian National Groundwater Data Transfer Standard (1999).
- HYGES hydrogeological database of University of Liege (Gogu et al. 2001).
- ArcHydro: ESRI hydrological data model (Maidment 2002).
- Water Framework Directive and its Geospatial information working group (Vogt 2002).
- GML: Geography Markup Language (Lake 2005).

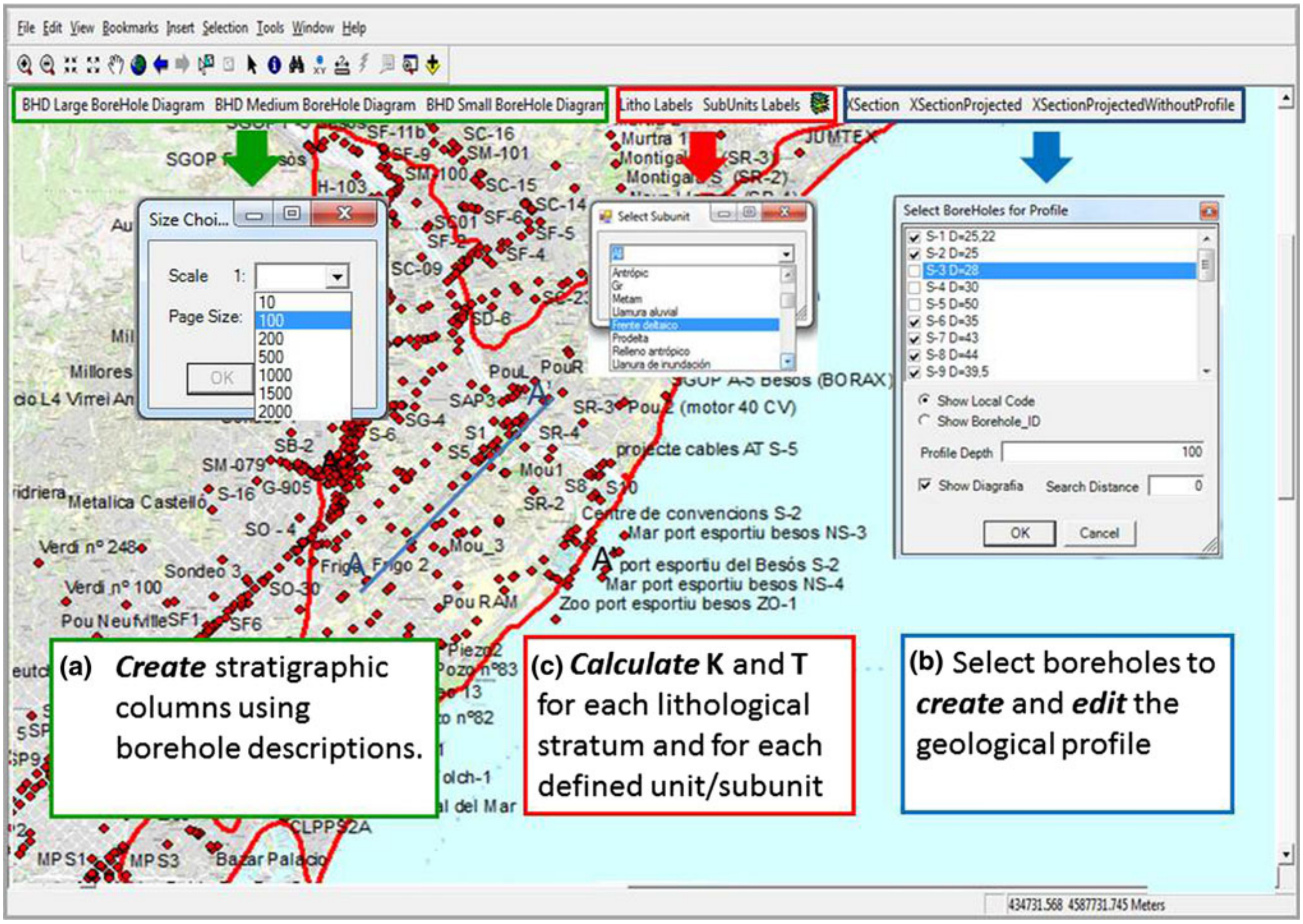


Fig. 3 Sketch representing the toolbar implemented in ArcMap (ArcGIS, ESRI) of the three main sets of instruments created to facilitate the detailed stratigraphic analysis and the estimation of the sedimentary media hydraulic conductivity: **a** Borehole diagram instruments; **b** stratigraphic cross-sections correlation tools; **c** tools for hydraulic conductivity initial estimation. For further details, please see epigraph *Lithological and stratigraphic analysis tool* and *Tool for the hydraulic conductivity initial estimation* of the section "GIS-based platform for 3D geological analysis"

- GeoSciML, a generic Geoscience Mark-up Language (Sen and Duffy 2005).
- Groundwater Model of University of Texas, (Strassberg 2005).
- XMML (eXploration and Mining Markup Language) as a GML application schema (Cox 2004; XMML 2006).

Based on these models a new and more comprehensive was prepared. This model characterizes additional hydrogeological information that is better suited to the particularities of the sedimentary media.

The main components of the hydrogeological database include groundwater features, hydrographic, drainage, and geologic features. The details of the hydrogeological database fall beyond the scope of this paper. However, further details of the geological components of the database and its relations are here given to illustrate the presented modelling platform.

The database structure allows us to store an accurate and very detailed geological description that can be generalized and upscaled (Fig. 2).

Petrological characteristics are described for sediments in terms of textural (sediment size, sorting, roundness, matrix support), lithological type, colour, and others. Likewise, fossil contents, sedimentary structures, and geological unit's chronology are also stored. Consequently, relationships between the petrological, paleontological, and chronological data can be established. Moreover, geotechnical properties (*N* value from Standard Penetration Test, total core recovery, geotechnical samples) obtained from boreholes and electrical geophysical logs (gamma logs, spontaneous potential, and resistivity logs) were also introduced into the database. Descriptions of boreholes or samples and their interpretations are stored separately, thus allowing further reinterpretations.

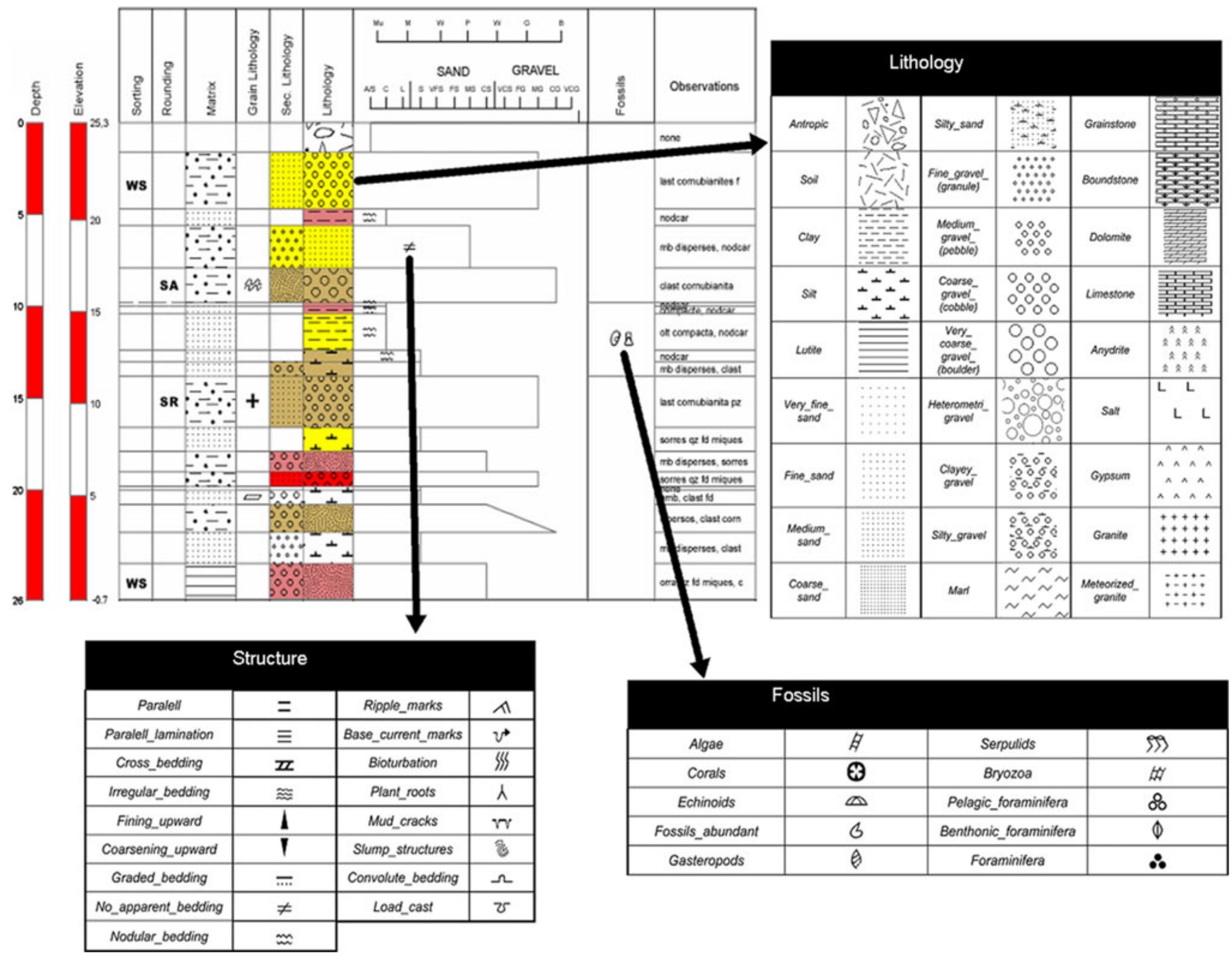


Fig. 4 Scheme showing the representation of the petrological characteristics for sediments in terms of textural (sediment size, sorting, roundness, matrix support), lithological, colour, and other properties in a stratigraphic column obtained using the tool *Borehole Diagram*

The general frame of the database scheme was designed taking into consideration the existing hydrogeological model of the Llobregat Delta (Vázquez-Suñé et al. 2006) and the Barcelona plain (Tubau et al. 2010) both located in Barcelona (Spain).

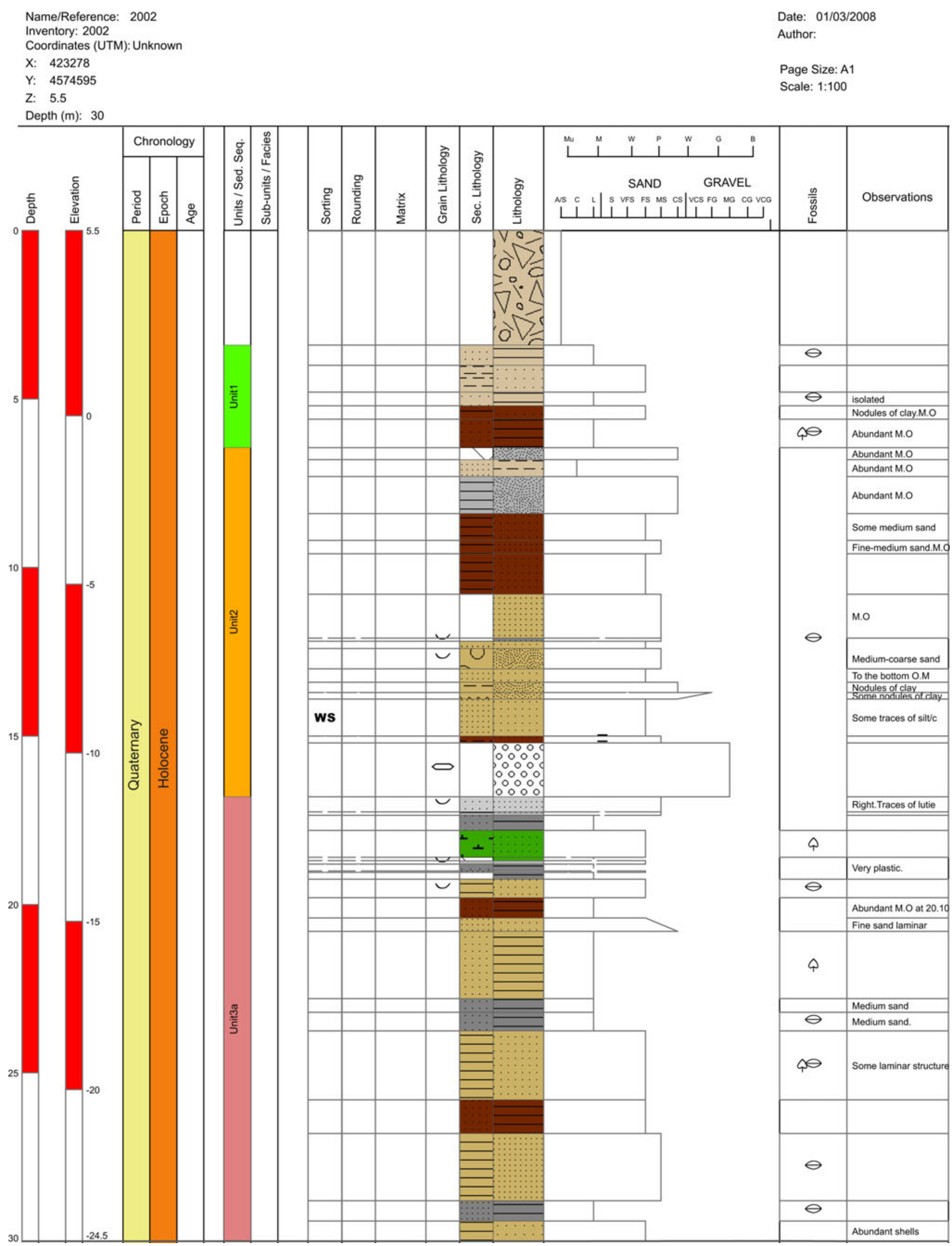
Lithological and stratigraphic analysis tool

The instruments of lithological and stratigraphic analysis were designed to facilitate the interpretation of the geological data. As stated above, this set of tools consists of two subcomponents: (1) *Borehole diagram instruments* and (2) *Stratigraphic cross-sections correlation tools.*

Both extensions have the form of a toolbar tightly integrated within the ArcMap environment (ArcGIS, ESRI) (See Fig. 3).

Borehole diagram instruments This tool was developed to facilitate the visualization and the analysis of the detailed geological core description of the borehole. To make the analysis easier, data visualization was designed in line with the classic working environment of the geologist. By selecting a point that represents a borehole on the map, the user is able to query the attached lithological and stratigraphic information. In addition, the user can optionally attach information of geophysical in situ tests such as diagraphies. Figure 4 shows that for each lithological stratum, the petrological characteristics can be visualized in terms of texture (sediment size, sorting, roundness, and matrix support), lithology, and colour. The sedimentary structures, the geological layer boundaries, the subdivisions in units or subunits, their chronology, and their paleontological content are also displayed.

The user can generate borehole core views in varying degrees of detail, at different vertical scales and in several paper formats. The resulting stratigraphic column diagram can then be exported to various graphical formats. An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Unit1
Unit2
Unit3a
WS
isolated
Nodules of clay.M.O
Abundant M.O
Abundant M.O
Abundant M.O
Abundant M.O
Some medium sand
Fine-medium sand.M.O
M.O
Medium-coarse sand
To the bottom O.M
Nodules of clay
Some nodules of clay
Some traces of silt/c
Right.Traces of lutie
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Abundant M.O at 20.10
Fine sand laminar
Medium sand
Medium sand.
Some laminar structure
Abundant shells

◀ **Fig. 5** Result of the Borehole diagram query procedure. The lithology is defined by three components: lithology (main litholgy), secondary lithology and matrix

example of a query resulting in a borehole diagram format is shown in Fig. 5.

Stratigraphic cross-section correlation tool This instrument facilitates the process of stratigraphic well correlation, in this way improving the geological interpretation of the sedimentary media.

It regroups a set of tools that starts from the creation of a geological profile (Fig. 6) by querying a buffer zone line on a map that the user draws on the screen. A wizard opens and enables us to select certain cross-section properties such as buffer distance, labels of the boreholes (name or code), display of graphical results of in situ tests, vertical and horizontal scales, etc. The cross sections can be created by keeping the distance between boreholes or by projecting them on a line. The profile is generated automatically by displaying the lithological columns of the boreholes together with the defined stratigraphic units/subunits and the graphical results of in situ tests. Complementary information such as the surface terrain profile extracted from the DEM, the distance between the boreholes, and the depth of each stratum is shown.

Thus, an interactive analysis environment (Fig. 7) is created for a subsequent set of instruments. The user is able to analyze and to vectorize on screen the existing stratigraphic elements using lines, polygons, or points. It is possible to store a set of attributes such as the type of the contact, the position between the hydrogeological units or subunits, and different hydraulic parameters or other observations for each feature. Existing faults and fractures can be identified and drawn on screen within the same environment.

Although a cross section is a 2D representation, the geological features defined by the user can be visualized in 3D in ArcScene. The export procedure provides spatial features such as points, lines, or polygons with their attached attributes. The visualization of several cross sections describes a 3D panel forming part of a fence-diagram.

Using inherent editing tools of ArcGIS, the user can generate a raster surface representing the top and the bottom of the defined geological units.

The resulting 3D features can be exported to external software packages for further stochastic analysis or for constructing a geological 3D model.

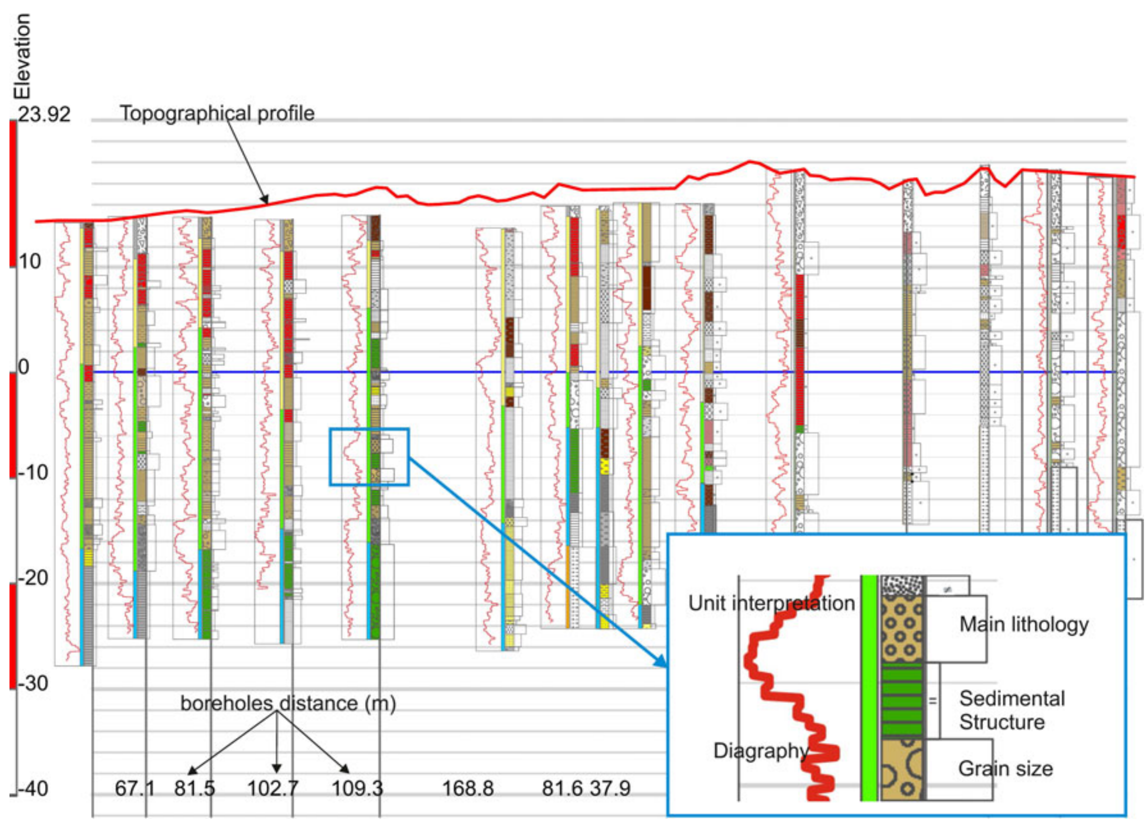

Fig. 6 Geological profile generated by displaying the boreholes lithological columns together with the related stratigraphic subunits and diagraphies

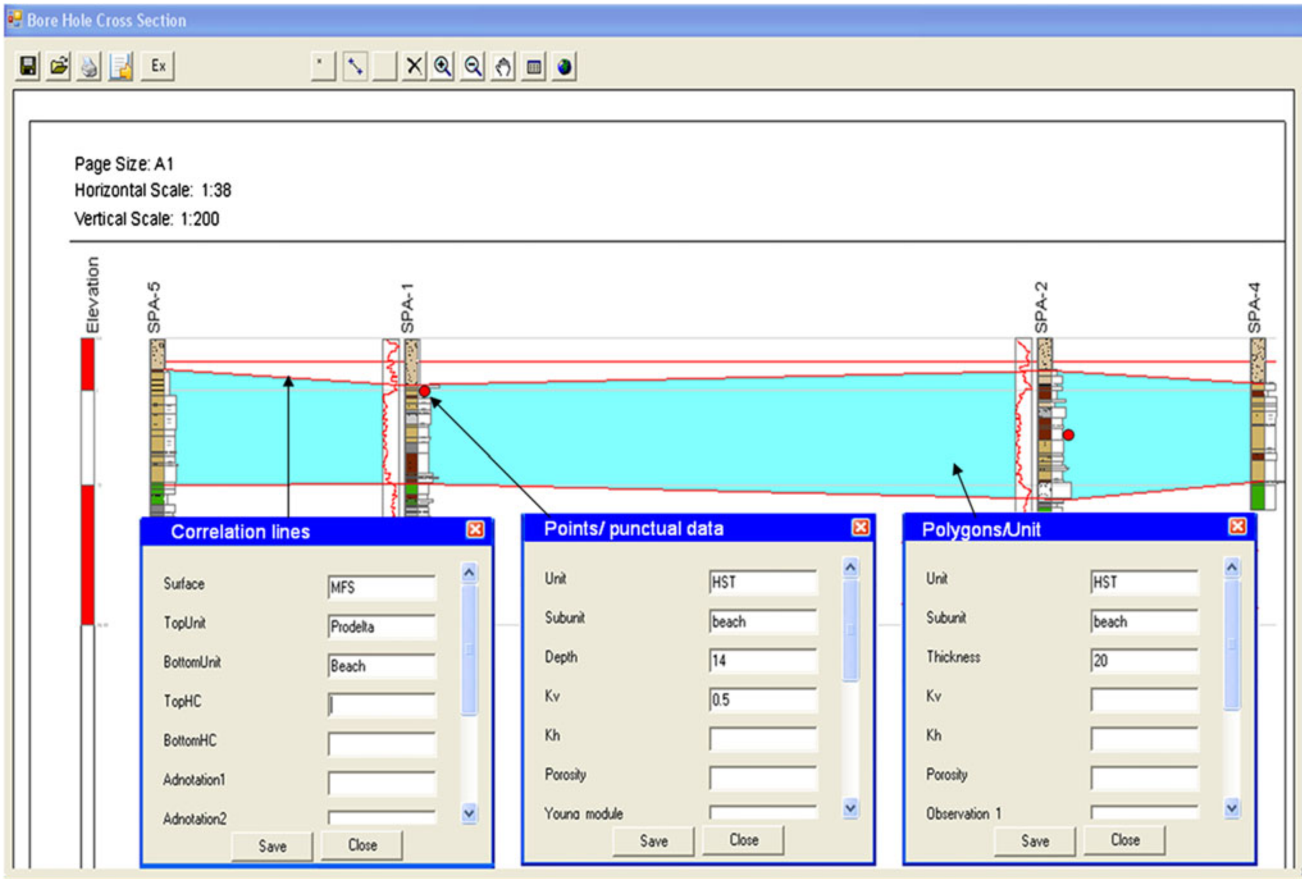

Fig. 7 The stratigraphic working environment (the geologists draw their sections based on different borehole-log correlation techniques)

Tool for the hydraulic conductivity initial estimation

Hydraulic conductivity is a function of material texture although it specifically represents the ease of water flow through the porous media (Bonomi 2009). Accordingly, several steps were undertaken to quantify the hydraulic conductivity based on the grain size distribution.

Hydraulic conductivity can be computed automatically for each lithological interval defined in the boreholes or for the user-defined hydrogeological units using a set of tools. This was based on the existing lithological descriptions using different approach.

Each lithology listed in the database is associated with hydraulic conductivity values obtained from the literature (Freeze and Cherry 1979; Custodio and Llamas 1983). In the lithological table (*Lithology*; see Fig. 2), the lithology of a downhole interval is defined by the main lithology field, the secondary lithology field and finally by the matrix field. Another field termed *proportion* provides the proportion of each lithology in this interval in terms of percentages.

An equivalent hydraulic conductivity can be calculated for each interval of the borehole, taking into account the permeability values assigned to each lithology and its grain size distribution in terms of percentages.

The approach adopted for the calculation of hydraulic conductivity of the defined units was based on the traditional calculation methods of hydrologically equivalent horizontal and vertical conductivity (Custodio and Llamas 1983).

This methodology calculates the hydrologically equivalent horizontal hydraulic conductivity (k_{h}) for the model units using:

$$(k_{\mathrm{h}}) = \frac{1}{L}\sum b_i \cdot k_i \tag{1}$$

where each lithological interval requires an assigned nominal hydraulic conductivity (k_i) and the thickness of each interval (b_i). Moreover, the unit thickness (L) is the sum of the thickness of each defined downhole interval:

$$L = \sum b_i \tag{2}$$

Furthermore, the hydrologically equivalent vertical hydraulic conductivity (k_{v}) for the model units is calculated using:

$$1/k_v = \frac{1}{L}\sum \frac{b_i}{k_i} \quad (3)$$

This approach has also been adopted by Brodie (1999).

Transmissivity values are also obtained automatically for each user-defined unit/subunit by multiplying the unit thickness with its equivalent hydraulic permeability.

The values of hydraulic conductivity and transmissivity can be used as initial estimated values for the hydrogeological model or as an additional geostatistic analysis in the ArcGIS environment or in external software. The dating of this procedure is on-going.

Application

One application of the software platform is discussed in Velasco et al. (2012). This consists in the geological and hydrogeological characterization of the entire emerged Besòs Delta (Barcelona, Spain) in addition to 5 km from the coast line of the submerged part.

Owing to the location of the delta, part of which is occupied by the city of Barcelona, the region has undergone considerable urbanization. As a result, most of the previous existing rocky and sedimentary outcrops have disappeared. However, the recent increase in the number of geological, hydrogeological, and civil engineering works has provided a great deal of new data. Consequently, this constitutes an optimum moment for constructing a geological model that integrates a database storing several boreholes, in situ tests, geotechnical, hydrogeological information and earlier geological interpretations, etc.

The Besòs delta is a depositional system created during the Quaternary by the sediments of the river Besòs. The deltaic succession shows an unconformity on a basement formed by Palaeozoic and Cenozoic rocks, The Palaeozoic lithology consists mainly of slates and granite. The Cenozoic rocks are mostly made up of matrix-rich gravels and sandstones of Miocene age and of massive grey marls attributed to the Pliocene.

Like the neighbouring Llobregat river delta (Gàmez et al. 2009), the Quaternary sedimentation of the Besòs river delta has been mainly controlled by sea-level changes, Quaternary glaciations and fault activity.

The geological model of the Besòs delta in this study is based on a sequence stratigraphic subdivision. This subdivision resulted from the identification of key stratigraphic surfaces and the general trends (progradational-retrogradational or coarsening-fining upwards) observed in the marine and transitional sediments in the boreholes.

In this paper, we focus on a case study of a portion of the aforementioned geological model. We undertook a hydrogeological characterization of this area to evaluate the potential impact of an exploitation of the aquifers with the main aim of providing an alternative to the heating and refrigeration system at a building located in the study area (Barcelona, Spain).

The details of the hydrogeological model fall beyond the scope of this paper. Only the creation of the geological model using the instruments and methodologies described is presented.

The location of the study area is shown in Fig. 8a. Nine stratigraphic units forming part of the hydrogeology of the regional domain were identified (A–F2, Table 1).

First, the *Borehole diagram instruments* of the developed software platform enabled us to visualize and analyze the borehole-log data and the geophysical log data to identify the aforementioned geological units.

The *Stratigraphic cross-section correlation tools* allowed us to correlate these units between the boreholes in six cross sections. Figure 8a displays the borehole location, and the section lines and Fig. 9 shows some of the resulting cross section.

Based on the features defined in the cross section, several raster layers and triangular irregular network (TIN) corresponding to the top surface of each geological layer were created using editing tools of ArcGIS.

With another set of editing tools of ArcGIS, isopachs maps were obtained from these raster layers and TIN. These surfaces with their attributes were then converted to *shapefile* and were directly exported to the groundwater modelling package Visual Transin (UPC 2003), which is a friendly user interface of TRANSIN (Medina and Carrera 2003) to build up a quasi-3D hydrogeological model.

The next step was the hydraulic parameterization of the interpreted geological units. The definition of different zones of hydraulic conductivity was calculated taking into account and comparing the estimated values obtained with the hydraulic conductivity tools and the punctual values derived from hydraulic tests (performed in this study and earlier studies) stored in the hydrogeological database. Further insight into the study area can be obtained by visualizing subsurface features in a 3D environment. Figure 8b shows the fence diagram in ArcScene obtained by visualizing the features defined in the cross sections. The model developed using the described GIS analysis instruments can also be used to construct a complete 3D geological model. Moreover, it can be exported to a numerical pre-processor to create a 3D hydrogeological model. To this end, GID software developed by CIMNE Centre (International Centre for Numerical Methods in Engineering; UPC –Generalitat de Catalunya) was selected as pre-processor to generate the 3D finite element mesh needed for groundwater modelling (see Fig. 8c).

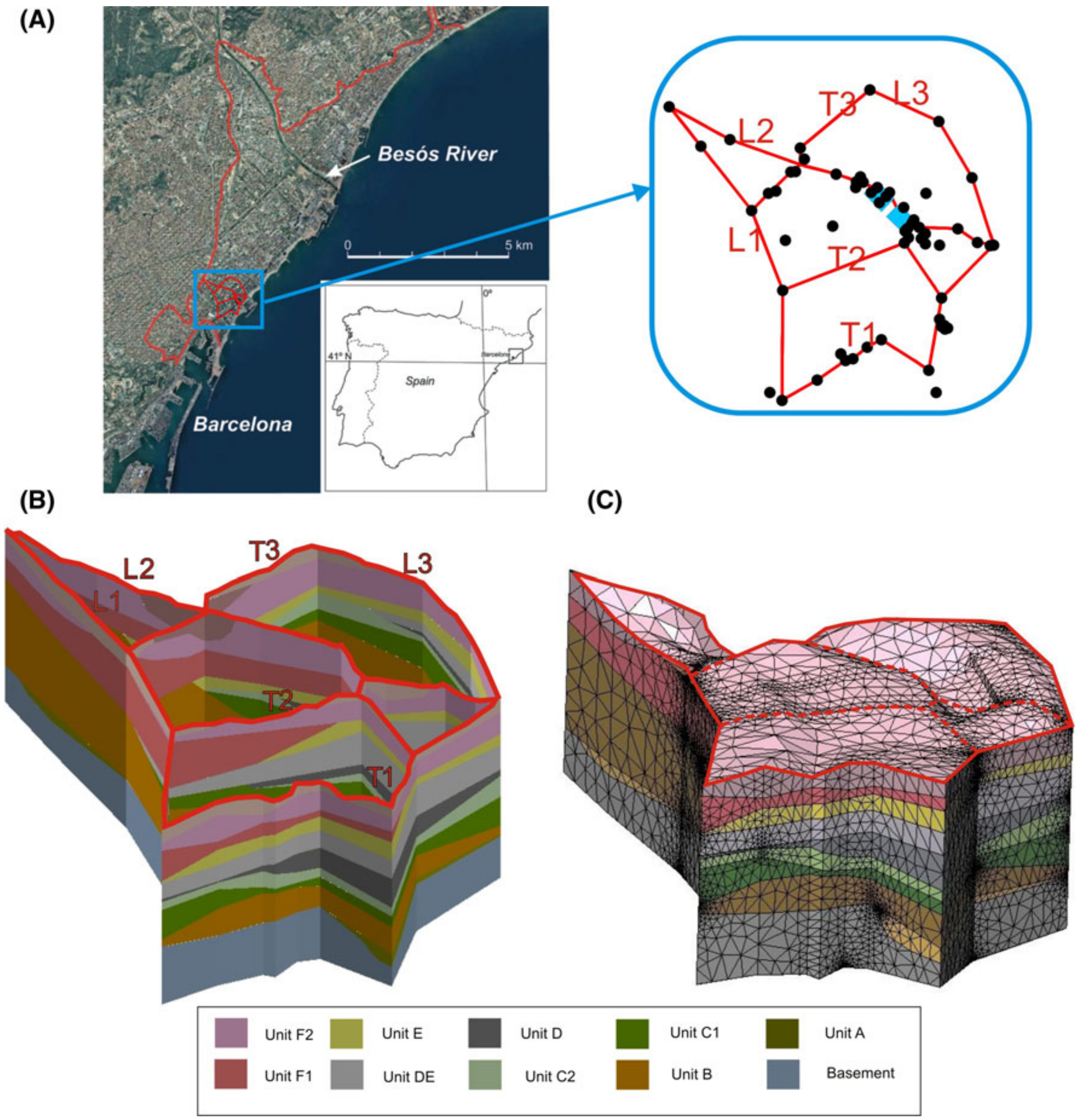

Fig. 8 **a** Location of the study area. The *red line* marks the boundary of the upper delta plain of the Besós river delta (Northeast Spain). The satellite image is provided by the Cartographical Institute of Catalonia. **b** Geological model of the Besòs delta viewed by means of seven cross-sections generated, showing the geometry and continuity of the seven geological units distinguished. This model has been visualized in ArcScene. **c** 3D geological model created by importing the 3D features defined with the developed instruments into the software platform GID

Discussion and conclusion

This study presents a software platform representing a working environment to integrate 3D geological models of the sedimentary media in regular hydrogeological modelling methodologies. In line with this approach, several advantages should be highlighted. First, the structure of the spatial database allows us to store data for most geological and hydrogeological studies. This type of database has been designed to manipulate spatial and time-dependent information more efficiently than other platforms and allows the user to store and manage an accurate geological description that can be further upscaled.

In addition, the possibility of querying and visualizing the stored information allows the user to integrate all the data and thus obtain further relevant information. The integration of detailed core stratigraphic and lithological descriptions with hydrogeological local and regional parameters, hydrogeological tests (pumping and tracer tests), hydrologic features and geophysical and geotechnical information, etc. provides the user with a consistent image of the aquifer behaviour under study.

Table 1 Description of the facies association of the different geological units identify in the Besòs delta and in the model of the study area

Age	Geological units	Sedimentary environmental deposits/facies association	Description
Post-glacial	F1	Delta plain (floodplain deposits)	Red and yellow clays
	F2	Delta plain (fluvial channel fill deposits and alluvial deposits)	Poorly sorted gravels, occasionally with sandy matrix and some lenses of organic matter. The pebbles are well rounded and polymictic
	E	Regressive delta front	Yellow to grey coarse grained facies belt made up by sands and gravels (from distal to proximal). Shells fragments
	DE	Transition between prodelta and regressive delta front	Yellow to grey coarse sand with clayey/silty matrix. Shells fragments
	D	Prodelta	Grey clay and silts with intercalation of fine sand and with marine fauna
	C2	Transgressive delta front	Gravels well rounded to angular pebbles with sand. Shell fragments
	C1	Fluvial channel fill deposits (delta plain)	Poorly sorted gravels, occasionally with sandy matrix and some lenses of organic matter. The pebbles are well rounded and polymictic
Pleistocene	B	Delta plain (floodplain deposits and channel fill deposits)	Red and yellow clays intercalated with fluvial channel fill deposits which consist of poorly sorted gravels and sand with some lenses of organic matter
	A	Fluvial channel deposits	Poorly sorted gravels, occasionally with sandy to silty matrix. The pebbles are well rounded and polymictic

Modify after Velasco et al. (2012)

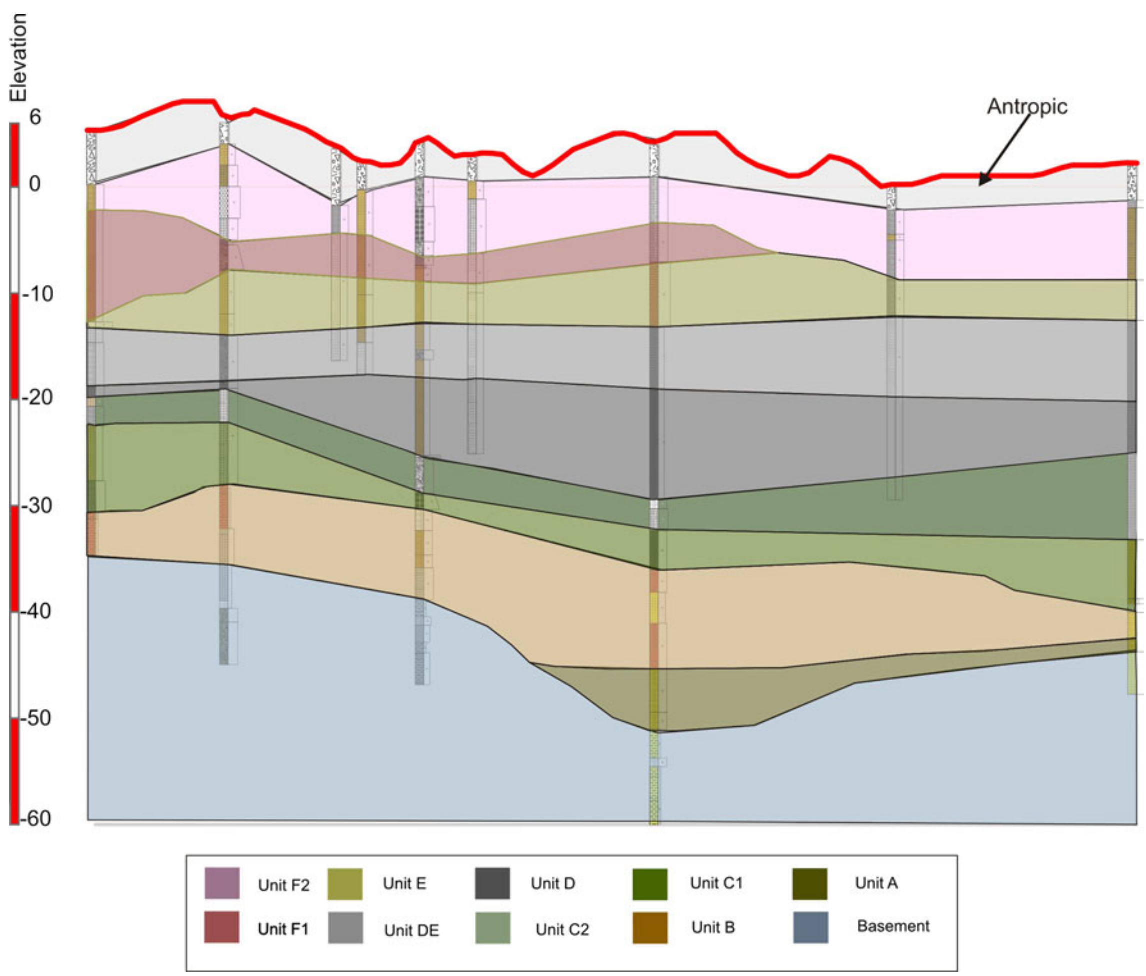

Fig. 9 Cross section parallel to the coast (T1, see Fig. 8a for location). The defined units can be visualized. See Table 1 and section "Application" for detailed description of the units

Another important advantage is that the use of the spatial database facilitates data integration concerning land-use, infrastructure design, and environmental aspects. The relationship between the groundwater and the main urban contaminant factors (sewerage system, water supply network, etc.) and the interaction of the groundwater with major civil works (subway tunnels, underground parking lots, etc.) is highlighted. As a result, it is possible to study different problems in a more realistic manner to improve our understanding of the geology and hydrogeology of urban areas.

Apart from the database, the software platform contains several specific tools developed in ArcGIS (ESRI) designed to exploit the stored data. The use of these tools in combination with the ArcGIS capabilities increases the functionality of the software, which provides a comprehensive stratigraphic analysis and a subsequent geological modelization with a minimized learning curve.

One of these tools enables us to obtain stratigraphic columns, where relevant information such as texture, lithology, fossil content, chronology, results of in situ test and earlier interpretations is shown together. This is an optimum environment for facilitating the interpretation and the identification of different sedimentary units/subunits.

The software platform also contains tools that support a variety of workflows for creating cross sections. This system allows the modelling of the distribution and geometry of the sedimentary bodies by knowledge-based control of the modeller.

As shown in this paper, the 2D features defined in the cross sections can be converted into a 3D environment. The resulting 3D features can be visualized as fence-diagrams in the same GIS environment using ArcScene or can be exported to external software packages to construct 3D geological models.

Despite these advances, there are still limitations in trying to construct 3D bodies using the 3D features defined in the cross sections. This is especially true for sedimentary bodies, the geometry of which is very complex and/or whose extent does not cover the whole area of the model (e.g. paleochannels).

Apart from these technical issues, the reliability of the geological model depends on the amount of data available, its nature and on its distribution over the area of interest.

This study seeks to provide a methodological approach and a set of tools for the detailed reconstruction of the hydraulic characteristics of sedimentary bodies.

Despite the fact that the hydraulic properties of the aquifers may be calculated automatically using a set of tools, further work on these techniques should be conducted in this line to improve the usefulness of the platform presented.

Several features are planned for a future version of the software, which will extend its functionality.

This software platform enables us to set up an updatable model database for further downscaling. We used the Besòs Delta Model as a framework for the modelization of the study area. Likewise, some details extracted from the study area contributed to our understanding of the regional model.

The design of the tools presented is in line with the classic working instruments used by the geologist to characterize a study area. Although the main goal of the instruments described was to yield further insights into groundwater modelling of sedimentary media, the field of applications can be easily extended.

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Preface

These two volumes contain the proceedings of the 9th International Congress of Hydrogeology and the 4th MEM Workshop on Fissured Rocks Hydrology, organized by the Hellenic Committee of Hydrogeology in collaboration with the Cyprus Association of Geologists and Mining Engineers.

The number of the manuscripts submitted to the Organizing Committee throughout 15 countries all over the world reflects the rapidly increasing interest that Hydrology gains nowadays worldwide. The papers cover more or less all fields, such as mathematical modeling, statistical, hydro-chemical methods, etc., focusing on the environmental aspect.

Aquatic environment, the main topic of the Congress, as it is shown by the title of the Proceedings "Advances in the research of aquatic environment" is covered by articles mostly dealing with ecological impacts *versus* water requirements, climate change implications on groundwater, anthropogenic impacts on the groundwater quality, groundwater vulnerability, and more.

Both volumes follow the general structure of the Congress topics. Moreover the keynote lectures are also included.

On behalf of the International Scientific Committee I would like to take this opportunity to thank all the authors for their contributions, as well as all participants for their cooperation, which made this Congress possible. Additionally, I would like to express my gratitude to the staff of Springer and especially Christian Witschel and Agata Oelschlaeger for their hard work, patience and support.

Last but not least, I would like to thank my wife Aggeliki and my children Athina and Ioannis for their patience and love.

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Sedimentary media analysis platform for groundwater modeling in urban areas

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Abstract In Europe numerous urban areas are located in the flood plains of the rivers. Sedimentary media (alluvial sediments, deltas, etc.) form particular frequently occurring environments within these valley fills. However, sedimentary media are normally significant aquifers due to their high permeability, storage capacity, interaction with surface water, etc. A reliable management of the hydraulic resources in urban areas can be performed only by using modeling. The models can provide accurate results if they correctly reproduce the hydrogeological processes. Tools and methodologies should allow the representation in three dimensions of the geological record heterogeneity and of its spatial distribution as well as the interaction of the groundwater with the urban infrastructure. The paper will focus on the main aspects of these instruments, which are currently developed within a national research project, that have to support 3D hydrogeological modeling. Within this project a software platform has been developed containing methodologies and tools that facilitate the integration of the 3D geological models in sedimentary media into the hydrogeological modeling of flow and contaminant transport. This is composed by a geospatial database and a set of tools allowing accurate stratigraphical analysis. An application of this platform is currently developed for the Moesic aquifer system (Bucharest city Region).

1 Introduction

In Europe numerous urban areas are located in the flood plains of the rivers. Sedimentary media form particular frequently occurring environments within these valley fills. However, sedimentary media are normally significant aquifers due to their high permeability, storage and management ability, interaction with surface water, etc. A reliable water management can be obtained by groundwater modeling. The models allow conceptualizing and quantifying the hydrogeological processes and simulate various scenarios as droughts, water resource exploitation, water quality evolution and contamination aspects, interaction with civil works in terms of hydraulical and geomechanical ground behavior.

These models can provide accurate results if they correctly reproduce the hydrogeological processes. Nevertheless, it is well-known that sedimentary media are normally extraordinarily heterogeneous, which is a paradox as it leads to simplified models based on the homogeneity of large zones characterizing the medium. The paper presents a software platform containing methodologies and tools that facilitate the integration of the 3D geological models in sedimentary media into the hydrogeological modeling of flow and contaminant transport. This is composed by a geospatial database and a set of tools allowing accurate stratigraphical analysis. The geospatial database is used for the management of a large amount of different data types coming from different sources (geophysical, geological, hydraulic, and others). Its structure allows storing accurate and very detailed geological core description that can be straightforwardly generalized and further upscaled.

The obtained methods and tools are used for spatial data manipulation, which support understanding the detailed geology of the sedimentary media and the integration of the geological processes that controlled their formation. From the existing data and the developed methods, the petrophysical characteristics could be extrapolated to the entire sedimentary volume considered at a local level, by using various techniques such as the deterministic or stochastic methods.

The described platform has been initially designed starting from the existing hydrogeological model of Barcelona region (Vázquez-Suñé et al. 2006). Currently an application of this platform is developed for the Moesic aquifer system of Bucharest city area. This involves: (1) 3D geological characterization - application of the methodologies and developments suggested, (2) 3D parameterization of the Moesic aquifer system (Fratesti strata, Mostistea, and Colentina), (3) Management of the hydrogeological data base (tests and hydraulic parameters, level data, hydrochemical data, etc.), (4) Hydraulic definition/parameterization of facies and other geological concepts and, (5) Interaction between underground infrastructure and groundwater.

2 Study case geological and hydrogeological conditions

In the Bucharest city region, the Moesic platform shows two main aquifer types (Fig. 1). One is a regional high depth fissured-karstic carbonate aquifer of the Superior Jurassic – Inferior Cretaceous and the other one is located in the Pliocene and Pleistocene raw deposits.

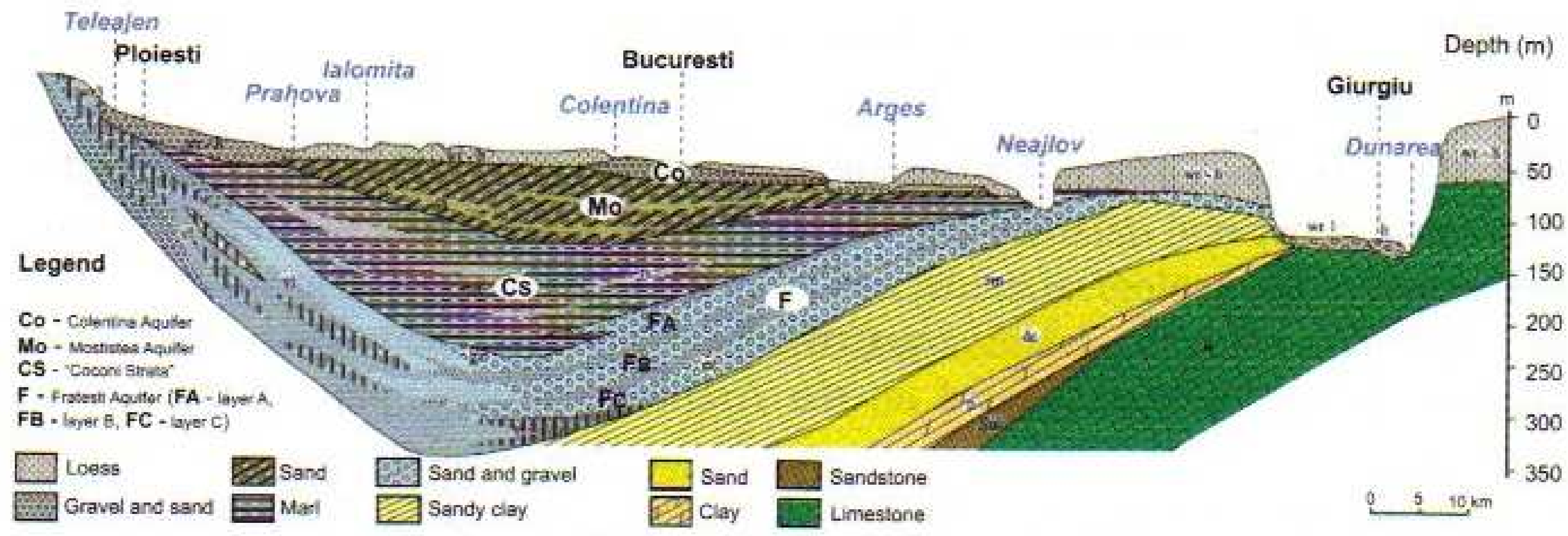

Fig. 1. Hydrogeological cross-section of the study area.

The second aquifer system called "Fratesti strata" (Liteanu 1953) is placed in the Tertiary deposits of the Upper Pleistocene and of Lower Pleistocene. This represents the main hydrogeological formation used for water supply of the South-Eastern Romania. It behaves as a confined multilayered aquifer. On the Northern side, the Fratesti strata aquifer system is made of three main layers indexed as A, B, C. These layers are regrouped in the Southern part forming a single aquifer layer. The thickness of the three layers shows a spatial variability. The mean thickness of the A aquifer layer is between 25 and 60 m. Its hydraulic conductivity takes values between 12 -24 m/day and 4-12 m/day in Northern Bucharest. The B aquifer layer is located at a higher depth and its mean thickness is between 5 and 50 m. The mean thickness of the deepest aquifer layer (C) is between 25 and 30 m. Between the three aquifer layers (A, B, and C) sandy-clayey strata with a thickness variation of 40 m to 5 m can be found (Pascu 1983). A sequence of marl and clay layers with slim sandy intercalations overlay the "Fratesti strata". In the Bucharest area its thickness decreases from north to south from about 150m to 40m. The marl sequence is covered by a permeable raw rocks layer made of fine and medium sands with gravel intercalations. This is called "Mostistea sands" aquifer and is located at depths between 25 m and 70 m. It is a confined aquifer and its hydraulic head takes values similar to another upper aquifer layer. The upper aquifer stratum of these quaternary formations called "Colentina gravels" is made of gravels and sands. This unconfined aquifer can be found mainly in the Bucharest city region at depths between 15 m and 20 m. However the water quality is quite low, the groundwater level can be found at 5 to 10 m depth. The aquifer thickness is between 3 to 5 m showings a variation of the particle size distribution. The hydraulic conductivity varies between 10 m/day and 70 m/day, sometimes being higher than 100 m/day. A clayey-marl layer is located between the "Mostistea sands" and the "Colentina gravels".

3 The analysis software platform

The 3D analysis platform for groundwater modeling is composed by a hydrogeological geospatial database and several sets of instruments facilitating the development of the geological model and allowing hydrogeological analysis. One set of instruments using the database spatial information is dedicated to stratigraphical analysis. It has been developed on the ArcMap software, part of the ArcGIS (ESRI) package. This considerably extends the functionalities of ArcMap. Another set of instruments allows borehole local estimation of hydraulic conductivity for lithological strata and for stratigraphical units.

The Hydrogeological Geospatial Database

The design of geospatial database has an Object-Oriented approach and is easily extensible. A large spectrum of data was identified, as many related domains are concerned: geography, geology, hydrology, hydrogeology, meteorology, water engineering, land management and others. The architecture of the hydrogeological database (Figure 2) follows international standards for geospatial data encoding. This is reflected in its object-oriented approach supported by the Open Geospatial Consortium (OGC) and the International Organization for Standardization (ISO).

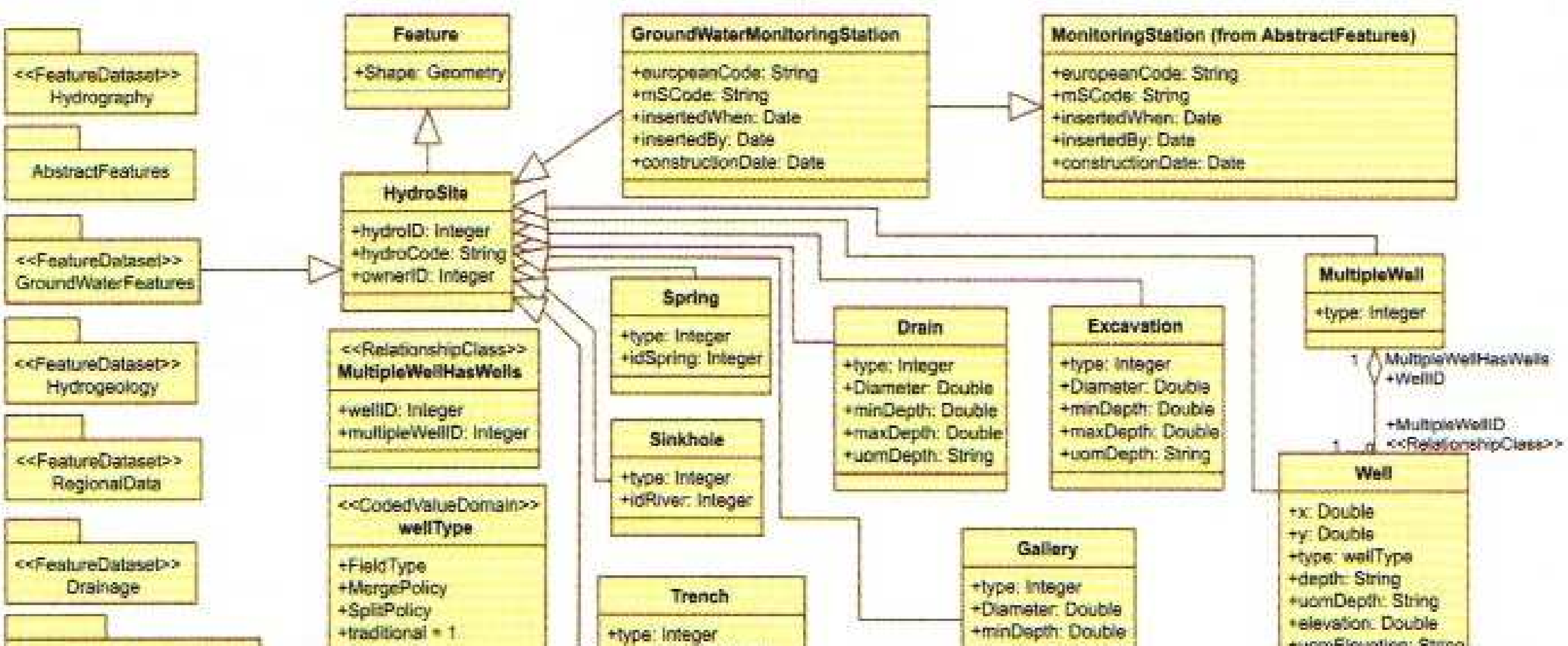

Fig. 2. Overview of the hydrogeological database scheme.

The database structure allows storing an accurate and very detailed geological core description that can be straightforwardly generalized and further upscaled. It serves to improve the quantification of the hydrogeological parameters. Relationships between the petrological, paleontological, chronological data could be established. Petrological characteristics are described for clastic and carbonated sediments in terms of textural (sediment size, sorting, roundness, matrix support), lithological, colour, and others. The sedimentary structures, the geological layers boundaries, the geological units chronology or facies assignment, the paleontological content, and some complementary information are represented.

Lithological and stratigraphical analysis tool

The design of the lithological and stratigraphical analysis instruments has been set up to facilitate firstly the hydrogeological data interpretation. This subset of tools is made of several subcomponents. One of them allows the visualization of the borehole core lithological and stratigraphical information. Another one allows generating the geological profiles by query and visualization of the lithological and stratigraphical information. By using the third set of instruments, the user is able to identify stratigraphic units, analyze their characteristics, and export them in a 3D environment.

Borehole diagram instruments

This tool has been developed in order to facilitate the visualization and the analysis of the borehole detailed geological core description. To ease the analysis, the data visualization was designed following the classical geologist working bearings. By selecting a point representing a borehole on the map, the user has the possibility of querying the attached lithological and stratigraphical information. For each lithological stratum can be visualized the petrological characteristics in terms of texture (sediment size, sorting, roundness, matrix support), lithology, and colour.

Stratigraphic cross-sections correlation tool

The basic idea of this instrument is to facilitate the process of stratigraphic well correlation to the geologist. This kind of perception pulls on the understanding of geological processes, examination of exposures, and theoretical knowledge gathered by the modeler. This set of tools starts from the creation of a geological profile by querying a buffer zone line on a map, the user is drawing on screen. The profile is generated automatically by displaying the boreholes lithological columns together with the defined stratigraphical units/subunits. Complementary information is shown like the surface terrain profile extracted from the DEM, the distance between the boreholes, and the depth of each stratum. On this basis, an interactive analysis environment is created for a subsequent set of instruments. The user is able to analyze and to vectorize on screen the identified existing stratigraphical elements by using lines, polygons, or points. For each feature a set of attributes like the type of the contact surface, the position between the hydrogeological units or subunits as well as different hydraulic parameters or other observations can be stored. Possible existing faults and fractures can be identified and drawn on screen within the same environment. The obtained information, represented by the user identified geological features, can be then converted within a 3D environment. The export procedure provides spatial features as points, lines, or polygons with their attached attributes. The resulted 3D features could be then used within the same GIS environment or by external software packages for further stochastic analysis or to build-up the geological 3D model.

Tool for the hydraulic conductivity initial estimation

Several steps have been made in quantifying hydraulic conductivity hydrogeological strata in boreholes, on the basis of the grain size distribution. For each lithological stratum or for the user defined hydrogeologic units, the hydraulic conductivity can be computed by using empiric formulas on the basis of the existing lithological description. This procedure could provide for the hydrogeologic models, hydraulic conductivity values closer to the reality.

4 Results and Discussions

Bucharest city area represents the first target for the software platform application on an alluvial environment. This is developed on the city region for the Moesic aquifer system. After analyzing large sets of data, the geological model is currently developed. Using the presented tools, several geological cross-sections are compiled. Figure 3 shows a cross-section located in the north-eastern part of the city.

The final target for the performed work focuses especially the characterization of groundwater, as well as the dynamics of water systems and their standard distribution in space. In this sense, the presented set of instruments represents a working environment for integrating the 3D sedimentary media spatial distribution standards of the different hydraulic parameters, in the regular hydrogeology modeling methodologies. The final goal is to explain the relationship between the computed hydraulic conductivity values and the effective-type values, which are the ones that in reality define the dynamics of the aquifers. This improves the conceptual model to build-up a hydrogeological model. The developed database structure allows storing data for most of the hydrogeological studies.

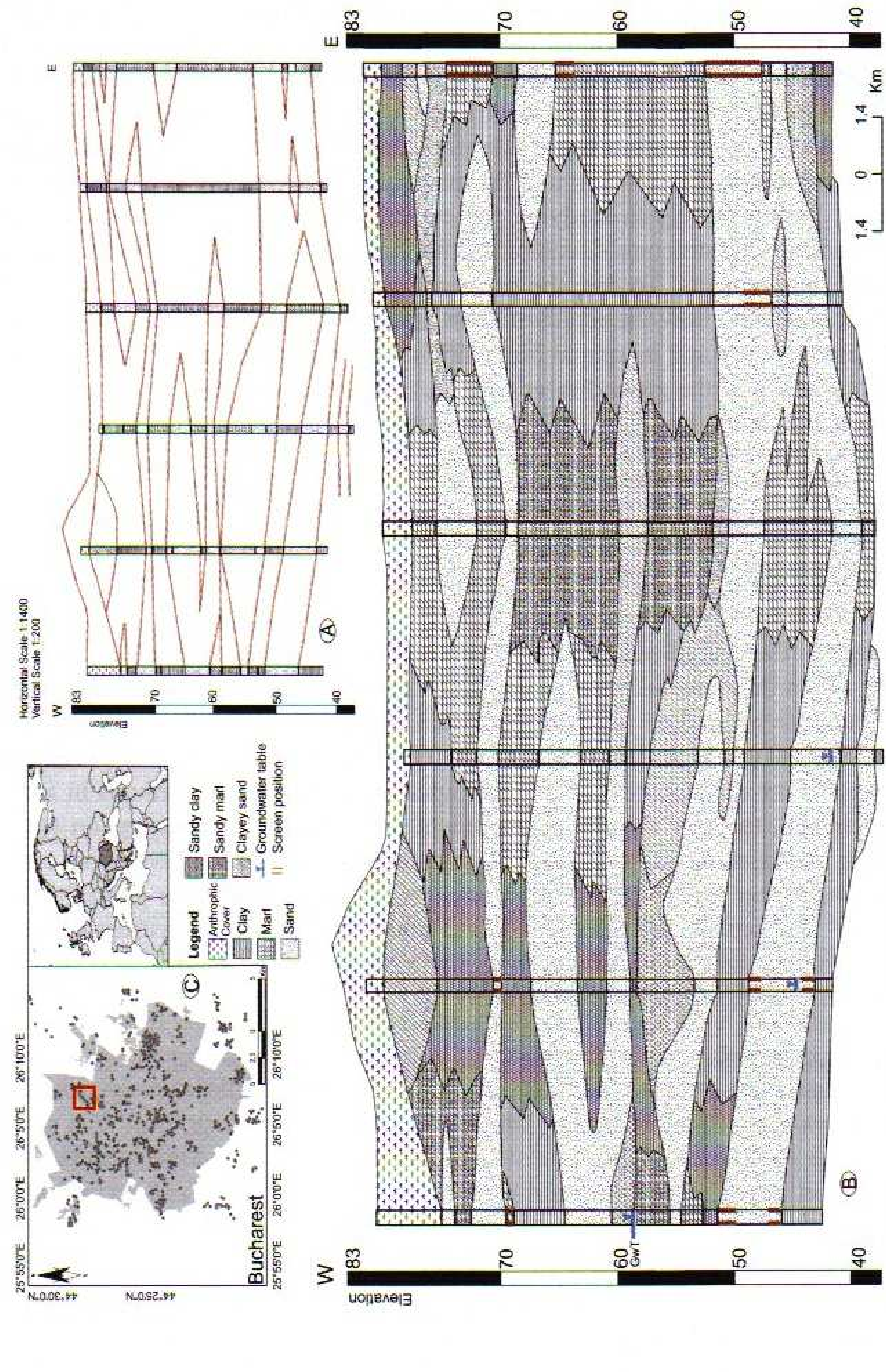

Fig. 3. Geological profile generated by using the stratigraphic cross-sections correlation tool (A - stratigraphic correlation tool output, B - geological cross-section interpretation, C - location of the geological profile on the map of Bucharest city).

The integration of detailed core stratigraphical and lithological description with hydrogeological local and regional parameters, hydrogeological tests as pumping and tracer tests, surface hydrology features, information related to different observations and measurements, give the user a consistent image on the studied aquifer behavior. As the described software allows performing detailed geological analysis, it also represents an excellent tool for managing and obtaining geotechnical information. This will help in studying the current geotechnical conditions and in recommending infrastructure development methods taking into account the environmental requirements. To date the presented software platform offers tools and methodologies that allow the representation in three dimensions of the geological record heterogeneity and its spatial distribution. The current research work focuses on the interaction of the groundwater with the urban infrastructure in terms of water supply and sewer systems, drainage systems of basements, subway network, and others.

5 Conclusions

The design of the described instruments is following the geologist classical way of working when they characterize geologically a study area. The instruments have been thought to be applied for hydrogeological analysis but they could be applied to other kinds of geological, geotechnical, or environmental studies. The presented work support the development of 3D geological characterization methods in sedimentary media, to carry out the development of hydraulic parametrization techniques for hydrogeological modeling. This represents the base for developing a reliable groundwater model facing urban aspects. The analysis of the geotechnical aspects in relationship to different ground and underground infrastructure elements as well as their interaction with groundwater will represent the next step of using the 3D geological software platform.

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Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments

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Abstract

Natural hazards like landslides, avalanches, floods and debris flows can result in enormous property damage and human casualties in mountainous regions. Switzerland has always been exposed to a wide variety of natural hazards mostly located in its alpine valleys. Recent natural disasters comprising avalanches, floods, debris flows and slope instabilities led to substantial loss of life and damage to property, infrastructure, cultural heritage and environment. In order to offer a solid technical infrastructure, a new concept and expert-tool based on an integrated web-based database/GIS structure is being developed under HazNETH. Given the HazNETH database design contemplates the detection and mapping of diagnostic features from remote sensors (e.g., ground, air and space borne) this paper analyses the use of remote sensing data in landslides studies during the 1980s, 1990s and 2000s, including a discussion of its potential and research challenges as result of new operational and forthcoming technologies such as the very high spatial resolution optical and infrared imagery of Ikonos, Quickbird, IRS CartoSat-1, ALOS, the satellite based interferometric SAR (InSAR and DInSAR of Radarsat, ERS, Envisat, TerraSAR-X, Cosmo/SkyMed, ALOS), micro-satellites like the Plèiades, DMC, RapidEye, airborne LASER altimetry or ground-based differential interferometric SAR. The use of remote sensing data, whether air-, satellite- or ground-based varies according to three main stages of a landslide related study, namely a) detection and identification; b) monitoring; c) spatial analysis and hazard prediction. Accordingly, this paper presents and discusses previous applications of remote sensing tools as related to these three main phases, proposing a conceptual framework for the contribution of remote sensing to the design of databases for natural hazards like debris flows, and identifying areas for further research.

Keywords: Remote sensing; Debris flows; Landslides; Mountainous hazards; Switzerland; Mapping; Monitoring; Spatial modelling; Hazard prediction; SAR; InSAR; DlnSAR; LiDAR

1. Introduction

Natural hazards like landslides, avalanches, floods and debris flows can result in enormous property damage and human casualties in mountainous regions. A recent world disaster report (International Federation of the Red Cross and Red Crescent Societies, 2001) shows that flooding, avalanches and landslides account for 42% of the global incidence of natural disasters, with average yearly economic losses due to landslides mounting to billions of US dollars (e.g., Japan, India, Italy, USA) to millions in countries like Canada, Nepal, Sweden. Furthermore, inventories conducted between 1964–1999 show a steady increase in the number of landslides disasters worldwide (Kjekstad, 2002).

Switzerland has always been exposed to a wide variety of natural hazards mostly located in its alpine valleys. Recent events such as those occurring in the Canton of Graubünden in November 2002, or the Canton Valais in October 2000 comprised avalanches, floods, debris flows and slope instabilities that led to substantial loss of life and damage to property, infrastructure, cultural heritage and environment. As consequence came into consideration the need to move towards "an integrated risk management and sustainable risk prevention culture", designing and implementing HazNETH

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to this end. HazNETH is a Research Network on Natural Hazards at ETH Zurich (http://www.hazneth.ethz.ch/) which combines expertise in Atmospheric Physics, Climatology, Hydrology, Hydraulic Engineering, Water Management, Risk Engineering, Construction engineering, Forest engineering, Engineering geology, Geotechnics, Seismology, Geodynamics, Geodesy, Cartography, Environmental Social Sciences and Economics. It provides a platform for transdisciplinary projects focusing on process analyses, hazard assessment, vulnerability of technical, ecological, economic and political systems, measures for prevention and upgrading, risk assessment and mitigation, contributing to the improvement of methods and tools for integral risk management as a base for sustainable development (Gogu et al., 2005).

In order to offer a solid technical infrastructure, a new concept and expert-tool based on an integrated web-based database/GIS structure is being developed under HazNETH. The final product will be a geo-spatial hazard and risk information system, comprising graphic and numeric geo-spatial data, aerial and satellite images, georeferenced thematic data and real time monitoring feeds. Within the first research step two main, interrelated hazards, namely torrent streams and debris flows have been selected. Debris flows are a type of landslide events common to mountainous areas (Innes, 1983), usually described as the rapid movement of blocky, mixed debris of rock and soil by flow of wet, lobate mass (Rapp & Nyberg, 1981), and as a rapid mass movement similar to viscous fluids (Varnes, 1978). These events are usually the result of a complex interaction between environmental (e.g., lithology, slope gradient, shape of the hillslope, land cover, microtopography) and human factors (e.g., land use), being triggered by intensive, relatively infrequent rainstorms falling onto a previously saturated landscape, the bursting of a natural dam formed by landslide debris, glacial moraines or glacier ice, earthquake shaking or ice melting (Blijenberg, 1998; Dai et al., 2002; Lorente et al., 2002). Furthermore, it is generally assumed that areas sensitive to debris flow initiation require the occurrence of steep and bare terrain units where large amounts of unconsolidated material are present (de Joode & van Steijn, 2003; Lin et al., 2002).

Given the HazNETH database design contemplates the detection and mapping of diagnostic debris flow features from remote sensors (e.g., ground, air and space borne), the objective of this paper is to analyse the use of remote sensing data in landslides studies undertaken during the 1980s, 1990s and 2000s, including a discussion of its potential and research challenges as result of new operational and forthcoming technologies such as the very high spatial resolution optical and infrared imagery of Ikonos, Quickbird, IRS CartoSat-1, ALOS, the satellite based interferometric SAR (InSAR and DInSAR of Radarsat, ERS, Envisat, TerraSAR-X, Cosmo/SkyMed, ALOS), micro-satellites like the Plèiades, DMC, RapidEye, airborne LASER altimetry, and ground-based differential interferometric SAR.

The use of remote sensing data, whether air-, satellite- or ground-based varies according to three main stages of a landslide related study, namely a) detection and identification; b) monitoring; c) spatial analysis and hazard prediction. Accordingly, following an introduction, this paper has been structured into a Section 2 discussing previous applications of remote sensing to landslide mapping tasks. Section 3 summarises techniques that exploit the optical, IR and microwave regions of the spectrum for monitoring landslide activities; whereas Section 4 establishes the link between remote detection and mapping of landslide diagnostic features, including monitoring activities, and their application to spatial analysis and modelling for hazard prediction. Taking into account the findings in terms of possibilities and limitations of space-, air-borne, and ground-based sensors used in previous studies, Section 5 presents a conceptual model describing the way in which a remote sensing database could be designed to fit the data input needs of a geo-spatial hazard information system like HazNETH. Lastly, Section 6 presents the main findings of this extensive literature review, including a discussion of the potential research challenges that current and forthcoming remote sensing technologies present for landslide hazard, specifically debris flow, analysis.

2. Remote sensing techniques applied to landslide detection and identification

A previous review on the application of remote sensing techniques for landslide studies and hazard zonation in Europe (Mantovani et al., 1996) argued that the use of remote sensing in the study of landslides was not fully exploited, with a limited number of researchers making a full use of multispectral images for evaluating landslide activity. This statement is supported by the data summarised in Table 1, which shows that even in the late 1990s stereoscopic air-photo interpretation continue being the most frequent remote sensing tool applied in the mapping and monitoring of landslide characteristics (e.g., distribution and classification) and factors (e.g., slope, lithology, geo-structure, landuse/land cover, rock anomalies), though the extent and detail of interpretation vary significantly.

Singhroy and Molch (2004a) and (Singhroy, 2002) mention two different approaches that can be adopted for determining the characteristics of landslides from remotely sensed data. The initial approach determines more 'qualitative' characteristics such as number, distribution, type and character of debris flows. This can be achieved with either satellite- or air-borne imagery collected in the visible and infrared regions of the spectrum. For the characterisation of some diagnostic features of landslides, stereo view (e.g., typically aerial photographs) is needed. The second approach complements the qualitative characterisation, estimating dimensions (e.g., length, width, thickness and local slope, motion, and debris distribution) along and

Table 1
Summary of previous studies that mapped and monitored diagnostic features and/or causative factors of mass movement using ground-based, air- and space-borne remote sensing tools

Diagnostic feature/ causative factors	Remote sensors	Method/techniques	Location	Scale	Authors	Comments
•Land use •Landslide distribution and classification (relative to age, degree of activity, typology)	Aerial photographs	Photo-interpretation integrated with topographic maps and field surveys.	Central Italy	1:10,000–1:25,000	Carrara et al. (1991)	Input to GIS database for multivariate modelling. Basin morphometry and land characteristics are associated to morphological meaningful slope-unit within which geomorphic processes take place.
•Volume of sediment eroded and deposited by debris flows	Multi-temporal aerial photographs	Multi-temporal DEMs derived from photogrammetric measurements. Volumetric analysis by calculating elevation differences between successive sets of cross-section or DEM measurements.	Yucca Mountain, Nevada (USA)	1:3000 to 1:8000	Coe et al. (1997)	Photogrammetric techniques provide an efficient means to obtain spatial data from an entire area of interest, as compared to boundary and cross-sectional data characterising field surveys. The accuracy of elevation measured from photographs in this study was about 1/10,000 of the flying height.
•Geomorphologic terrain units	Colour aerial photographs	Photo-interpretation, integration with a DEM data set.	Tirajana Basin (Spain)	1:18,000 (data sources)–1:25,000 model outputs.	Barredo et al. (2000)	GIS-based hazard assessment. Two different knowledge-base driven models were applied: direct and indirect.
•Glacier retreats over terrain ridges (e.g., retreating glaciers destabilise steep valley flanks and uncover large debris reservoirs increasing the likelihood of debris flows) •Horizontal and vertical displacements of glaciers' tongue •Change in glaciers' surface elevation •Surface displacements on creeping mountain permafrost •Glacier lake outburst	Multi-temporal B/W aerial photographs	Analytical photogrammetry for the creation of stereoplotters of multi-temporal photographs.	Swiss Alps	Data sources at scales 1:23,000– 1:16,000	Kääb (2000)	Digital photogrammetric techniques enable monitoring medium- and long-term development of glaciers activity, and to provide area-wide boundary conditions for 2D and 3D-modelling of kinetic and dynamic processes.
•Distance from direct faults •Parallelism between fractures and landslides scarps •Landuse and lithology •Distance from streams •Slope orientation and steepness	Aerial photographs	Photo-interpretation combined with field surveys.	Perugia (Italy)	1:5000–1:13,000	Donati and Turrini (2002)	Factors used to derive a geological–geomorphological map. Remote Sensing integrated with GIS for spatial modelling of causative factors. The method examines the main predisposing factors to landslide, and it subdivides the territory in areas of variable hazard.

•Land cover •Rock formation, fault length, landslide area	SPOT aerial photographs	NDVI photo-interpretation.	Chen-Yu-Lan catchment (Taiwan)	1:5000–1:10,000 (Aerial photos) 1:25,000 (terrain map)	Lin et al. (2002)	Nine factors, grouped into three categories: topography, geology and hydrology are used for assessing debris flow hazard. Two indices, debris flow hazard (DH) and overall hazard (ODH) are implemented within a GIS.
•Location of debris flow sites •Vegetation cover •Bulk density, relative relief	Aerial photographs	Photo-interpretation, historical data on debris flow, field information.	Xiaojiang Basin, Yunan (China)	1:50,000	He et al. (2003)	GIS-based quantitative model of hazard assessment and zonation.
•Surface changes associated to landsliding: rock outcrops, new vegetation	Scanned multi-temporal B/W aerial photographs to simulate Ikonos images	Scanning, georeferencing, relative radiometric normalisation, change detection by image difference and thresholding, spatial filtering.	Tessina (Italy)	Aerial photos at 1:75,000. Output products: scales up to 1:10,000	Hervás et al. (2003)	Image-based approach useful for monitoring surface changes caused by moderate-velocity landslides. Unique to monitor past landslide activity in unstable areas. It works well in woodland areas where SAR interferometry and photogrammetric techniques cannot usually be applied.
•Historical qualitative and quantitative mapping of landslides •Cartography of recent landslide activity	Multi-temporal B/W aerial photographs (1954–1991)	Scanning and orthorectification of aerial photographs; stereo interpretation of photographs, followed by conversion to the orthoimages and digitizing.	Tessina (Italy)	Aerial photographs: 1:15,000–1:66,000. Topographic maps: 1:5000	van Westen and Getahun (2003)	The qualitative mapping of landslides was complemented with a quantitative volumetric analysis was undertaken using a series of DEMs derived from the available topographic maps for 1948–1993. The total volume of material removed and accumulated was computed for the area. Accuracy of volumetric computations depends on the quality of the DEMs.
•Landslide scars •Absence of vegetation •Depositional cone •Debris flow track	IRS-1C/1D PAN	Georeferencing, visual interpretation.	Uttarkashi (Garhwal Himalayas)	N/A	Gupta and Saha (2001)	Useful for landslide inventory purposes. Given the high resolution of IRS-1C/D (5.8 m) debris flows of small spatial extent can be mapped.
•Landuse and vegetation •Past landslide events	SPOT Landsat TM IRS-1 Radarsat aerial photog.	Georeferencing; visual interpretation combined with supervised classification photo-interpretation.	Lantau Island (Hong Kong)	N/A	Zhou et al. (2002)	Data input into GIS for determining spatial correlation of landslides and their causative factors.
•Glacier Lake detection (area) •Large debris deposits •Vegetated/non-vegetated areas	Landsat TM, SPOT Pan	Spectral index (Normalised difference water index), data fusion, and change detection.	Swiss Alps	Data sources: spatial resolution of 10 to 30 m	Huggel et al. (2002)	Outburst floods from glacial and periglacial lakes can result in flood waves and often debris flows where erodable debris reservoirs are present. Remote sensing data provides input for empirical modelling of lakes' outburst characteristics.

(continued on next page)

Table 1 (*continued*)

Diagnostic feature/ causative factors	Remote sensors	Method/techniques	Location	Scale	Authors	Comments
•Steep rocks affected by advanced argillic alteration, that may be susceptible to slope failure	AVIRIS, Hyperion, ASTER, DEM, laboratory spectrometer	Image orthorectification; radiometric correction on AVIRIS; linear unmixing of hyperspectral data.	Mount Shasta (USA)	Data sources: 10 to 30 m	Crowley et al. (2003)	Technique useful to analyse debris flow hazards based solely on remote sensing of altered rocks. Altered rocks obscured by unaltered rocks, or by snow and ice cover, will not be discernable in remotely sensed images. Remote sensing outputs integrated with slope information within a DEM for volume estimation of altered rocks.
•Steep glaciers as related to hazard potential of ice avalanches	Landsat TM	Orthorectified Landsat TM. Image ratio TM4/ TM5 followed by image thresholding and spatial filtering (median). Output results are integrated with high quality DEMs products within a GIS-based spatial modelling.	Bernese Alps (Switzerland)	Multi-scale approach	Salzmann et al. (2004)	Based on statistical parameters, GIS and remote sensing, the method makes it possible to perform a fast and systematic first-order regional mapping (1 : 25,000 – 1 : 50,000) of potentially dangerous steep glaciers that can trigger ice avalanches which in turn, transform into mud or debris flows due to friction of melting. The approach can be used as a support in decision making, and must be complemented by specific interpretation in situ by experts.
•Rock/ice avalanche •Glacial lake size	ASTER	ASTER stereo data used to map avalanche's track. False color composites used to map areal extent of glacier's lake.	Kolka-Karmadon (Russia) and Belvedere Glacier (Italy)	N/A	Kääb et al. (2003)	ASTER imagery formed the base for a rapid, first order assessment of the surge-type glacier dynamics, in that if detected enhanced glacier speed and crevassing.
•Sediment volumes •Geomorphic attributes: hydrography, surface properties, lithology, •Vegetation	Aerial photographs and seismic refraction soundings	Air photo-interpretation, geomorphometric GIS-based analysis, mapping of geomorphological attributes. Seismic refraction surveys for determining sediment thickness.	Bavarian Alps (Germany)	1 : 5000	Schrott et al. (2003)	GIS modelling for calculating sediment thicknesses and sediment volumes using DEMs and information derived from geo-morphometric cross-section analysis and seismic refraction survey. The approach requires the availability of a high resolution DEM.
•Debris covered glaciers •Vegetation •Clean ice	ASTER, IRS-1C/D, SPOT, ASTER-derived DEM.	HIS, band ratios, multispectral classification (ANN) and change detection.	Swiss Alps	DEM: 25 m. Remote sensing data: 30 – 5.8 m	Paul et al. (2004)	Semi-automated method for delineation of debris-covered glaciers, which combines multispectral image classification with DEM data, neighbourhood analysis and change detection.

•Identification of landslide sites •Landuse changes	Multi-temporal SPOT images, aerial photographs	Image registration and rectification, spectral ratioing (IR/R), image differencing, image thresholding.	Central Taiwan	Data sources: 20 m spatial resolution	Cheng et al. (2004)	Useful for detection of changes pre- and post-landslide occurrence.
•Velocity field measurement of landslides	Aerial photographs, Quickbird	Correlation of aerial photographs and a QuickBird image.	La Clapiere (France)	Images with spatial resolution of 1 m or less are needed	Delacourt et al. (2004)	The optical correlation using images from airborne and satellite sensors is a promising technique for improving the spatial resolution of velocity field observations over several years. Landslide movements ranging from 2.5 to 20 m per year were mapped.
•Terrain mapping units •Identification of cloud clusters most likely to result in intense rainfall which are, in turn, likely to initiate debris flow events	Meteosat Stereo SPOT imagery	Infrared Meteosat data for detection of cloud clusters prone to intense rainfall. Visual interpretation of stereo SPOT imagery for generation of TMU and their relation to debris flow hazard.	Bachelard valley, French Alps (France)	Meteosat: 5 km spatial resolution. SPOT: 20 m spatial resolution	Kniveton et al. (2000), Buchtroithner (2002)	Meteorological remote sensing data are not used to retrieve rainfall amounts, but to derive rain cloud properties that produce debris flow triggering conditions. Terrain mapping units delineated according to geology, relief and genesis within a GIS environment. The Bristol approaches uses infrared (e.g., cloud temperature information), Barrett and Cheng, 1996.
•Landslide features: faults, rock slump, block slides, and scars	Radarsat (fine mode imagery), Landsat TM	SAR Interferometry. Georeferencing of SAR and Landsat TM, data fusion.	Fraser Valley, Saskatchewan valleys and Ottawa valleys (Canada)	InSAR: 10 m	Singhroy et al. (1998)	Interferometric SAR provided a good representation of changes in elevation and slope, and as such, landslide features on steep valley slopes were recognised. Fine mode images with incidence angles between 40° and 59° are recommended.
•Unstable slopes from rock glaciers (e.g., debris forming frozen streams which can creep decimetres to meters per year)	ERS-1/2 SAR	SAR Interferometry	Swiss Alps	10 m	Gamma Remote Sensing Ltd (2003)	In Alpine regions the coherence is only suitable for areas with sparse or no vegetation in the snow-free period. For a regional detection of unstable slopes very short baselines (e.g., shorter than 10–20 m) are preferred.
•Multitemporal velocity field measurement of landslides	ERS-1 and ERS-2	15 interferograms from generated from satellite radar images acquired between 1991–1999.	La Valette (southern French Alps)	10 m resolution interferograms	Squarzoni et al. (2003)	Displacement values deduced from InSAR interpretations and compared with ground laser measurements.

(continued on next page)

Table 1 (*continued*)

Diagnostic feature/ causative factors	Remote sensors	Method/techniques	Location	Scale	Authors	Comments
•Landslides motion	ERS SAR	Multitemporal differential SAR interferometry (DInSAR), using between 61–55 images. Identification and measurement of Permanent Scatterers (PS).	Southern California (USA); Ancona (Italy); Basilicata (Italy)	Data source: 26 m spatial resolution	Berardino et al. (2003), Colesanti et al. (2003), Prati et al. (2004)	The pixel-by-pixel character of the PS analysis enables exploiting individual phase stable radar targes in low-coherence areas, making spaceborne interferometric measurements possible in vegetated areas. Though sufficient spatial density of individual isolated man-made structures or exposed rocks are needed. Successful mapping of continuos slow landslide movements. Movements of −5 to 5 mm/year detected.
•Debris size and distribution •Post-slide motion	Radarsat SAR (fine mode) and InSAR ERS	InSAR processing, DEM generation, interferogram generation, removal of topographic phase, coherence image generation, interferogram filtering, generation of height change images. Radarsat: geocoding and extraction of texture measures by analysis of local histograms.	Frank Slide, Alberta (Canada)	Radarsat: 5.6 m. ERS: 10 m	Singhroy and Molch (2004a)	Roughness and distribution of landslide debris and has not been study in detail using remote sensing. Roughness is the topographic expression of surfaces at horizontal scales of cm to a few hundred meters. Landslide surface structures and roughness provide information on flow emplacement parameters (e.g., emplacement rte, velocity, and rheology) useful to characterise landslide debris. SAR interferometry enables monitoring post-slide motion.
•Monitoring landslide processes	Radarsat-2	D-InSAR	Canada	Fine mode, 3 m resolution	(Singhroy & Molch, 2004b)	D-InSAR techniques used to monitor seasonal motion related to spring snow melt and fall rain storms, as debris flow triggering factors.

across the mass movement using stereo SAR, interferometric SAR (InSAR) and topographic profiles (e.g., LASER altimeter). Dimensional data should be compared, or complemented, with field information or previous studies.

Table 1 shows that for the mapping of landslide related factors that fall more within the environmental and human categories, the main contribution has been from the optical-IR sun-synchronic satellites and aerial photographs providing morphological, land use, and geological details to assist in analysing the relationships between landslides and causative factors. Subsequent to this task, many of the approaches incorporate these parameters within GIS-based spatial models of deterministic, inventory, statistical or heuristic nature that aim to assess the probability of landslides to occur in areas where similar characteristics are present.

The following subsections analyse the applications of remote sensing tools according to their spectral band locations (e.g., optical/infrared, active microwave, LASER altimetry) for detection and classification (e.g., including characterisation) of landslide diagnostic features.

2.1. Panchromatic, multi-and hyper-spectral sensors of the visible, near and short wave infrared

Table 1 shows that most of previous studies aiming at the recognition of landslide features have used aerial photographs (scales varying from 1:50,000–1:10,000), in addition to satellite imagery of the Landsat TM and SPOT (Cheng et al., 2004; Lin et al., 2002; Zhou et al., 2002). For glacier related mapping, Terra ASTER and Landsat TM have been trailed (Huggel et al., 2002; Kääb et al., 2003; Paul et al., 2004; Salzmann et al., 2004).

The use of stereoscopic images (e.g., mostly from aerial photographs) in slope instability studies is considered important because of the diagnostic morphology created by some mass movements (e.g., disrupted vegetation cover, scarps) that can clearly be seen in large scale aerial photographs. Considering the size of most landslides and debris flows to be in the order of several tens to a few hundred meters (e.g., for hillslope debris flows less than 10 m scar width and 50- to 100 m run-out according to Lorente et al., 2002), the most useful photographic scale is around 1:15,000 (Mantovani et al., 1996). This scale enables mapping slope instability features and other individual elements of a landslide (e.g., scarp, body, rotated blocks).

A scale of 1:25,000 should be considered as the smallest scale to analyse slope instability phenomena on aerial photographs. Using smaller scale imagery, a slope failure may be recognised if size and contrast are sufficiently large, though previous studies have concluded that the amount of analytical information enabling to make conclusions on type and causes of a mass movement are very limited at scales smaller than 1:25,000 (Singhroy, 2002). That justifies the fact that satellite images that have been available until recently, with a spatial resolution of 10 m (SPOT) to 30 m (Landsat TM), have been used only to derive terrain conditions associated with landslides, such as lithology, differences in vegetation, land use, soil humidity (Cheng et al., 2004; Huang & Chen, 1991; Lin et al., 2002; Mantovani et al., 1996; Zhou et al., 2002). Furthermore, Tropeano and Turconi (2003) mention that on site measurements combined with aerial photographs can help mapping debris load potential, as most of the materials likely to be carried down during an event usually lie in the form of deposits in the stream channel itself, or debris along the banks or slopes, or even terraces actively eroded. Mantovani et al. (1996) also emphasise on the usefulness of remote sensing to support the selection of field sampling points (e.g., field description of soil and rock outcrops and laboratory analyses of selected samples).

With the availability of high spatial resolution satellite imagery (Table 2) from Ikonos, Quickbird, SPOT-5 and the Indian satellites of the IRS series, a new window for research is open for the production of landslide inventory maps. Some initial research has been conducted using the 5.8 m resolution IRS-1D (Gupta & Saha, 2001), or simulated Ikonos data (Hervás et al., 2003). The later study scanned multi-temporal aerial photographs (see Table 1) to simulate 1-m resolution Ikonos data for implementing a semi-automated approach of digital change detection for mapping slope deformation at scales of up to 1:10,000. The authors report the approach enables to classify image pixels according to landslide activity conditions. Paganini (2004) further mentions that in areas where conventional stereoscopic aerial photos are not available or updated, current and forthcoming high spatial resolution satellite data may allow large-scale mapping (1:5000–1:15,000).

Studies focussed on detection and mapping of glaciers and potential ice avalanches, considered as potential triggering factors of debris flows, mention a successful use of the Terra ASTER images that cover the visible to thermal infrared with images varying in spatial resolution from 15 to 90 m (depending on the region of the spectrum mapped)(Huggel et al., 2002; Kääb et al., 2003; Paul et al., 2004). Only one study reports on the use of hyperspectral air-borne (AVIRIS) and satellite-borne (Hyperion) data for debris flow-related applications (Crowley et al., 2003). The study mostly looks at detecting rock anomalies that can be related to the occurrence of debris flows. Altered rocks obscured by unaltered rocks, or by snow and ice cover, are not be discernable in these remotely sensed images. Remote sensing outputs (e.g., ASTER, Hyperion, and AVIRIS) are integrated with slope information within a DEM for volume estimation of altered rocks.

A volumetric estimation of sediment eroded and deposited by debris flows using multi-temporal DEMs derived from photogrammetric measurements using aerial photographs of scales between 1:3000–1:8000, is reported by Coe et al. (1997). Volumetric analysis is undertaken by calculating elevation differences between successive sets of cross-sections or DEM measurements. The authors mention

Table 2
Main parameters of current and forthcoming optical/IR satellite and micro-satellite systems of medium to high spatial resolution

Optical satellite	Sensor	Spatial resolution (meters) and (# bands)					Swath (Km)	Repeat cycle	Year launch
		PAN	VNIR	SWIR	MWIR	TIR			
Landsat 5	MSS		80 (4)			120 (1)	185	16	1984
	TM		30 (4)	30 (2)					
SPOT 2	HRV	10	20 (3)				60 (80)	26 (4)	1990
IRS-1C and	LISS-III		23.5 (3)	70.5 (1)			142	24	1995
IRS-1D	PAN	5.8					70	24	
	WiFS		188 (2)	188 (1)			774	5	1997
IRS-P2	LISS-II		36.4 (4)				74	22	1994
IRS-P3	WiFS		188 (2)	188 (1)			774	5	1996
Landsat 7	ETM+	15	30 (4)	30 (2)		60 (1)	185	16	1999
SPOT 4	HRVIR	10	20 (3)	20 (1)			60 (80)	26 (4)	1998
	Vegetation		1000 (3)	1000 (1)					
CBERS 1 and 2	HRCC	20	20 (4)				113	26	1999
	IR-MSS	80		80 (2)		160 (1)	120	26	
	WFI		260 (2)				890	3 to 5	
Ikonos 2	OSA	1	4 (4)				11	3	1999
Terra	ASTER		15 (3)	30 (6)		90 (5)	60	16	1999
KOMPSAT-1**	EOC	6.6					17	28	1999
	OSMI		1000 (6)						
EROS A1**	PIC	1.9					14	2.5–4.5	2000
MTI	MTI		5 (4), 20 (3)	20 (3)	20 (2)	20 (3)	12		2000
SPOT 5	HRG	2.5–5	10 (3)	20 (1)			60	26 (5)	2002
	HRS	10					120	26	
	Vegetation 2		1000 (3)	1000 (1)			2200	1	
Quickbird 2	BGIS 2000	0.6	2.5 (4)				16	3	2001
IRS-P6 (ResourceSat-1)	LISS-4	6	6 (3)				23.9 (70)	5	2003
	LISS-3		23.5 (3)	23.5 (1)			141	24	
	AWiFS		56 (3)	56 (1)			740		
DMC2-AlSat1[a]	ESIS		32 (3)				600	4	2003
DMC2-BILSAT-1[a]	PanCam	12					25 (300)	4	2003
	MSIS		26 (2)				55 (300)		
	COBAN		120 (4)						
DMC2-NigeriaSat 1[a]	ESIS		32 (3)				600	4	2003
UK-DMC[a]	ESIS		32 (3)				600	4	2003
ROCSat-2/FormoSat-2[b]	RSI	2	8 (4)				24	14	2004
OrbView-3[b]	OHRIS	1	4 (4)				8	3	2003
KOMPSAT-2[b]	MSC	1	4 (4)				15	28	2004
IRS-P5 (CartoSat-1)	PAN-F	2.5					30	5	2005
ALOS	PRISM,	2.5					35 (70)	46 (2)	2005
	AVNIR-2		10 (4)				70		
CBERS 3 and 4	MUX		20 (4)				120	26	2008
	PAN	5					60	1–26	2011
	ISR		40	40 (2)		80	120	26	
	WFI		73 (4)				866	5	
TopSat[b]	RALCam1	2.5	5 (3)				25	4	2005
Plèiades[c]-1 and 2	HiRI	0.7	2.8 (4)				20	26 to 4	2008–2009
RapidEye A–E[d]	REIS	6.5	6.5 (5)				78	1	2007
EROS B– C	PIC	0.7	2.8				11		2005–2008
RazakSat[e]	MAC	2.5	5 (4)				20	13–15[f]	2005
China DMC+4 (Tsinghua-1)	MS DMC	4	32 (3)					600	2005
Resurs DK-1[g]	ESI	1	3 (3)				28.3	N/A	2005

[a] DMC (Disaster Monitoring Constellation of 4 satellites) of sun-synchronic circular orbit, daily revisit cycle.
[b] Circular, sun-synchronic orbit.
[c] Two-spacecraft constellation of CNES (Space Agency of France), with provision of stereo images.
[d] Five-satellite constellation.
[e] Near equatorial low Earth orbit (NEO).
[f] Passes/day.
[g] Near-circular non-sun synchronous orbit.

that photogrammetric techniques provide an efficient means to obtain spatial data from an entire area of interest, as compared to boundary and cross-sectional data characterising field surveys. The accuracy of the method is controlled by pre-events photographs, as post-events photographs can be flown at any desired scale. The accuracy of elevation measured from photographs reported for this study was about 1/10,000 of the flying height.

2.2. Thermal infrared sensors

An early study by Bison et al. (1990) reports on experimental results of using a remote sensing system from a ground platform for slope stability studies. The approach consists on the survey of the surface's hydraulic conditions based on a sequence of images collected on the thermal IR region, followed by digital analyses to eliminate shaded and vegetated areas of the image. The thermograms produced as output allowed the identification of zones with different water content indicative of high risk hydrogeological situations. Though Carrara et al. (1991) suggest that multitemporal thermal infrared imagery may be useful for detecting the hydrogeologic conditions of slopes as a parameter for determining slope stability conditions, we noted a lack of investigation in this area during the last decade.

2.3. Active microwave sensors

Singhroy and Molch (2004a) mention that the relationship between roughness and distribution of landslide debris has not been studied in detail using remote sensing. Thus, they undertook a study to characterise debris size and distribution of a rock avalanche in the Canadian Rockies, analysing the relationship between radar backscatter and the size of the landslide's blocks. Considering roughness as the topographic expression of surfaces at horizontal scales of centimetres to a few hundred meters, landslide surface structures and roughness can provide information on flow emplacement parameters such as rate, velocity and rheology (Singhroy & Molch, 2004a). A Radarsat fine mode image (6.25 m spatial resolution and incidence angle 43–46°), was used to this end, applying textural analysis to the SAR imagery, supported by field observations and aerial photographs. The close relationship found between SAR textural measurements and the debris size distribution and ridge morphology, suggest that high resolution SAR images are useful tools to characterise landslide debris (Singhroy & Molch, 2004a).

Likewise, earlier studies by Singhroy et al. (1998) analysed the capabilities of integrated SAR (Radarsat) and Landsat TM imagery, and interferometric SAR for landslide characterisation and inventory. Using examples from different physiographic regions of Canada they concluded that the synergistic use of microwave and optical/IR imagery and SAR interferometric techniques can supplement current airphoto interpretation techniques used to this end. Furthermore they found that for mountainous terrain, a) Radarsat images collected in fine mode imaging, with incidence angles varying from 40–59°, are the most suitable to map landslide features; b) interferometric SAR enables a better characterisation of landslide features on steep valley slopes; c) synergistic use of SAR/TM imagery is suitable to characterise retrogressive slope failures and flow features in low relief areas.

2.4. Active VNIR sensors: LASER altimetry

Like radar sensors discussed in the previous section, LiDAR (e.g., Light Detection and Ranging) is an active sensor using electromagnetic energy in the visible and near infrared wavelengths that provide data in a nadir-looking mode, at discrete points across a swath (Mather, 2004). Most LiDAR sensors are flown on board of aircrafts, and can be subdivided on 'small footprints' (5–30 cm), commonly used for detailed local mapping of surface elevations, and 'large footprint' (e.g., 10–25 m), collecting an average value for a greater surface area (e.g., forest mapping). McKean and Roering (2004) mention that traditional methods of landslide mapping based on stereoscopy or visual interpretation of airphotos or panchromatic/multispectral imagery, and selective ground thruthing are difficult to apply in rugged terrain covered by dense vegetation, and therefore propose a new method that exploits measurements of local topographic roughness to detect and map deep-seated landslides using high resolution DEMs (1.5 to 10 m) derived from LiDAR airborne data. To this end, LiDAR data were obtained with an average density of one laser strike per 2.6 m in six flight lines over the landslide and surrounding area. Statistical, Laplacian and spectral analysis of the LiDAR derived DEMs were used to quantify the local surface roughness, so that resulting spatial patterns of roughness could be used to distinguish slide from non-slide areas, and for identifying individual morphologic domains within the landslide complex. They conclude that such topographic based analyses may be used to objectively delineate landslide features, generate mechanical inferences about landslide behaviour, and evaluate relatively recent landslide activity.

2.5. Geophysical approaches

Schrott et al. (2003) present a novel approach for mapping spatial patterns of sediment storage types and associated volumes, including the quantification of valley fill deposits for alpine catchment areas. A combination of polynomial functions of cross-sections extracted from a high resolution DEM for geomorphometric analysis, seismic refraction profiles and GIS modelling were used to this end. Seismic refraction surveys were carried out with individual, georeferenced profile lengths between 72 and 96 m, and geophone spacing between 3 and 4 m. Each profile was measured by 10 to 15 shots. By varying primary seismic wave

(P-wave) velocities, different layers could be identified. The depth of the different refractor horizons was calculated using the Intercept method (one-dimensional) and the wavefront inversion method for two-dimensional interpretation. The geophysical survey enabled interpretation of possible and probable bedrock depths based on measured primary seismic wave velocities. These results were further used to test and validate the geomorphometric analysis results. Schrott et al. (2003) recommend a combined application of bedrock data derived from polynomials and geophysical prospecting for the quantification of valley fill deposits.

3. Landslide monitoring

Monitoring is defined as the comparison of landslide conditions like areal extent, speed of movement, surface topography, soil humidity from different periods in order to assess landslide activity (Mantovani et al., 1996). Interferometric SAR, whether satellite- or ground-based (InSAR and DInSAR) are the techniques most researched during the last decade for slope motion monitoring (see Table 1). A summary of techniques that exploit the optical-IR and microwave regions of the spectrum to measure landslide activity is presented hereafter.

3.1. Optical and infrared regions of the spectrum for monitoring purposes

Cheng et al. (2004) present an approach for locating landslides using band ratios of multi-temporal satellite images (e.g., SPOT) to detect changes on land use pre- and post-landslide occurrence. A similar approach was used by Nagarajan et al. (1998) using multispectral IRS imagery.

The study of Hervás et al. (2003) proposes a more semi-automated approach to monitor landslides from optical remotely sensed imagery. Basically this approach proposes the use of very high resolution images (e.g., Ikonos or Quickbird type) acquired at different dates. The method consists on image orthorectification, relative radiometric normalisation, change detection using image difference, thresholding and spatial filtering to eliminate pixel clusters that could correspond to man-made land use changes. Perhaps, a more interesting application of this type of very high resolution satellites comes from Delacourt et al. (2004) who propose to use aerial photographs and Quickbird imagery to monitor landslide displacements. This study is an example of how improved spatial resolution can help improving landslide mapping and monitoring tasks. The small spatial extent of landslides determines that SPOT 1–4 or Landsat TM or MSS could rarely be used for measuring deformations. Delacourt et al. (2004) propose a very interesting technique based on optical correlation of aerial photographs (for time baselines that require imagery previous to the launch of the Quickbird satellite) and Quickbird imagery. Applied to very high spatial resolution data (e.g., one meter or less) this technique can detect motion as low as 0.1 m for two images acquired by the same sensor.

More traditional applications of aerial photogrammetry for monitoring landslide movements have been used in Italy by van Westen and Getahun (2003) who mapped landslide activity and obtained a quantitative volumetric analysis using a series of DEMs derived from the available topographic maps and aerial photographs. The total volume of material removed and accumulated was computed for the area of study. The authors mentioned that the accuracy of volumetric computations depends on the quality of the DEMs. Likewise, a study by Kääb (2000) used digital photogrammetry in a multi-temporal context to determine surface velocity fields in 3D. Multi-temporal aerial photographs and digital photogrammetry for early recognition of glacial and peri-glacial hazards that can be related to debris flows were used to this end. Kääb (2000) concludes that analytical and digital photogrammetry techniques are highly suitable for monitoring geometric changes in high mountains, such as terrain displacement. Furthermore, photogrammetry has the potential to determine surface information, whereas it has no access to depth information that has to be obtained from geophysical approaches or in combination with physical or numerical models.

3.2. Space and air-borne microwave applications for monitoring movement

Another application of sensors collecting information in the microwave region of the spectrum is SAR interferometry from satellites like the Radarsat, ERS, JERS (no longer operational), Envisat ASAR or forthcoming TerraSAR-X, ALOS, and Cosmo/Skymed (Table 3). A SAR image provides along and cross-track measurements. Because the across-track position represents a range measurement, the SAR image is distorted in this direction. Steep slopes facing in direction of the antenna appear shortened or are affected by layover, which often inhibits the interferometric analysis on these slopes; thus the selection of suitable radar look direction (ascending or descending orbit) is important (Rott, 2004). Hervás et al. (2003) mention this as one severe limitation in the use of InSAR for debris flow mapping, given that many times debris flow occur in steep slope areas.

SAR interferometry uses mainly the phase measurements of two or more SAR images of the same scene, acquired at two different times and/or slightly different locations. The inteferogram resulting as output represent very small slant-range changes which can be related to topography and/or surface deformation (Klees & Massonnet, 1999). In the case of spaceborne SAR (e.g., Radarsat, ERS, Envisat) the images are acquired from repeat pass orbits. For the Europeans ERS and Envisat, the standard orbital repeat interval is 35 days, for the Canadian Radarsat is 24 days (Table 3). The fractional phase difference between two repeat pass images result from topography and from

Table 3
Main characteristics of current and forthcoming microwave satellites

Satellite	ERS-1	ERS2	Radarsat-1	JERS-1	Envisat	Radarsat-2	Alos	TerraSAR-X	Cosmo/SkyMed[a]
Sensor	AMI	AMI	SAR	SAR	ASAR	SAR	PALSAR	TSX-1	SAR-2000
Space agency	ESA	ESA	RadarSat Int	NASDA	ESA	RadarSat Int	NASDA	DLR/Infoterra GmbH	ASI
Operational since	1991	1995	1995	1992	2002	2005	2004	2006	2005
Out of service since	2000			1998					
Band	C	C	C	L	C	C	L	X	X
Wavelength (cm)	5.7	5.7	5.7	23.5	5.7	5.7	23.5	3	3
Polarization	VV	VV	HH	HH	HH/VV	QUAD-Pol[b]	All	All	HH/VV
Incidence angle (°)	23	23	20–50	35	15–45	10–60	8–60	15–60	Variable
Resolution range (m)	26	26	10–100	18	30–150	3–100	7–100	1–16	1–100
Resolution azimuth (m)	28	28	9–100	18	30–150	3–100	7–100	1–16	1–100
Scene width (km)	100	100	45–500	75	56–400	50–500	40–350	5–100 (up to 350)	10–200 (up to 1300)
Repeat cycle (days)	35	35 (3)	24	44	35	24	2–46	2–11	5–16
Orbital elevation (km)	785	785	798	568	800	798	660	514	619

Source: ITC's database of satellites and sensors (Online: http://www.itc.nl/research/products/sensordb/AllSatellites.aspx), Connecting Earth Observation Resources: http://directory.eoportal.org/res_p1_Earthobservation.html#note.
[a] Constellation of 4 satellites.
[b] QUAD-Pol mode (all four polarizations: HH, HV, VV, VH).

changes in the line-of-sight distance (range) to the radar due to displacement of the surface or change in the atmospheric propagation path length (Klees & Massonnet, 1999). For a non-moving target the phase differences can be converted into a digital elevation map if very precise satellite orbit data are available. There are techniques to reduce the noise effects due to atmospheric conditions (Singhroy, 2002).

For motion mapping (e.g., multitemporal velocity field measurement of landslides, slope instability) as done by Singhroy and Molch (2004a,b), and Squarzoni et al. (2003) it is necessary to separate the motion-related and the topographic phase contributions. This can be done by differential processing, using multi-pass interferograms which can map small time-sequential relative topographic displacements on the order of one centimetre although field calibration is usually needed to define absolute movements (Fruneau et al., 1996). The data processing technique known as differential SAR interferometry (DInSAR), applied to satellite images, enables the removal of the topographic component (Canuti et al., 2004).

A study by a Swiss company (Gamma Remote Sensing, 2003) investigated the possibilities and limitations of detecting unstable slopes in the Swiss Alps using ERS-1/2 SAR data. Their database included temporal baselines of one to several years. Similarly to Rott (2004), they found that in Alpine regions the coherence is only suitable for areas with sparse or no vegetation (i.e., above the tree line) during snow-free periods of summer and autumn. In spite of these limitations they identified various unstable slopes, most of them related to the creeping of frozen debris (e.g., related to glacier events). Given the typical SAR repeat orbits of the order of 24 to 35 days, InSAR is mainly suitable for monitoring very slow movements of slopes and individual objects. The main advantage over other conventional techniques is the possibility of very precise displacement measurements over large, sparsely vegetated areas at reasonable costs (Rott, 2004; Singhroy, 2002).

Rott (2004), Paganini (2004) and (Singhroy, 2002) summarise the potentials and opportunities of space-borne SAR sensors for monitoring slope instability as follows:

a) The availability of less than three meter resolution stereo images from C-band SAR (e.g., Radarsat-2) and optical sensors increase the geomorphologic information on slopes, generating more reliable landslide inventory maps;
b) Detailed motion maps produced from C-band, whether using techniques such as Permanent Scatterers (PS), DInSAR or InSAR can assist in more accuracy slope stability studies. When the conditions are correct (e.g., coherence, imaging geometry) C-band SAR interferometry is a useful tool for mapping and monitoring mass movements;
c) If SAR time series are available, accurate analysis of displacement is possible using PS technique. Successful mapping of continuos slow landslide movements has been achieved using multi-temporal DInSAR techniques. Movements of −5 to 5 mm/year have been detected;
d) The access to archived SAR data (e.g., in excess of 10 years) is useful to study temporal variations of motion that enable assessing slope stability, complementary to other information;
e) Future SAR systems with higher spatial resolution (e.g., Radarsat-2, TerraSat-X, Cosmo/SkyMed) will enable the mapping of smaller slides. With the Permanent Scatterer technique, the movement of small objects (e.g., down to about one square meter) can be monitored.

Though it looks promising as a technique to monitor slope motion, Klees and Massonnet (1999), McKean and Roering (2004), Rott (2004) highlight some constraints, as reported by several studies:

f) InSAR only measures displacement in slant range (e.g., the displacement in direction of the radar illumination), the component of velocity vector in the flight direction cannot be measured (Rott, 2004);

g) Really large displacements cannot be detected with InSAR. There is a limit with respect to the displacement gradient between adjacent pixels, which must be less than half the radar wavelength (e.g., about 2.8 cm in range for ERS-2; or 11.7 cm for ALOS);
h) Interferometry can be complicated by changes on vegetation canopy overtime (Fruneau et al., 1996);
i) Loss of radar coherence can occur if there has been excessive landslide deformation between successive data acquisitions (Carnec et al., 1996);
j) Decorrelation caused by dense vegetation (e.g., forest) is the main limiting factor for DInSAR or InSAR applications in Alpine valleys. L-band data is less affected than higher SAR frequencies (Rott, 2004);
k) InSAR can only map the motion at characteristic temporal and spatial scales related to the spatial resolution of the sensor and the repeat interval of imaging. Thus, for ERS interferometry applications to landslide movements are millimetres to cm per month (35 days repeat cycle) to millimetres to centimetres per year. Canuti et al. (2004) and Rott (2004) mention that current satellite SARs are unsuitable for a systematic monitoring of relatively rapid movements (e.g., mudflows, rock fall, debris falls) concentrated in small areas and on steep slopes or narrow valleys. Best quantitative information can be obtained in the case of extremely slow movements (velocity less than a few centimetres per month), affecting large areas with sparse vegetation.
l) For instance, with the resolution of ERS (9.6 m slant range, 6.5 m. across track, 5.6 cm wavelength) the minimum horizontal dimension of a landslide for area-extended interferometric analysis, which can be applied with a single image pair, is about 200 m across and along track (Singhroy, 2002).
m) Data availability: the European ERS SAR is useful for repeat-pass SAR interferometry. However, a system failure that occurred on ERS-2 on January 2001 has resulted in the orbit deadband being relaxed from ±1 to ±5 km. This means a decrease on the availability of images for interferometric applications (CEOS Disaster Management Support Group, 2001). Other sensors like the Envisat ASAR have interferometric capabilities, but due to the varying operation modes, the availability of pass interferometric data is reduced as well (Canuti et al., 2004).

Perhaps a way to overcome the issue of data availability may be by applying the approach proposed by Guarnieri et al. (2003) who introduce a technique to obtain interferometric surveys by combining two images, coming from any SAR mode, with a DEM. The DEM is applied during the interferogram generation for noise removal and compensation for the topographic-dependent fringes. The final result is a topography-compensated (e.g., differential) interferogram that can be used for monitoring landslide activities. Furthermore, Canuti et al. (2004) mention the acquisition parameters of the SAR missions such as the Japanese ALOS, the Italian Cosmo/SkyMed or the German TerraSat-X seem to meet the operational requirements for an effective and systematic monitoring of slope movement.

The technique of Permanent Scatterers (PS) developed by Ferretti et al. (2001) allows a significant reduction of atmospheric and noise effect as well as measurements close to one millimetre (Canuti et al., 2004; Colesanti et al., 2003). The pixel-by-pixel character of the PS analysis enables exploiting individual phase stable radar targets in low-coherence areas, making spaceborne interferometric measurements possible in vegetated areas. The technique requires sufficient spatial density of natural stable ground reflectors like individual isolated man-made structures or exposed rock. Successful mapping of continuos slow landslide movements has been reported by Berardino et al. (2003), Colesanti et al. (2003) and Prati et al. (2004) who report that movements of −5 to 5 mm/year were detected in different study areas of Italy.

3.3. Ground based differential SAR interferometry

Many of the limitations associated to space borne SAR interferometry mentioned in the preceding sections can be overcome with the recent availability of the ground based differential SAR interferometry (Canuti et al., 2004). The Joint Research Centre of the European Commission developed a mobile imaging radar system known as LISA (Linear SAR) for the monitoring of ground displacements such as velocity fields of landslides (Canuti et al., 2004; Fortuny-Guasch, 2004; Leva et al., 2003; Tarchi et al., 2003a). The system operates with microwaves on the Ku band (17 GHz), providing a high resolution map of ground displacements with a precision of one millimetre every 10 min. However, because in the Ku band the phase is strongly disturbed by the presence of vegetation, the acquired data are significant only for bare or sparsely vegetated areas (Canuti et al., 2004). The raw SAR data is acquired, calibrated and geocoded, and multitemporal interferometric analysis is undertaken to recognise slowly deforming areas. The system has been successfully trailed to monitor field displacements and deformations in the Italian Alps and Apennines. With a spatial resolution of few meters, and accuracy of displacement detection equal to fractions of a millimetre, this ground based technique allows to derive multitemporal surface deformation maps that quantitatively show displacement rates of up to 1.2 mm h^{-1} with a pixel resolution of 5 m, and a measurement precision of 0.75 mm (Tarchi et al., 2003b). Canuti et al. (2004) and Leva et al. (2003) mention this technique to be a valid complement to space- and air-borne SAR. Furthermore, given that the LISA instrument can acquire imagery every 10 min, it is more suitable for monitoring fast slope movements. Following the standard landslide velocity scale proposed by the IUGS

Table 4
Velocity scale proposed by the IGUS/WGL (1995) and present capability of spaceborne and ground-based SAR interferometry to assess the indicated displacement rates

Class	Description	Speed	Speed (m/s)	Satellite DInSAR	GB DInSAR
1	Extremely slow	16 mm/year	$5\ 10^{-10}$	Yes	Partly
2	Very slow	1.6 m/year	$5\ 10^{-8}$	Partially	Yes
3	Slow	13 m/month	$5\ 10^{-6}$	No	Yes
4	Moderate	1.8 m/h	$5\ 10^{-4}$	No	Partly
5	Rapid	3 m/min	$5\ 10^{-2}$	No	No
6	Very rapid	5 m/s	5	No	No
7	Extremely rapid			No	No

Working Group on landslides (IUGS/WGL, 1995), Canuti et al. (2004) discuss how a synergistic use of space- and ground-based SAR instrumentation can overcome constraints enabling: a) satellite data monitoring extremely or very slow movements, while LISA devices allow the assessment of moderate velocity landslides (see Table 4).

4. Remote sensing in landslides spatial analysis and hazard prediction

The concept of hazard zonation (e.g., maps that show the spatial distribution of hazard classes) is central to the phase of spatial analysis and hazard prediction of landslide occurrence. According to Varnes (1984), zonation refers to the division of the land in homogeneous areas and their ranking according to degree of actual or potential hazard caused by mass movements. Consequently, it requires knowledge of the factors determining the probability of landslide for a particular slope or area, which according to Dai et al. (2002) can be grouped into two categories: (1) preparatory variables which make the slope susceptible to failure without triggering it, such as geology, slope gradient and aspect, elevation, soil geotechnical properties, vegetation cover and long term drainage patterns and weathering; and (2) the triggering variables such as heavy rainfall, glacier outburst. As shown in Table 1, remote sensing has been used in the detection and identification of diagnostic features mostly related to the first category, and to a lesser extent, to the detection of potentially triggering factors as shown by studies of Kniveton et al. (2000), Buchroithner (2002), Huggel et al. (2002), Kääb et al. (2003).

As mentioned in Section 2.2, the mapping requirements for input data for landslide hazard is scale dependant, with generally three scales of spatial analysis being defined (Mantovani et al., 1996): a regional scale (<100,000), a medium scale (1 : 50,000–1 : 25,000) and a large scale (>1 : 10,000). Dai et al. (2002) mention that when assessing the probability of landsliding on regional scales, it might be feasible considering landslide ‘susceptibility’ (e.g., omitting the inclusion of triggering factors in the spatial analysis) as the probability of landsliding. This is based on the assumption that long-term historical landslide records tend to smooth out the spatio-temporal effect of triggering factors on landslide occurrence. For large scale hazard assessments, in which work is undertaken over relatively small areas or specific slopes, data collection at this scale should relate to the quantitative parameters needed for slope stability modelling (Dai et al., 2002). So far, space-, air-borne and ground based SAR systems have provided most quantitative parameters as shown in Table 1 and discussed in Sections 2 and 3.

Previous work (Soeters & van Westen, 1996; van Westen et al., 1997) have grouped methods for landslide hazard assessment into inventory, heuristic, statistical and deterministic approaches. A landslide inventory map based on aerial photo-interpretation, satellite images, ground survey and database of historical occurrence of landslide in an area as done by He et al. (2003) is the most straightforward approach (Mantovani et al., 1996). The output provides the spatial distribution of mass movements, represented as polygons or points (Wieczorek, 1984). Such maps can be used as an elementary form of hazard map because they show the spatial location of recorded landslides, though they fail to identify areas that may be susceptible to landsliding unless landslides have already occurred (Dai et al., 2002). Furthermore, Mantovani et al. (1996) mention this approach provide information for the period shortly preceding the date of remote data collection or field checking, without an insight into the temporal changes in mass movement distribution. Therefore, a refinement is the construction of landslide activity maps, based on multi-temporal aerial photo- or satellite interpretation as done by Nagarajan et al. (1998), Zhou et al. (2002), van Westen and Getahun (2003), Cheng et al. (2004).

Heuristic approaches require expert opinions to estimate landslide potential from data on preparatory variables. Barredo et al. (2000) provide a good application example of this expert-driven approach, where geomorphology experts decide on the type and degree of hazard for each area, using either a direct or indirect mapping approach. In the direct mapping approach the degree of hazard is mapped directly in the field, or is determined after fieldwork using a very detailed geomorphologic map, that in most cases is derived from stereoscopic interpretation of large scale aerial photographs. The indirect approach uses data integration techniques, including qualitative parameter combination, with the analyst assigning weighting values to a series of terrain parameters and to individual classes within each parameter. The parameters are then combined within a GIS to produce hazard values. Dai et al. (2002) mention the need for long-term information on the landslides and their causative factors, the reproducibility of the results and the subjectivity of weightings and ratings of the variables as the main limitations to the applicability of such models.

Statistical/stochastic approaches have generally taken the form of bivariate or multivariate statistical analyses of landscape characteristics that have led to landslides in the past (Carrara et al., 1991; Lorente et al., 2002) or weighted hazard ratings based on environmental attributes related to landsliding (Donati & Turrini, 2002; Lin et al., 2002; Lineback Gritzner et al., 2001). On those bases quantitative predictions are made for areas currently free of landslides. The complex statistics these methods apply require the collection of large amounts of data to produce reliable results (Barredo et al., 2000). The method is said most suitable for landslide hazard prediction at medium scale (1:25,000–1:50,000). Zhou et al. (2002) propose a statistical–spatial analysis approach for interactive and exploratory analyses of the relationship between landslides and their causative factors. Analysing the relationship between landslides and their causative factors not only provides an insight into the understanding of its operating mechanisms, but also forms a basis for predicting future landslides and assessing the landslide hazard (Zhou et al., 2002).

Lastly, the deterministic approaches (i.e., process-based) include the physical processes involved in landsliding and therefore can often better pinpoint causes of mass movement (Miller, 1995). These models of hazard mapping usually provide the most detailed results, expressing the hazard in absolute values in the form of safety factors, or the probability of failure given a set of conditions (Barredo et al., 2000). However, Barredo et al. (2000), Lineback Gritzner et al. (2001), Dai et al. (2002) mention data requirements for such models can be prohibitive, leading to oversimplification of the results when data are only partially available.

Mantovani et al. (1996) summarise the feasibility and usefulness of obtaining information needed for such approaches of hazard zonation using remote sensing techniques at three different scales (Table 5). According to this table, landslide hazard mapping based on landslide inventory maps benefits most from information collected using remotely sensed data, followed by heuristic approaches at regional and medium scales, statistical and landslide frequency analysis using indirect methods (for medium and large scale studies). Hazard analyses at large scale based on deterministic approaches benefit from the incorporation of remote sensing information, though such models require a considerable investment in terms of money; whereas the process-based models at regional and medium scale are the least feasible of benefiting from the incorporation of parameters derived from remotely sensed data (Table 5). It is worth noting this table was produced before the launch of high resolution satellite sensors and the reporting of successful applications of InSAR, DInSAR, PS, which as shown in Table 1, are mostly post 1996.

In summary, the understanding and modelling of landslides requires access to spatially referenced data from a

Table 5
Summary of the feasibility and usefulness of applying remote techniques for landslide hazard zonation in three working scales (after: Mantovani et al., 1996)

Type of landslide hazard analysis	Main characteristics	Regional scale	Medium scale	Large scale
Distribution analysis (landslide inventory approach)	Direct mapping of mass movement features resulting in a map that gives information only for those sites where landslides have occurred in the past.	2–3	3–3	3–3
Qualitative analysis (heuristic approach)	Direct or semi-direct methods in which the geomorphologic map is reclassed to a hazard map, or in which several maps are combined into one using subjective decision rules based expert-knowledge.	3–3	3–2	3–1
Statistical approach (stochastic approach)	Indirect methods in which statistical analysis are used to obtain predictions of mass movement from a number of parameter maps.	1–1	3–3	3–2
Deterministic approach (process-based)	Indirect methods in which parameter are combined in slope stability calculations.	1–1	1–2	2–3
Landslide frequency analysis	Indirect methods in which earthquakes and/or rainfall records or hydrological models are used for correlation with known landslide dates to obtain threshold values with a certain frequency.	2–2	3–3	3–2

The first number indicates the feasibility of obtaining the information using remote sensing techniques (1 = low: it would take too much time and money to gather sufficient information in relation to the expected output; 2 = moderate: a considerable investment would be needed, which only moderately justifies the output; 3 = good: the necessary input data can be gathered with a reasonable investment related to the expected output). The second number indicates the usefulness (1 = of no use: the method doe not result in very useful maps at the particular scale; 2 = of limited use: other techniques would be better; 3 = useful).

wide variety of sources, including remote sensing at different scales, resolutions and reliability, often multi-temporal, as well as the analyses of such data in a multi-dimensional space (Cruden & Varnes, 1996). Thus, having reviewed remote sensing sources and spatial modelling techniques used in previous research related to landslide mapping and monitoring in mountainous areas, the next section proposes a conceptual framework for the design of the remote sensing database of HazNETH.

5. Integrating remote sensing and GIS for a geo-spatial hazard information system: Conceptual framework for database design

The concept of integrated hazard assessment analysis (Fig. 1) of HazNETH requires designing a database concept as a basis for analysis and natural hazard assessment. To this end, a team of experts on natural hazards common to Switzerland identified parameters relevant to the natural hazard phenomena, grouping them into thematic categories and known relationships between diagnostic features and phenomena were documented (Fig. 2). Subsequently, there is a need to quantitatively describe the landslides and their attributes, identifying the data categories and general data groups with variables that could be mapped or monitored from remote sensing systems.

Taking into account the findings in terms of possibilities and limitations of satellite and airborne remote sensors used in previous studies (Sections 2 and 3), and also considering the cost of image acquisition and the fact that HazNETH has been conceived as a multi-scale database of local (alpine valley), regional (river basin) and general (whole country) levels as shown in Fig. 3, the conceptual model as to how the remote sensing database could be designed follows also a hierarchical approach of three levels. The approach considers the integration of remote sensing and GIS techniques, given that most current models of hazard prediction and landslide zonation (either of inventory, heuristic, deterministic or statistical) are GIS-based or derive model parameters (e.g., slope, aspect, drainage) with the support of GIS. The approach is an adaptation of the one proposed by Huggel et al. (2002) for the assessment of hazards from glacier outburst, and it is structured as discussed below.

5.1. Level 1

A level of basic detection of ‘diagnostic features’ related to debris flows over large areas (e.g., regional scale). Satellite imagery that could be used for this purpose includes Terra ASTER, Landsat TM, IRS, SPOT and/or microwave ERS, Radarsat, Envisat. At this level, we would aim to map more ‘qualitative’ characteristics of debris flows (number, distribution, type); following the models of inventory map described in Section 4. Multi-temporal and/or multi-sensor images could be used for mapping changes of environment-related factors over time (e.g., vegetation, land use). Some small landslides may not be detected at this level due to the resolution of the sensors proposed. However, these sensors are of low cost and the images cover a large area (e.g., Landsat 36,000 km^2). This level

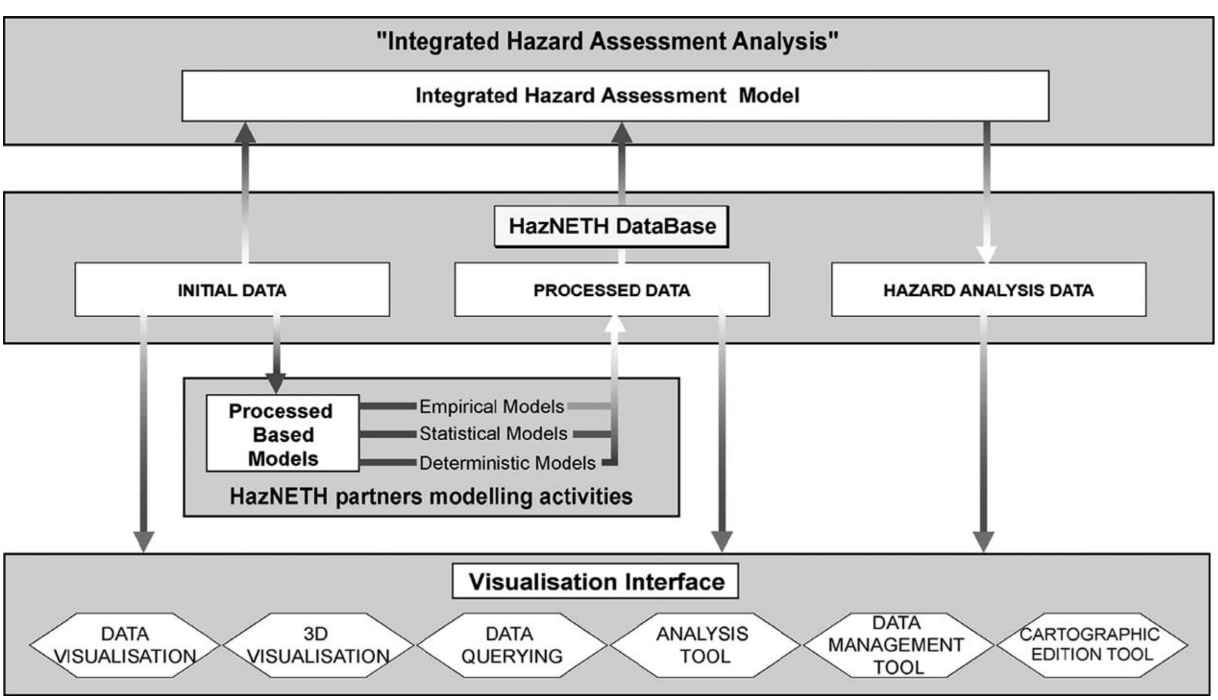

Fig. 1. The general scheme of the HazTool system.

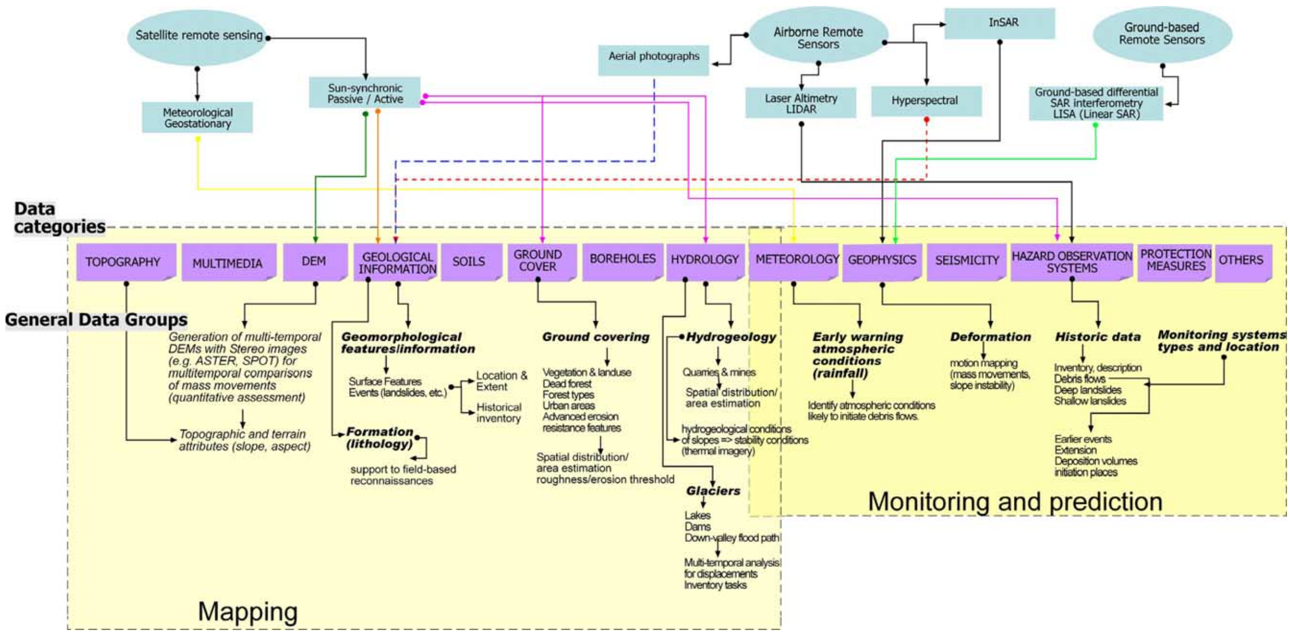

Fig. 2. Contribution of remote sensing techniques to the HazNETH project.

would detect 'potentially dangerous areas of debris flow and associated hazards' like glacier outburst that cause debris flows. Scales of output products: 1 : 50,000 – 1 : 100,000.

This level could also explore the use of meteorological satellites (Meteosat) to detect and monitor the presence of raining clouds that produce debris flow triggering conditions as discussed by Kniveton et al. (2000) and Buchroithner (2002), given that shallow landsliding triggered by high-intensity rainstorms appear to be the most general case of debris flow initiation for the European Alps (Blijenberg, 1998), and empirical GIS-based process models for debris flow hazard at catchment level in Alpine areas (de Joode & van Steijn, 2003) adopt this type of rainfall as the main triggering factor.

5.2. Level 2

This level could assess the 'hazard potential' of the debris flows or 'diagnostic features' mapped in level 1 (e.g., after a zoning of potentially dangerous areas, higher spatial resolution satellite imagery could be acquired over specific areas, regardless their cost). Image analysis and spatial modelling within a GIS-environment, where other topographic, geomorphometric and geologic attributes (e.g., lithology) are incorporated into the modelling phase. Basically, with the availability of higher spatial resolution satellites (e.g., Ikonos, Quickbird, SPOT-5, ASTER, IRS CartoSat-1) and satellites with interferometric capabilities (InSAR), other diagnostic features, of more 'quantitative nature' such as the measuring of dimensions (length, width, local slope) could be mapped and incorporated into the HazNETH database. Scale of output products: 1 : 25,000 – 1 : 50,000.

5.3. Level 3

Deals with detailed investigations, at a large scale (1 : 15,000 and larger) of debris flow hazard potential areas

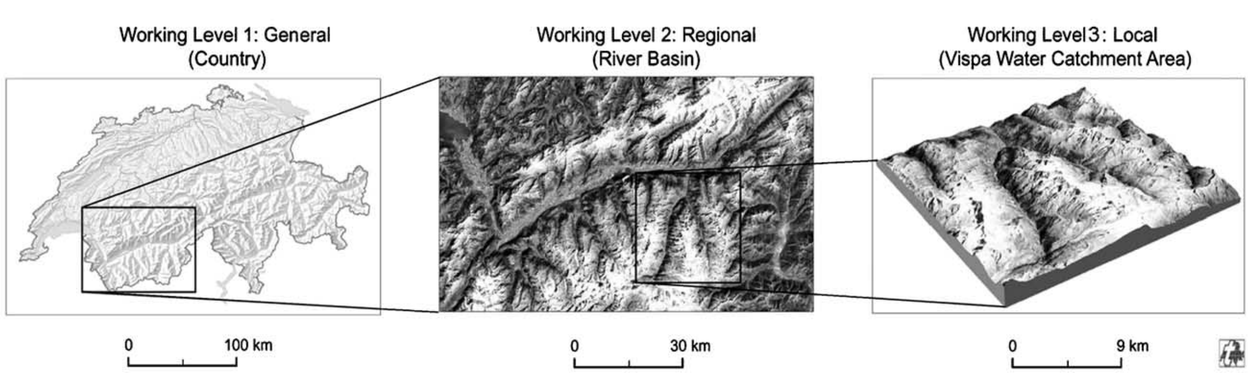

Fig. 3. Different spatial scales of data collection and analysis.

identified in Levels 1 and 2. Such investigations are concerned with very specific debris flow. The diagnostic features to be mapped at this scale should be quantitative, such as deposits thickness, motion, and debris distribution along and across the debris flow deposit. According to the literature reviewed in this paper, the remote sensing techniques would be mostly limited to using SAR remote sensing (DInSAR, InSAR), high resolution satellite imagery, and topographic profiles (e.g., laser altimeter profiles) or digital photogrammetry. Given the issues of InSAR data availability, the presence of alpine vegetation, topographic constraints mentioned previously and also the cost of imagery, approaches to measure slope instability like proposed by Delacourt et al. (2004) using aerial photographs and Quickbird imagery may be worth to be investigated.

6. Conclusions and challenges for future research

Results from recent projects focussed on assessing major risks from rapid, large volume landslides in Europe (Kilburn & Pasuto, 2003), highlight the importance of multidisciplinary studies of landslides hazards, combining subjects as diverse as geology and geomorphology, remote sensing, geodesy, fluid dynamics, and social profiling. Furthermore, previous projects like EPOCH (Mantovani et al., 1996), Carrara et al. (1991) and Zhou et al. (2002) mention that prediction of natural hazards such as debris flows and landslides, caused by interaction of factors which are not always fully understood, and vary over areas and time, pose limitations to the tasks of mapping and analysing the spatio-temporal patterns of relationships between landslide occurrence and causative factors. For extensive areas mapped at small scale (e.g., regional/country levels) it is possible to make general predictions over specific areas based on the number of landslides that have occurred in the past within a land unit. However, using this type of map inventory approach, predictions are complicated on areas currently free of landslides, and thus in such cases it appears more suitable implementing process-based, stochastic or heuristic models based on the assumption that landslides are more likely to occur in places where a combination of conditions that led to landslides in the past exist. This requires knowledge of causative factors, the ability to represent these on a map (or GIS layer), and detailed knowledge of past mass movements (Mantovani et al., 1996).

The literature reviewed shows that the contribution of remote sensing to the mapping, monitoring, spatial analysis and hazard prediction of mass movements (e.g., landslides, debris flows) has largely been in the form of stereo airphoto and satellite image interpretations of landslide characteristics (e.g., distribution and classification) and factors (e.g., slope, lithology, geostructure, landuse/land cover, rock anomalies). The 1 : 15,000 or larger scale is said the best for detecting individual elements related to landslides. In the past only aerial photographs could be used at this scale, but a new window for research and operational applications is now open with the availability of high resolutions data from satellites like Ikonos, Quickbird, ALOS, SPOT-5, IRS Cartosat-1, KOMPSAT-2, EROS (see Table 2).

Though Carrara et al. (1991) suggest that multi-temporal thermal infrared imagery may be useful for detecting the hydrogeologic conditions of slopes as a parameter for determining slope stability conditions, we noted a lack of investigation in this area during the last decade. The availability of satellite imagery with higher spatial and spectral resolutions in the thermal range of the spectrum (e.g., Terra ASTER) may develop some interest for research on its potential for landslide hazard applications.

Monitoring of landslide activity (e.g., field velocity) or motion mapping has been mostly undertaken applying satellite InSAR and DInSAR techniques. For alpine areas current limitations relate to their inability to provide information in steep slope areas, vegetated and/or snow covered areas, in addition to problems of data availability. Opportunities for further research to overcome some of the limitations mentioned in Section 3.2 are open with the availability of new satellite systems (ALOS, TerraSat-X, Radarsat-2, Cosmo/SkyMed), offering higher spatial resolution and higher temporal frequency. Likewise, improved motion mapping in Alpine areas may result from new processing techniques as proposed by Guarnieri et al. (2003) to obtain interferometric surveys by combining two images from any SAR mode, or by Ferretti et al. (2001), who argue that the PS technique enables spaceborne interferometric measurements over vegetated areas, in addition facilitating the mapping of continuous slow landslide movements. As L-band data is less affected than higher SAR frequencies (Rott, 2004) to decorrelation caused by dense vegetation like alpine forest, the availability of interferometric ALOS imagery (7 m spatial resolution) could provide an avenue for further research of DInSAR or InSAR applications in alpine valleys. Furthermore, motion mapping as proposed by Delacourt et al. (2004) using optical high resolution imagery (e.g., aerial photographs, Quickbird, Ikonos, SPOT-5) could be applied complementary to DInSAR techniques to overcome some of the limitations this technique suffers in steep, vegetated mountainous areas.

Lastly, it is worth highlighting some advantages of airborne LIDAR over SAR imagery and radar interferometry for the study of landslide in steep, rugged terrain. Firstly, LIDAR data are gathered over a narrow vertical swath angle (usually less then 20 degrees off nadir), being usually not affected by topographic shadowing, unlike SAR (see Section 3.2). Secondly, LIDAR data are much easier to process than SAR information and the data can be obtained with a density of around one meter, and vertical accuracy of around 10 cm (McKean & Roering, 2004). They mention that assessing how well landslide displacements can be evaluated in multi-temporal DEMs produced from LIDAR deserves further research.

As concluding remark, is worth remembering that besides the application of geospatial technologies like GIS, remote sensing and advanced modelling techniques, the crucial step of the whole landslide hazard analysis and prediction still relies heavily on the ability to gather sound, relevant predictors of landslides (Carrara et al., 1991). In the case of debris flow, perhaps one of the main challenges remains on accurate remote mapping of potential debris flow volume.

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GIS-based hydrogeological databases and groundwater modelling

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Abstract Reliability and validity of groundwater analysis strongly depend on the availability of large volumes of high-quality data. Putting all data into a coherent and logical structure supported by a computing environment helps ensure validity and availability and provides a powerful tool for hydrogeological studies. A hydrogeological geographic information system (GIS) database that offers facilities for groundwater-vulnerability analysis and hydrogeological modelling has been designed in Belgium for the Walloon region. Data from five river basins, chosen for their contrasting hydrogeological characteristics, have been included in the database, and a set of applications that have been developed now allow further advances. Interest is growing in the potential for integrating GIS technology and groundwater simulation models. A "loose-coupling" tool was created between the spatial-database scheme and the groundwater numerical model interface GMS (Groundwater Modelling System). Following time and spatial queries, the hydrogeological data stored in the database can be easily used within different groundwater numerical models.

Résumé La validité et la reproductibilité de l'analyse d'un aquifère dépend étroitement de la disponibilité de grandes quantités de données de très bonne qualité. Le fait de mettre toutes les données dans une structure cohérente et logique soutenue par les logiciels nécessaires aide à assurer la validité et la disponibilité et fournit un outil puissant pour les études hydrogéologiques. Une base de données pour un système d'information géographique (SIG) hydrogéologique qui offre toutes les facilités pour l'analyse de la vulnérabilité des eaux souterraines et la modélisation hydrogéologique a été établi en Belgique pour la région Wallonne. Les données de cinq bassins de rivières, choisis pour leurs caractéristiques hydrogéologiques différentes, ont été introduites dans la base de données, et un ensemble d'applications qui ont été développées permet dès maintenant de prochaines avancées. L'intérêt grandit pour le potentiel d'intégration de la technologie des SIG et les modèles de simulation des nappes. Un outil de couplage a été créé entre le schéma de base de données spatiales et l'interface GMS (GroundWater Modelling System, système de modélisation de nappe) du modèle numérique de nappe. Suivant les requêtes en fonction du temps et de l'espace, les données hydrogéologiques stockées dans la base de données peuvent être aisément utilisées dans différents modèles numériques de nappes.

Resumen La fiabilidad y validez de los análisis de aguas subterráneas dependen enormemente de la disponibilidad de muchos datos de alta calidad. Integrarlos en una estructura consistente y lógica mediante un entorno informático sirve para asegurar su validez y disponibilidad, y rrepresenta una herramienta muy potente para ulteriores estudios hidrogeológicos. Se ha diseñado en la región de Valonia (Bélgica) una base de datos hidrogeológica basada en un sistema de información geográfica (GIS), con el que se dispone de útiles para elaborar análisis de vulnerabilidad y modelos hidregeológicos. Se ha utilizado datos de cinco cuencas fluviales, elegidas por sus características hidrogeológicas contrastadas, así como un conjunto de aplicaciones desarrolladas con vistas al futuro. El interés por el potencial que ofrece la integración de la tecnología GIS y los modelos de simulación de aguas subterráneas está en auge. Se ha desarrollado un "emulador" que integra el esquema espacial de la base de datos y la interfaz GMS (GroundWater Modelling System) de modelación numérica de aguas subterráneas. A partir de búsquedas temporales y espaciales, los datos hidrogeológicos almacenados en la base de datos pueden ser utilizados fácilmente en modelos numéricos diferentes de aguas subterráneas.

Keywords Groundwater management · Database management · Geographic Information Systems · Numerical modelling · Belgium

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Introduction

In recent years, the use of the Geographic Information System (GIS) has grown rapidly in groundwater management and research. GIS is now widely used to create digital geographic databases, to manipulate and prepare data as input for various model parameters, and to display model output. These functions allow primarily overlay or index operations, but new GIS functions that are available or under development could further support the requirements of process-based approaches.

A GIS-managed hydrogeological database has been developed in order to support data used in vulnerability-assessment techniques and numerical modelling for groundwater flow and contaminant-transport studies. The database contains the hydrogeological specificity of the environment of the Walloon region, Belgium. In addition, the coupling between the database and process-based numerical models was implemented. Subsequent projects have dealt with the preparation of groundwater-quality maps and hydrogeological maps.

Work with hydrogeological data and the study of several commercial hydrogeological database schemes, such as ERMA (Environmental Resource Management Applications; Intergraph 1995), have led to the intent to design the scheme of a new hydrogeological spatial database. A need exists for an advanced structure to be used for different environmental studies and consulting activities as well as research and modelling. The design has to address: (1) data management, processing, and analysis, as well as hydrogeological-map production; (2) numerical modelling, as well as overlay and index techniques used in aquifer vulnerability assessment; and (3) support for water authorities' decision-making processes.

GIS and Hydrogeology

Representation of Data and Databases

Data and information required by hydrogeological studies are complex. Information concerning geology, hydrology, geomorphology, soil, climate, land use, topography, and man-made (anthropogenic) features needs to be analysed and combined. Data are collected from existing databases and maps as well as through new field measurements.

Point automatic-collecting systems for some of the physical and chemical parameters are being increasingly used. So too are remote-sensing techniques to assess parameters related to soil, the unsaturated zone, geomorphology, and climate. Some of the techniques for measurement of hydrogeological parameters (sampling, monitoring of hydraulic heads and flow rates, geophysical techniques) show a steady improvement. All these data need to be managed, and this can be achieved using databases, particularly GIS databases.

Storing data implies data analysis, conceptual design of data models, and data representation. In hydrogeology, because of a limited number of sample locations, point-attribute data also need to be processed by applying adequate kinds of interpolation or modelling algorithms. The derived data also need to be managed.

Basic Concepts of GIS

A GIS is defined as a system for input, storage, manipulation, and output of geographically referenced data (Goodchild 1996). GIS provides a means of representing the real world through integrated layers of constituent spatial information (Corwin 1996). Geographic information can be represented in GIS as *objects* or *fields*. The object approach represents the real world through simple objects such as points, lines, and areas. The objects, representing entities, are characterised by geometry, topology, and non-spatial attribute values (Heuvelink 1998).

In hydrogeology, some examples of spatial objects are wells, piezometers, boreholes, galleries, and zones of protection. Attribute values of objects could be the number of a well, the ownership, and the diameter of a gallery or drain. The field approach represents the real world as fields of attribute data without defining objects; some examples are strata elevation, hydraulic head, and vulnerability zones. This approach provides attribute values in any location. In GIS, this distinction between *objects* and *fields* is often associated with *vector* data models and *raster* data models. The *vector model* represents spatial phenomena through differences in the distribution of properties of points, lines, and areas. In this system, each layer is an adapted combination of one or more classes of geometrical features. A *raster model* consists of a rectangular array of cells with values being assigned to each cell. In the raster model, each cell is usually restricted to a single value. Thus, representing the spatial distribution of a number of parameters or variables requires multiple layers.

In their work, environmental specialists need to have available clear representations of the spatial variation of the data. In GIS, two ways exist to solve this problem: (1) field variables (a variable can be given a single, well-defined value at every location), and (2) kernel functions (spatially continuous functions). For digital representation of the spatial variation characterised by fields, six methods are distinguished: the raster model, grid model (rectangular array of sample points), point model (areally irregularly distributed sample points), contour model (isolines), polygon model (polygons holding average attribute values), and triangular irregular network (TIN).

Storing and manipulating data through spatial relationships can be achieved with the GIS packages using the "georelational" model or the "geodatabase" model. The first consists of linking a relational database to geometrical features. The modelled entities are organised into categories sharing common characteristics (points representing wells, piezometers, or gallery wells). A table represents each category. The different attributes occur as columns of the table, and the rows assure the data registration. Relationships "one to one" or "one to

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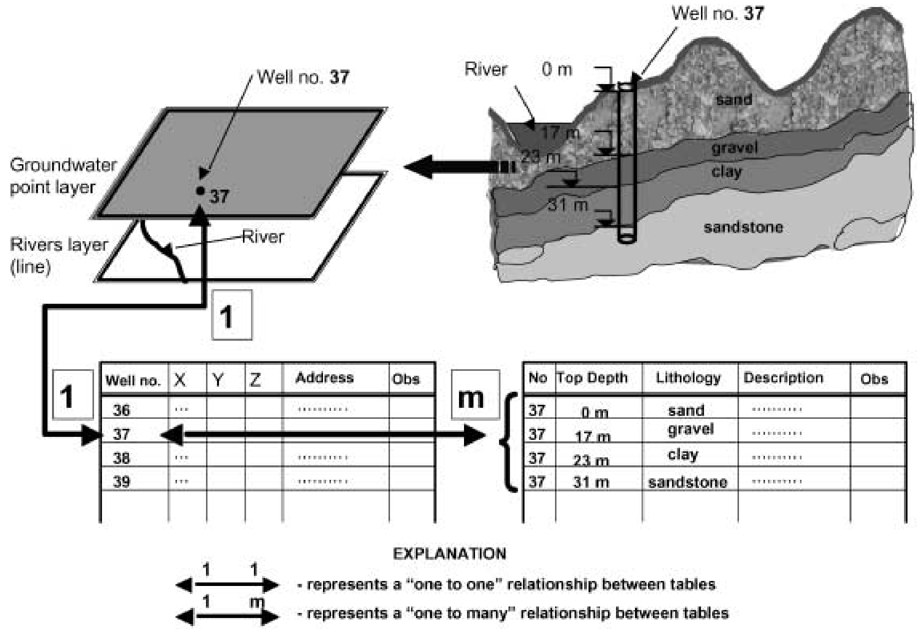

Fig. 1 Example of representing hydrogeological features using the georelational model

many" can be established between tables (Levene and Loizou 1999).

A small example can make the georelational model more comprehensible. In GIS, the real world is described using digital-map data, which define positions in space, and attribute data, which usually consist of alphanumeric lists of characteristics and, frequently, temporal information describing when the other data are valid in time. The various *objects*, such as rivers or wells, are represented on different layers using an appropriate geometry; the rivers are represented as lines, the wells as points. Attribute data may be converted to graphic symbols presented together with other data on a map. Simply moving a pointer to a symbol on a screen display and entering a command can retrieve the attribute data. Geometric data and attribute data are usually separated in the software hierarchy. Identical identifiers for the two kinds of data (geometric and attribute) facilitate matching for retrieval and processing. Figure 1 shows a geological cross section. The point element of the digital-map layer possesses the identifier 37 and represents the well number 37. The same identifier 37 can be found in the first table of Fig. 1 containing the well locations. This represents a "one to one" relationship; one point on the map related to one row. The well number 37 penetrates the sand, gravel, clay, and sandstone strata. This is described in the second table of Fig. 1, such that the user knows that sand is found between 0 and 17 m, gravel between 17 and 23 m, clay between 23 and 31, and sandstone starting from 31 m depth. All rows describing the lithology of well number 37 have the same identifier. This represents a "one to many" relationship. Data presenting a temporal variation such as hydraulic heads or pumping rates are represented in a similar way.

If the georelational model uses points, lines, polygons, and related attribute tables to define various properties in the geodatabase model, entities are represented as objects with properties, behaviour, and relationships. For example, a well object can be found within a library of objects with the entire attribute scheme attached. The user can simply take it, place it on the map, and enter the data in the attached tables. The georelational and geodatabase models are actually very similar. However, the geodatabase model represents a recent improvement in the implementation of the georelational model.

Assembling Groundwater Models and GIS

Geographic data processing can be seen as a subfield of data processing in general. A clear distinction exists between *geographic data processing* and *process-based modelling*. In order to create a digital version of the real geographic form or pattern, geographic features and attributes have to be modelled. For understanding and prediction behaviour, process-based modelling uses the equations that describe the physical or biochemical processes that are to be simulated. Between these two forms of modelling, useful relationships can be established.

Most of GIS can easily accomplish overlay and index operations, but cannot perform the process-based groundwater modelling functions related to groundwater flow and transport processes. However, coupling a GIS to "process-based" models can provide an efficient tool for processing, storing, manipulating, and displaying hydrogeological data. Even though process-based models do not require the use of GIS, a well-designed GIS can significantly reduce the time needed for data preparation and presentation.

The process-based models used in hydrogeology include the simulation of steady- or transient-state groundwater flow, advection, hydrodynamic dispersion, adsorption, desorption, retardation, and multi-component chemical reaction. Very often, exchanges with the unsaturated

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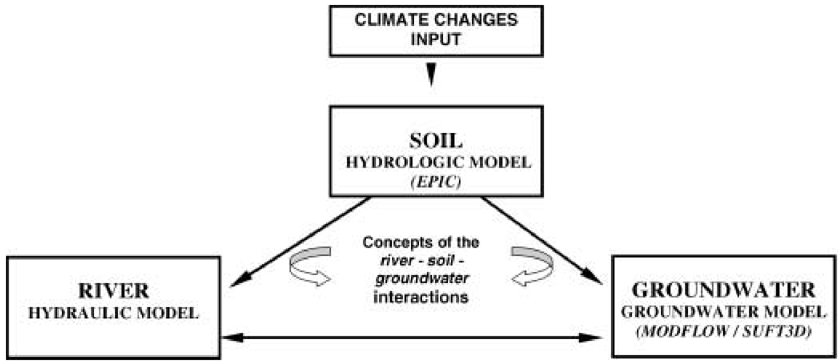
Fig. 2 General framework for integrating the hydrogeological database, as support for study of the impact of climatic changes in the hydrological cycle at the small basin scale



zone and with rivers are also addressed. In these models, equations based on physical processes are solved.

Modelling groundwater flow and contaminant transport in aquifers represents a spatial and temporal problem that requires the integration of deterministic process-based models with GIS. In order to model the physical and chemical processes in the aquifer, each model parameter or variable is represented on a three- or four-dimensional (x, y, z, and time) information layer. Due to the heterogeneity of aquifers, representing the spatial distribution of the parameters and variables that are involved in the constitutive laws describing the simulated processes creates a huge data volume. Managing these data can be done most effectively through GIS.

Data used in groundwater modelling consist of four categories: (1) the aquifer-system *stress factors*, (2) the aquifer-system and strata *geometry*, (3) the *hydrogeological parameters* of the simulated process; and (4) the main *measured variables*. *Stress factors* for groundwater flow include: effective recharge, pumping volumes, water-surface flow exchanges, etc. In contaminant-transport modelling, the input and output contaminant mass flows are *stress factors*. These *stress factors* are imposed on the model through the "boundary" conditions or "source/sink" terms. An appropriate aquifer-system *geometry* can be determined using geological information (maps and cross sections), topographic maps, and contour maps of the upper and lower limits for the aquifer strata and aquitards. Initial estimates of the distributed values and spatial distributions of the *hydrogeological parameters* (hydraulic conductivity, storage coefficient, dispersivity, etc.) need to be made using raw data and interpretations. Of course, the interpretation is based on knowledge of the aquifer geology and hydrogeology. Maps and cross sections representing the spatial variations of *hydrogeological parameter values* are used. For a flow problem, the main *measured variable* is the hydraulic head, and for a contaminant-transport problem, it is the contaminant concentration. These consist of point values measured at different time periods in the entire aquifer. They are required for model calibration and validation.

Links can be organised between models and GIS using three techniques: *loose coupling*, *tight coupling*, and *embedded coupling*. *Loose coupling* is when the GIS and the model represent distinct software packages and the data transfer is made through input/output model predefined files. The GIS software is used to pre-process and post-process the spatial data. An advantage of this solution is that the coupled software packages are independent systems, facilitating potential future changes in an independent manner. In *tight coupling*, an export of data to the model from GIS is performed, but the GIS tools can interactively access input model subroutines. In this case, the data exchange is fully automatic. An example of this coupling is the groundwater modeller link (Steyaert and Goodchild 1994) between the ERMA spatial database scheme [supported by modular GIS environment; Intergraph (1995)] and MODFLOW, MODPATH, and MT3D finite-difference software packages. When a model is created using the GIS programming language or when a simple GIS is assimilated by a complex modelling system, *embedded coupling* is used. *Tight coupling* as well as *embedded coupling* involves a significant investment in programming and data management that is not always justified. Also, this could be constraining when changes are required.

Applications of GIS Data Processing for Groundwater Numerical Modelling

For groundwater studies, four main distinct applications of GIS are recognised: (1) the management of hydrogeological data and general hydrogeological analysis, (2) hydrogeological map elaboration, (3) vulnerability assessment (based on overlay and index methods), and (4) hydrogeological database support for process-based numerical modelling. The first three represent the extension in hydrogeology of classical GIS technology. The last one consists mainly of developing interactions between GIS and dynamic models used in groundwater studies.

A good example of developing a hydrogeological database is given by the study of the impact of climate changes on the hydrological cycle at the basin scale. This study was conducted as part of the Belgian research project "Integrated Modelling of the Hydrological Cycle in Relation to Global Climate Change". The modelled system involves the simulation of quantitative interactions between river, soil, and groundwater, as shown in Fig. 2.

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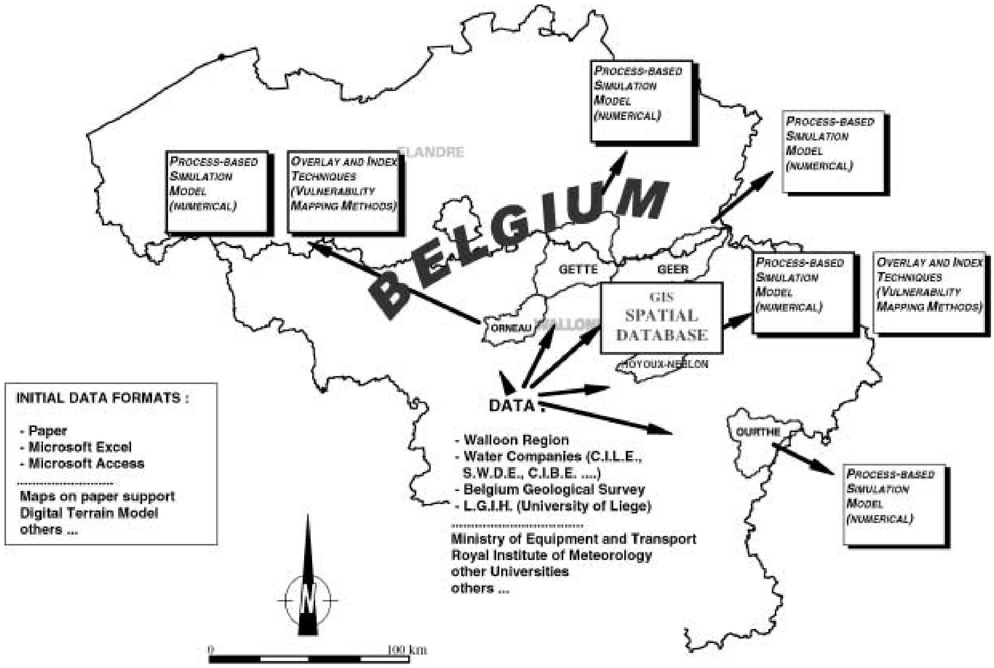

Fig. 3 Schematic representation of applications related to the hydrogeological database and the analysed hydrogeological basins of Geer, Gette, Hoyoux-Neblon, Orneau, and Ourthe, Belgium

Three process-based models are coupled to simulate the water flow in each of the three media (Fig. 2). The three submodels deal with different compartments of the water cycle. The EPIC-GRID soil model (Sohier et al. 2001) computes a general water budget at the soil surface and in the unsaturated zone, differentiating water between evapotranspiration, overland flow, slow and fast subsurface flows, and percolation. The unsaturated zone includes the root zone in relation to crop growth. The surface-water model deals with water flows in the river network and the groundwater model deals with the groundwater flows and the base-flow at discharge to the rivers. Water fluxes are exchanged between the three sub-models at different locations and over time. To handle these exchanges efficiently, some spatial and temporal mapping procedures had to be developed. Interactions between rivers and aquifers (Carabin and Dassargues 1999; Dassargues et al. 1999) are expressed as computed water-flow rates depending on the difference between the piezometric head in the aquifer and the water level in the river and the dynamic Fourier boundary condition (Carabin and Dassargues 2000). A 1-day time step was chosen for exchange among the three models. However, the soil and river models have internal shorter time steps of 1 h. The groundwater models use finite-element or finite-difference software. For application, five hydrogeological basins were chosen for their contrasting hydrogeological characteristics: Gette (sand and chalk), Geer (chalk), Hoyoux-Neblon (limestone and sandstone), Orneau (sand and limestone), and Ourthe (fissured-shale bedrock). Locations are shown in Fig. 3. The Gette, Geer, and Orneau basins are located in areas where intensive agricultural activities take place in addition to urban zones of small cities (less than 25,000 inhabitants). The Hoyoux-Neblon and Ourthe basins are extensive livestock farming areas with only small villages and with a high portion of forested areas in the Ourthe basin.

Specific aspects of the integration of these three models and on the calibration and results of the integrated model applied to these basins are described in an internal report (Belgian Office for Scientific, Technical and Cultural Affairs 2001) and will probably be published very soon.

An Advanced Approach for Managing Hydrogeological Data: The HYGES Database Scheme

Recognising that field hydrogeologists, modellers, and regulators all need to manage data, the purpose of developing the hydrogeological database concept (called HYGES) was to integrate the main data and information that the hydrogeologist uses. The objectives for the final database were: (1) to provide an organised scheme for capturing, storing, editing, and displaying geographically referenced hydrological data and information, (2) to process and analyse spatially distributed data, (3) to properly support aquifer-vulnerability assessments, (4) to easily provide values for numerical-model parameters and variables, and (5) to create hydrogeological maps.

Existing and required data types were examined in order to design the database scheme. Parameters and information were reclassified and regrouped several times. Many hydrogeological parameters and relationships were analysed in order to be placed in the database. Maximum information, minimum data redundancy, reduction of storage capacity, and optimum retrievability of data for analysis were the constraints that defined the final scheme. Data-integration limits were imposed because of different restrictions concerning the hardware and software storage capacity and limitations in current activities and in available information.

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Table 1 Layers of the primary hydrogeological database. *DBMS* Database Management System; *QM* quarries and mines

Layer no.	Groups of layers	Characteristics represented	Geometry	Main table DBMS	Structure and format
1	Topography	Land elevation – contour lines	Arc	–	Info
2	Geological map	Geological formations	Polygon	–	Info
3	Map of soils	Soils	Polygon	–	Info
4	Surface-water bodies	Surface waters (lakes, ponds)	Polygon	Hydro	Info+Access
5	Hydrological basins	Hydrological basin	Polygon	Basin	Info+Access
6	Hydrological network	Rivers, interactions – aquifers	Arc	River	Info+Access
7	Irrigation drains	Irrigation drains (unexploited)	Arc	Drain	Info+Access
8	Surface water (point)	Quantitative measurement sections	Point	Surface	Info+Access
	Qualitative measurement sections	Point			
	Springs	Point			
	Springs for water supply	Point			
	Swallow holes and resurgences	Point			
	Irrigation drains	Point			
9	Climatic stations	Climatic measurement stations	Point	Climate	Info+Access
10	Groundwater (point)	Wells, piezometers	Point	Groundwater	Info+Access
	Water-supply galleries and drains	Point			
	Quarries, mines – hydrogeological information	Point			
	Unknown points of measurement	Point			
	Geological boreholes (drilling)	Point			
11	Quarries and mines	Quarries, mines – description	Polygon	QM	Info+Access
12	Water-supply galleries and drains	Water-supply galleries and drains	Arc	Gallery	Info+Access
13	Protection zones	Protection zones	Polygon	Zones	Info+Access
14	Hydrogeologic cross sections	Hydrogeologic cross sections	Arc	–	Info
15	Sewer network system	Sewer network system	Arc	–	Info
16	Karst atlas	Karst geomorphology	–	–	Info
17	Land-use map (three layers)	Topographical map	–	–	Topo raster map
	Communities	Polygon	–	Info	
	Provinces	Polygon	–	Info	

Technical Aspects of the HYGES Database Construction

Data analysis is an important consideration in database construction. In order to identify the data needs and to provide the optimal data representation, accurate assessments of all types of data and data formats are extremely important before designing a database.

The data-collection operation showed that hydrological and hydrogeological data come from very different sources: water regulators, water companies, environmental agencies, geological research organizations, and many others. In this case, the main data providers were the Ministry of Walloon region; Walloon Society for Water Distribution (SWDE); Water Supply Company of Liege (CILE); Water Supply Company of Brussels (CIBE); Belgian Geological Survey; Laboratory of Engineering Geology, Hydrogeology and Geophysical Prospecting (LGIH); and others. These various sources have strong dissimilarities in data type, in quality and in quantity, as well as in storage media. All the data were analysed for transfer to a single system. Data that appear to be redundant had to be specified in the database scheme to avoid loss of information. Such decisions were based on (1) pumping schedules, (2) data-registration formats, (3) uncertainty of existing data (measures and registration), and (4) insufficiency in data-registration system.

Depending on the characteristics of the accepted conceptual model (basic assumptions) and needs, additional data could appear. Also, data that were not explicit or sufficient needed to be flagged or supplied with fields of information or even entire tables. An example is the case where flow-rate registrations related to several wells were available, without distinguishing the pumping schedule of each well. There, a field containing wells sharing the same flow-rate value had to be specified.

Data formats are also an important issue, because the pre-treatment of data consists of hours of encoding or of writing import/export codes. Data coming from paper sources, such as tables, maps, and singular data, as well as different spreadsheets and data existing in databases having distinct schemes, were analysed in order to create a unified database system.

After structuring the spatial-database scheme, hydrological and hydrogeological data, obtained from the Ministry of Walloon region, SWDE, CILE, and elsewhere were introduced into a GIS project using Arc/Info (Envi-

Fig. 4 Simplified version of the attribute data scheme for "surface-water points" ▶

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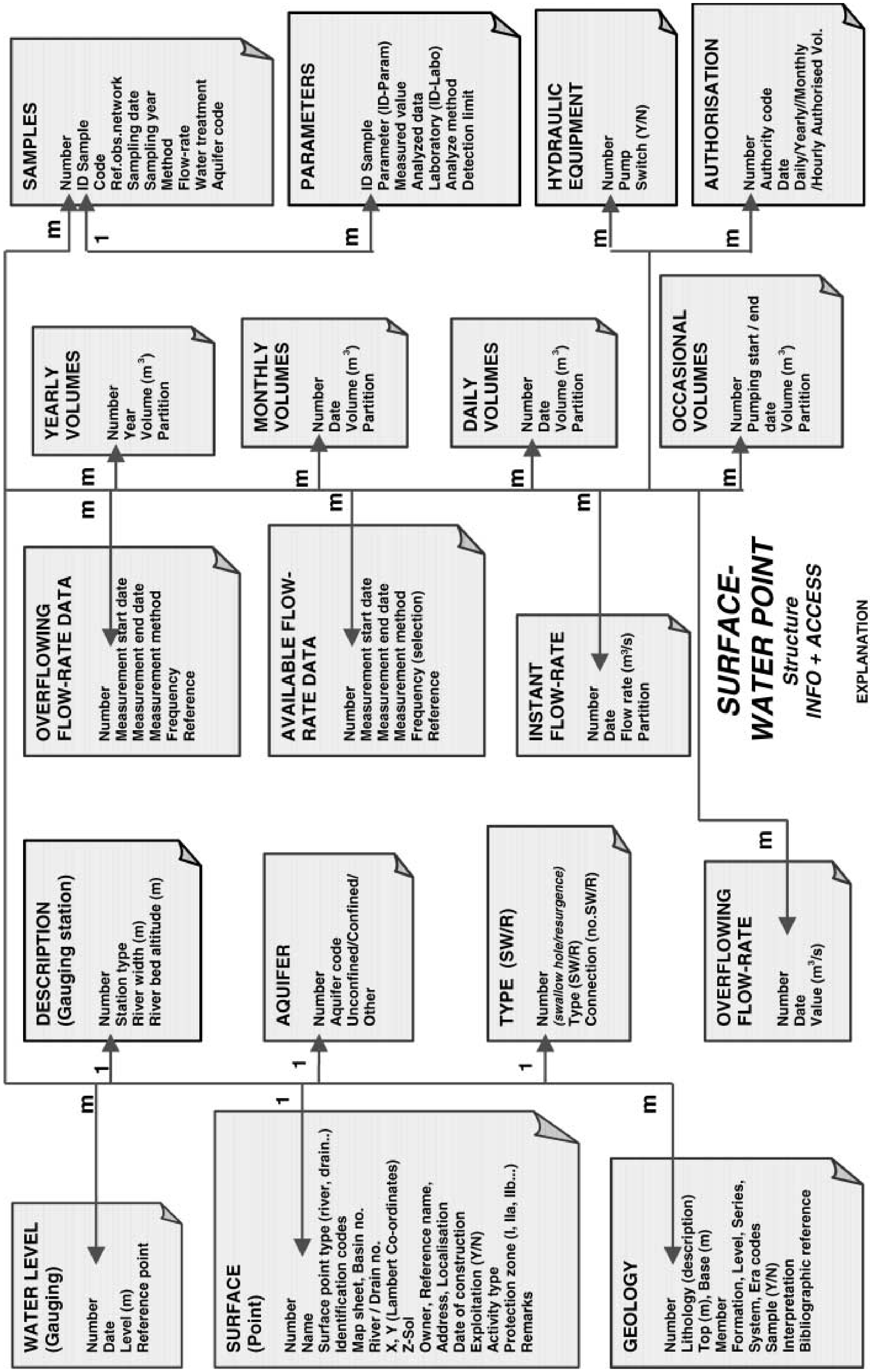

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ronmental Systems Research Institute, ESRI) with Access (Microsoft). This solution was chosen after analysing the software platforms used by different hydrological and hydrogeological research teams, Belgian regulators, water companies, and water authorities, in order to ensure compatibility in future data-exchange operations.

In the first step, information was collected for the following hydrogeological entities: wells and wells systems, piezometers, drains, water-supply galleries, and quarries and mines exploited for water. For these features, the following characteristics were incorporated: location (in Belgian Lambert coordinates), address, altitude, depth, local aquifer information, and owners. More than 50 years (1947–1999) of time-dependent data were encoded, including hydraulic heads and annual and monthly pumping rates. Quality data represented by 147 water-quality parameters determined on 2,316 groundwater samples are now registered in the database. The information was supplemented with digital maps showing the geology and strata elevations, land-use maps, zones of hydrogeological protection, and others.

Description of the HYGES Database Scheme

Data and information specific to geomorphologic, geologic, and hydrologic conditions were divided into two parts, primary and secondary data. The primary-data section contains layers of general environmental information, such as topography, geological maps, soils maps, hydrological and hydrogeological raw data, or data undergoing an initial minor pre-treatment; information related to hydrogeological investigations and developmental means, such as wells, piezometers, drains, mines, and quarries; and land-use maps. Secondary data consist of data derived from processed primary data; examples include maps of hydraulic head, hydraulic conductivity, and groundwater vulnerability.

A spatial reference for the represented hydrogeological features was used based on the topographical map of Belgium at a scale of 1:25,000. This map uses the Lambert Conformal Conic projection with the following parameters (Belgium Lambert): spheroid International 1909; 1st standard parallel 49°50′ 0.002″N; 2nd standard parallel 51°10′0.002″N; central meridian 4°22′2.952″E; latitude of projection's origin 90°0′0.000″; false easting (meters) 150000.01300; and false northing (meters) 5400088.43800. The current geological map of Belgium uses the same scale and the same projection as the topographical map.

The composition of the primary database is given in Table 1, which shows that the information is divided into several groups of layers. One or several layers compose each information group. The number of layers, the name of each layer, the represented entities, the format or geometric characteristic, and some characteristics of the attribute database link to GIS layers are specified in the same table. Topography is represented by contour lines. Because of the available encoded data, the "geological map" and the "map of soils" are polygon layers and simple attributes are attached directly to them. The same approach is applied to the "karst geomorphology atlas", "land-use plan", and "sewer network system". The "hydrogeologic cross sections" are represented by line features. They have attached computer-aided design (CAD) drawings or scanned images showing the cross sections. Point information is classified into two main layers, depending on the position relative to the ground surface: "surface-water points" and "groundwater points".

"Surface-water points" information layer

The information layer "surface-water points" contains points representing river-gauging information, water-quality sampling data, irrigation-drain point data, springs, springs used for water supply, and swallow hole and resurgence hydrogeologic characteristics. The attribute scheme of this layer, shown in Fig. 4, contains several related tables. *Surface* is the main table where using a relation of "one to one", the scheme is linked to the geographic location of the point in the GIS software. The linkage is done through the unique item called "Number" at the top of each table. The relationships "one to one" and "one to many" between the *Surface* table and the various derived tables marked "m" are defined using the same item. The *Water levels* and *Description (Gauging station*) tables contain the characteristics of river cross sections. *Geology* and *Aquifer* are tables that are needed to describe the environmental conditions of springs, water-supply springs, surface drains (irrigation), and karst features. The *Type (Swallow hole/Resurgence)* table is specific to the karst features. The table *Aquifer* shows the connection to the water-supply springs via the tables *Overflowing flow rate* and *Overflowing flow-rate data*, as well as to the swallow holes and resurgences. As seen in Fig. 4, six tables of flow-rate data are introduced: *Water level (gauging)*, *Description (gauging station)*, *Overflowing flow rate*, *Overflowing flow-rate data*, *Available flow-rate data*, and *Instant flow rate*. Specific data for the water-supply springs are also stored in *Hydraulic equipment* and *Authorisation* tables. Water-quality data for all the six entities represented in this layer are described using the *Samples* and *Parameters* tables.

"Groundwater points" information layer

The "groundwater points" information layer is registered in the database with a more extended attribute scheme. This layer regroups the following entities: wells, traditional hand-dug wells and simple piezometers, galleries and gallery wells, rock quarries and mines; and boreholes. The main table linked to the layer points is *Groundwater*. The relationships between tables are made using the unique layer item at the top of each table, also called "number". As shown in Fig. 5, the table *Groundwater* contains information concerning the geographic

Fig. 5 Simplified version of the attribute data scheme for "groundwater points" ▶

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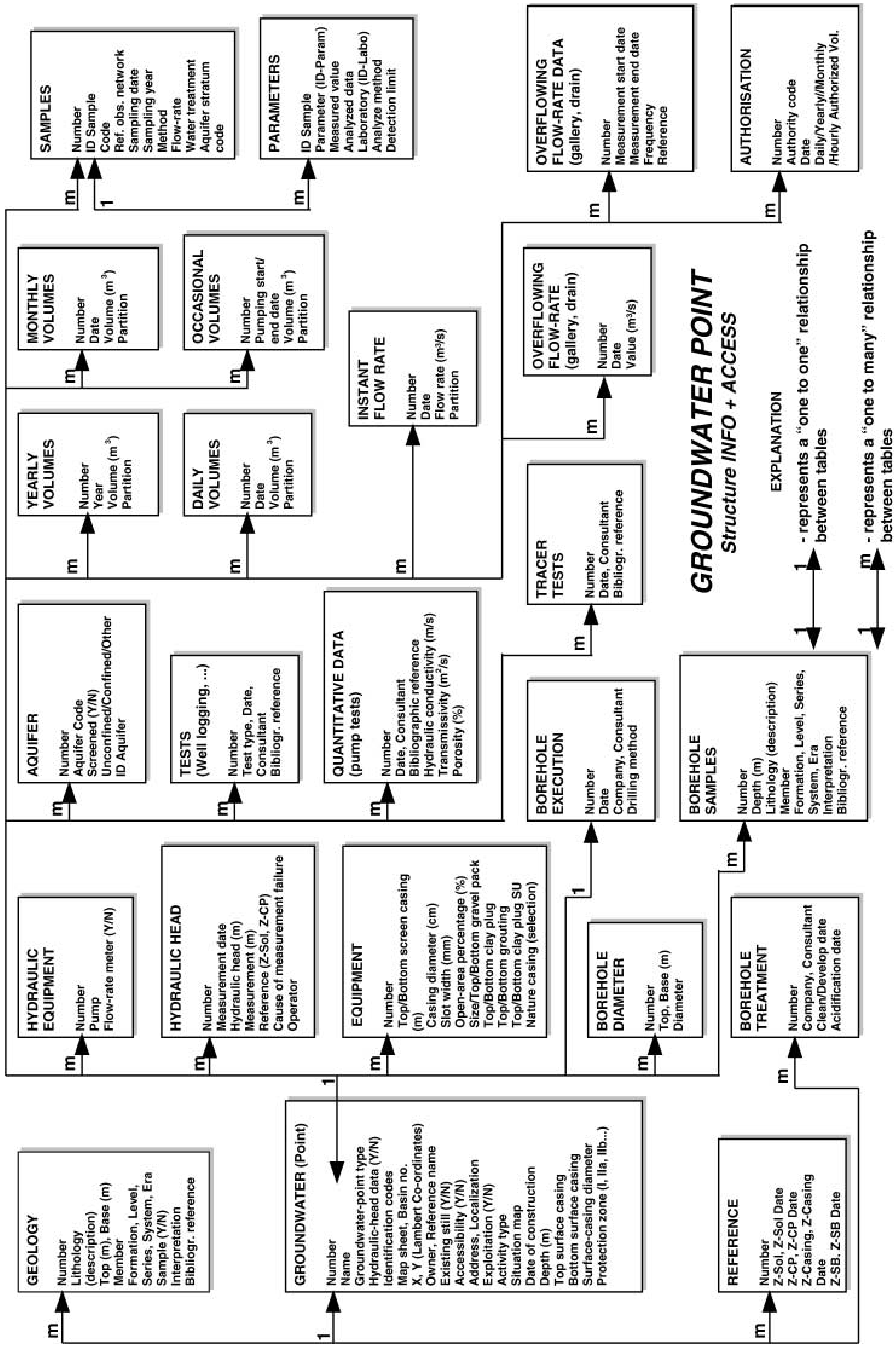

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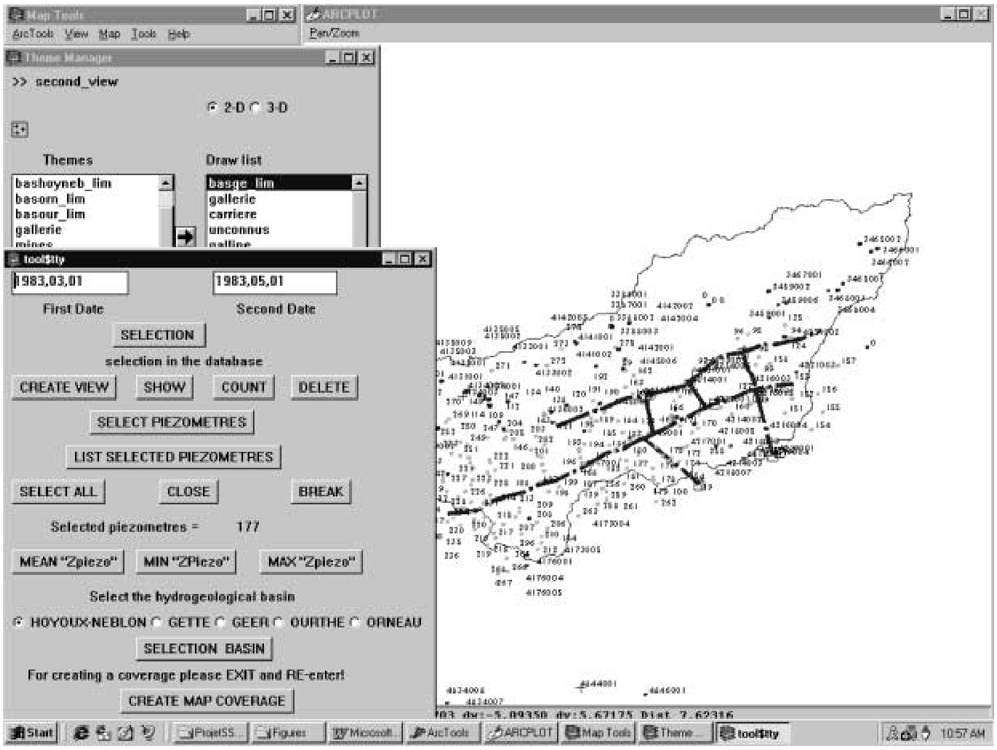

Fig. 6 A spatial database query menu for hydraulic heads

position (coordinates, address), type of represented entity (well, traditional well, borehole, gallery well, piezometer, etc.), name (or official names), system of codes (used by several regulators in order to identify the entity), and some technical characteristics related to the represented entity (such as date of execution, type of exploitation, depth, kind of a protection zone to which it belongs, and others).

Data containing the lithology and stratigraphy are in the *Geology* table. Each stratum penetrated by a borehole is described here by a "one to many" relationship. Other information related to the borehole and geological parameters (considering that each well or piezometer is initially a borehole) is included in the tables: *Borehole diameter*, *Borehole execution*, *Borehole treatment*, *Borehole samples*, and *Reference*. Information related to the tests conducted in the boreholes (well logging, etc.) is stored in the table *Tests*. Data related to technical characteristics of wells and equipment are in the tables under *Hydraulic equipment* and *Equipment*. The table *Equipment* is used to store information relating to the completion of wells.

The *Aquifer* table is used to store information that describes the succession of aquifer strata penetrated by wells. The code of the aquifer (placed in a dictionary of terms), whether the aquifer is under confined/unconfined conditions, as well as the position of the screens, are stored here. The hydraulic-head values are stored in the *Hydraulic head* table. Seven tables representing diverse kinds of flow-rate measurements are present. Two of them contain specific data for galleries and drains (Fig. 5).

Information that identifies the analysed groundwater quality samples and describes the results is stored in two tables (*Samples* and *Parameters*). Because for each analysed sample several parameters are identified, a "one to many" relationship is established. The link is made using a unique point item called Sample-ID. The *Samples* table contains the sample code, the sampling date, the sampling method, the value of the flow rate when the sample was taken, the water treatment technique, and the aquifer stratum code where the sample has been taken. The *Parameters* table contains the name of each measured parameter (in a dictionary of terms), its respective value, the date the analysis was done, the analysis type, and its limit of detection. Also, the name of the laboratory and its coordinates are introduced here in a dictionary of terms.

Information about hydrogeological tests is stored in the table *Quantitative data* (information related to quantitative tests made in a well) and in the *Tracer tests* table (an inventory and references of the performed tracer tests). Representative values of hydraulic conductivity (in meters per second), transmissivity (in square meters per second), and porosity (in percent) parameters associated with a bibliographic reference are also stored here. A table containing the authorised volumes of extracted water for each well (approved by regulators) completes the scheme. The *Authorisation* table represents a good reference for the environmental-impact studies and other hydrogeologic investigations.

"Climatic stations" are represented in the analysis as a separate layer of points having also an attached attribute scheme. Simpler attribute schemes are developed also

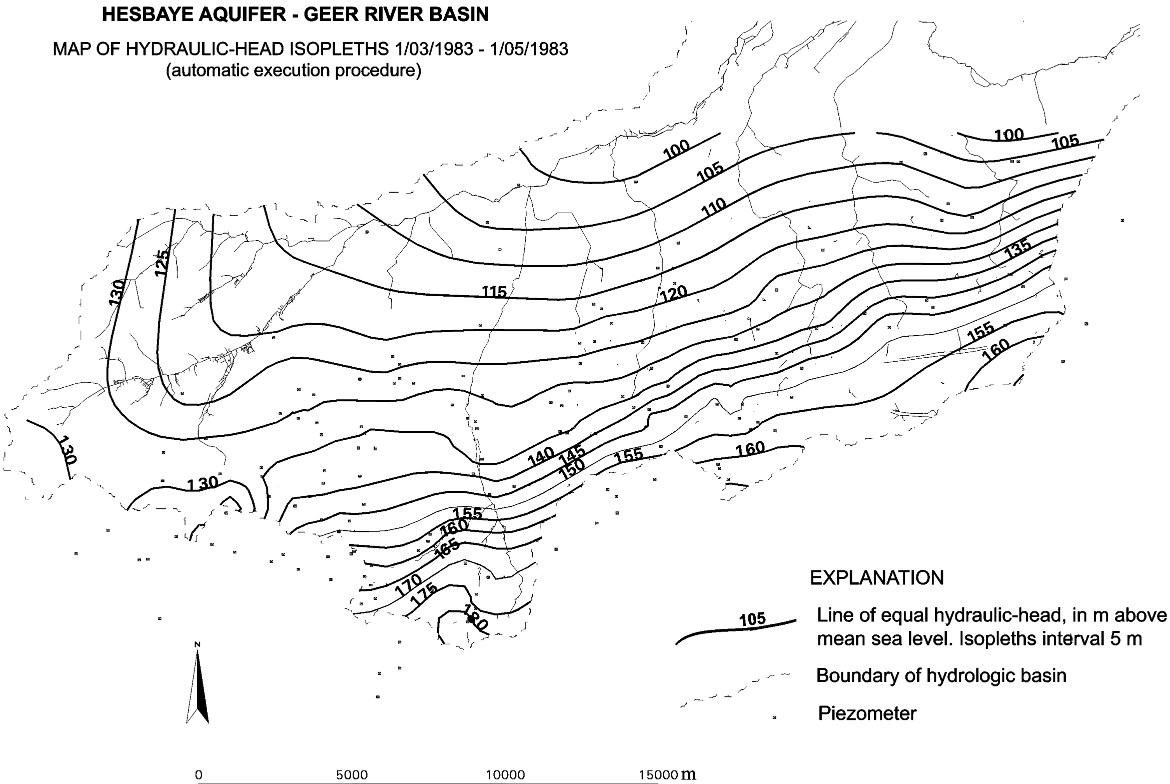

Fig. 7 Map based on the generating procedure for obtaining isopleth maps of hydraulic heads

for "Hydrological network" (line), "Tables of surface water" (polygon), "Irrigation drains" (line), "Quarries and mines" (polygon), "Water-supply galleries and drains" (line), and "Protection zones" (polygon).

Spatial Analysis of Hydrogeological Data Using GIS

Powerful spatial analysis is feasible once the database is established. Maps representing database attribute queries (time- and space-dependent parameter values) can be created. Simple statistics related to hydrogeological entities can be displayed on the computer screen or printed on paper support maps. Geostatistical procedures (i.e., kriging) complete the analysis. Some of the tools needed to achieve the objectives are already implemented in the base software package, but most of them require knowledge of GIS techniques, database philosophy, and targeted programming using specific programming languages.

In this case, spatial query procedures having a user-friendly interface were written in AML (Arc Macro Language) and SQL (Standard Query Language). These new query tools were designed to complete and combine the existing GIS package functions. Now, maps displaying maximum, minimum, or mean values of hydraulic heads for a required period of time can be automatically displayed by choosing the required dates; an example is shown in Fig. 6. Also, the number of hydraulic-head measurement points and the associated standard deviation can be shown. Flow rates of wells or a specified pumping schedule can be displayed in the same way graphically or on maps. In addition, new layers or new maps resulting from the inclusion of any existing layer of information can be generated.

Using a chosen interpolation procedure, results obtained by different queries can be treated further. Obtaining maps of hydraulic-head distribution for a chosen time interval is one possibility. Spatial interpolation can be done by using the existing software tools or by programming new ones. Arc/Info contains several reliable tools for interpolation. The information contained in the vector format layer has to be rasterised to apply these tools. To do this, the information layer has to be transformed into a uniform cell-based grid, where each cell is assigned the attribute information. In order to increase the accuracy of interpolated results, the cell size should be chosen based on the spatial distribution and accuracy of the data. In this case, to obtain isopleths of hydraulic heads, the cell size was selected taking into account the spatial distribution of the point information in the hydrological basin, the basin area, the distance between point hydrogeological entities (wells, piezometers, etc.), and the computing time. The interpolation method uses an iterative finite-difference interpolation technique. It is optimised to have the computational efficiency of "local" interpolation methods such as inverse distance weighted interpolation (Environmental Systems Research Institute 1997). Isopleth maps of hydraulic heads can be generated using the optimised grid of interpolated hydraulic heads; an example is shown in Fig. 7.

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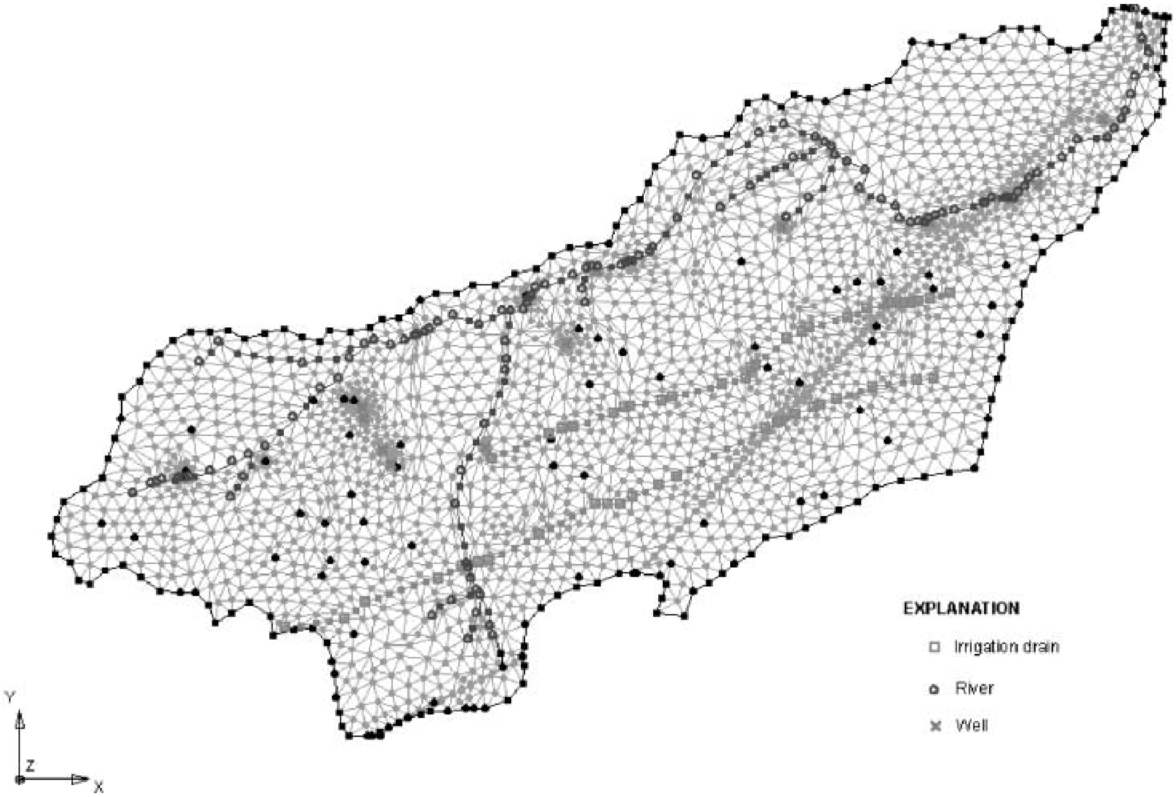

Fig. 8 A 2D finite-element mesh generated using “feature objects”

Particular Aspects of Groundwater Numerical Modelling

The Groundwater Modelling System (GMS) is a powerful pre-processor and post-processor (Engineering Computer Graphics Laboratory 1998) that can be used for various groundwater numerical modelling operations. For simulating the groundwater flow in the concerned hydrogeological basins, numerical models were created using this package with the SUFT3D (Carabin and Dassargues 1999) finite-element software and the MODFLOW (McDonald and Harbaugh 1988) finite-difference software.

For the chosen GMS version (GMS 2.1, 1998), the hydrogeological-attribute data can be directly introduced or they can be imported from a specific format file. The need for importing data in GMS exists in the three steps of groundwater flow modelling: *conceptual model* design, *model* construction, and *calibration*.

The boundaries, constraints, stresses, and other features defining the *conceptual model* are created using the socalled feature objects represented by points, arcs, and polygons. Points define pumping wells and piezometers; arcs define boundaries, rivers, and drains; and polygons define different material zones as well as water surfaces (lakes). For 3D modelling, triangular irregular networks (TINs) are used to represent the ground surface and the theoretical surfaces between the limits of geological strata. These “feature objects” can be imported in GMS from GIS packages.

Starting from the defined *conceptual model*, the *model* can be built within GMS using automatic tools. Depending on the chosen model (finite element or finite difference), the method of using these tools is different. For finite-difference models, serried attributes can be given to all “feature objects”. These include pumping rates and stress layers for wells, prescribed total heads for boundaries and lakes, elevations and conductances (hydraulic conductivity of the prevailing thickness of the streambed) for rivers and irrigation drains, hydrogeological properties of each stratum, and recharge rates for the defined areas. The finite-difference grid is automatically constructed to fit the conceptual model and the data are transposed from the conceptual model to the grid cells. For the mesh of the finite-element models, only the material properties can be imported. GMS uses the “feature objects” defining the conceptual model to generate a 2D mesh, such as is shown in Fig. 8. The procedure follows the geometric constraints; refinements may be required around points and element sides corresponding to arc edges. The 3D mesh is built using the 2D mesh and TINs.

Model *calibration* is the process of modifying the input parameter values until the model output matches an observed data set. In groundwater modelling, the observed data are usually the point values of the hydraulic head, and a set of “observation points” can be imported in GMS, allowing further statistical treatment.

Coupling HYGES to the GMS Interface

GMS contains several tools for exchanging data with GIS packages, but a real coupling tool has not been

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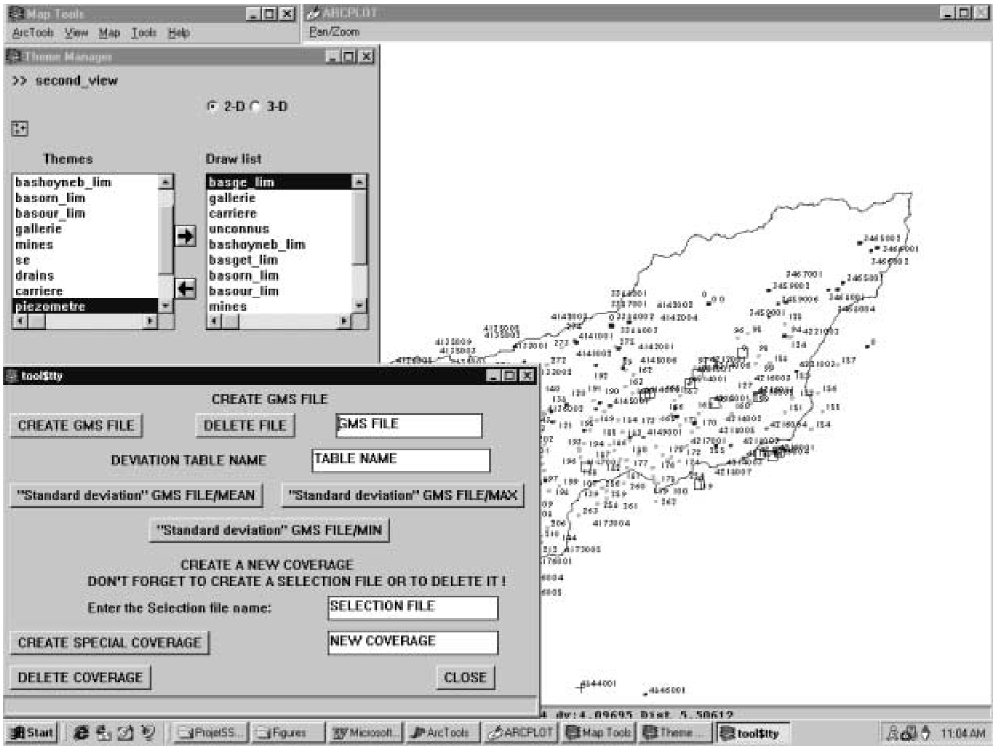

Fig. 9 Interface menu for creating readable Groundwater Modelling System (GMS) files and new layers of processed information

developed yet. Arc/Info can interchange geometric data (point, arc, and polygon) with GMS through the existing "Generate/Ungenerate" functions. Attribute data cannot be automatically exchanged; however, GMS is continuously being improved to meet users' requirements. Enlarging the GMS software capacities through programming could theoretically solve this issue, but in practice this depends on the entire spatial data scheme (geometric features layers and attribute data) or even on the database structure.

In order to solve the coupling aspect, different programs were developed to automatically use the attributes of wells, rivers, and drains in GMS for the mesh of the finite-element models. They make the attribute-data transfer between Arc/Info and GMS software through "feature objects" and "observation points". The codes were created using Arc Macro Language (AML) and Standard Query Language (SQL). These programs represent a coupling tool between the GIS package and the groundwater modelling software. This tool allows maintenance of the coupled software packages as independent systems, facilitating any future changes in the spatial database scheme or in any particular module of the software.

A user-friendly interface, illustrated in Fig. 9, manages the data query and transfer for the "loose coupling" tool. By introducing several query characteristics (spatial or time dependent) for flow rates or hydraulic-head values, a readable GMS file is easily created. Further, GMS handles this file for attributing values (flow rates, hydraulic-head values, and statistical parameters) to each location point of the model discretisation.

The Hydrogeological Database Scheme Within a GIS Structure

The presented scheme can satisfy the hydrogeologist's immediate needs in terms of research and various environmental studies. However, hydrogeologists are advised that a complete GIS structure is more that a database scheme. The scheme implementation within a complex GIS structure supposes another design step related to concepts and formalisms (Pantazis and Donnay 1996). First of all, "GIS development is a process of technological innovation and requires management attention appropriate to this type of activity very dependent on proper management participation and supervision" (New York State Archives and Records Administration 1997).

Even though this complex direction is beyond the objectives of the present work, the main tasks that must be completed to have a successful organisational GIS are discussed. As stated by the above-mentioned institution, these are: Needs Assessment, Conceptual Design of the GIS, Survey of Available Data, Survey of GIS Hardware and Software, Detailed Database Planning and Design, Database Construction, Pilot Study and Benchmark Test, Acquisition of GIS Hardware and Software, GIS System Integration, GIS Application Development, and GIS Use and Maintenance. These steps are related, as illustrated in Fig. 10.

Conclusions and Further Developments

The hydrogeological GIS database described in this paper offers capabilities for hydrogeological modelling

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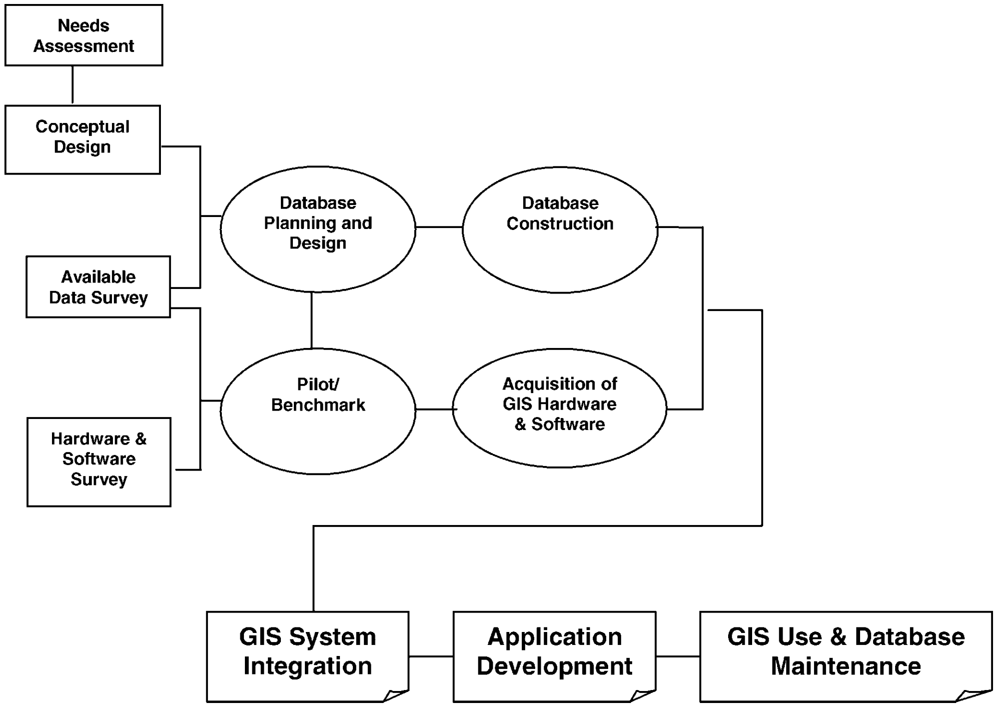

Fig. 10 Relationships between the main steps of a GIS-development process

as well as other hydrogeological studies, as described below:

1. *Data verification and validation* are essential. Using an advanced database supported by GIS, this operation could be done in a simple way. For example, anomalies in hydraulic-head data could be observed directly on the generated hydraulic-head maps.
2. *Automatic data treatment* is required before input to the numerical model. Because of the huge amount of work that is required to prepare the data used in the process-based models, the GIS database is essential.
3. *A global view of the hydrogeological data* can be obtained by using the generated maps. Hydraulic-head maps, maps of pumping-rate allocations, and maps of statistical data show very clearly the data distribution and allow a view of conditions of the aquifer behaviour and stress factors.
4. *Maps of aquifer parameters* can be generated. They can be created starting from existing point data using statistical procedures (geostatistics) supported by the GIS software. These maps are needed to start the calibration procedure of any groundwater model. Potential sites for groundwater utilisation can be detected using these maps. The vertical variability of hydrogeologic parameters (e.g., hydraulic conductivity, porosity) that have a great influence on the conditions for extracting water from the aquifer also can be analysed.
5. *Correlations between groundwater hydrochemical parameters, aquifer depth, lithology, and land use* can be made using the recorded data and statistical procedures already implemented in the GIS software.
6. *Aquifer vulnerability studies* can be performed using the existing spatial database. New procedures for quantification of physically significant parameters can be developed using this hydrogeologic database. From this point of view, coupling GIS to process-based numerical models with applications to groundwater phenomena as well as to the unsaturated zone would represent one of the most interesting steps in future hydrogeological research.

The presented database schema is implemented in the Laboratory of Engineering Geology, Hydrogeology and Geophysical Prospecting of the University of Liege, Belgium. The software support is Arc/Info (Environmental Systems Research Institute 1997) in connection with Access (Microsoft). The schema could be applied to other GIS and Relational Database Management Systems (RDBMS) that may be connected.

This database still has limitations which were discussed in the previous sections. However, the authors consider that this scheme fully satisfies the requirements of their hydrogeologic studies. Changes, updates, or further developments of the schema could be incorporated in a simple way. At the same time, the database was designed so that its flexibility makes the data-retrieval process easy. Also, the spatial database was conceived as being modular. Users who are using only an RDBMS in the absence of a GIS tool can handle the attribute data.

Starting from this schema, new developments are already underway. One of them consists of designing new hydrogeological maps for other areas. A pilot project was set up and regulators and researchers are working together to implement this database concept in Belgium for the Walloon region administration.

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Sensitivity analysis for the EPIK method of vulnerability assessment in a small karstic aquifer, southern Belgium

Radu Constantin Gogu · Alain Dassargues

Abstract Applying the EPIK parametric method, a vulnerability assessment has been made for a small karstic groundwater system in southern Belgium. The aquifer is a karstified limestone of Devonian age. A map of intrinsic vulnerability of the aquifer and of the local water-supply system shows three vulnerability areas. A parameter-balance study and a sensitivity analysis were performed to evaluate the influence of single parameters on aquifer-vulnerability assessment using the EPIK method. This approach provides a methodology for the evaluation of vulnerability mapping and for more reliable interpretation of vulnerability indices for karst groundwater resources.

Résumé Une analyse de la vulnérabilité d'un petit aquifère karstique du sud de la Belgique a été réalisée en appliquant la méthode paramétrique EPIK. L'aquifère est logé dans des calcaires karstifiés du Dévonien. Une carte de la vulnérabilité intrinsèque de l'aquifère et du captage existant montre trois zones de vulnérabilité. Une étude d'évaluation des paramètres et une analyse de sensibilité ont été conduites pour juger l'influence des paramètres sur l'estimation de la vulnérabilité de l'aquifère au moyen de la méthode EPIK. Cette approche fournit une méthodologie pour évaluer la cartographie de la vulnérabilité et pour interpréter d'une façon plus sûre les indices de vulnérabilité des ressources en eau des milieux karstiques.

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Resumen Se ha efectuado un estudio de vulnerabilidad de un pequeño acuífero kárstico en el Sur de Bélgica mediante el método paramétrico EPIK. El acuífero consiste en calizas karstificadas del Devónico. El mapa de vulnerabilidad intrínseca del acuífero y del sistema local de abastecimiento indica la existencia de tres áreas vulnerables. Se estudió el balance de los parámetros y se hizo un análisis de sensibilidad para evaluar la influencia de cada parámetro en las valoraciones de vulnerabilidad de acuíferos utilizando el método EPIK. Este enfoque proporciona una metodología para evaluar zonas vulnerables y para obtener interpretaciones más robustas de los índices de vulnerabilidad en relación con los recursos de aguas subterráneas en medios kársticos.

Key words vulnerability · karst · groundwater protection · sensitivity analysis · Belgium

Introduction

Assessing vulnerability of aquifers using overlay and index methods is an empirical procedure, but for karstic aquifers this kind of technique represents one of the only meaningful ways to delineate the zones most vulnerable to groundwater contamination. Some subjectivity is, to some extent, unavoidable in the selection of rating values and weights in the EPIK method (Epikarst, Protective cover, Infiltration conditions, and Karst network development) as in other similar methods, such as DRASTIC (Aller et al. 1987) and SINTACS (Vrba and Zaporozec 1994).

In order to investigate the impact of this subjectivity on the final results, a small karstic aquifer near Beauraing, Belgium, was selected to test the sensitivity of vulnerability to selected values of ratings and weight in the EPIK method. The first step was to prepare a detailed vulnerability map according to the EPIK technique (Doerfliger and Zwahlen 1997). Then, using a sensitivity analysis of the applied parameters, an evaluation of this vulnerability-mapping method was done. The analysis allows one to study the parameter balance in the vulnerability method, in order to reduce or increase the importance of a parameter in the calculation of the vulnerability index.

The results could lead to changes in the parameter estimation within the basic equation of the vulnerability method.

Intrinsic Vulnerability of the Aquifer

Hydrogeological Framework

The Beauraing study site is an area of 2.5 km^2 in the southern part of the Dinant synclinorium near the France–Belgium border. Location is shown in *Figure 1*. The main karstic aquifer is composed of Devonian limestone. These limestone deposits are bounded to the north and south by Frasnian and Eifelian siltstone bands; the rocks are folded into an anticline–syncline structure with a WNW-trending axis. The geology is shown in *Figure 2*. The siltstone bands act as impermeable boundaries for the limestone aquifer. Consequently, the study area was confined to the karstic aquifer. Four joint systems have been identified. One of them is orthogonal to the strike of the main strata, two others are at 45° angles, and the fourth one trends NE (Gontier et al. 1997).

The aquifer is unconfined and water supply is provided to the small city of Beauraing by pumping from one of the natural caves of the aquifer. In order to study the protection zones around the water-supply system, six piezometers with depths of 65–80 m were drilled in 1994–1995. The measured potentiometric levels indicate that the depth to the water table ranges from 18–40 m. Regional studies (Gontier et al. 1997) indicate that the general groundwater flow direction is from west to east. In the study area, groundwater flows from the area of the Hilau stream to the Biran stream, as confirmed by measured losses of water in the Hilau stream. The aquifer has two discrete natural groundwater outlets. The principal one is in a natural cavern in the eastern part of the area. This outlet has been developed to collect groundwater (25–40 m^3/h)

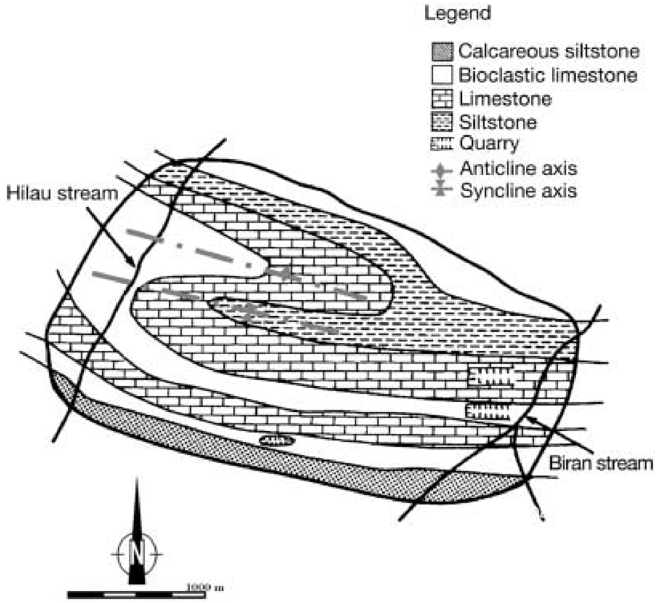


Figure 2 Geology of study area

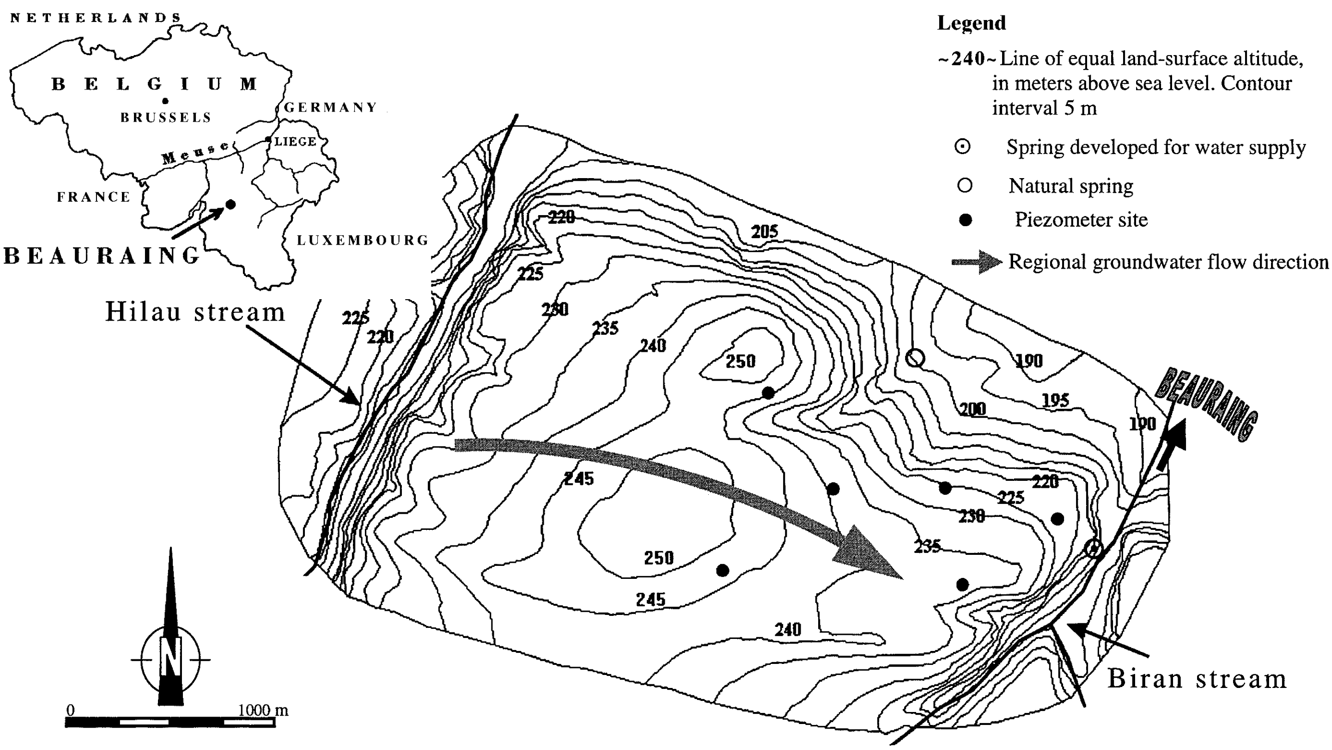


Figure 1 Location of study area, near Beauraing, Belgium

for water supply. The second one is a small natural spring in the northern part of the area, on the lithological transition from limestone to siltstone; flow rate is 1 m^3/h.

Karstic Features

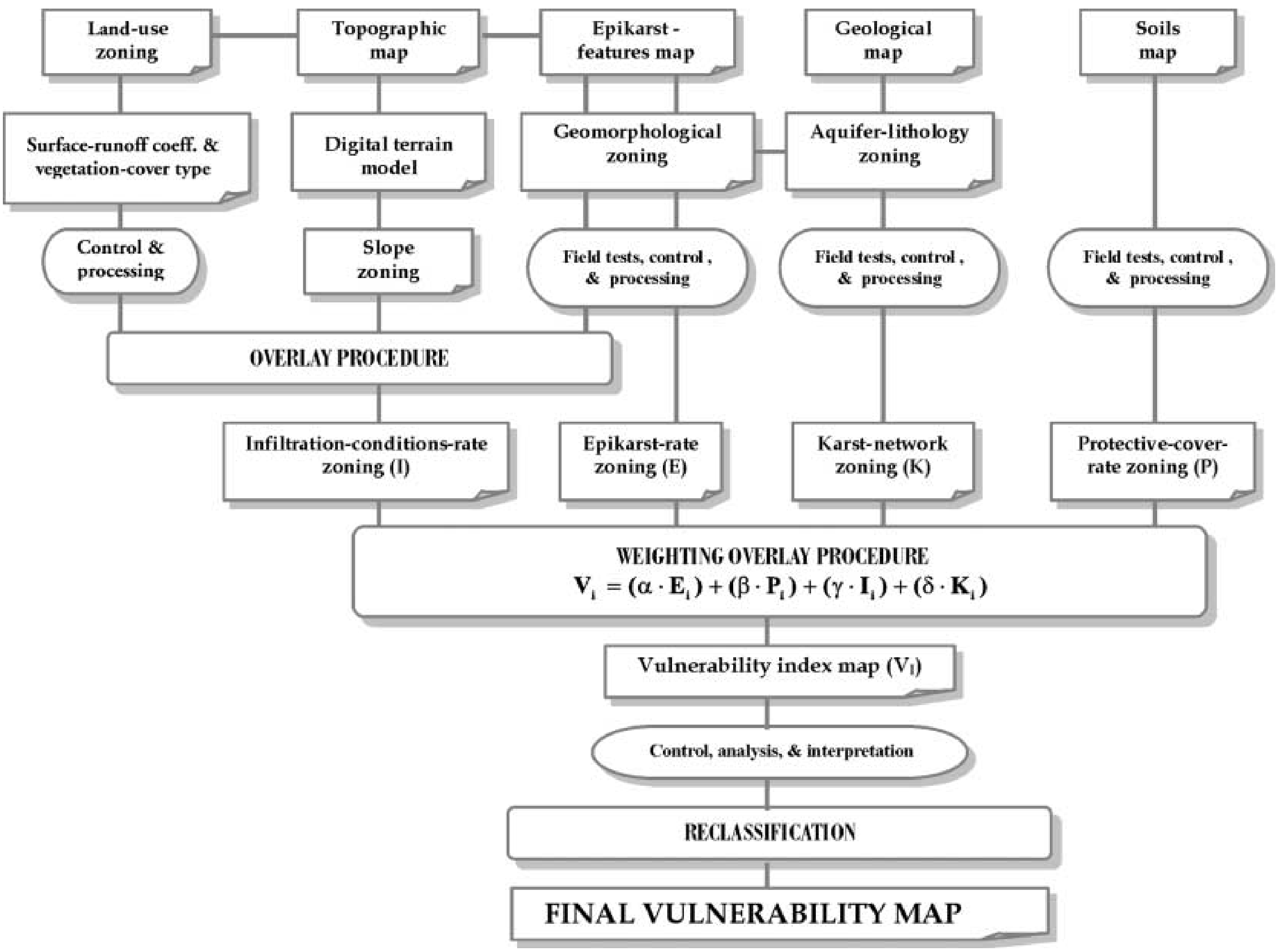
The limestone aquifer is overlain by a thin (less than 0.8 m) soil cover and has several external features of karstification (epikarst). At the western boundary of the study area, five swallow holes and a small cave occur in the course of the Hilau stream. Several aligned dolines were mapped in the study area. Geophysical investigations include geoelectrical sounding and profiling and local seismic sounding. The geophysical data helped delineate the local geological structure, assess thickness of the overlying soil cover, and accurately delineate the position of the limestone–siltstone contact (Gontier et al. 1997).

Several tracer tests were conducted, in which injections were made in observation wells and in a swallow hole in the course of the Biran stream, and the possible arrivals of the tracers were monitored at the outlets. Results indicate that the possible karstic conduits are not directly connected to the two natural groundwater outlets. Therefore, based on the EPIK classification scheme proposed by Doerfliger and Zwahlen (1997), the karst network of these Devonian limestones is characterised as having a medium–poor degree of development.

The EPIK Method

The EPIK method represents an original "parameter weighting and rating method" (Vrba and Zaporozec 1994) developed for outlining and classifying the intrinsic vulnerability of groundwater in karst aquifers to contamination (Doerfliger and Zwahlen 1997). In contrast to other groundwater vulnerability methods, this one uses specific karstic-system features, assuming that a network of connected joints and conduits divides more compact zones of limestone. The method is based on observed geological, geomorphological, and hydrogeological features. The procedure is shown in *Figure 3*. In the EPIK method, four parameters are considered: epikarst (E), protective cover (P), infiltration conditions (I), and karst-network development

Figure 3 Procedure for applying the EPIK method



(K). These criteria correspond to four characteristics that affect water-flow and transport conditions through the karstic system. A value is assigned to each parameter in one of three (or four) classes that characterise the anticipated impact of this parameter on vulnerability to contamination. For details about values assigned to the parameters in the EPIK method, see Doerfliger and Zwahlen (1997).

Epikarst is defined as "an intensively karstified and highly permeable near-surface zone" (Tripet et al. 1997). The epikarst parameter has three classes: E1, for epikarst associated with the karstic network (drained dolines, caves, etc.); E2, for epikarst associated with the fissured matrix zone (dry valleys, alignment of dolines, etc.); and E3, for the absence of epikarst morphology. Doerfliger and Zwahlen (1997) include in the protective cover parameter (P) the soil and other overburden deposits, such as Quaternary deposits (glacial till, silt, loess, rock debris, etc.), and other non-karst layers (for example, clay and sandstone). Values are assigned to the protective-cover parameter (P1, P2, P3, P4) principally on the basis of the thickness of the overlying sediments.

The infiltration parameter (I) is the most complex parameter to be estimated. I1 is assigned to zones, such as swallow holes, where direct concentrated infiltration is possible. I2 and I3 are assigned values by taking into account three slope ranges (0–10 %, 10–25 %, and >25 %) as well as the surface-runoff coefficients and the vegetation-cover type. Contrary to other parametric methods, here vulnerability increases with increasing slope, on the assumption that surface runoff is directed toward karstified infiltration points. This feature is characteristic for well-developed karstic systems.

The karst network parameter (K) is assigned one of three possible values: K1, for areas presenting a well-developed karstic network; K2, for areas presenting a poorly developed karstic network; and K3, for karstic aquifers having an outlet in porous media or showing fissure-matrix intercalations.

Weighting factors (α, β, γ, and δ; see *Figure 3*) are used for each parameter to balance their importance in the calculation of a vulnerability index, V_i. This vulnerability index, called "the protection factor" (Doerfliger and Zwahlen 1997), is calculated as:

$$V_i = (\alpha \cdot E_i) + (\beta \cdot P_i) + (\gamma \cdot I_i) + (\delta \cdot K_i) \qquad (1)$$

where:

V_i = vulnerability index in subarea i
E_i = rating value for the "epikarst" parameter
P_i = rating value for the "protective cover" parameter
I_i = rating value for the "infiltration conditions" parameter
K_i = rating value for the "karst network development" parameter
α, β, γ, and δ = the weighting factors corresponding to E, P, I, and K parameters.

Table 1 Rating values for E, P, I, and K parameters (Note: the lower the rating value, the higher the vulnerability)

E1	E2	E3	P1	P2	P3	P4	I1	I2	I3	I4	K1	K2	K3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

Doerfliger and Zwahlen (1997) use the rating values shown in *Table 1* for E, P, I, and K parameters and the following weighting factors: $\alpha = 3$, $\beta = 1$, $\gamma = 3$, and $\delta = 2$. The final vulnerability index (V_i) ranges from 9–34, and different intrinsic vulnerability categories could be distinguished. For karstic systems of the Swiss Jura mountains, Doerfliger and Zwahlen (1997) recommend four categories of vulnerability: high (9–19), medium (20–25), low (26–34), and very low, where at least 8 m exists of a soil-protective cover that consists of sedimentary detrital deposits with very low hydraulic conductivity. These categories can be modified to fit other kinds of karstic systems.

Map of Intrinsic Vulnerability

In order to map aquifer intrinsic vulnerability for the study area, a raster-based geographical information system (GIS) software (IDRISI) was used. The epikarst (E) parameter was determined using morphostructural analysis on aerial photos and a topographical map (scale 1:10,000) and through geomorphological field surveying. Values of soil protective cover (P) were determined using a detailed local map of the soil-cover thickness. This last was developed from data obtained from the published *Map of the Soils in Belgium* (Avril et al. 1984) and integrated results from boreholes, piezometers, seismic soundings, and from 35 hand-auger short holes executed for this purpose. A map of classified slopes was prepared by slope-computing and slope-classification operations using a digital elevation model (DEM) of the region (1:10,000). The infiltration parameter map indicated a rating value I1 in zones with possible direct infiltration. An overlay operation between the map of classified slope and the land-use map was carried out to delineate zones with I2 or I3 rating values. The data from tracer tests show that this site is not characterised by a highly developed karst network. Therefore, a K2 rating was assigned to the entire area for the karst network parameter (K). The zones of old quarries were considered separately. They were considered as a geomorphological attribute and assigned appropriate E and I parameters. The rating value of extreme vulnerability was given to these zones of old quarry works.

All four parameters were mapped on the E, P, I, and K maps, shown in *Figure 4*. A detailed analysis was performed using a raster model with a 16-m^2 cell size. This resolution corresponds to the surface of the smallest morphological element to be mapped. Using the vulnerability index of Eq. (1), the four parameter

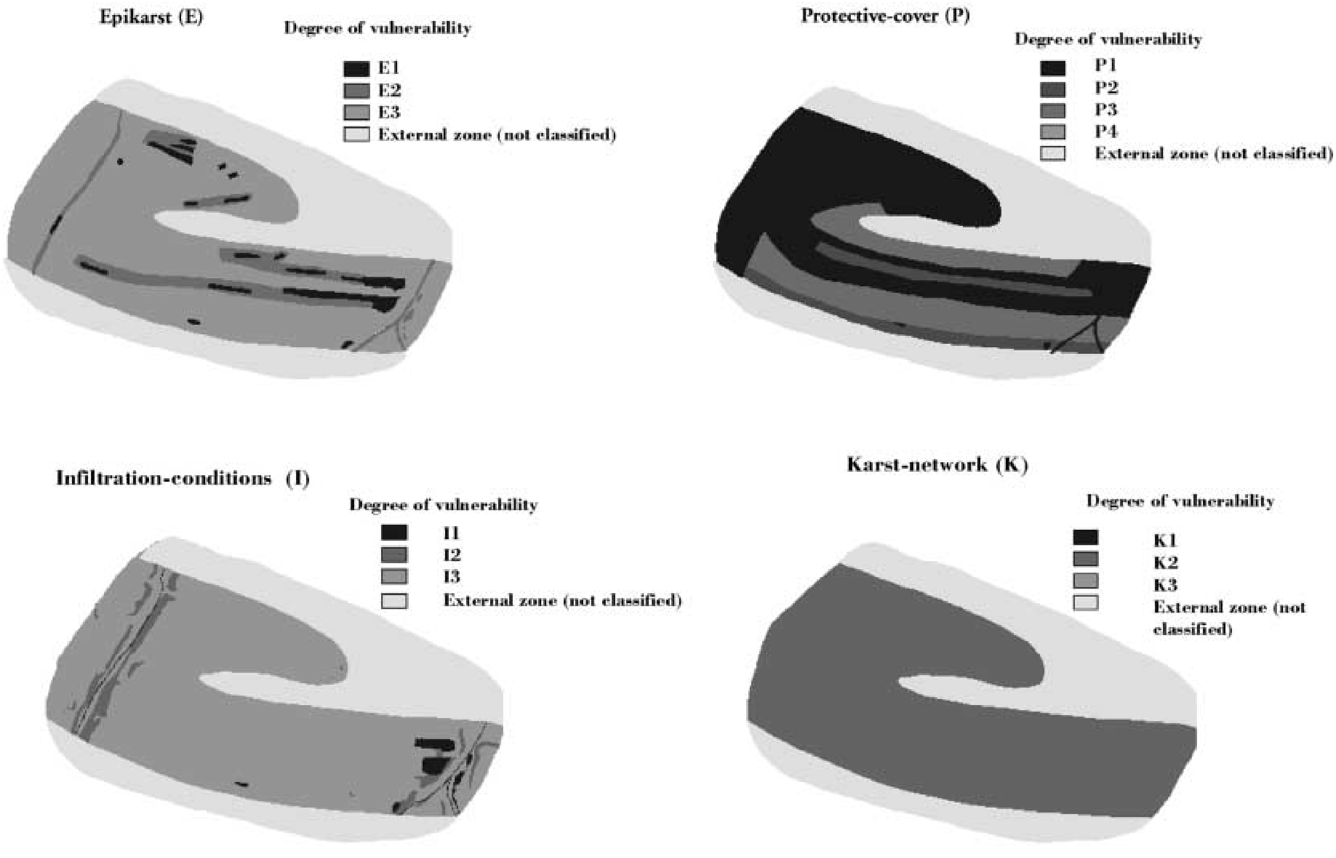


Figure 4 Parameter maps (*E*, *P*, *I*, and *K*) estimated for the Beauraing study area

maps were overlaid cell by cell to produce a "vulnerability index map." For the study area, calculated values of the vulnerability index range from 11–28 and were classified in three vulnerability classes: high, medium, and low. No zones were classified in the very low category. The final vulnerability map is shown in *Figure 5*.

A comparison of the four parameter maps (*Figure 4*) with the final vulnerability map (*Figure 5*) indicates that the epikarst parameter (E) plays a major role in delineating the high-vulnerability zones. The conditions of infiltration (I) also make a noticeable contribution. Parameters E and I both play an important role in determining medium-vulnerability zones.

Parameter Sensitivity

Method

As in all other parametric techniques, subjectivity is inevitable in the selection of rating values and weights related to the EPIK parameters, and this subjectivity can strongly affect the final vulnerability map. Sensitivity analysis provides valuable information on the influence of rating values and weights assigned to each parameter and helps the analyst to judge the significance of subjective elements.

An analysis, based on the concept of "unique condition subareas," was performed to study the sensitivity of each parameter in operations between map layers. Similar analyses have been applied in the assessment of aquifer vulnerability using DRASTIC and SINTACS methods (Napolitano and Fabbri 1996).

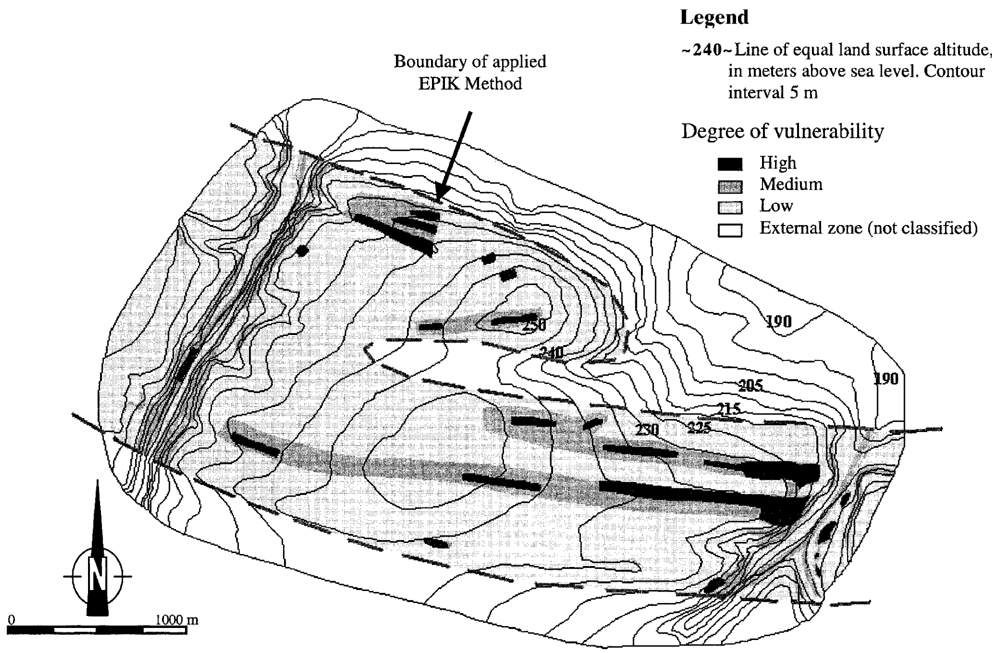
The general flow-chart of the procedure is presented in *Figure 6*. After determination of unique condition subareas, "map-removal" sensitivity and "single-parameter" sensitivity analyses were performed, as described below. The sensitivity-analysis results were then processed to obtain tables with statistics.

Unique Condition Subareas

A "unique condition subarea" consists of one or more zones (consisting of cells) where a unique combination of E, P, I, and K rating values of the four layers is used to compute the vulnerability index. In this study, the weights were not taken into consideration because they are constant for each parameter.

Starting from the four parameter maps (E, P, I, and K), all possible combinations of rating values are recorded in one resulting map and in one exhaustive table. In practice, this stage is performed using the GIS "crossing" function. This function performs two operations: cross-tabulation and cross-classification. In the first operation, the existing values of one of the

Figure 5 Vulnerability map of the Beauraing study area, based on the EPIK method



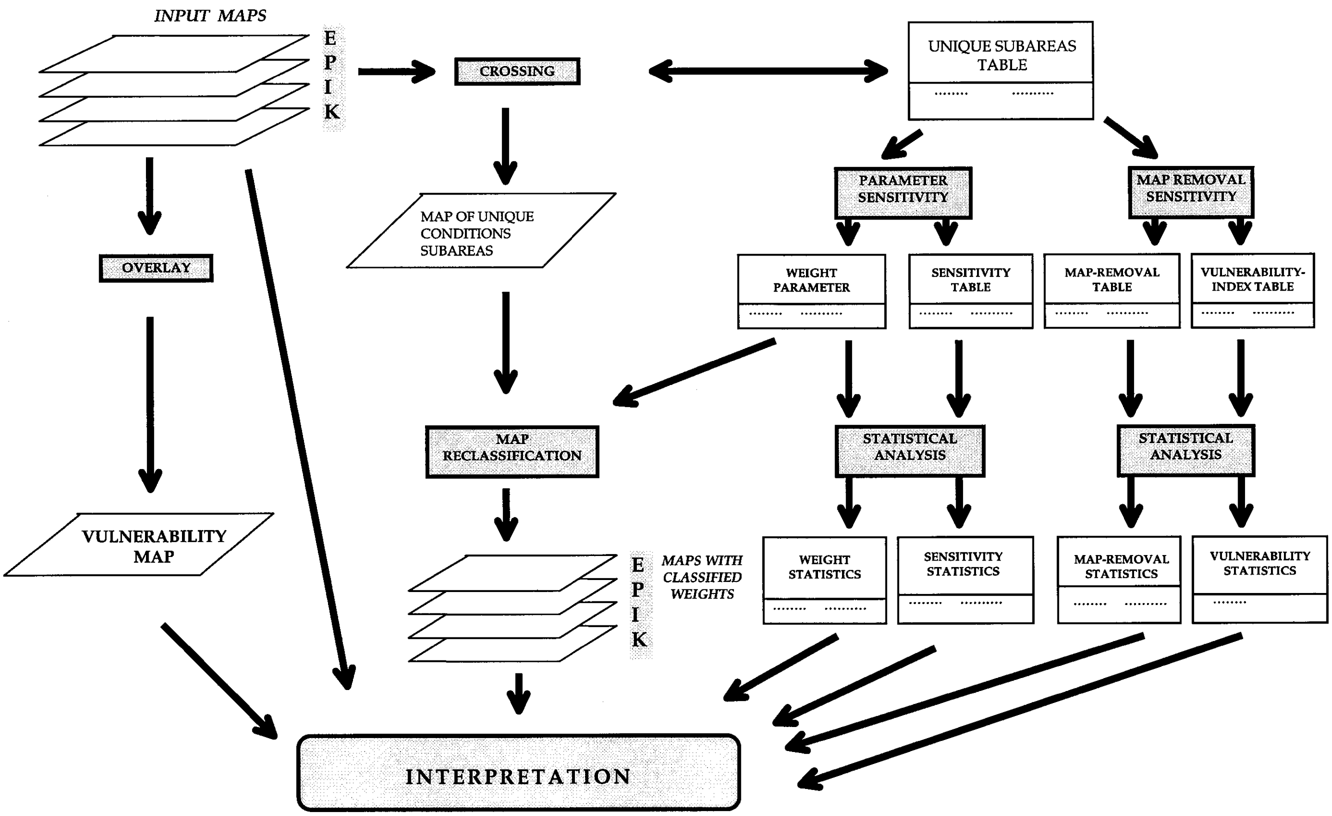


Figure 6 Procedure for applying sensitivity analysis. (Modified after Napolitano and Fabbri 1996)

four raster images (one for each parameter) are compared with those of a second parameter, and a tabulation with the number of cells in each combination is registered. In effect, cross-classification is as a multiple overlay showing all combinations of the logical "AND" operation. The result is a new image that shows the locations of all combinations of the parameters' rating values.

The study area was divided into 145,935 cells. The concept of unique conditions subareas was used to avoid problems in handling such a large number of pixels. The unique condition subareas were obtained by crossing the four layers, two at a time. The calculation procedure was conducted using IDRISI macrolanguage as well as EXCELL macros. Applying this method, 25 subareas were obtained. Due to the digitising data process, inevitable residual slivers consisting of areas smaller then 6 pixels occurred. Three such small subareas were not considered in the analysis. This procedure reduced the computation time as well as the analytical complexity.

Table 2 Statistics on sensitivity to removal of one parameter

Parameter	Average	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value (%)
S_E	1.21	0.75	1.29	0.00	2.33
S_P	1.03	0.42	1.08	0.08	1.83
S_I	0.62	0.46	0.67	0.00	1.58
S_K	0.44	0.27	0.42	0.08	1.00

Map-Removal Sensitivity

The first stage of this analysis was to compute the vulnerability values using three maps instead of four (i.e., removing one map). For each subarea, four vulnerability indexes were calculated using combinations of three of the four parameters. For comparability, the output values were re-scaled by a factor 4/3. Comparing the new index with the initial one provides a direct measure of the influence of the missing parameter. Results indicate that the relative influence on the final vulnerability index is E > I > K > P.

Lodwik et al. (1990) define a map-removal sensitivity measure that represents the sensitivity associated with removing one or more maps. This measure can be expressed as:

$$S_{Xi} = \left| \frac{V_i}{N} - \frac{V_{Xi}}{n} \right| \tag{2}$$

where:

S_{Xi} = sensitivity (for the i^{th} unique condition subarea) associated with the removal of one map (of parameter X)
V_i = vulnerability index computed using Eq. (1) on the i^{th} subarea
V_{Xi} = vulnerability index of the i^{th} subarea without considering parameter X (E, P, I, or K)
N = number of maps used in primary suitability (four maps)
n = number of maps used in perturbed suitability (three maps).

In each subarea, this measure reflects the variability of each parameter but not the contribution of the weighting factors. For each subarea, four values of sensitivity associated with the removal of one parameter were computed.

On the entire domain, the statistical parameters, shown in *Table 2*, confirm the greater sensitivity of parameter E and show that the average sensitivity of parameter P is greater than that of parameter I. The role of P becomes significant when the entire analysed area is examined. The sensitivity of the parameter K is indeed the lowest, because it was kept constant throughout the entire domain.

In order to assess the magnitude of the variation created by removal of one parameter, the variation index VX was computed as:

$$VX_i = \frac{V_i - V_{Xi}}{V_i} \cdot 100 \qquad 1 \le i \le 22 \tag{3}$$

where:

VX = variation index of the removal parameter X(E, P, I, or K)
V_i = vulnerability index computed using Eq. (1) in the i^{th} subarea
V_{Xi} = vulnerability index of the i^{th} subarea without considering parameter X(E, P, I, or K).

This variation index measures the effect of the removal of each parameter. Its value can be positive or negative, depending on the vulnerability index. A positive value means that removal of the parameter reduces the vulnerability index, thereby increasing the calculated vulnerability. A negative value means that removal of the parameter increases the vulnerability index, thereby reducing the calculated vulnerability. Here, this variation index directly depends on the weighting system.

For the studied domain, the averaged variation index is positive for parameters E (VE) and I (VI) and negative for P (VP) and K (VK). Because the whole analysed area was examined, it is concluded that the removal of parameters E and I decreases the vulnerability index (calculated vulnerability is increased) and the removal of P and K increases the vulnerability index (calculated vulnerability is decreased).

Effective Weighting Factors

Each parameter contributes with an effective weight (Napolitano and Fabbri 1996) to the final vulnerability index. This effective weight (W_{Xi}) can be calculated for each subarea as:

$$W_{Xi} = \frac{X_{Ri} \cdot X_{Wi}}{V_i} \cdot 100 \tag{4}$$

where X_{Ri} and X_{wi} are, respectively, the rating values and the weights for the parameter X assigned in the subarea i, and V_i is the vulnerability index as computed in Eq. (1) in the subarea i. For each subarea, the sum of the four parameter effective weights is 100 %.

To obtain the effective weight of each parameter in each subarea, the map representing the unique con-

Table 3 Statistical analysis of effective weight

Parameter	Theoretical weight	Theoretical weight (%)	Average effective weight (%)	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value (%)
E	3	33.33	39.00	13.69	42.86	15.79	60.00
P	1	11.11	10.10	4.64	9.52	3.85	23.08
I	3	33.33	29.82	11.21	27.92	13.64	52.94
K	2	22.22	21.09	5.81	19.52	14.29	36.36

dition subareas was reclassified according to the attribute values of effective weight for each parameter. Then, the effective weights expressed in percentage were mapped according to classes defined every 5%. The procedure is shown in *Figure 6*.

Discussion

Interpretation of the results is based on analysis, comparisons, and statistical computation of the input maps relative to each parameter (E, P, I, and K), the final vulnerability map, and the maps representing the effective weights used in each subarea. Statistical analysis of the sensitivity of the effective-weight parameters, shown in *Table 3*, indicates that the epikarst parameter (E) dominates the vulnerability index with an average weight of 39.00% against the theoretical weight of 33.33%. The real weight of parameter I (29.82%) is smaller than the theoretical one (33.33%). Comparison of the maps prepared for each individual parameter with the maps of effective weight shows that all the effective-weight maps are strongly dependent on the value of the epikarst parameter. Also, significant variations in the effective weight distribution exist, depending on the values of parameters I and P. High effective weights are attached to parameter I, corresponding to high-vulnerability and medium-vulnerability areas. These areas are strongly conditioned by the parameter E values. The presence of a thick soil protection layer (P3) reduces the weight attached to parameter I. For the E2 and E3 areas, respectively, effective weights of E are quite strong. They become stronger for slopes greater than 25%, corresponding to I2 areas.

These effective weights depend on the variability of each parameter rating and on the theoretical weights chosen in Eq. (1). If the same rating value is chosen for one of the parameters over the entire area, its effective weight will vary as a function of the rating values of the other parameters. Therefore, for each case study it is desirable to know the effective weights that result from the theoretical ones.

However, there is no need to go further by using the effective weights in place of the theoretical ones. On the basis of the presented analysis, changes of the weights in Eq. (1) can be considered in order to reduce or increase the importance of a parameter in the vulnerability index determination.

Conclusions

Sensitivity analysis helps to validate and evaluate the consistency of the analytical results and is the basis for a correct evaluation of the vulnerability maps. The methodology that is presented should be developed and applied to each vulnerability case study in order to make hydrogeologists more aware of the subjective element of vulnerability assessment. In this way, vulnerability-assessment parametric methods can be judged more effectively. Using sensitivity analysis, a more efficient interpretation of the vulnerability index can be achieved.

In the presented case study, the effective weights for each parameter in each subarea are not equal to the theoretical weights (assigned by the EPIK method). In fact, the effective weights are strongly related to the value of the single parameter in the context of values chosen for the other parameters. For the study site in particular, the parameter E has a strong influence on the vulnerability. This influence is the result of the combined influence of the theoretical weights [Eq. (1)] and the relative uniformity of the chosen values for the other parameters. The effective-weights analysis is very useful when the user of the vulnerability-assessment method wishes to revise the weights in the chosen equation for computing the vulnerability index.

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Modular Web-Based Atlas Information Systems

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Abstract

Atlas information systems (AIS) present spatial information on predefined themes and localities in the form of maps and other representations, generally focusing on correct cartographic appearance and offering a certain degree of user interaction. This article introduces the concept of modular AIS, a concept that is essential for the development of an AIS with modern computer technology. The main advantages of a modular architecture are twofold: first, an AIS software framework based on a modular architecture allows for easy and rapid customization to a certain theme and locality; second, functional enhancements and new technologies can be easily integrated into a modular AIS in order to optimally present and analyse the data at hand.

Web-based AIS can benefit from the concept of modularity at three different levels: (1) The AIS client can adjust its functionality and adapt to the available technology on the present computer platform. (2) The AIS server can build an AIS client with custom-tailored data and functionality in real time, depending on the user's access rights, needs, or expertise. (3) Distributed, modular data storage greatly simplifies the design, implementation and maintainance of an AIS by using a mediation system.

To illustrate the concepts presented, we will discuss selected technical aspects (e.g., Web-based map viewer technology, client–server communication), and describe an exemplary Web-based AIS that extends the modular core architecture through specialized functionalities for the analysis of geophysical data. It is the authors' hope that the ideas presented will provide an introduction to the technical concepts for designers and developers of similar Web-based atlas information systems.

Keywords: interactive web cartography, customizable, distributed, component-based mapping architecture, Java, SVG, natural hazards

Résumé

Les systèmes d'information cartographique (AIS) schématisent des données spatiales sur des localités et des thèmes prédéfinis sous forme de cartes ou d'autres modes de représentation, orientés en général vers une apparence cartographique précise et attribuant un certain degré d'interaction à l'utilisateur. Le présent article présente le concept d'un AIS modulaire, en tant que concept essentiel au développement d'un AIS lié à la technologie informatique moderne. Deux des principaux avantages d'une architecture modulaire sont d'abord un cadre logiciel AIS basé sur une architecture modulaire qui permet de personnaliser facilement et rapidement un certain thème et une certaine localité, et ensuite l'intégration facile des améliorations fonctionnelles et des nouvelles technologies dans un AIS modulaire afin de d'analyser et de présenter les données existantes de façon optimale.

Un AIS sur le Web peut tirer avantage du concept de modularité à trois niveaux : 1) le client AIS peut régler sa fonctionnalité et s'adapter à la technologie disponible sur la plateforme informatique actuelle; 2) le serveur AIS peut créer un client AIS avec des données sur mesure et une fonctionnalité en temps réel en fonction des droits d'accès, des besoins, ou de l'expertise de l'utilisateur; et 3) le stockage modulaire des données réparties simplifie la conception, la mise en oeuvre et la maintenance d'un AIS à l'aide d'un système de médiation.

Pour illustrer les concepts présentés, nous discutons d'aspects techniques sélectionnés (par ex., technologie de visualisation cartographique sur le Web, communication client–serveur), et donnons un exemple d'un AIS sur le Web qui étend l'architecture modulaire de base par le truchement de fonctionnalités spécialisées pour l'analyse des données géographiques. Les auteurs espèrent que les idées présentées serviront d'introduction aux concepts techniques pour les concepteurs et les développeurs de systèmes d'information cartographique similaires sur le Web.

Mots clés : cartographie web interactive, architecture cartographique adaptable et distribuée basée sur des composants, Java, SVG, dangers naturels

Today's Atlas Information Systems

Enhancing computer-based atlas information systems (AIS) with the concept of modularity offers many advantages, the two most important being effortless adaptation of the AIS to new themes and geographic areas and easy extension of an AIS with specialized functionality. This article will present the proposed modularity concept that was developed for Web-based AIS before describing the details of the proposed enhancements.

The term "geographic information systems" (GIS) does not refer to a single, clearly defined type of software application. Instead, it encompasses a family of different applications that share the common aspects of storing, mapping, and analysing spatial data. An atlas information system (AIS) can be considered a type of GIS that differs substantially in certain respects from conventional GIS: "Atlas Information Systems are computerized geographic information systems related to a certain area or theme in conjunction with a given purpose – with an additional narrative faculty, in which maps play a dominant role" (van Elzakker 1993, cited in Ormeling 1995, 2127). Analogous to the classical paper atlas, an AIS presents spatial information on predefined themes and localities. Using digital media, the AIS provides information in the form of maps, alternative spatial representations, and multimedia content. The user influences map content and appearance by combining map layers and changing visualization parameters. The system may also allow the user to integrate personal geo-information. An AIS must offer an interface that inexperienced users can easily grasp. To promote user interest, and so as not to overstress the user's patience, system response time should be fast, a requirement that disqualifies slow-performing simulations and computations. Barbara Schneider (1999) provides a more detailed characterization of atlas information systems.

The distribution of AIS relies on two methods: (1) physical media, such as CD-ROM; or (2) Internet retrieval. We concentrate in this article on AIS provided via the Internet, which we classify as follows:

- *Entirely Web-based AIS* are client–server applications that rely on the Internet to transmit all data and program code. The client component is integrated into a Web page and uses a Web browser as the host application. For the system programmer, this integration reduces the range of viable technologies and programming languages, since only those supported by Web browsers are available. Entirely Web-based AIS do not require users to install software applications on their computers. Instead, the Web browser always receives the most up-to-date data and system functionalities. Despite these advantages, however, the limited bandwidth of the Internet still hinders the distribution of large data sets, including those involved in distributing AIS.
- *AIS with online update capability* require initial installation from a CD-ROM or similar medium (Hurni, Bär, and Sieber 1999). Up-to-date information is subsequently downloaded from a server, allowing the system author to distribute updated or corrected maps. Since such an AIS may run independently from a Web browser, the programmer can

choose from a wider range of different technologies and programming languages.

Modularization of AIS

In the previous section of this paper we reiterate that today's Web-based AIS offer a user-friendly graphical interface and emphasize the quality of cartographic presentation. Their functionality and data are (fully or partially) distributed throughout the Internet.

Modularity is an advantageous enhancement of current AIS. A modular software architecture consists of a core framework combined with a set of task-specific modules. The author of a new AIS can select the required modules and combine them with the core framework to build a custom-tailored AIS. The resulting system offers exactly the functionality that the user needs. If an AIS requires a specialized functionality that is currently not offered by any module, an additional module must be developed. The new module must adhere to well-defined communication rules and behavioural patterns. This ensures that the core framework can handle any module, independent of its specific functionality.

An Internet-based AIS usually follows the classical client–server paradigm. Modularity can be successfully applied to the implementation of both parties. On the server side, modular software architectures such as Enterprise Java Beans (EJB) are widely used today, not only by GIS-related server applications but also by almost every imaginable area of computing, because they greatly facilitate the development of new software.

In contrast to the well-established server-side modularity, AIS clients generally do not use modular architectures. Modularity allows for the customization of client software by integrating only the required functionality into the final client. This offers three main advantages:

1. The size of the client software is minimized, which reduces download time.
2. The user interface contains only indispensable elements, which makes the AIS easy to learn and control. Our example client-side framework uses two types of modules: (1) general-purpose mapping modules that accomplish functions required by most AIS (e.g., map layer composition or navigation in a map) and (2) specialized modules that extend the functionality of an AIS in a particular area of expertise.
3. Modularity also allows for the construction of customized applications in real time. A server can add selected modules to the framework depending on the user's access rights, needs, or expertise. The user then receives a personalized AIS "on demand."

Data storage is another important area that can be extended by the concept of modularity. Distributed (or modular) data storage can facilitate maintenance of AIS data. Modular data-storage systems are generally accessed through a central access point provided by a server that hides the underlying modularity (or distribution) of data sources.

In the context of this article, therefore, we define a modular Web-based AIS as follows: A modular Web-based AIS is an AIS as defined by van Elzakker (1993, cited in Ormeling 1995) that additionally possesses a customizable, modular system architecture and the capability of retrieving data and system functionalities via the Internet.

A Modular Web-Based AIS Client

The modular Web-based AIS client presented in this section can be easily and rapidly adapted to different types of applications. Its core framework implements the basic elements of an *entirely Web-based* AIS. Our AIS client uses vector data for map rendering and accesses distributed sources to retrieve data. A series of modules extends the framework and offers the user AIS functionality combined with a graphical user interface.

AIS FOR THE INTERNET

Our Web-based AIS follows the client–server architecture with a series of clients connecting to one central server. The client can download raw attribute data and transform them to interactive and animated maps, diagrams, and other presentations. The client does not necessarily have to perform all the computation that an analysis or visualization requires. Time- or data-intensive tasks can also be delegated to an application server in order to accelerate computation and reduce data transfer time.

In the developed system, the client is integrated into a platform-independent Internet browser. The core framework uses Java technology. Java is a cross-platform, object-oriented programming language, complemented by a powerful set of functionalities. To the developer of an AIS, it offers important functionalities such as networking, security management, object serialization, database connection, and data retrieval. Most importantly, it facilitates the design of modular software architectures.

CUSTOMIZING AN AIS CLIENT BY MODULES

Our client consists of a core framework and a set of standard and specialized modules. This architecture allows for flexible adaptation of the system to different AIS scenarios (i.e., customized AISs for different users)

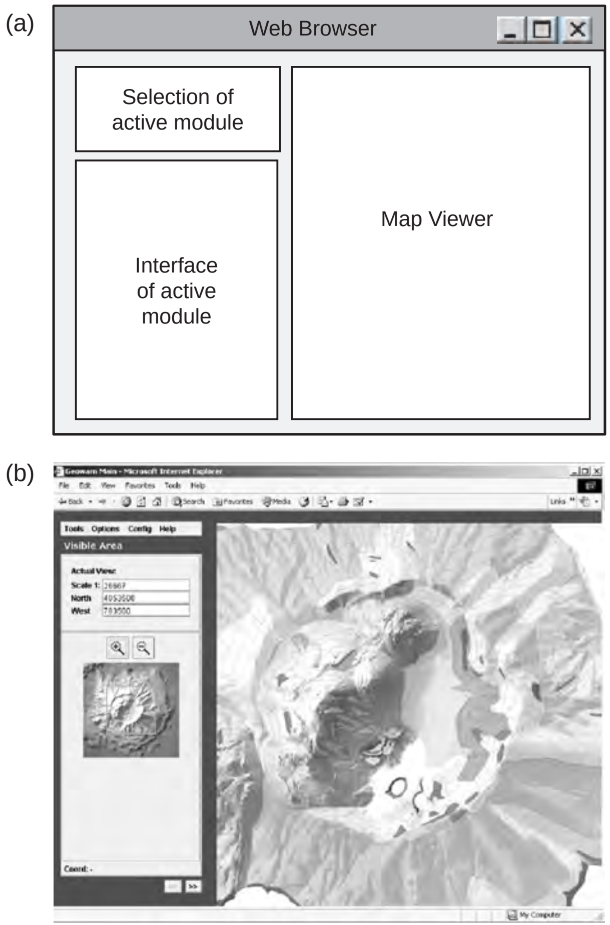

Figure 1. The active module and the map share space on the Web browser interface. Above: Schema of the active module and the Map Viewer. Below: Screenshot of the GEOWARN AIS (described in the last section of the article).

and different localities or themes. When loading the access page, the Web server assembles the needed modules in order to form the custom-tailored application.

After the modules are assembled with the core framework, the client software is delivered to the client's computer. The framework is then responsible for activating exactly one module at a time. The active module provides the currently visible graphical user interface and interacts with the map. The user of the AIS can choose the active module using a graphical control element (Figure 1). Upon user request, the framework deactivates the currently active module and configures and activates the newly chosen one (Figure 2). This mechanism requires the modules to comply with a straightforward application programming interface (API). The API is used to load, activate, and configure modules.

The framework offers a pool of services to the currently active module (Figure 2). For instance, the Resource

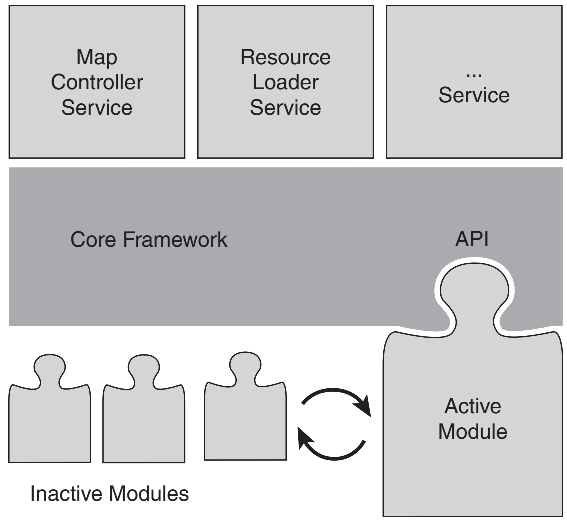

Figure 2. Framework for managing modules and services.

Loader service loads data from a server, while the Map Controller service interacts with the map; both will be discussed later. These services facilitate the implementation of additional modules, since they assume tasks that are recurrent or are critical to performance or security. Using the services reduces the complexity of additional modules and minimizes the programming effort necessary to implement them. A welcome side effect is the reduction of the application size, which, in turn, reduces download time.

MAP VIEWER MODULARITY

High-quality rendering of interactive maps in vector format requires time-consuming computations. At the time of implementation, four technologies were available for this task: Macromedia Flash (Adobe 2006), Scalable Vector Graphics (SVG; W3C 2006), Java 2D (SDN 1994–2006), and Virtual Reality Modeling Language (VRML; Web3D Consortium n.d.). Each comes with its respective advantages and problems, depending on the platform and Web browser on which it is running. We compared the four technologies during an evaluation phase (Jenny, Freimark, and Terribilini 2002). The result was that the development of a Java 2D–based viewer would have been more time intensive because of the required programming effort. Additionally, Java 2D rendering with anti-aliasing was found to be slower than rendering with Flash or SVG viewers; response time is a crucial criterion for maps that react on user actions (e.g., mouseover events that change the colour of map elements). The two-dimensional output of current VRML renderers (which are primarily optimized for three-dimensional models) could not meet our demands for high-quality graphics. Finally, SVG was favoured over

Flash because SVG is an XML-based format that is easily generated and can be edited with standard text editors. An SVG graphic may contain text, images, and Bézier line art. The Adobe SVG Viewer is the most widespread plug-in for Web browsers. It renders high-quality graphics with anti-aliasing and transparency.

Since we cannot foresee the development of future graphics standards for the Internet, the rendering module should be easily replaceable. The described framework therefore wraps the rendering engine in an exchangeable code module called Map Viewer. The Map Controller is a complementary service module that supervises the Map Viewer. As described in the previous section, the Map Controller is an example of a service provided by the core framework (see Figure 2). It manages the two-way communication between the active module and the Map Viewer (Figure 3). The active module can send commands to the Map Viewer to hide, show, add, remove, or graphically change a map element. In the other direction, the Map Viewer alerts the active module when mouse events occur (mouse-over-element, click-on-element, etc.).

The Map Controller offers a viewer-independent programming interface for communication between the active module and the Map Viewer. It relies on an exchangeable Communication Bridge that converts the Map Controller's messages to commands understandable by the Map Viewer, and vice versa. This architecture ensures effortless integration of future rendering technologies. It can also be used to select a specific viewer from a range of supported alternatives, depending on their availability on the client's computer. In the event of integrating a new type of Map Viewer, only a new Communication Bridge has to be created.

Figure 4 illustrates how the Map Controller communicates with the Adobe SVG Viewer using a specialized Communication Bridge component. Messages between the Map Controller and the Map Viewer traverse two layers that transform Java commands to JavaScript code that can be understood by the SVG Viewer (ECMAScript is the standardized version of JavaScript; see ECMA International 1999). This modular architecture can be easily adapted to other JavaScript-based viewer technologies by exchanging the second layer, labelled ''JavaScript to SVG Converter'' in Figure 4. For future alternative map viewers that do not understand JavaScript (e.g., a map viewer based on Java 2D), the Communication Bridge component would have to be replaced.

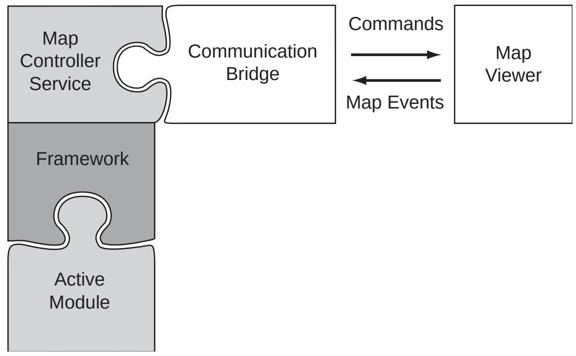

Figure 3. Communication between the active module and the map viewer.

CLIENT–SERVER COMMUNICATION

AIS clients access their server for data retrieval. Server access can be triggered by a user action or autonomously, by a software module, when it needs additional data to analyse or display. This section explains how clients query data from a server. Access of the server to distributed data sources will be discussed in a later section.

Client–server communication is illustrated by means of an exemplary AIS client module that queries the temperature of a water spring and displays the temperature in its user interface (see upper part of Figure 5). In our example, the data flow is initialized when the user clicks on a map symbol representing a spring. The click generates an event that is transferred to the module, which subsequently requests the temperature of the spring from the server. The server returns this information, and the module displays the temperature in a text field.

Figure 5 illustrates the data flow through the different components. The Map Viewer informs the Map Controller of the event by sending it a click event (1). The Map Controller delegates this event to the currently active module (2). After analysing the event, the active module delegates the loading of the temperature data to the Resource Loader Service provided by the core framework (3). The Resource Loader Service sends a request to the server using standard HTML technique (4). The server returns the requested data in the form of an XML-formatted table (5). The Resource Loader Service passes the data to the active module that started the request (6). It is then the module's task to parse and interpret the data and present them to the user in graphical form. In our example, the resulting table contains a single value, the spring's temperature. The module finally extracts the temperature from the table and displays it in the user interface (7).

The complete process, starting with a click by the user on a spring symbol and ending with a temperature being displayed, may appear rather complicated. Yet the programmer of the module can use the services provided by the core framework. Most modules will use the Map Controller Service to interact with the map and the Resource Loader Service to communicate with the server. If needed, additional services can be used, for example,

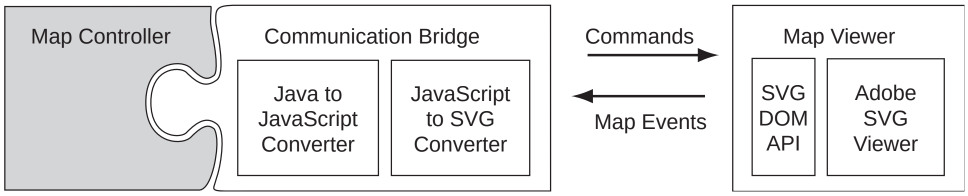

Figure 4. The Communication Bridge for the Adobe SVG Viewer.

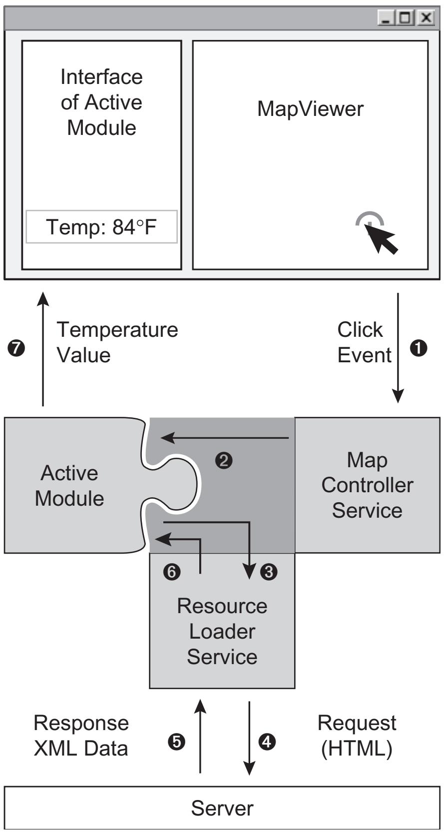

Figure 5. Data flow of an exemplary module displaying the temperature of springs.

to display data in diagrams, to analyse special types of data, or to parse XML data. The services will greatly simplify the task of the programmer, who only has to take care of the following three steps:

1. Receive mouse-click events and communicate with the Resource Loader Service to retrieve data.
2. Display the returned data in a graphical user interface.
3. Write an XML description of the query and the connection for server-side data retrieval (described in the next section).

MODULAR AIS SERVER AND DATABASE

The server side of Web-based AIS uses modularity in two distinctive areas. First, the software application running on the server and providing clients with data and services is usually based on a modular architecture. Second, data are modularly distributed to multiple databases for data storage.

The server-side software of an AIS server fulfils three AIS-specific tasks:

1. It generates the AIS clients by adding modules to the clients' core framework.
2. It provides and coordinates access to distributed data sources.
3. It supplies specialized services to client modules that require server-based functionality (e.g., data analysis or computation of visualizations that require large data sets or large computation capacity). The required functions are very specific to the AIS and its data. Furthermore, this type of modular architecture is well established and widely used (e.g., Servlets or EJB). For these two reasons, this type of server task is not discussed in this article.

ASSEMBLING AIS CLIENTS

An entirely Web-based AIS does not require users to install any software or data on their computers. Instead, the user accesses the AIS through a standard Web browser and loads a Web page that embeds the client software. The server can deliver the same assembled software to every client computer or deliver different software depending on the user's access rights, needs, or expertise. The client software can be further individualized by assembling the application at runtime. This allows for a completely customized AIS client whereby users can choose not only which data they would like to see and analyse but also which functionality they would like to use.

When assembling an AIS client, the server creates a copy (or "instance") of a module before adding it to the framework. Thus, the server can add multiple instances of a module to the framework and configure them differently. In our previous example, an AIS could use a first instance to display the springs' temperatures and a second one to display their discharges. The server would pass different data sources to the two instances. This mechanism not only allows for configuring the data source but can also be used to alter the instances' graphical user interface. In the example, the server would pass appropriate parameters to change the graphical interface from "Temp.: 84 F" to "Discharge: 0.8m^3 per min." A module could offer even more advanced options to configure its behaviour, data sources, graphical user interface, and so on.

DISTRIBUTED DATA SOURCES

An entirely Web-based AIS usually cannot hold all potentially necessary data on the client's computer. This would strain the storage capabilities of the host browser and cause unacceptably long download periods. To overcome these shortcomings, a Web-based AIS relies on a server for storage, extraction, analysis, and synthesis of data. AIS need very different types of data that are best stored in their native formats. It may also be advantageous to store data on different servers (e.g., in spatial data infrastructures) for distributed updating and maintenance of the data. This results in programmers having to confront a wide variety of different formats, query languages, and data locations. To facilitate the development of AIS modules, a single access point is required that hides the details of the underlying data sources, structures, locations, and access mechanisms. Mediator-based data access provides this type of service.

DATA MEDIATOR

A mediator-based system includes an application layer, a mediation layer, and a foundation layer, portrayed from left to right in Figure 6 (Wiederhold 1992). In the case of an AIS, the application layer corresponds to the AIS client. It requests and receives data from the mediation layer, which is a specialized part of the AIS server. The foundation layer may consist of heterogeneous data sources that can be stored on diverse servers and use different database engines and formats. Specialized software wraps each data source and offers a homogenized view.

With this architecture in place, the AIS client can request data by sending a query to the server-side mediator system. The mediator subsequently asks for data from the foundation layer and returns the result in an easily readable XML format. Note that a single query may request data from more than one source. In such a case, the mediator dispatches the request to the data sources concerned, assembles the returned fragments, and sends this final result back to the client.

The AIS described here stores the details of each request on the server (the databases involved, the SQL commands to execute, etc.). Each request is labelled with a unique name that is used by the client to identify the desired request. Thus, the client does not need to know anything about the data sources involved; the name of the request, together with some parameters, completely defines the request. The main advantage of this strict separation is that changes to the data structure are possible without modifying the client. After changing the database structure, only the descriptions on the server must be updated – changes to the client-side code are not necessary.

Extending an AIS Client by Modules

This section presents example client modules that have been developed and used for different projects. All modules extend the basic framework and use its different services.

GENERAL–PURPOSE MAPPING MODULES

The module for layer editing shows and hides map layers and changes their symbolization (Figure 7). It allows the user to load additional map layers by selecting them from a list. Currently, three different types of layers are supported: raster images, vector line work, and points. The module relies on the Resource Loader service to load additional map layers. It uses the Map Controller service to integrate the new layers into the map. The module also allows the user to change the graphical appearance of vector layers by specifying colours, line widths, and transparency.

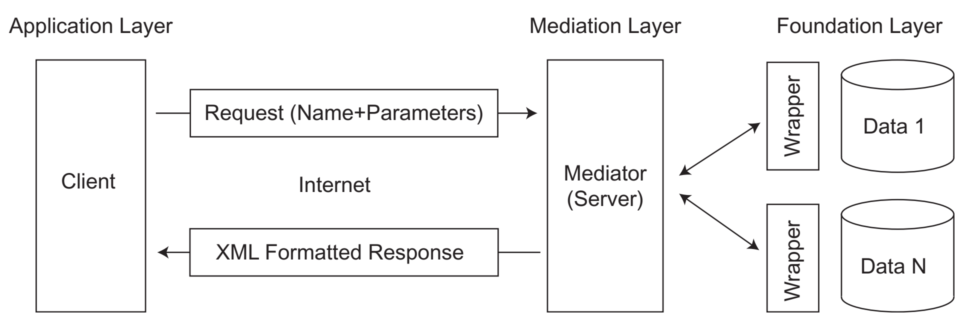

Figure 6. Mediator system wrapping heterogeneous data sources.

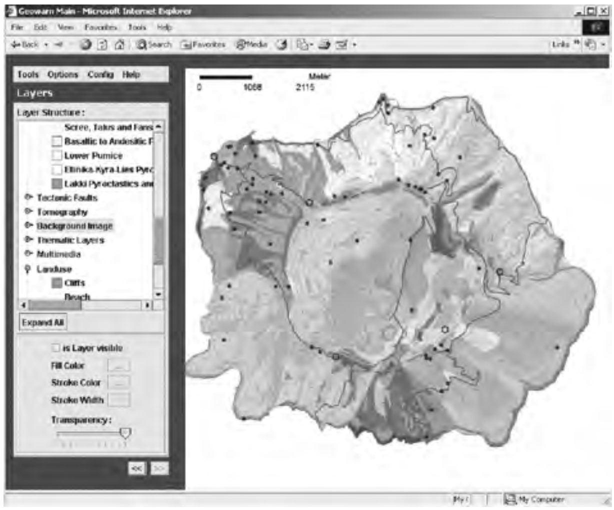

Figure 7. Screenshots of the module for layer editing.

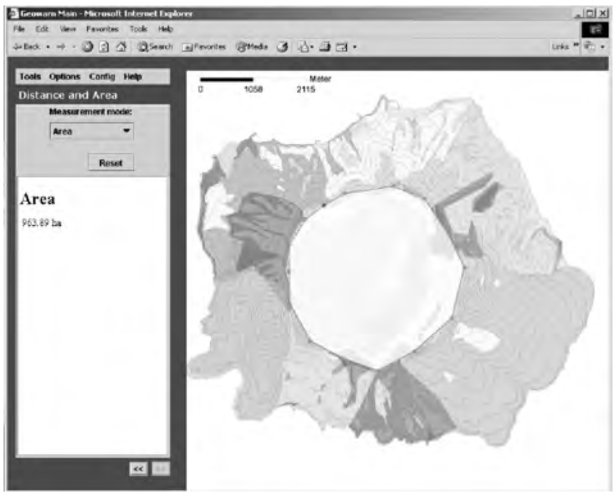

Figure 8. Measurement of an area.

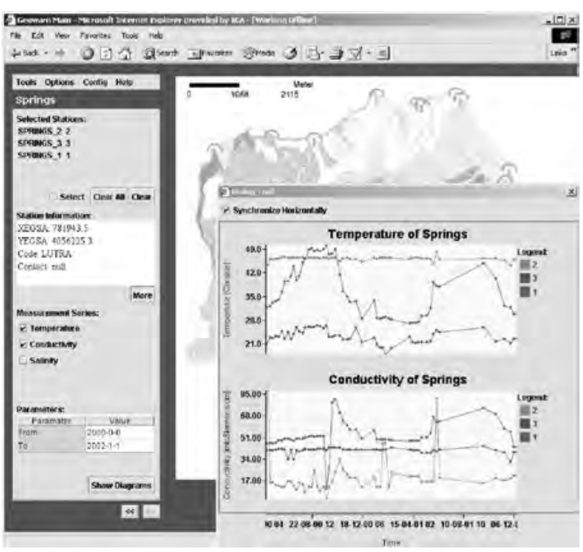

Figure 9. Display of diagrams.

Another elementary module offers zooming and panning capabilities (see Figure 1). Using this module, the user can graphically or numerically enter the new centre of the view and the new map scale. The Navigation Module uses the Map Controller service to scale and re-centre the map.

The user can measure distances and areas on a map using the module shown in Figure 8, which also interacts with the map through the Map Controller service.

The diagrams in Figure 9 show the evolution of temperature and electrical conductivity of three different springs over time. A specialized module produces the diagrams. Parameters passed at initialization determine the module's interface, the data sources, and the type of diagram. The module can thus be easily adapted to different data types, data sources, and database structures.

GEOWARN AIS

The concept of modular Web-based AIS was originally developed for the Geo-Spatial Warning Systems (GEOWARN) project, funded by the European Commission (GEOWARN 2003). The aim of GEOWARN is to develop methods and systems for the surveillance of quiescent but still active volcanoes (Lagios and others 2001). A major part of the project was dedicated to the development of an AIS that embeds all relevant data sets of a volcanic field into a single cartographic system. Uses of the application include scientific analysis, emergency and land use planning, and allowing casual users (civil protection) to make decisions in the event of a seismic or volcanic crisis. GEOWARN uses the volcanic island of Nisyros (in Greece, south of Kos) as a test site that shows high seismic unrest and widespread fumarolic activity. The GEOWARN AIS extends the core framework with a set of custom-tailored modules that facilitate analysis and visualization of diversified geophysical data collected during the project (Chiodini and others 2002; Dietrich and Hurni 2002; Gogu and others 2006; Lagios and others 2001).

The screenshot in Figure 10 shows the module for the analysis of a regularly spaced raster grid. The example shows heat flux in a volcanic caldera. The corresponding module loads and displays a thematic grid using a customizable colour scale. The module handles queries of single grid values and allows for statistical measurements and animated time series of grids.

The module illustrated by Figure 11 extracts profiles from a three-dimensional tomographic model of subsurface geology below Nisyros. The user defines the position of the desired profile graphically on the map. The module then sends the position of the profile to an application server that extracts the profile from a tomographic

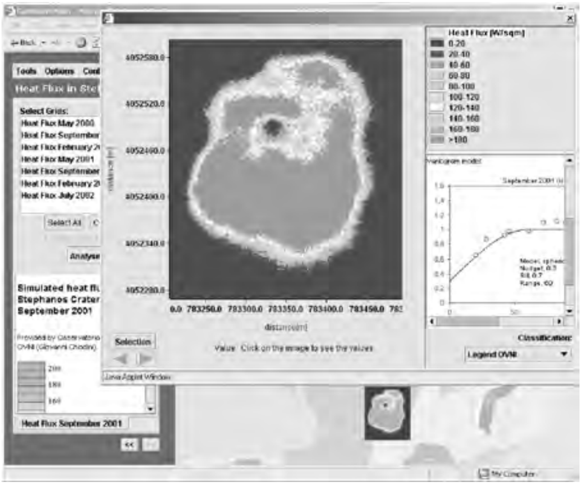

Figure 10. Analysis of raster grid.

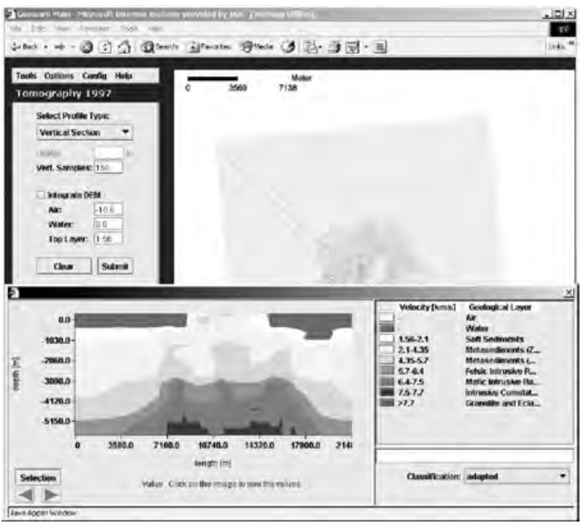

Figure 11. Extraction of 3D model.

voxel model. The server returns the resulting profile as a thematic grid to the active module. The user finally analyses this grid with the functionality described above.

Microseismic events (i.e., seismic events with a magnitude of 3 or less on the Richter scale) are important for the understanding of volcanic processes. A seismic event is defined by a three-dimensional position and a magnitude. The module shown in Figure 12 projects seismic events on a vertical profile, which is then shown in a diagram. The position of the profile can be chosen interactively on the map. The diagram includes only those points lying within a certain distance of the profile.

Conclusion

In addition to the GEOWARN AIS described above, the architecture presented was successfully implemented for

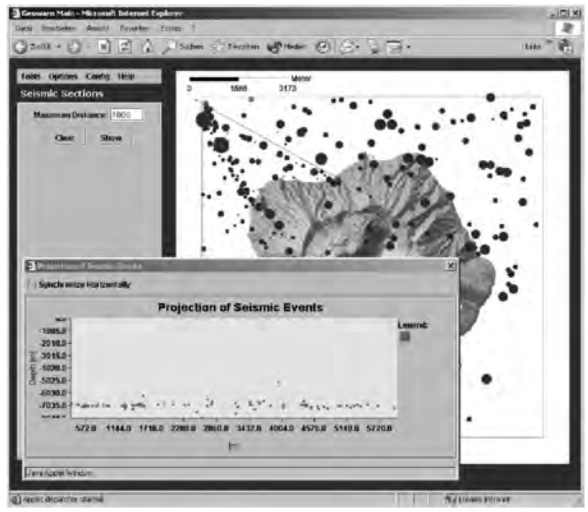

Figure 12. Projection of seismic events on a profile.

AIS of other locations (e.g., an AIS for Campi Flegrei, a volcanic area near Naples, Italy) and in other specialized applications (e.g., a hiking route planner supporting multi-criteria net analysis). Our experience with the modular system was very positive, since it proved to be easily configurable and adaptable to these applications.

On the client side, the modular AIS uses a thin, platform-independent client that is easily scalable to different applications. Its modular architecture allows for rapid integration of new custom-tailored functionality, and its map-viewer architecture can be adapted to future or alternative Web techniques.

The server side uses standard technology (EJB and Java Servlets) that greatly accelerates and simplifies the development of the application server. The separation of the data sources from the rest of the AIS allows multiple data owners to independently update or correct their data, which ensures long-term usability of the AIS.

An entirely Web-based AIS automatically provides the end user with the most recent data and functionalities; complicated installation procedures are unnecessary. The utility of the system is further enhanced by a user-friendly interface and map data that are cartographically pre-treated in order to optimally communicate the information.

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Comparison of aquifer vulnerability assessment techniques. Application to the Néblon river basin (Belgium)

Radu Constantin Gogu · Vincent Hallet · Alain Dassargues

Abstract Five different methods for assessing intrinsic aquifer vulnerability were tested in a case study and their results compared. The test area was a slightly karstified district in the Condroz region of Belgium. The basin covers about 65 km^2 and the karst aquifer provides a water-supply of about 28,000 m^3d^{-1}. The methods tested were: EPIK (Doerfliger et al. 1999), DRASTIC (Aller et al. 1987), 'German method' (von Hoyer and Söfner 1998), GOD (Foster 1987) and ISIS (Civita and De Regibus 1995). The results are compared and critically examined. From the analysis, it seems that reducing the number of parameters is unsatisfactory, due to the variety of geological conditions. The various methods produce very different results at any given site. As only physically-based methods can be checked for their reliability, it is clear that future vulnerability mapping techniques must incorporate such methods.

Keywords Groundwater protection · Vulnerability · Aquifer · GIS · Belgium

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Study outline and hydrogeological context

Up to now, it has not been possible to evaluate vulnerability methods quantitatively . Comparing different vulnerability maps is one way partially to assess the reliability of results. The use of a large number of parameters in vulnerability assessment allows one to describe complex hydrogeological settings. A substantial effort is required to obtain the necessary input data and to ensure an adequate level of accuracy. One way to develop easily applicable methods is to reduce the number of parameters. Unfortunately, due to simplification, methods involving fewer parameters present serious difficulties when used in different geological conditions.

In order to compare their suitability for delineating groundwater vulnerability in the limestone aquifers of the Walloon Region (Belgium), several vulnerability assessment methods have been examined. Five methods were selected for this study: EPIK (Doerfliger et al.1999), DRASTIC (Aller et al. 1987), the German method (von Hoyer and Söfner 1998), GOD (Foster 1987), and ISIS (Civita and De Regibus 1995). DRASTIC and GOD represent classic approaches to vulnerability assessment. ISIS is a method based on DRASTIC, SINTACS (Civita 1994), and GOD, where the authors give more importance to recharge. EPIK and the German method are procedures developed recently in Europe for the geological conditions present respectively in Switzerland and in Germany. The analysis was conducted using the raster data model called GRID within the Arc/Info software package (ESRI 1997).

The test area is located in the Condroz region, about 30 km south of Liège in Belgium (Fig. 1). Geologically, this zone belongs to the eastern part of the Dinant synclinorium. Hydrogeologically, it forms a part of the Néblon river basin. The area includes several villages and the main land uses are agriculture and forestry.

The hydrological basin covers about 65 km^2 and is an important hydrogeological resource. The aquifer is located upgradient from the springs in the Neblon valley. It is exploited by means of drainage galleries to provide water for Liège city and for local water supplies. It yields a daily supply of about 28,000 m^3.

Many previous studies and data collections were performed in the scope of PhD researches (Meus 1993), as well as expertise studies for the local water company. They

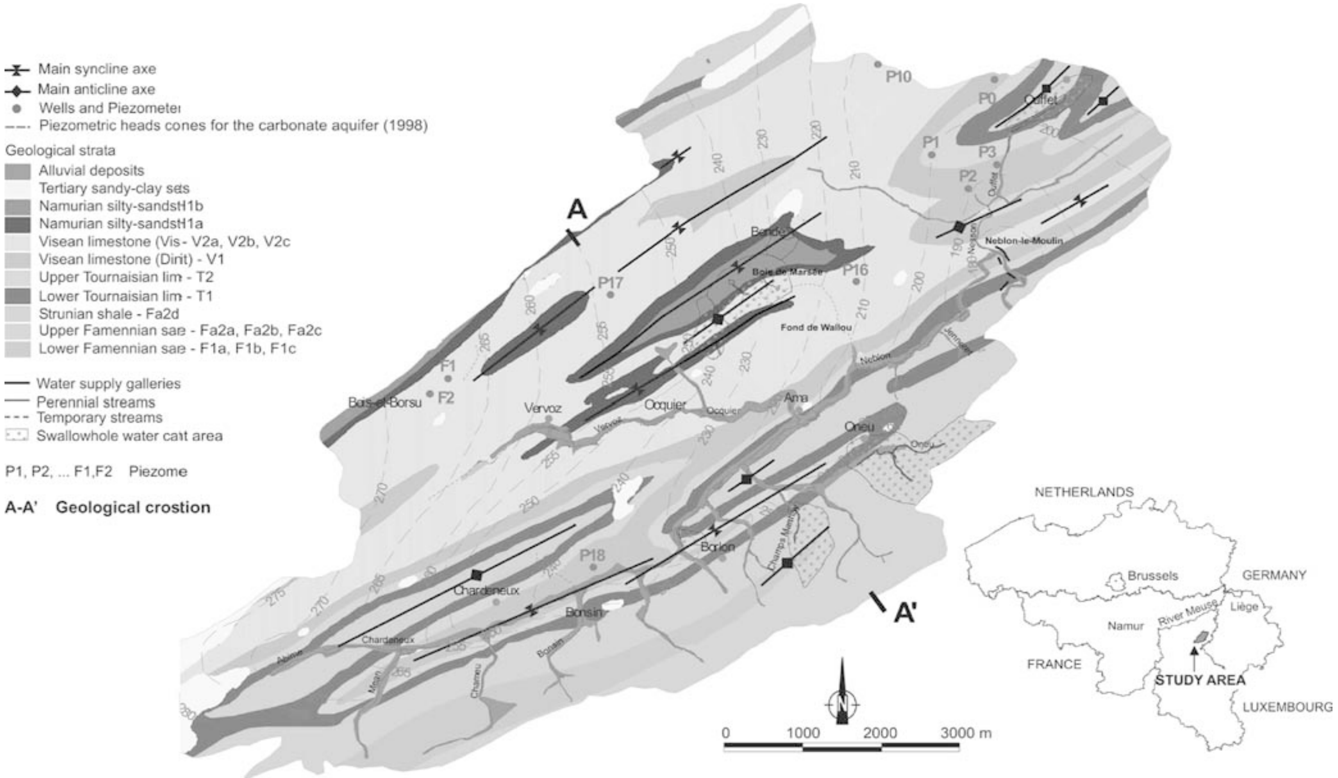

Fig. 1
Location, geology, and hydrogeology of the Néblon river basin, Belgium

have involved morphostructural analysis, geophysical prospecting, pumping and tracer tests, balance studies, hydrogeological mapping (Hallet et al. 2000, unpublished data) and groundwater modeling (Dassargues and Derouane 1997). Nowadays, the whole data set consists of information on the geometry of the geological strata, hydrological and hydrogeological boundaries of the basin, location and characterization of faults, lineaments and fracture zones, evolution of piezometric heads, hydrological water balance, hydrogeochemical analyses, and hydraulic conductivity, storage coefficient, and effective porosity values.

Geomorphology

The Néblon basin is a part of the Devonian-Carboniferous folded formations of the eastern edge of the Dinant synclinorium that crosses Belgium from west to east. The region is called the "Condroz anticlinorium".
The Condroz region typically has alternating anticlinal crests of shales and sandstones (Upper Devonian or Famennian) and calcareous synclinal depressions (Lower Carboniferous or Dinantian), that contain several carbonate aquifers, locally connected through sandstone layers.
The Hoyoux, the Néblon and the Ourthe are the main rivers of the region (Meus 1993). The river network cuts the relief and the tributary streams of the Néblon flow transversely following the general east-west geological structure. Most of these streams have their sources in the southern part of the water catchment area, in the Famennian sandstone. Due to karstification, several streams end in swallow holes at the following locations: Oneu, Bois de Marsée, and Champs Manhay (Fig. 1). Several temporary and losing streams as well as five areas of diffuse losses are also present.

Hydrogeology

General description

The Néblon basin aquifers are located in Tournaisian and Visean limestone, in Famennian fractured sandstone, and in Namurian silty-sandstone.
The main aquifer of the basin is composed of Tournaisian and Visean limestone. The aquifer is highly fissured, locally showing distinctive karst features. In this karst limestone, the Hastiere formation of the Lower Tournaisian includes shale intercalations and consequently has lower hydraulic conductivity values. The Ivorian (Upper Tournaisian) and the Visean limestone can be considered as forming a single hydrogeological unit (Hallet et al. 2000, unpublished data). The Visean is generally purer limestone than the Tournaisian and is easily karstified.
The Néblon river is considered as draining the main aquifer. The natural outflows of the aquifer were the diffuse discharges, point sources along the Neblon river and the springs of Neblon-le-Moulin. These springs are exploited via four collecting galleries by the CILE Water Company, abstracting 25,000 and 30,000 $m^3 day^{-1}$. The

galleries are parallel to the axis of the Neblon valley and located upgradient of the natural outlets of the hydrogeological basin on both sides of the Néblon river. The main gallery ("Principale") located on the left side of the river provides about 50% of the water-supply.
The Famennian sandstone is another exploitable aquifer. This aquifer has a large storage capacity principally in the weathered zones and in the strongly fissured/fractured zones. The connection with the limestone aquifer (Fig. 1) is mainly by several springs rising upgradient of the separating Strunian shale band or possibly through fissured zones.
The silty-sandstone Namurian formations of the Bois-et-Borsu and Bende synclines act like small perched aquifers. These aquifers have a limited storage capacity. The Namurian groundwater is exploited for agricultural purposes by a few local wells with yields of several cubic meters per day. It is believed that a shale belt provides an impervious layer in the Namurian synclines at depth. A connection with the limestone aquifer can only result by overflowing this shale belt or through the existing faults (Fig. 1).

Table 1
Hydrodynamic and hydrodispersive parameter values used in the regional 2D and 1D numerical models

Carbonate rock aquifer (Tournaisian and Visean)		
Transmissivity	Mean value	10^{-3}–10^{-4} $m^2\ s^{-1}$
	Fractures	10^{-2}
	Karstic conduits	>>>(Darcy's law not valid)
	Rock mass	$<10^{-5}$
Effective porosity	Mean value	1–2%
Longitudinal dispersivity	Mean value	max. 30 m
	Karstic conduits	max. 100 m
Transverse dispersivity	Mean value	1 to 5 m
Molecular diffusivity	Mean value	10^{-9} $m^2\ s^{-1}$
Sandstone aquifer (Famenian)		
Transmissivity ($m^2\ s^{-1}$)	Mean value	10^{-4}–10^{-5} $m^2\ s^{-1}$
Effective porosity	Mean value	10%
Longitudinal dispersivity	Mean value	10 m
Transverse dispersivity	Mean value	1 m
Molecular diffusivity	Mean value	10^{-9} $m^2\ s^{-1}$
Strunian shale		
Transmissivity	Value	10^{-6} $m^2\ s^{-1}$

Karstic features

Several karstic features are present in the Neblon basin, the most significant being dry valleys, swallow holes, resurgences and dolines. The high discharge springs of Neblon-le Moulin indicate the presence of a karstic conduit. Three large swallow holes have been identified: Bois de Marsée, Bende, and Oneu (Fig. 1).
Tracers injected in the swallowhole of Bois de Marsee, have been recovered in two of the collecting galleries ("Communale" and "Principale" galleries). This clearly indicates a network of karst conduits (Meus 1993). In the "Communale gallery", the tracers' arrival times were less than 50 h or had a velocity of about 73 m hr^{-1}. Such velocities confirm that some zones are affected by a high degree of karstification where Darcy's law does not apply.
Several dry valleys can be seen in the area. The largest one is the Fond de Bende, located to the east of the village of Bende. During rainy periods the bottom of this dry valley becomes a tributary stream of the Nesson. Two other dry valleys joining the Nesson stream are the Himbe ravine in the North-East and the Ouffet ravine in the North. Starting from the Bois de Marsée, a dry valley called the Fond de Walou (it has several names: Fond de Marsée, Fond de Sartre, and Fond de Walou) joins the Néblon between Ama village and the Jenneret stream. Another dry valley runs parallel to the Fond de Wallou. This latter starts some 1,000 m SE of the Fond de Wallou, and also ends in the Néblon river. A small swallow hole is present in the upper part of this dry valley but is not included in the karst atlas of De Boyer et al. (1996).
Extended karstic cavities are unknown in this region. Only a few poorly developed karst caves occur along the Néblon cliffs as well as a small doline located south of Ouffet.

Hydrogeological parameters

Several pumping tests were performed in existing wells in the karstic aquifer. Data interpretation indicated transmissivity values between 10^{-3}–10^{-5} m^2s^{-1} (Dassargues and Derouane 1997). In the entire catchment area, the effective porosity was estimated between 1.5–2%. This global estimate is based on interpretation of annual groundwater storage variations (Dassargues and Derouane 1997).
A longitudinal dispersivity of 15 m was deduced from the tracer tests performed in the Bois de Marsée swallow hole (Meus 1993). This value was obtained by modeling the tracer test results using an analytical formula assuming a single drain. No additional data were obtained from the tracing tests performed in the wells.
There is no data available for hydraulic conductivity in the Famennian aquifer in the Néblon basin. However, several pumping tests were performed in these Famennian sandstones in the Condroz region. These tests performed in similar neighboring aquifers, indicate hydraulic conductivity values between 1.4×10^{-4}–5.5×10^{-6} m s^{-1}. This value was also seen to decrease with depth.
An initial numerical model approach was performed (Dassargues and Derouane 1997) in order to try to describe globally the aquifer behavior for the groundwater flow and solute transport. The resulting parameter values are shown in Table 1.

Conceptual scheme required for the vulnerability assessment of the aquifer

This vulnerability study examined the aquifer within the Néblon hydrological basin that feeds the groundwater supply galleries.
The hydrogeological boundaries of the Néblon basin show spatial and temporal variations in some zones. In the southern part, shale forms the impervious boundary of the Borlon Famennian anticline. The northern and eastern boundaries are mainly situated in Visean limestone. These

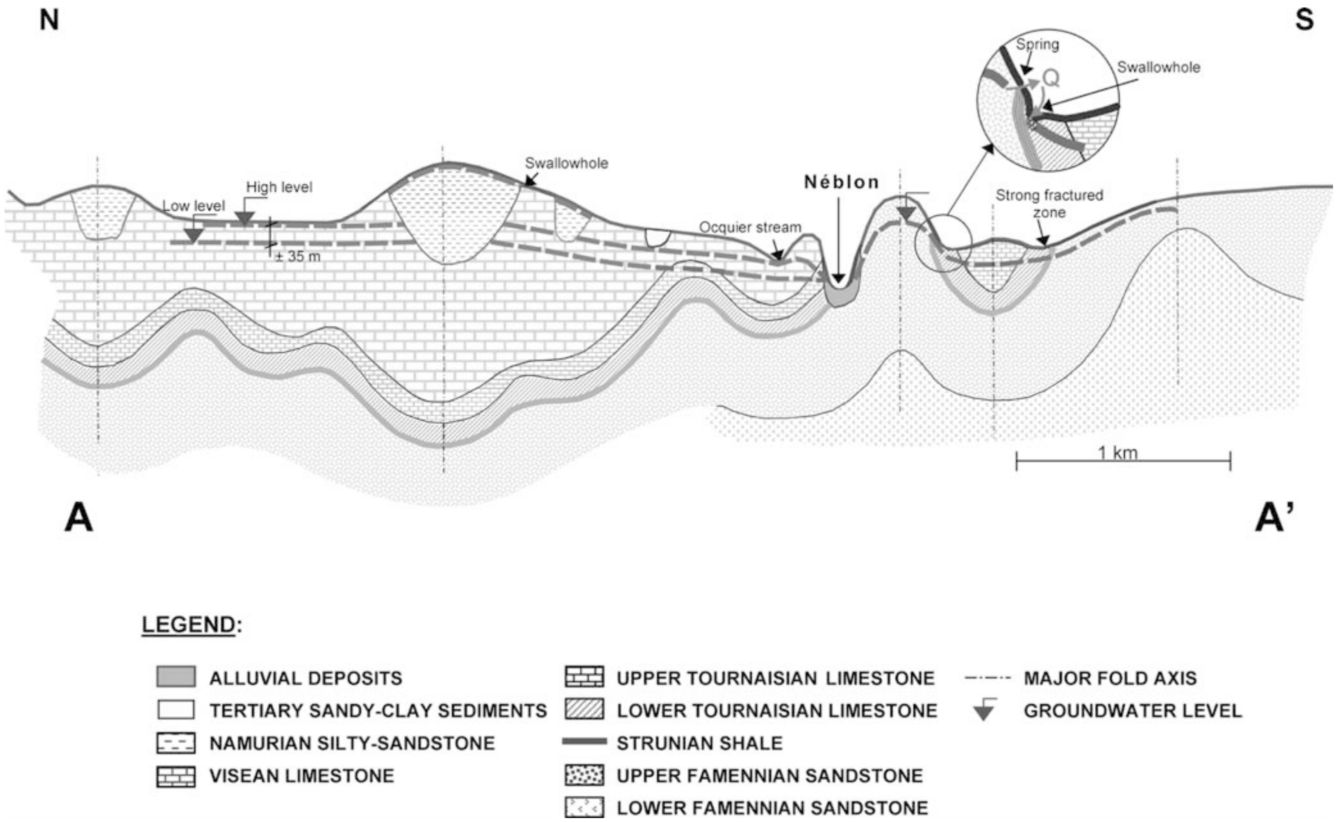

Fig. 2
Schematic north-south geological and hydrogeological cross-section of the Néblon River basin

boundaries are often considered as corresponding to the crest of the respective hydrological basins of Hoyoux and Anthisnes, however the hydrogeological and hydrological boundaries do not coincide. The choice of these boundaries does not rule out groundwater transfers. The eastern boundary with the neighboring basins is complex. To the west, the hydrogeological boundary is often considered as the same as the hydrological one. However a possible extension of the hydrogeological basin to the west is indicated by water-balance studies, which show a high summer base flow in the Ocquier river. This could be explained by a groundwater discharge from the neighboring western basin.

The Néblon karst system is moderately karstified, corresponding to a young stage of karstification. The few measurements of groundwater levels in the existing piezometers do not permit a full understanding of the aquifer. However, considerable variations in the hydraulic heads have been observed. A piezometric head map of low groundwater levels in 1998 (Fig. 1) was prepared by Hallet et al. (2000, unpublished data). This piezometric map clearly shows a general groundwater flow to the East with a lower piezometric level in the Néblon river valley as groundwater levels are observed nearly in equilibrium with the river water levels.

The conceptual model for the karst aquifer, used in this vulnerability analysis, has well defined karst conduits with a limited extension of karstification.

The link between the karst aquifer and the Famennian sandstone aquifer is believed to be limited. The Namurian aquifers can be considered as isolated. A good groundwater connection can be seen between the Tertiary sandy-clayey deposits filling the paleokarst pockets and the limestone aquifer.

A clear relationship between the karstic aquifer and the surface river network was pointed out. There is inflow to the aquifer through various sections of the river bed. This raises the possibility of contamination of the supply galleries by the river, especially in the alluvial plain. Di Clemente and Laurent (1986, unpublished data), observed an identical chemical composition of groundwater as well as a similar temporal variation of the groundwater chemical and physical parameters (conductivity, pH, and ionic content) between the Vervoz springs feeding the Ocquier stream (Fig. 1) and the water in the galleries. These observations point to possible links between the Néblon river and the galleries.

Recession coefficients calculated for some of the stream basins crossing the Famennian sandstone present values similar to those calculated for the stream basins crossing the limestone. This indicates a generally good storage capacity in the sandstone aquifer and of course an important effective porosity.

The depth of the Namurian synclines is not known. Often they are considered as allowing a deep groundwater connection in the underlying limestone aquifer (Fig. 2). This hypothesis is supported by water-balance results, showing an excess for the Ama and Vervoz streams basins (Dassargues and Derouane 1997).

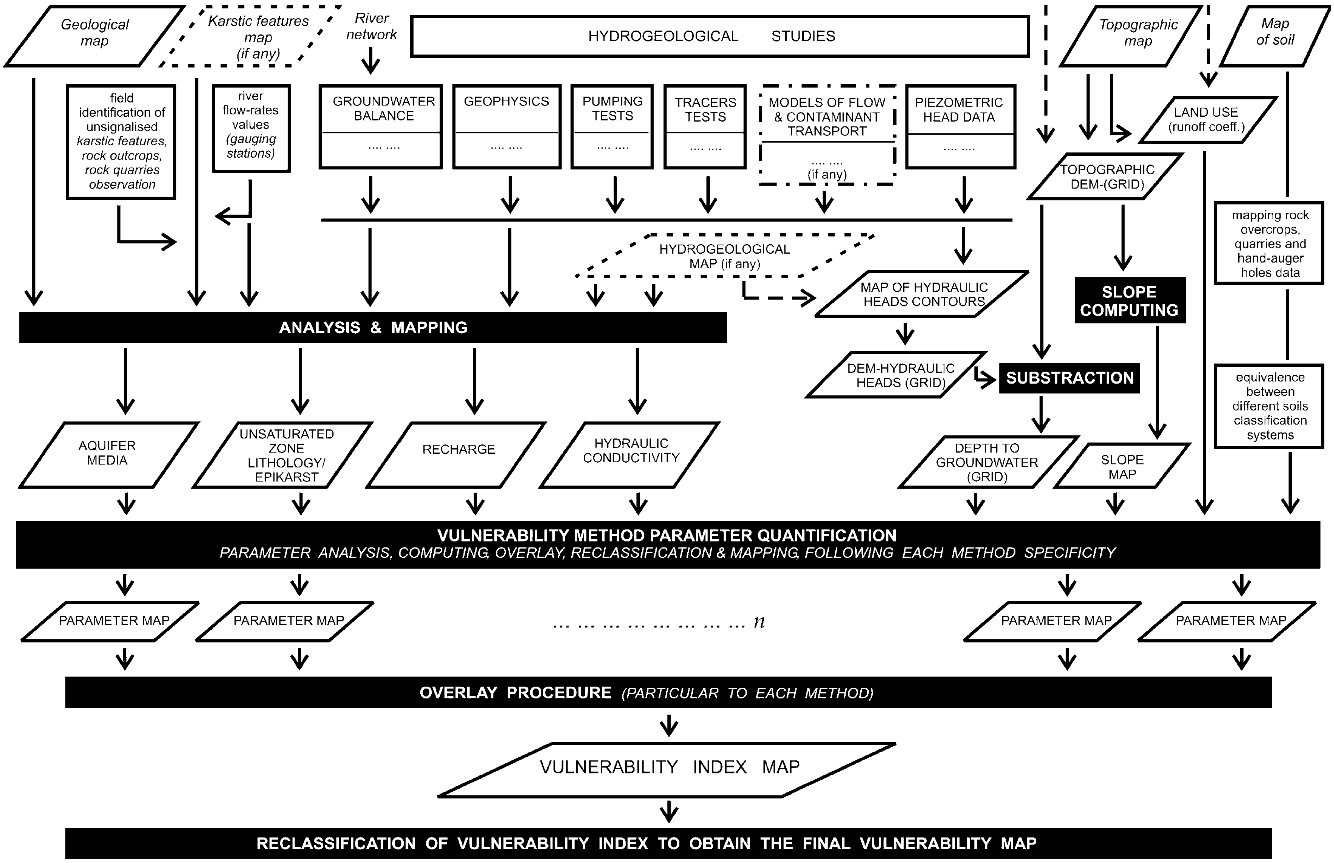

Fig. 3
Main steps in groundwater vulnerability assessment for Néblon aquifer

Overview on the quantification of the parameters used by the vulnerability-assessment methods

The study was conducted on the area of 64.70 km^2 calculated for the Néblon hydrological basin. The quantification of the parameters was done in parallel for the five applied methods. As hydrogeological parameters can be to some extent interdependent, evaluation of the different vulnerability parameters needed by each method was done by considering the possible relationship between them.
The necessary steps for obtaining reliable results were the following: (1) a careful analysis of the existing raw and treated data, (2) an evaluation of the data sources, (3) a correlation between hydrogeological parameters, and finally (4) an hydrogeological interpretation of each method parameter.
A brief description of the most important steps in vulnerability parameter estimation is needed. However, in this paper all the GIS terms and definitions (DeMers 1997), the types of geographical modeling, the means of obtaining data, the GIS functions, operational procedures, spatial manipulation issues and errors are considered as known.
Aquifer vulnerability assessment is based on different data sources as is shown in Fig. 3. In this case study the data comes from: geological maps, maps of karst features (De Boyer et al. 1996), hydrogeological maps (Hallet et al. 2000, unpublished data), various local and regional hydrogeological studies, topographical maps, soil maps, the digital numerical model of Belgium, and land-use maps. These data were augmented by a series of field tests: geophysical investigations (electrical sounding and profiling, seismic soundings), piezometric head measurements, pumping tests, tracer tests, field observations (geomorphology, quarries, springs), river flow-rate measurements (gauging stations), short auger hole interpretation, identification and mapping of rock outcrops, quarries, and newly discovered karst features.
Information and data coming from the various studies (Fig. 3) and from the geological maps, the maps of karst features, and the hydrogeological maps, provided a basic outline of the aquifer, the unsaturated zone lithology, the epikarst zone, the hydraulic conductivity, and the recharge of the aquifer.
The digital elevation model (DEM) of the region formed the basis for the calculation of the slopes needed for some of the methods. A hydraulic head contour map was created using piezometric head values from the existing hydrogeological map (Hallet et al. 2000, unpublished data) and augmented with data obtained from the 1998 field measurements. This hydraulic head map was used to generate a GIS grid layer of information of hydraulic heads. Subtraction of the piezometric head grid from the DEM, produced the GIS grid layer of “depth to water table” for the aquifer.

The existing soils map was the data source for the soil parameters map. Additional information on soil thickness, rock outcrops and quarries, was obtained in the field. The map representing the runoff coefficients corresponding to land-use was derived from the land-use map of the National Geographical Institute of Belgium.

Vulnerability analysis results

Description of the vulnerability maps

Following the procedures of each vulnerability method, the quantified parameter maps were overlaid and six different final vulnerability maps were produced. These maps are respectively Figs. 4, 5, 6, 7, 8, and 9 for the EPIK, DRASTIC, modified DRASTIC, "German Method", ISIS and GOD methods. Table 2 gives by percentage the portion of the total area mapped in each vulnerability class for each method.

The EPIK vulnerability map (Fig. 4) shows three vulnerability classes. Moderate vulnerability covers about 91.5% of the examined area and high vulnerability 7.8%. The concentrated or diffuse swallow holes and the losing streams feeding the swallow holes are characterized by a very high degree of vulnerability (0.7%). Fissured outcrops are also in the same category. The river Néblon, where it is in contact with the aquifer, its tributary streams crossing the limestone or the sandstone, and the few mapped dolines are placed in the high vulnerability class. Likewise are dry valleys, the Néblon gorges, and other small areas of steep slopes. The effect of weighting and rating results in parameter E exerting the main influence on the final vulnerability map (Gogu and Dassargues 2000b). Vulnerability can be overestimated for some outcropping epikarst features. Highly fractured natural outcrops are given the same vulnerability rating as artificial outcrops (quarries, road or railway cuttings). However, the non-fissured outcrops or those having no direct contact with the aquifer may be much less vulnerable than the zones between dolines or dry valleys.

The original DRASTIC method published by Aller et al. (1987) does not provide vulnerability classification ranges, but allows the user to interpret the vulnerability index using their own field knowledge and hydrogeological experience. In the literature two distinct classification ranges are found. The commonly used vulnerability index classification (Civita and De Regibus 1995, Corniello et al. 1997) produced the vulnerability map shown in Fig. 5. This classification system defines five classes of vulnerability: very high vulnerability (vulnerability index >199), high vulnerability (160–199), moderate vulnerability (120–159), low vulnerability (80–119), and very low vulnerability (<79). As can be seen on the map, moderate vulnerability is by far the largest zone with about 73% of the area including most of the fissured limestone and the Famennian sandstone. The stream zones occurring on the Namurian and feeding the swallow holes are not shown as more vulnerable than the adjacent zones. However, in general the main karst features are accurately outlined by this method.

A second map was prepared employing the DRASTIC method with the use of vulnerability categories suggested by Navulur and Engel (1997, unpublished data). This was done only for a quantitative reference and not considered as a valid result in the analysis (this classification is confined to the specific vulnerability assessment of pesticides). The authors define four vulnerability classes (Fig. 6) : very

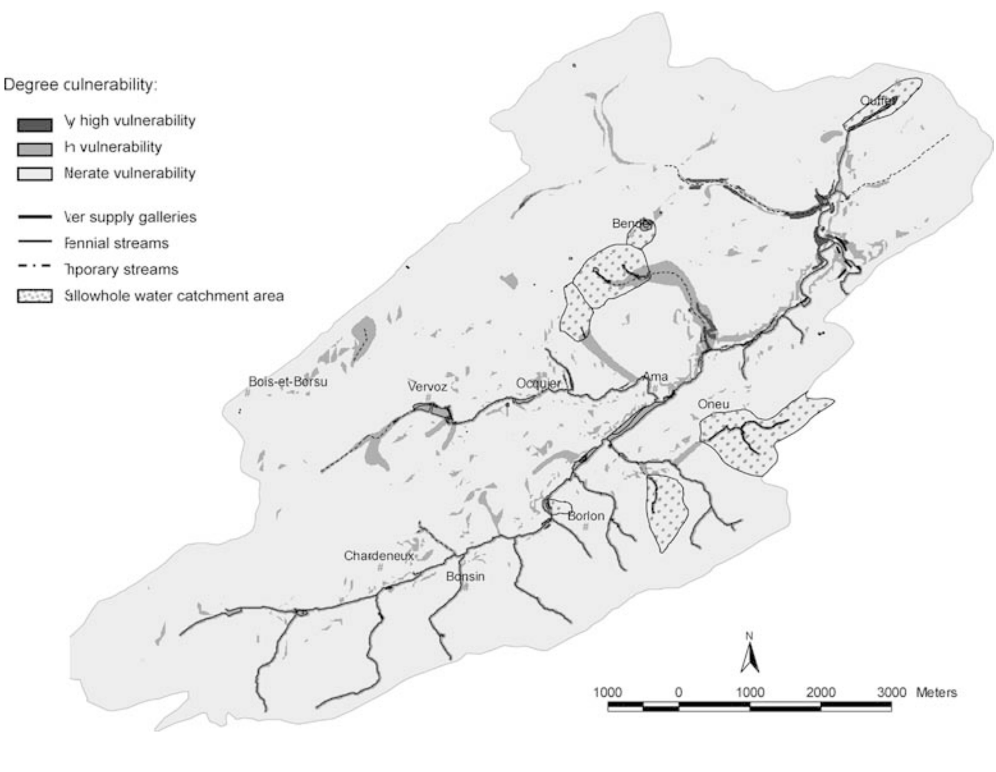

Fig. 4
Final vulnerability map using EPIK method

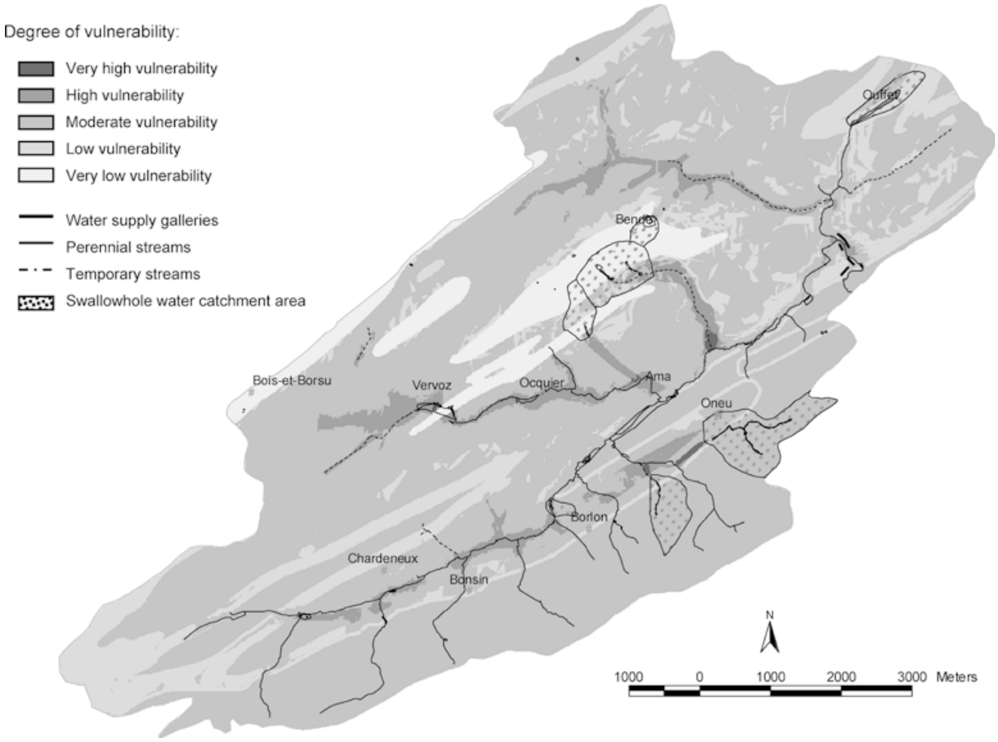

Fig. 5
Final vulnerability map using DRASTIC method and the commonly used final classes of vulnerability

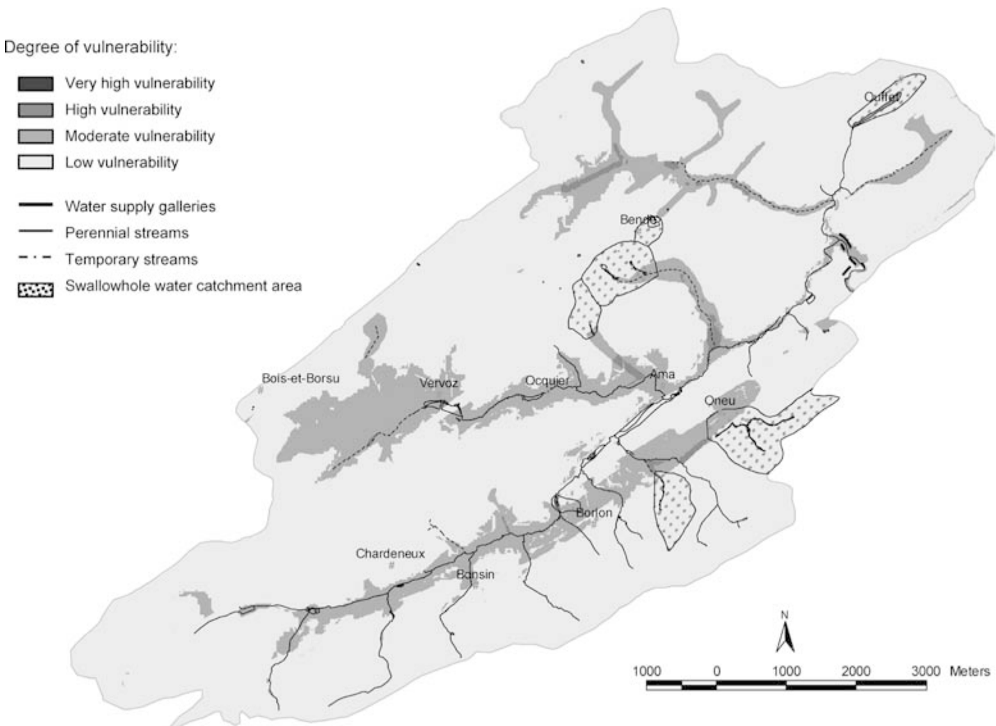

Fig. 6
Final vulnerability map using DRASTIC method and classes of vulnerability defined by Navulur and Engel (1997, unpublished data)—DRASTIC b

high vulnerability (DRASTIC vulnerability index >230), high vulnerability (181–230), moderate vulnerability (141–180), and low vulnerability (1–140). In Table 2, areas corresponding to this classification are placed in the DRASTIC (b) column.

The German method, as with most of the parametric systems, provides its own classes of vulnerability, as shown in Fig. 7. This method shows 48.3% of the basin with high vulnerability and 34.3% with very high vulnerability. These classes of vulnerability include the entire limestone aquifer as well as the Famennian aquifer. Moderate vulnerability makes up just 7.6% of the studied area corresponding to the Strunian bands, to parts of the Lower Tournaisian bands, and to the alluvial valleys crossing the Famennian. Low vulnerability is assigned to the Tertiary sandy-clay formations and to small sectors corresponding to the

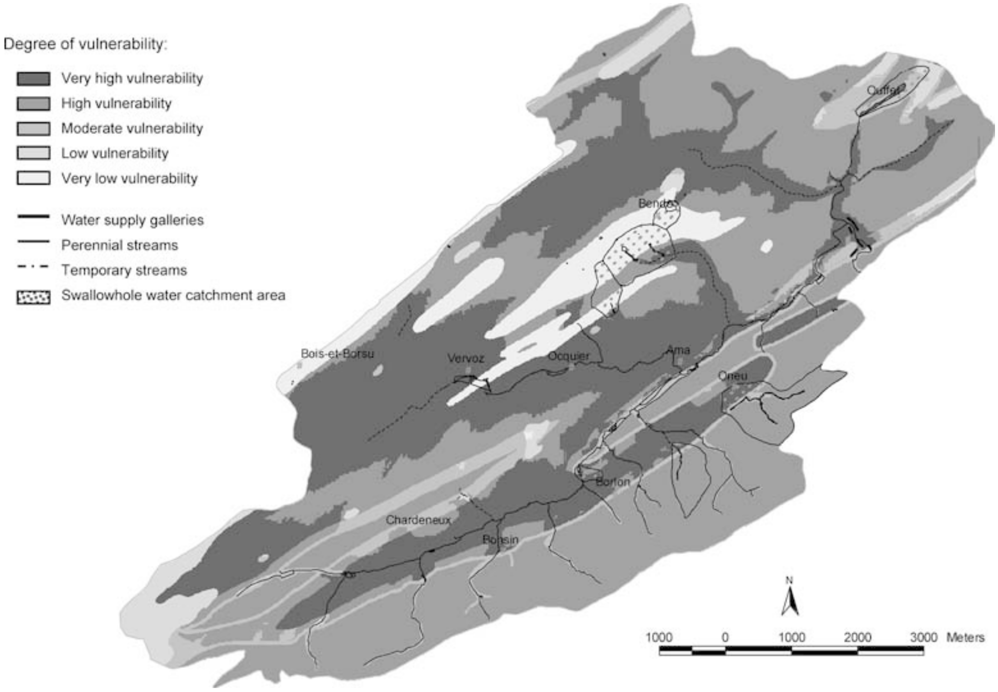

Fig. 7
Final vulnerability map using German method

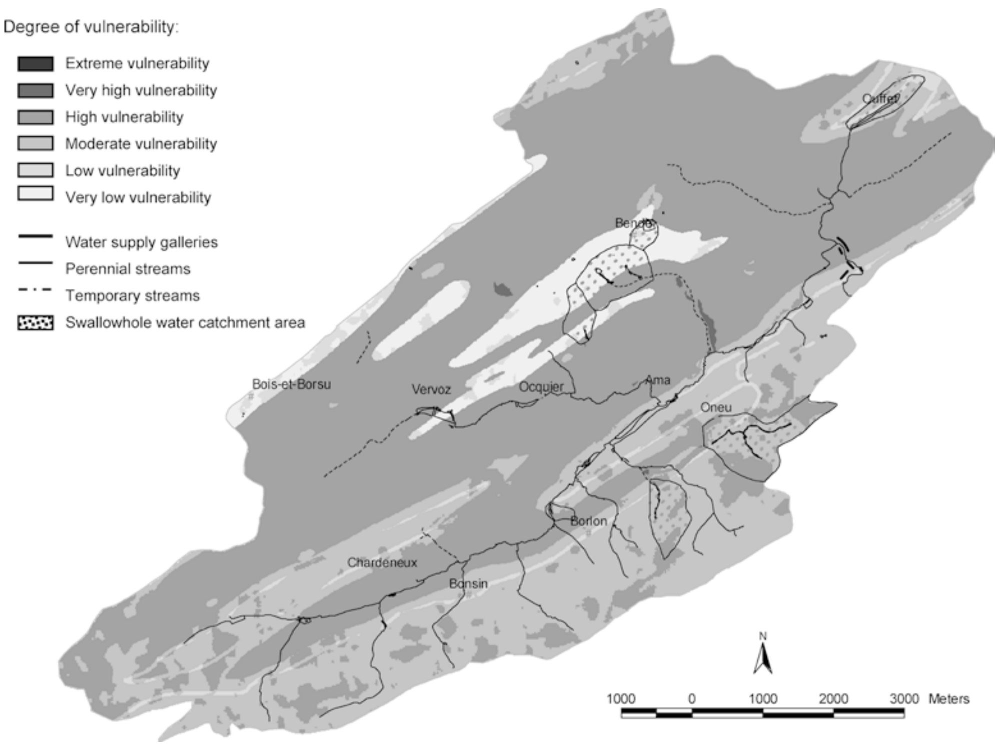

Fig. 8
Final vulnerability map using ISIS method

Lower Tournaisian and to the Strunian. Very low vulnerability is confined to the Namurian districts. The karst features are apparently correctly assessed, most of them being shown as very high vulnerability zones.

The ISIS method (Fig. 8) has six vulnerability categories. The extreme vulnerability category was not found in the area and very high vulnerability is limited to a few outcrops (Fond de Wallou and a rock-quarry located in the North). High vulnerability is assigned to 62.9% of the study area. Moderate vulnerability (about 29.1%) is mainly found in the Fameninan standstone and the Lower Tournaisian areas. Low vulnerability occurs along the Strunian bands. Very low vulnerability is confined only to the districts underlain by the Namurian. The role played by runoff coefficients corresponding to land-use can be clearly seen in the low vulnerability Namurian districts as well as the high vulnerability zones in the sandstone and in the Lower Tournaisian limestone. Karst features are

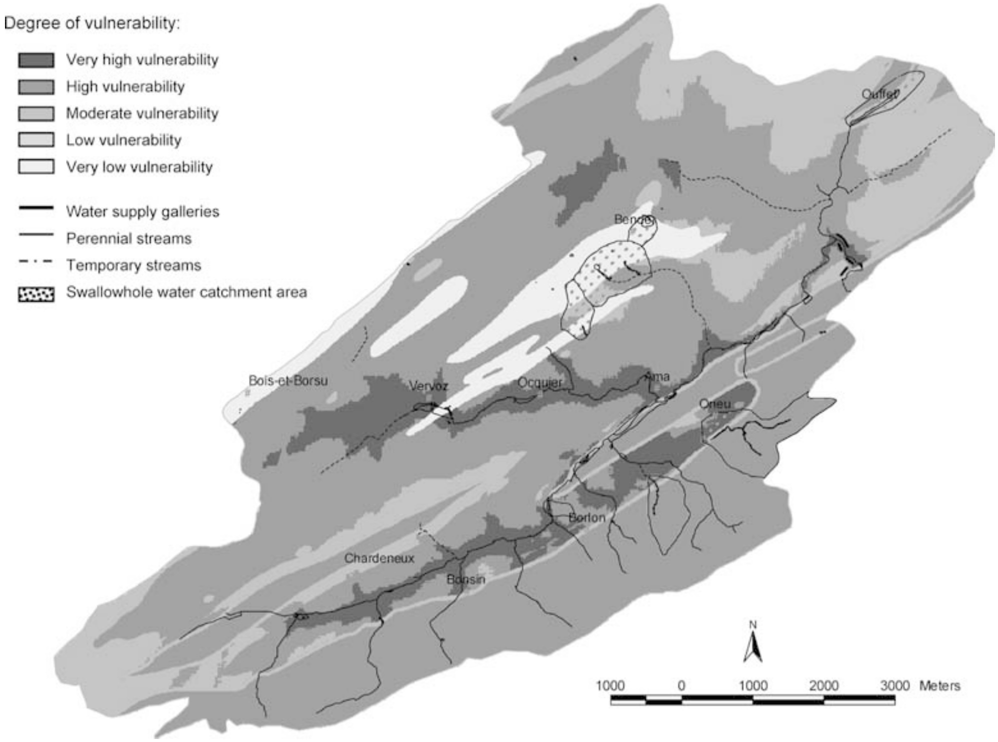

Fig. 9
Final vulnerability map using GOD method

Table 2
Comparison between the areas representing the vulnerability classes, obtained with the five methods (areas are expressed as percentage related to the entire study area; 100% represents 64.7 km^2)

	EPIK	DRASTIC	GERMAN	ISIS	GOD	DRASTIC (b)
Extreme	–	–	–	0.0	–	–
Very high	0.7	0.2	34.3	0.2	9.5	0.0
High	7.8	5.0	48.3	62.9	63.7	0.6
Moderate	91.5	73.0	7.6	29.1	20.5	14.8
Low	–	15.6	3.6	2.7	0.0	84.6
Very low	–	6.2	6.2	5.1	6.3	–

generally assessed with high vulnerability but very few of them show a contrast with the surrounding zones.
The results using the GOD method are shown in Fig. 9. There is no low vulnerability and very low vulnerability is shown for the Namurian districts . Most of the study area is assessed as having high vulnerability (63.7%). Very high vulnerability is assigned to 9.5% of the study area. The Famennian aquifer cannot usually be distinguished from most of the limestone. The karst features are generally assigned high vulnerability. Moderate vulnerability covers about 20.5% of the study area. It includes the Tertiary sandy-clay deposits and those parts of the carbonate aquifer with a thick unsaturated zone. The method does not accurately show karst features: the area of the Ouffet swallow hole is shown with moderate vulnerability, while the diffuse swallow hole of Bende is assigned very low vulnerability.

Comparison between vulnerability maps

Classic DRASTIC has the zones of very high and high vulnerability covering 5.2% of the study area. EPIK has the zones of high and very high vulnerability covering 8.5%. The very high and high vulnerability zones for the other three methods make up more than a half of the study area (Table 2). EPIK rates most of the area with moderate vulnerability (91.5%). This is because EPIK was designed only for karstified limestones.
A general similarity can be seen between GOD, ISIS, and the German method (Figs. 9, 8, and 7). Important differences can be observed for EPIK (Fig. 4) and DRASTIC (Fig. 5) results. The German method produces the largest high and very high vulnerability zones (high 48.3% and very high 34.3%). ISIS shows 62.9% of the area with high vulnerability.
All the methods except DRASTIC and EPIK classify the limestone aquifer with high or very high vulnerability. DRASTIC and EPIK assess it with moderate vulnerability The difference between high and very high vulnerability in the German method and the GOD method vulnerability maps is largely influenced by the depth to the water table. Furthermore, these two methods use the depth to water table as a direct multiplier for the other parameters. This procedure also increases the vulnerability rating. The ISIS method uses the depth to water table parameter differently and unfortunately smoothes out the vulnerability index results. It is evident that in the DRASTIC vulnerability

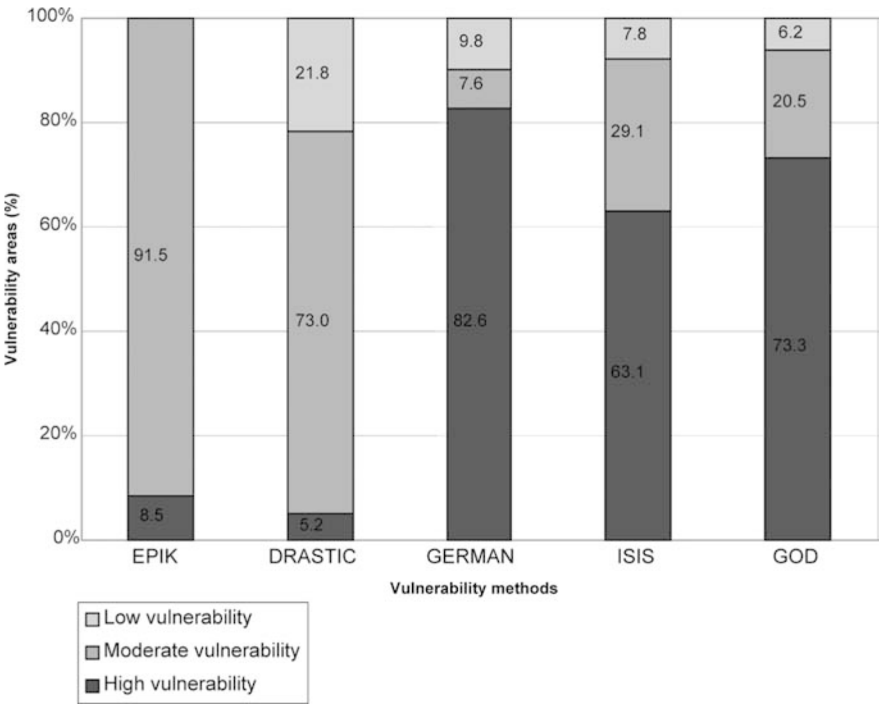

Fig. 10
Comparison between the regrouped classes of vulnerability defined by the applied methods

map, the depth to the water table determines whether an area is classed as moderate vulnerability or high vulnerability (Fig. 5).
Karst features are not always shown with high or very high vulnerability. For example in the GOD method, the small diffuse swallow hole at Bende and the swallow holes and resurgences located near Ouffet are assigned respectively low and moderate vulnerability. The streams feeding the swallow holes are classed as high vulnerability zones by EPIK, the German method, and by GOD. ISIS and DRASTIC rate these zones, partly as high vulnerability and partly as moderate vulnerability. The dry valleys and the dolines are shown by all the methods except ISIS, as being more vulnerable than the rest of the limestone.
The Lower Tournaisian is mostly assigned moderate or high vulnerability and the Strunian bands are shown with moderate or low vulnerability.
A feature of the ISIS method is the use of the parameter representing the runoff coefficients corresponding to land-use as a multiplier factor for all the other parameters. This can be easily seen on the resulting vulnerability map in the vulnerability class given to the Famennian sandstone, the Namurian, the Lower Tournaisian, and the Strunian bands.
Comparing the vulnerability maps obtained by EPIK (Fig. 4), DRASTIC (Fig. 5) and DRASTIC modified by Navulur and Engel (1997, unpublished data) in Fig. 6, shows that DRASTIC b can be considered as a step between DRASTIC and EPIK, in the vulnerability index reclassification. Further reclassification of the vulnerability index, results in an even greater similarity between DRASTIC and EPIK. Thus DRASTIC and EPIK seem to mainly stress the same hydrogeological and geomorphological features, even if the two approaches are different.

Regrouped classes of vulnerability

A different kind of interpretation can be obtained by regrouping the vulnerability classes. This was done for each vulnerability map, creating three main categories: high (including high, very high, and extreme vulnerability), moderate vulnerability (the same class for all five methods), and low vulnerability (including low and very low vulnerability). To facilitate the comparison, the results are shown in Fig. 10.
All five methods class the Namurian districts as low vulnerability. The German method shows the most extensive area of high vulnerability, with 82.6%. The DRASTIC results show little variation in vulnerability classes in the study area with 73.0% of the area with moderate vulnerability and 21.8% with low vulnerability.
For this basin, these regrouped classes of vulnerability indicate two main trends in vulnerability assessment: (a) the German method, the GOD method, and the ISIS method rate the study area as having mainly high vulnerability; (b) The EPIK and the DRASTIC methods show the study area with largely moderate vulnerability of 91.5% and 73.0% respectively. These results show a major disagreement between the different methods.

Conclusions

Some conclusions can now be drawn based on the results of the vulnerability assessment using the five methods:

1. The German method, the GOD method, and the ISIS method (Fig. 10) indicate more than half of the study zone has high vulnerability.
2. the DRASTIC and the EPIK methods show most of the study area with moderate vulnerability.

3. Namurian districts are assessed with low vulnerability, except in the case of EPIK.
4. The Famennian sandstone is shown as less vulnerable than the limestone aquifer except for the GOD method and in part the German method.
5. The Strunian bands are considered to have moderate or low vulnerability by all the methods.
6. The Lower Tournaisian is mostly assessed with moderate or high vulnerability.
7. The Tertiary sandy-clay deposits are assessed as having moderate vulnerability, with the exception of DRASTIC and the German method.

Karst features are correctly shown with high or very high vulnerability by all the methods except for GOD and to a lesser extent ISIS. EPIK is the best method at assessing karst features and is the only one that classifies the small streams within the Namurian district as having high vulnerability.
Most of these vulnerability methods only take into account vertical permeability, so inaccurate assessments can arise. For example, most methods ignore possible contamination coming directly from streams and bypassing the soil and the unsaturated zone.
The EPIK method has important strengths as well as serious weaknesses. The assumption of relating a steeper slope to a higher degree of vulnerability is not realistic when open valleys and fissured matrix predominate. It is valid only in karst drainage basins. Another problem is that EPIK produces results whereby most of the study area (91.5%) has moderate vulnerability. This is because the relatively high vulnerability of karst systems does not relate to other types of aquifers in EPIK. As the basic concept of vulnerability *to delineate land areas that are more vulnerable than others* (Vrba and Zaporozec 1994; Gogu and Dassargues 2000a) is a relative concept, ignoring other lithological and hydrogeological conditions reduces contrasts.
A Comparison between the DRASTIC and EPIK vulnerability maps shows that the two methods stress the same hydrogeological and geomorphological characteristics. However, it demonstrates the DRASTIC capacity of satisfactorily outlining karst morphology. These conclusions indicate the need for new research into procedures of parameter quantification and weighting. For example, the recharge of an aquifer seems to be one of the most important parameters in vulnerability assessment. All five methods explicitly or implicitly take this parameter into account. Results in vulnerability assessment can be significantly influenced and improved if the recharge parameter becomes a spatially variable datum.
Progress is needed to better differentiate fissure matrix from compact rock and from major discontinuities or karst conduits. Information from geophysical investigations should help to better delineate and to infer fault boundaries, dips, geometry, relative roughness, and filling.
Too many classes of vulnerability are not of practical value: as for example the *extreme vulnerability* class in the ISIS method. In this study, the *extreme vulnerability* class was not used even in the case of a karst aquifer. Thus, defining four classes of vulnerability appears to be a more sensible choice. It fully meets the needs and the resulting maps are more easily understood and utilised.
The choice of vulnerability method remains a subjective decision for the hydrogeologist. Besides, all the methods are to some extent flexible with regard to parameter quantification. As stressed by Aller et al. (1987), vulnerability methods are screening tools. They must not replace the professional expertise and field studies needed for more quantified answers. The choice of parameter rating should be based on prolonged studies of the hydrogeological conditions. The so called vulnerability "rapid assessments" performed by unqualified persons and using very large pixels for calculating their assessment can lead to serious errors. The only way to accurately depict aquifer vulnerability is to combine at an appropriate scale (ideally 1:25,000) all the relevant data on geology, hydrogeology, hydrology, soil, topography, climate, and land-use.
Subsequent to the attempt to find a uniform "European Approach" for vulnerability mapping in karst systems (Daly et al. 2001), new ways forward are now being discussed. These try to eliminate the inadequacies in the existing vulnerability methods, by taking a more physical approach to the concept of vulnerability. An applied definition is being drawn up from what currently underpins the concept of groundwater contamination. For intrinsic vulnerability, three factors describing contamination by a conservative contaminant are defined: contaminant transfer time, contamination duration, and the level of concentration reached by the contaminant (Brouyère et al. 2001). Clearly new methodologies more consistent with the physics of flow and contaminant transport represent the only way forward. Developing these new concepts in order to obtain a good and lasting method represents the next serious challenge in groundwater vulnerability assessment. Moreover it seems the only way to obtain vulnerability maps that can be validated.

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Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods

R.C. Gogu · A. Dassargues

Abstract The concept of groundwater vulnerability is a useful tool for environmental planning and decision-making. Many different methods have been developed for assessing this vulnerability. Hydrogeologists have failed to reach a consensus concerning the definitions of and reference terms for groundwater vulnerability assessment. Therefore, a review of vulnerability assessment and mapping methods providing a new classification system is necessary. This is focused on techniques that use the overlay and index class methods. New research challenges in vulnerability assessment are identified, especially the need for developing dynamic links between numerical models and overlay and index methods.

Key words Groundwater · Vulnerability · Overlay and index methods

General concepts for groundwater vulnerability assessment

Vulnerability assessment of groundwater, as used in many methods, is not a characteristic that can be directly measured in the field. It is an idea based on the fundamental concept "that some land areas are more vulnerable to groundwater contamination than others" (Vrba and Zaporozec 1994). Nevertheless mapping the degree of groundwater vulnerability to contaminants, as a function of hydrogeological conditions, shows that effective protection provided by the natural environment may vary drastically from one place to another.

Often, the groundwater contamination level is determined by the natural attenuation processes, occurring within the zone located between the pollution source and the aquifer. Various natural, physical processes, and chemical reactions that operate in the soil, unsaturated, and saturated zones, may cause the pollutant to change its physical state and chemical form. These changes may attenuate the degree of pollution or change the nature of the contamination. Especially in soil and the unsaturated zone, some mechanisms may affect the contaminant concentration much more than in the saturated zone.

Chemical processes can be very complex and may work individually or in combination with other processes to provide varying attenuation degrees. These reactions depend on site specific soil and aquifer characteristics as well as on the particular geochemical properties of each pollutant. Although the importance of these chemical reactions for attenuation of pollution is widely recognized and sometimes modelled, attenuation processes can be partially or completely bypassed depending on geochemical conditions in the aquifer and the infiltration conditions.

Pollution sensitive areas

Pollution sensitive areas can be divided into three groups: naturally vulnerable areas, well-protection zones, and potential problem areas.

Naturally vulnerable areas are more sensitive zones where the soils, subsoil, and bedrock do not provide adequate protection and the potential exists for rapid transfer of pollutants to groundwater. Areas of concern are, for example, the recharge zones of shallow aquifers.

In the vicinity of pumping wells, each pollutant can potentially contaminate the pumped groundwater relatively quickly. In many countries, the methods for delineating well-protection zones are standardised using different criteria, based on the piezometric heads, on the advective transport time, on the advective-dispersion transport time or other parameters.

Overlaying maps of the most vulnerable zones, with maps showing the location of each potential contamination sources or polluting land-use activities, generates the map of potential problem areas (risk maps).

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Concepts and methods of vulnerability assessment

The aquifer vulnerability concept mainly entails two particular notions: intrinsic vulnerability and specific vulnerability. European specialists of the COST Action 620 "vulnerability and risk mapping for the protection of carbonate (karst) aquifers", agreed on the fact that intrinsic vulnerability is a "term used to define the vulnerability of groundwater to contaminants generated by human activities", taking "account of the inherent geological, hydrological and hydrogeological characteristics of an area", but being "independent of the nature of contaminants". On the contrary, specific vulnerability notion is used "to define the vulnerability of groundwater to a particular contaminant or group of contaminants", taking "account of the contaminant properties and their relationship with the various components of intrinsic vulnerability".

In relation to groundwater protection, three main approaches can be distinguished in the assessment of groundwater vulnerability to contamination:

1. Vulnerability assessment considering only the soil and unsaturated zone without taking into account the transport processes within the saturated zone. In this case, the assessment is limited to the relative probability that troublesome concentrations of contaminants reach the saturated zone. Many classical vulnerability methods, are based on this approach : the GOD method (Foster 1987), the Irish approach (Daly and Drew 1999) or AVI method (Van Stempvoort and others 1993).
2. The approach based on delineation of protection zones for groundwater supply systems, where groundwater flow and contaminant transport processes within the saturated zone are considered to some extent (including dispersion transport as it is done in Walloon Region of Belgium, Derouane and Dassargues 1998).
3. An approach, targeting the soil and unsaturated zones as well as the aquifer medium.

Based on these different approaches, various methods of groundwater vulnerability assessment have been developed. They range from sophisticated numerical models simulating the physical, chemical and biological processes occurring in the subsurface, to techniques using weighting factors affecting vulnerability and also to statistical methods. Coupled, physically-based models considering soil, unsaturated and saturated zones in order to compute contaminant transport time in the system and at the opposite various empirical vulnerability methods like DRASTIC (Aller and others 1987), SINTACS (Civita 1994), EPIK (Doerfliger and Zwahlen 1997) could be cited here.

In this paper, only the current methods used for groundwater vulnerability assessment are discussed. Most often they are based on overlay and index techniques. The combination of maps with spatial distributions of specific attribute data (soil, geology, depth to water, etc.) leads to an assigned numerical index or score for each attribute. They are combined to produce a vulnerability score. Attempts are made to obtain values as quantitative as possible.

Current trends in vulnerability assessment using overlay and index methods

Overlay and index methods rely mainly on the quantitative or semi-quantitative compilation and interpretation of mapped data. Starting from the fundamental concept of vulnerability of the U.S. Committee on Techniques for Assessing Ground Water Vulnerability (National Research Council 1993) and from the definitions of the International Association of Hydrogeologists (Vrba and Zaporozec 1994), some general characteristics of these methods must be emphasised:

- Groundwater vulnerability is a relative, non-measurable, dimensionless property.
- The main attributes used for the intrinsic vulnerability assessment are recharge value, soil properties and characteristics of unsaturated and saturated zones. Attributes of secondary importance include topography, groundwater/surface water relation, and the nature of the underlying unit of the aquifer.
- Specific vulnerability is mostly assessed in terms of danger for the groundwater system becoming exposed to specific contamination. The most important parameters in specific vulnerability assessment are: contaminant travel time within the unsaturated zone and its residence time inside the aquifer medium, attenuation capability of the soil-rock-groundwater system with respect to the properties of individual contaminants.
- The assessment of groundwater vulnerability is site or area specific.

A summary of some significant methods used for groundwater intrinsic vulnerability assessment can be found in Table 1. The existing methods can be grouped into two basic categories: hydrogeological complex and settings methods, and parametric system methods.

Hydrogeological complex and settings methods (HCS)

This kind of method implies a qualitative assessment. First, one must decide the hydrogeological, hydrographical and morphological conditions that correspond to each class in a vulnerability scale. Then the entire area is analysed and divided following the criteria established (Albinet and Margat 1970). Generally, a map overlay procedure is used. Large areas with various hydrographical and morphostructural features are best suited for assessment through these methods and thematic maps are produced from medium to large scale.

Parametric system methods

These are the Matrix Systems (MS) and Rating Systems (RS) methods and the Point Count System Models (PCSM) for the groundwater vulnerability assessment.

For all parametric system methods the procedure is almost the same. The system definition depends on the selection of those parameters considered to be representative for groundwater vulnerability assessment. Each pa-

Table 1
Significant methods for the assessment of the intrinsic vulnerability of groundwater, Explanation: HCS hydrogeological complex and settings methods, MS matrix system methods, RS rating systems methods, PCSM point count system models (rating and weighting systems)

METHOD	TYPE	BASIC PARAMETERS													
REFERENCE		Topo-grafic surface slope variability	Stream flow net-work density	CHARACTERISTICS OF SOILS				Aquifer connect to surface water	Net recharge	Charac-teristics unsaturated zone	Depth to water	Hydro-geological features	Aquifer hydraulic conduc-tivity	Thickness of the aquifer	Landuse type[a]
				Thickness texture and mineralogy	Effective moisture	Perme-ability	Physical and chemical properties								
Albinet and Margat 1970	HCS							•		•	•	•	•		
Goossens and Van Damme 1987	MS			•			•				•	•			
Carter and Palmer 1987	MS			•		•	•					•			
GOD, Foster 1987	RS									•	•	•			
DRASTIC, Aller and other 1987	PCSM	•		•					•	•	•	•	•		
SEEPAGE	RS	•		•	•	•	•			•	•	•			
SINTACS, Civita 1994	PCSM	•	•	•				•	•	•	•	•	•		•
AVI -Van Stempvoort and others 1993	RS			•		•				•	•				
ISIS, Civita and De Regibus 1995	RS	•		•			•		•	•	•	•		•	•
EPIK, Doerfliger and Zwahlen 1997	PCSM Karst aquifers	•		•				•	•	•		•			•

[a] The land use parameter characterise the human activity impact as effect on the runoff coefficients and not as the nature of contaminants

rameter has a defined natural range divided into discrete hierarchical intervals. To all intervals are assigned specific values reflecting the relative degree of sensitivity to contamination.
Matrix Systems (MS) methods are based on a restricted number of carefully chosen parameters. To obtain a quantified degree of vulnerability, these parameters are combined following a number of strategies developed by different research groups. These research applications are site-specific methods developed for local case studies, such as the method selected for the Flemish Region of Belgium (Goossens and Van Damme 1987) and the system used by Severn-Trent Water Authority in some areas of Central England (Carter and others 1987).
Rating Systems (RS) methods provide a fixed range of values for any parameter considered to be necessary and adequate to assess the vulnerability. This range is properly and subjectively, divided according to the variation interval of each parameter. The sum of rating points gives the required evaluation for any point or area. The final numerical score is divided into intervals expressing a relative vulnerability degree. The rating systems are based upon the assumption of a generic contaminant. Examples are GOD system (Foster 1987), AVI Method (Van Stempvoort and others 1993), and the ISIS method (Civita and De Regibus 1995).
Point Count System Models or Parameter Weighting and Rating Methods (PCSM) are also a rating parameters system. Additionally, a multiplier identified as a weight is assigned to each parameter to correctly reflect the relationship between the parameters. Rating parameters for each interval are multiplied accordingly with the weight factor and the results are added to obtain the final score. This score provides a relative measure of vulnerability degree of one area compared to other areas and the higher the score, the greater the sensitivity of the area. One of the most difficult aspects of these methods with chosen weighting factors and rating parameters remains distinguishing different classes of vulnerability (high, moderate, low etc.), on basis of the final numerical score. Examples are the DRASTIC method developed by U.S. EPA in 1985 (Aller and others 1987), SINTACS method (Civita 1994), and the EPIK method used in karst groundwater protection strategy developed by Doerfliger and Zwahlen (1997).

Uses and limitations

Groundwater vulnerability predictions are made in a relative, not an absolute, sense.
In many cases vulnerability maps are created to obtain a fast assessment of pollution risk, however they could be used as a meaningful tool in the environmental decision-making process. Methods applied to obtain groundwater vulnerability maps, have to portray a correct view on the site vulnerability and subsequent site-specific investigations are essential in many situations.
The UK National River Authority recognised that a full assessment of aquifer vulnerability and groundwater pollution risk can only be achieved by local studies (Robins and others 1994). These kinds of methods can reduce the number of areas to be studied in detail by identifying the most vulnerable areas. However, vulnerability assessment is a useful management concept for guiding decisions on groundwater protection tasks. It requires co-operative efforts of policy makers, natural resource managers, technical and scientific experts.

Main methods

GOD rating system

This method (Foster 1987) has a simple and pragmatic structure. It is an empirical system for quick assessment of the aquifer vulnerability to pollution. Three main parameters are considered: the groundwater occurrence, the lithology of the overlying layers, and the depth to groundwater (in unconfined or confined conditions). The vulnerability index (Fig. 1) is the result of the values assigned to these three parameters. Following the GOD flowchart, the area vulnerability index is computed by choosing first the rating of groundwater occurrence parameter and then multiplying by the overlying lithology rating as well as with the depth to water parameter rating. The overlying lithology parameter contributes to the vulnerability index only in the case of unconfined aquifers.
Because the parameters can only take values from 0 to 1, the computation result is usually a value less than the score assigned to each parameter. In the particular case where two parameters have a value equal to 1, the vulnerability score is equal to the score of the third parameter.

DRASTIC point count system model

The U.S. Environmental Protection Agency (EPA) developed DRASTIC (Aller and others 1987) as a method for assessing groundwater pollution potential. This method considers the following seven parameters: depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity. Each mapped factor is classified either into ranges (for continuous variables) or into significant media types (for thematic data) which have an impact on pollution potential. The typical rating range is from 1 to 10. Weight factors are used for each parameter to balance and enhance their importance. The final vulnerability index (D_i) is a weighted sum of the seven parameters and can be computed using the formula:

$$D_i = \sum_{j=1}^{7} (W_j \times R_j) \qquad (1)$$

D_i = DRASTIC Index for a mapping unit
W_j = Weight factor for parameter j
R_j = Rating for parameter j
DRASTIC provides two weight classifications (Table 2), one for normal conditions and the other one for conditions with intense agricultural activity. This last one, called pesticide DRASTIC index, represent a specific vul-

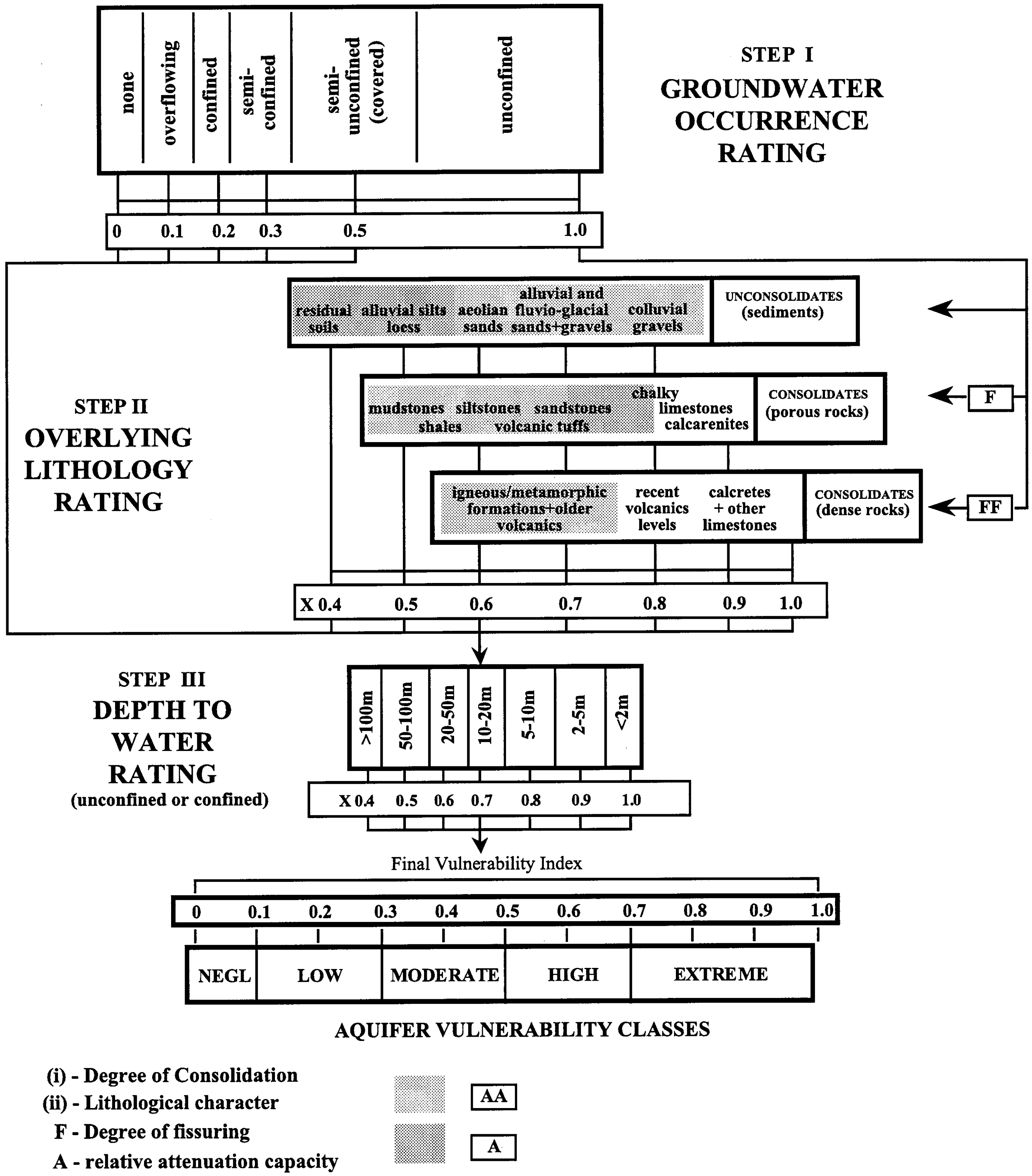

Fig. 1
The GOD parameters rating method, from Foster (1987)

nerability assessment approach. In a specific area only one weight classification should be selected for the whole area.

Once DRASTIC indices have been computed, it is possible to identify areas that are more susceptible to groundwater contamination than others. The higher the DRASTIC index, the greater the groundwater contamination

Table 2
Weight factors for DRASTIC and Pesticide DRASTIC

Parameter	DRASTIC weight	Pesticide DRASTIC weight
Depth to ground water	5	5
Net recharge	4	4
Aquifer media	3	3
Soil media	2	5
Topography	1	3
Impact of vadose zone	5	4
Hydraulic conductivity	3	2

potential. The DRASTIC index provides only a relative evaluation tool and is not designed to provide absolute answers. Moreover, the values generated by DRASTIC index and pesticide DRASTIC index are not similar.
To facilitate interpretation, some users have tried to divide the final index into vulnerability classes such as: low, moderate, high, and very high potential (Corniello and others 1997).

SEEPAGE method

The system for early evaluation of pollution potential of agricultural groundwater environments (SEEPAGE) considers various hydrogeologic settings and soil physical properties that affect groundwater vulnerability to pollution potential (Navulur KCS and Engel BA, unpublished data). It is also a numerical ranking model analysing contamination potential from both concentrated and dispersed sources. The SEEPAGE model considers the following parameters: soil slope, depth to water table, vadose zone material, aquifer material, soil depth, and attenuation potential. Attenuation potential takes into account the texture of surface soils, texture of subsoil, surface layer pH, organic matter content of the surface, soil drainage class and soil permeability.
To each parameter a weight factor ranging from 1 to 50 is assigned, based on its relative significance. A weight factor of 50 is assigned to the most significant parameter affecting the water quality and a weight factor of 1 is assigned for the least significant. These weights are different for concentrated sources and dispersed ones. As with DRASTIC, each parameter can be divided into ranges, but the rate value assigned for each parameter vary from 1 to 50. The ratings of the aquifer media and vadose zone are subjective and can be changed for a particular region. Once the scores for the six parameters are obtained, these are summed to get the SEEPAGE Index Number (SIN). SIN numbers are ordered in four categories of pollution potential: low, moderate, high, and very high. A high or very high SIN category indicates that the site is highly vulnerable.

AVI rating system

This method (Van Stempvoort and others 1993) estimates the aquifer vulnerability index (AVI) using only two parameters: the thickness of each sedimentary unit above the uppermost aquifer (d); and the estimated hydraulic conductivity of each of these layers (k). The hydraulic resistance is given by:

$$c = \sum_{i=1}^{n} d_i/k_i; \qquad (2)$$

c = the hydraulic resistance given by AVI rating system
n = the numbers of layers
k = estimated hydraulic conductivity of each of the n layers

The c or $\log(c)$ value is related to a qualitative Aquifer Vulnerability Index by a relationship table. The authors suggest calculating c for each well or test hole and then to generate the iso-resistance contour to classify the study area in AVI zones.

SINTACS method

Derived from DRASTIC model, this method has been developed for vulnerability assessment and mapping requirements (medium and large-scale maps) by Italian hydrogeologists (Civita 1994). The SINTACS point-count system has a complex structure (Fig. 2). A number of weight strings are used in parallel, to define the existing conditions. These parameter values are then rated and divided into intervals. The final results outline six vulnerability classes.
In fact, SINTACS proposed by Civita (1994) uses the same seven parameters as DRASTIC but the rating and weighting procedure is more flexible. It provides four weight classifications but it also allows the creation of new ones. The user encodes the input data as functions of local conditions in each area, and has the possibility of using different classifications depending on circumstances.
SINTACS vulnerability index can be computed as follows:

$$I_v = \sum P_{(1,7)} \times W_{(1,n)}; \qquad (3)$$

I_v = vulnerability index by SINTACS method
$P_{(1,7)}$ = the rating of each of the seven parameters used
$W_{(1,n)}$ = the associated weight
n = the number of weight classification arrays

ISIS method

This method is a synthesis of various studies on aquifers intrinsic vulnerability assessment (Civita and De Regibus 1995) and can be classed with the rating systems group of methods.
ISIS is a hybrid method, based on the comparative evaluation of the existing hydrogeological situations. It has been developed taking into account the rating and weighting systems of DRASTIC and SINTACS methods and the GOD method for the general structure design.
Parameters used by ISIS method are: the annual mean of the net recharge (it is possible to introduce the rainfall value and the mean annual temperature or other related parameters), topography, soil type, soil thickness, lithology of the unsaturated zone, thickness of the unsaturated zone, aquifer medium, and aquifer thickness.

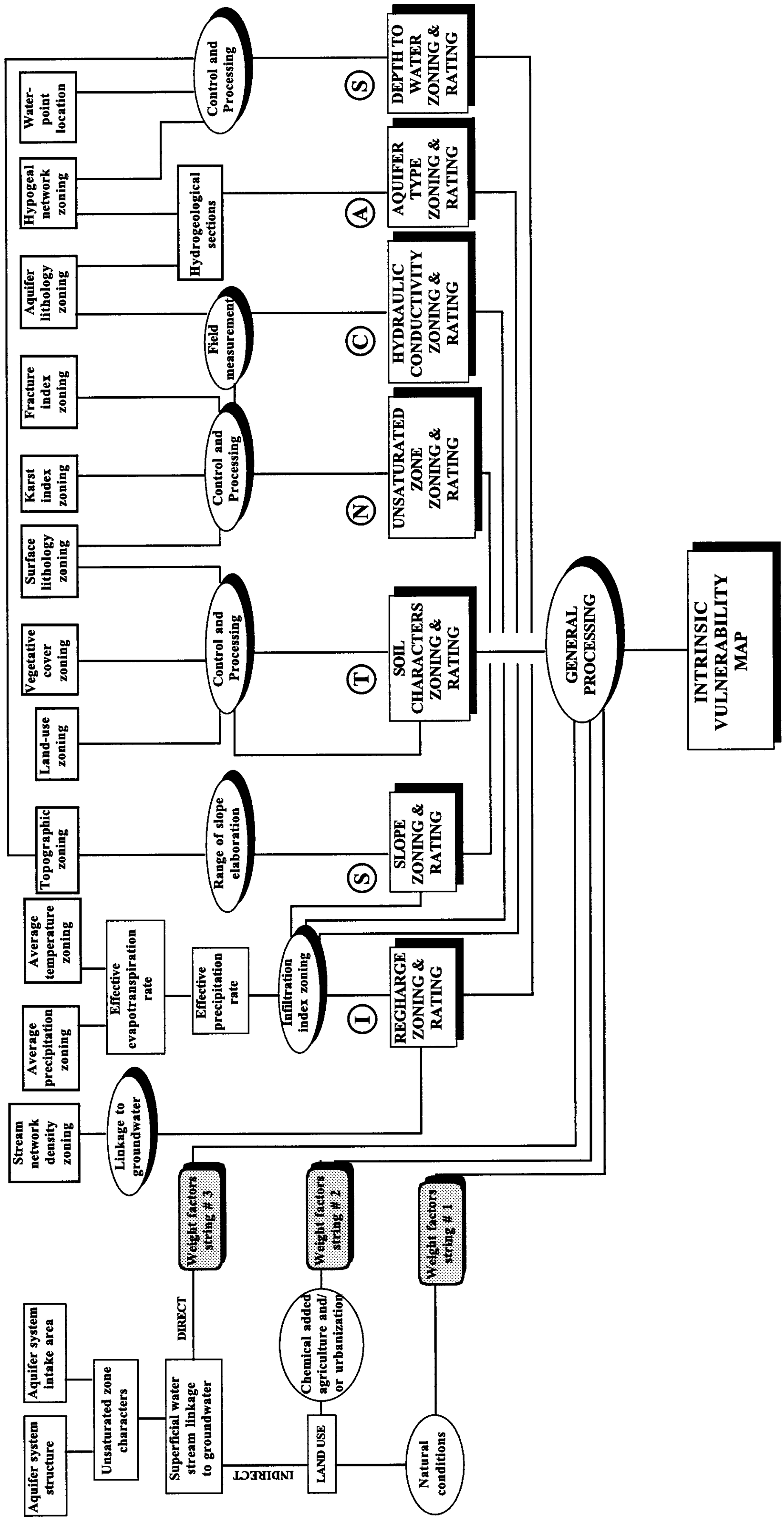

Fig. 2
SINTACS method recipe, adapted from Vrba and Zaporozec (1994)

The land-use parameter, as the human activity impact feature, has been adopted from the SINTACS methodology and quantified. It has been divided in three areal units: areas with normal conditions, strong contaminated agricultural area, strong superficial drained area. This parameter is used as a weighting element for modulating the relative importance of the direct used parameters, as a function of the different land use conditions.
To estimate the vulnerability index I_v, ISIS method is using the following formula:

$$I_v = p_{Inf} \times f_{Inf} + p_{Su} \times f_{Sus} \times f_{Su} + p_{Ins} \times f_{Si} \times f_{Ins} + p_{Sat} \times f_{Ss} \times f_{Sat} \tag{4}$$

Where:
p_{Inf} = the rating values for ranges on the net recharge;
f_{Inf} = infiltration coefficient dependent on land use;
p_{Su} = the rating values for the soil media;
f_{Sus} = soil coefficient dependent on land use;
f_{Su} = weighting coefficient dependent on soil thickness;
p_{Ins} = the rating values assigned to the vadose zone;
f_{Si} = weighting coefficient dependent on the unsaturated zone lithology and thickness;
f_{Ins} = vadose zone coefficient dependent on land use;
p_{Sat} = the rating values assigned to aquifer media;
f_{Ss} = weighting coefficient dependent on the aquifer thickness;
f_{Sat} = aquifer coefficient dependent on land use.
The final vulnerability index, varying between 24 and 180 is divided in 6 vulnerability classes: extreme (141–180); very high (124–140); high (88–123); medium (64–87); low (44–63); very low (24–43).

EPIK method

EPIK method has been specifically created for the vulnerability assessment of the karst aquifers (Doerfliger and Zwahlen 1997) in Switzerland. It is a clear and original parameter weighting and rating method (Fig. 3). Four main parameters are considered: epikarst (*E*), protective cover (*P*), infiltration conditions (*I*), and karst network development (*K*). Considering the impact on pollution potential, each parameter is classified into ranges (Table 3). Weighting factors are used for each parameter to balance their importance. The final "protection factor" (vulnerability index) is calculated with the following basic formula:

$$F_p = (\alpha \times E_i) + (\beta \times P_j) + (\gamma \times I_k) + (\delta \times K_l) \tag{5}$$

F_p = vulnerability Index in the EPIK method
E_i = rating value for the "epikarst" parameter
P_j = rating value for the "protective cover" parameter
I_k = rating value for the "infiltration conditions" parameter
K_l = rating value for the "karst network development" parameter
$\alpha, \beta, \gamma, \delta$ = weight factors for EPIK parameters
Assigned relative weights for EPIK parameters are: $\alpha = 3$, $\beta = 1$, $\gamma = 3$, $\delta = 2$

Table 3
Rating values for E, P, I, and K parameters, note: the lower the rating value, the higher the vulnerability

E_1	E_2	E_3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

The vulnerability index is found in an interval of values from 9 to 34 and is divided in four categories of vulnerability degree: high (9–19); medium (20–25); low (26–34) and very low (in conditions of a soil protective cover of thick detrital layers with very low hydraulic conductivity – having a thickness of minimum 8 m).

Comparison studies

One of the few cases where an attempt has been made to compare methods was by an Italian research team in "Piana Campana" region, Southern Italy (Corniello and others 1997). To assess the vulnerability of the aquifer in this area, four methods were tested: DRASTIC, SINTACS, GOD, and the AVI model. For an operational qualitative comparison, specific aspects of vulnerability classes were considered.
It was shown that the SINTACS method, compared with the others, generates "very high vulnerability zones in the areas concerned with surface waters and aquifer interactions. This result is strongly influenced by the aquifer identification and by different weight classification series used for the area affected by drainage. A similar result was obtained in a vulnerability assessment study made on the alluvial cone Prahova – Teleajen (Gogu and others 1996), by applying the SINTACS method together with a matrix system method locally developed by a Romanian research team.
Using the DRASTIC model, the low vulnerability class was wider than within SINTACS. At the same time, SINTACS model seems to give more importance to the land-use parameter, because of using different weight classification strings. In areas where the degree of vulnerability has modest variations, the GOD method provided homogeneous distributions of values. In consequence this method can only be used in areas with high contrasted vulnerability. Even with fewer parameters, the vulnerability map generated through AVI method was similar to those obtained from DRASTIC and SINTACS models. Moreover, a statistical comparison of all vulnerability maps showed the greatest similarity between the DRASTIC and SINTACS methods as well as a good correlation between those two and the AVI method.
Civita and De Regibus (1995) performed another significant comparative study of five methods of groundwater vulnerability assessment. To cover different hydrogeological situations, the study targeted three specific areas in Northern Italy, respectively flat, hilly and mountainous regions. The methods considered were DRASTIC, SINTACS, GOD, the Flemish Method (Goossens and Van Damme 1987), SINTACS, ISIS, and the CNR – GNDCI

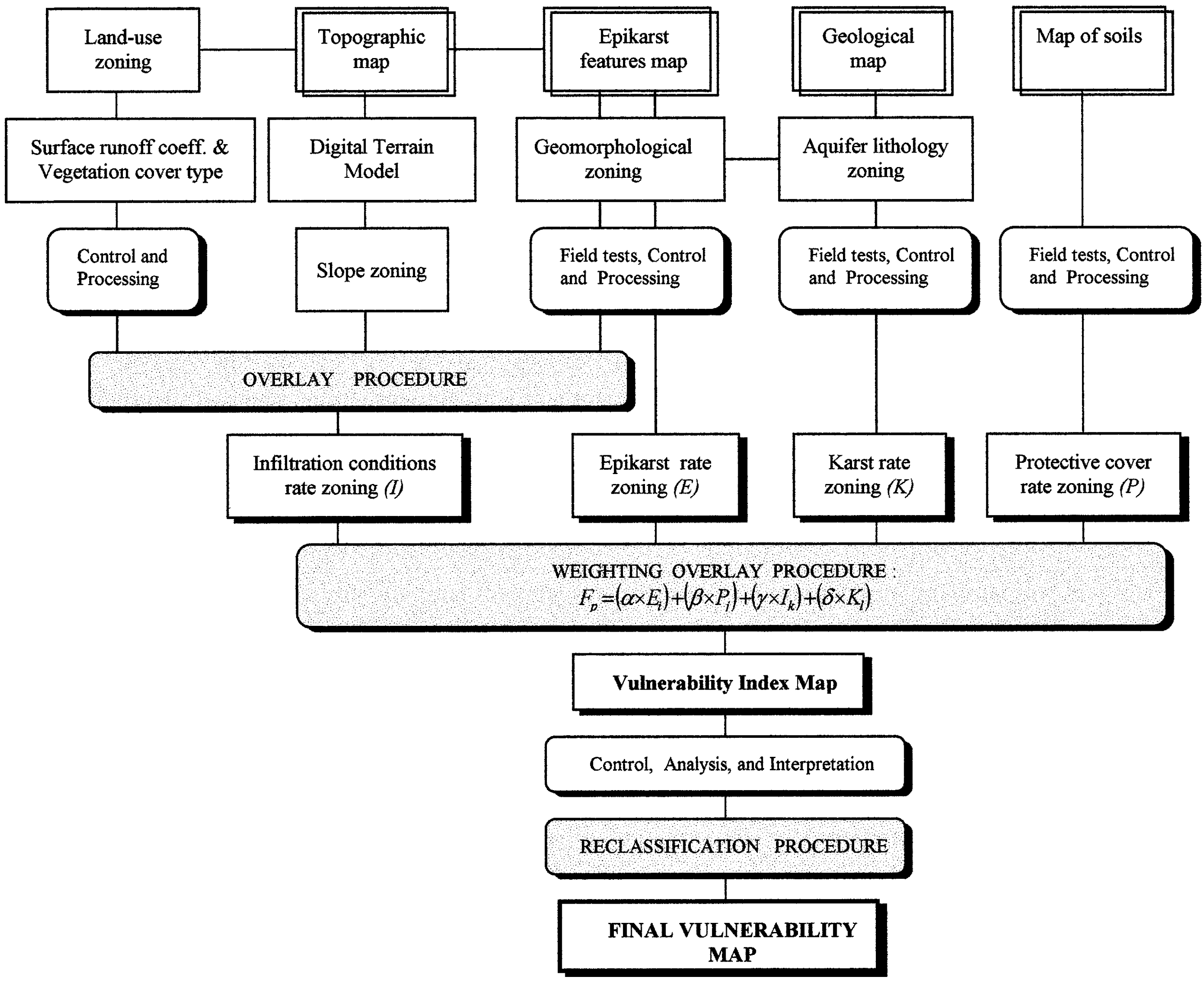

Fig. 3
The main steps of the EPIK method

method based on direct confrontation with hydrogeological predefined situations (Civita 1990).
Applying different methods to the same zone and using the same data showed that the relatively simple methods could provide similar results to the complex ones. It could be confirmed that these methods (as GOD for example) are best suited for designing large areas (used in land management). Having a good precision and flexibility, DRASTIC and SINTACS methods are much more effective in detailed studies. Other methods, such as the Flemish one, were not able to be adapted to situations other than those they were designed for.
A sensitivity analysis to evaluate a single parameter influence on the aquifer vulnerability assessment was performed on the same ”Piana Campana“ region by Napolitano and Fabbri (1996). Comparing SINTACS and DRASTIC methods, they observed that removing each of the seven parameters one by one, created relevant and significant changes in the vulnerability maps. They concluded that all the seven DRASTIC parameters are important in assessing aquifer vulnerability.
Comparing vulnerability methods using different parameters is not a comfortable operation however it represents the single manner to estimate their efficiency on a case study. This can be done mainly by examining the resulted vulnerability maps obtained with each method. A confrontation between them as well as with the initial hydrogeological information is always very interesting. In general, a method providing more contrasted results for a specific area can be considered as presenting a higher sensibility, so that results can be used and interpreted.

Future challenges in groundwater vulnerability assessment

Hydrogeologists are trying to agree on issues concerning intrinsic and specific vulnerability, on the different models and assessing methods, and on risk mapping and management aspects. For improvement of the vulnerability assessment analysis, research challenges can be found in the following aspects:

- To determine circumstances in which properties of the intermediate vadose zone are critical to vulnerability assessment and to develop methods for characterising this zone with more accuracy. A better quantification of physical and chemical processes that are taking place in this zone as well as the relationship with the other important factors influencing vulnerability will result in better results of the assessment procedure.
- To develop methods for accounting preferential flow pathways (for examples, soil macropores, fissure network, etc.) that can affect severely the vulnerability.
- To gather more information on uncertainty associated with vulnerability assessments and to develop ways to handle and display this aspect.
- To improve the hydrochemical database structures, and to find ways of introducing them in specific vulnerability assessments.
- To define more meaningful categories of vulnerability and determine which processes are most important to be incorporated into vulnerability assessment at different spatial scales. For instance, the UK National review on aquifer vulnerability defines the relative vulnerability of aquifers in terms of land zonation, based on the average time taken by infiltrating water to reach the aquifer. The accompanying maps, therefore, have classes of 1 week, 1 year, 20 years, greater than 20 years, plus three other categories (multizone, no information and no aquifers). The multizone category was designed to overcome the limitation of detail at the used map scale (Robins and others 1994).
- To set up unified models integrating the soil and geologic information in vulnerability assessment models. Also, the land-use and census data integration can improve the quality of groundwater overlaying vulnerability assessment by creating the potential risk maps. This correlation should be done by integrating information associated to potential contaminators (for example, industrial activity, highways' traffic parameters, etc.) and data about indirect influence of the human activities (artificial drainage created by agricultural activities).
- To create tools for merging data obtained at different spatial and temporal scales into a common scale for vulnerability assessment.
- To seek for useful comparative techniques and procedures to evaluate assessment methods and groundwater quality monitoring data. For instance, it was attempted in some overlay and index methods to address contamination (that might occur by wells and boreholes) by mapping those features in combination with results derived from other assessment methods. In these kinds of approaches, an essential point is the fact that contaminant load distribution is taken into account.
- To improve analytical tools in GIS software for effective integration of assessment methods with spatial attribute databases as well as with statistical and process based modelling techniques.

Process-based simulation models are used to predict groundwater flow and contaminant transport in both space and time. They mostly include a comprehensive description of the physical, chemical, and biological processes affecting groundwater vulnerability, they require extensive data sets, which often are not available. When missing data are estimated by indirect means, these models are not as reliable as they are in theory. Moreover based on the Representative Elementary Volume (REV) concept, these models simulate the flow and transport processes at the spatial scale of the chosen REV. In addition, most of them do not consider cases where preferential groundwater flow exists. (The assumption of considering a karst aquifer as a continuous porous medium is made in order to use numerical procedures developed for continuum mechanic).

One of the main future challenges of hydrogeology is to establish conceptual and operational basis for combining vulnerability methods and the results of process based models. This should be achieved, first at the theoretical level and later as a complex expert tool that could merge the data from spatial databases, vulnerability methods and process-based and statistical models into an integrated assessment concept.

To meet such a challenge, it will be necessary to use numerical model results in order to provide values of parameters in vulnerability assessment analysis (for DRASTIC: hydraulic conductivity, aquifer media, impact of the vadose zone, recharge of the aquifer). Integration of the "transfer time zones", related to the aquifer media, as rating parameter in the vulnerability assessment methods is also needed.

Conclusions

Trying to reach consensus on the terminology (vulnerability, hazards, risks), comparing methods, establishing models, discussions on weighting and rating, development of sensitivity analysis, could be accomplished by dedicated workshops and meetings. In this topic, the work being done in the scope of the COST620 Action on "vulnerability and risk mapping for the protection of carbonate (karst) aquifers", is not only useful for future research development but also needed for immediate practical purposes.

New challenges for hydrogeologists will consist in the integration of results from process based numerical model in the vulnerability mapping techniques. Using the existing software, GIS packages and interfaces the problem could theoretically be solved, but real integrated tools are expected and according to needed parameters data are to be collected and better quantified.

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A geo-spatial data management system for potentially active volcanoes—GEOWARN project

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Abstract

Integrated studies of active volcanic systems for the purpose of long-term monitoring and forecast and short-term eruption prediction require large numbers of data-sets from various disciplines. A modern database concept has been developed for managing and analyzing multi-disciplinary volcanological data-sets. The GEOWARN project (choosing the ''Kos–Yali–Nisyros–Tilos volcanic field, Greece'' and the ''Campi Flegrei, Italy'' as test sites) is oriented toward potentially active volcanoes situated in regions of high geodynamic unrest. This article describes the volcanological database of the spatial and temporal data acquired within the GEOWARN project. As a first step, a spatial database embedded in a Geographic Information System (GIS) environment was created. Digital data of different spatial resolution, and time-series data collected at different intervals or periods, were unified in a common, four-dimensional representation of space and time. The database scheme comprises various information layers containing geographic data (e.g. seafloor and land digital elevation model, satellite imagery, anthropogenic structures, land-use), geophysical data (e.g. from active and passive seismicity, gravity, tomography, SAR interferometry, thermal imagery, differential GPS), geological data (e.g. lithology, structural geology, oceanography), and geochemical data (e.g. from hydrothermal fluid chemistry and diffuse degassing features). As a second step based on the presented database, spatial data analysis has been performed using custom-programmed interfaces that execute query scripts resulting in a graphical visualization of data. These query tools were designed and compiled following scenarios of known ''behavior'' patterns of dormant volcanoes and first candidate signs of potential unrest. The spatial database and query approach is intended to facilitate scientific research on volcanic processes and phenomena, and volcanic surveillance.

Keywords: Spatial database; GIS; Volcanic hazards; Data modeling; Query tools

1. Introduction

1.1. The ''GEOWARN'' project

The major aim of the European-funded project GEOWARN was the development of a multimedia-based geo-spatial warning system (a modular web-based

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Atlas Information System) which comprises graphical and numerical geo-spatial data, visualizations, derived satellite images (e.g. infrared thermal imaging), real time monitoring of surface movements (interferometric analysis), seismic activity, heat and gas fluxes and chemical changes in fumarolic gases and hydrothermal waters. The software system consists of a set of customized components that facilitate analysis and visualization of this huge amount of data. Integration of these parameters in a geospatial database has led to development of modeling techniques that are suitable to detect dynamic processes such as reactivation of a quiescent volcano and the occurrence of earthquakes related to fluid pressure changes in magmatic-hydrothermal systems. Deep crustal seismic soundings have provided a regional volcano-tectonic and structural model derived by tomographic processing. All relevant data were set up in a Geographical Information System (GIS).

As is typical for volcanological research, the different data sets have various spatial resolutions and are often collected in diverse time periods. In our database, however, they are unified in a common, four-dimensional data representation in space and time. Despite large differences in data acquired by different methods, groups, and instruments, and over varying time scales, the data-sets nevertheless keep a good degree of accuracy.

During the three and a half year project, the proposed multiparametric approach has been applied to Nisyros (Greece) and to Campi Flegrei (Solfatara volcano, Italy). The volcanological and geochemical differences between the two areas proved the transferability to other active volcanic systems.

1.2. The volcanic field of Kos–Yali–Nisyros–Tilos

The volcanic field of Kos–Yali–Nisyros–Tilos is situated in the Eastern Aegean Sea, part of the Dodecanese archipelago near the Turkish coast (Fig. 1). It belongs to the eastern limb of the Quaternary South Aegean volcanic arc, spanning from Nisyros/Kos via Santorini, Milos, into the Saronic Gulf (Aegina, Poros, Methana, Crommyonia). Magmatic activity in the current arc started about 10 MA as a result of northeastward-directed subduction of the African plate underneath the Eurasian Aegean continental microplate. The volcanic field of Kos–Nisyros constitutes the largest volume of volcanic products in the Aegean Arc.

The unique situation of Nisyros island as a test site can be based on the complexity of the volcanic and related hazards and the increasing impact of tourism on the island. The Nisyros volcano and its hydrothermal craters are visited daily by hundreds of tourists (Fig. 2).

Although the last magmatic eruption on Nisyros dates back at least 15,000 years, the present geodynamic activity encompasses high seismic unrest and widespread fumarolic activity. Violent earthquakes and steam blasts accompanied the most recent hydrothermal eruptions in 1871–1873 and 1887, leaving large craters behind. Mudflows and hydrothermal vapors rich in CO_2 and H_2S were emitted from fracture zones that cut the Nisyros caldera and extend north-northwest through the vicinity of the village of Mandraki into the island of Yali and toward Kos. In 1996 and 1997, seismic activity started with earthquakes up to M 5.5 with hypocenters down to 10 km depth, damaging 30 houses in Mandraki.

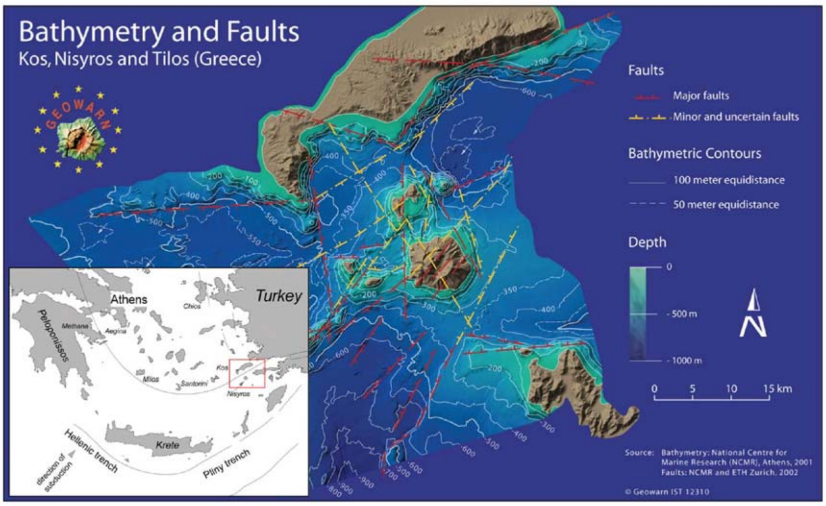

Fig. 1. Nisyros Island and Kos–Nisyros–Tilos volcanic area.

Fig. 2. Stephanos crater, Nisyros caldera.

Five different kinds of natural hazards are possible:

- gas and steam hydrothermal eruptions within the Nisyros crater field;
- seismic activity due to the regional tectonic movements;
- magmato-tectonic seismic activity related to magmatic unrest in the crust;
- a volcanic eruption;
- landslides and Tsunami hazards subsequent to earthquakes, magmatic and volcanic activity.

2. The GEOWARN geo-spatial database concept

2.1. Data management

A well-organized database with accurate procedures of data retrieval can provide the basis for reliable interdisciplinary research in active volcanic environments. The purpose of developing a comprehensive volcanic database concept was to integrate the main data and information that volcanologists typically use when investigating *dormant* volcanoes that may show future unrest. The objectives for the final database were (1) to provide an organized scheme for capturing, storing, editing, and displaying geographically referenced volcanological data and information, (2) to process and analyze spatially distributed data, (3) to support hazard and risk assessment, (4) to create various thematic maps.

2.2. The geo-spatial database design

The GIS database developed in this study contains large sets of volcanological data compilations, regrouped and structured following the *Geodatabase model* (Zeiler, 1999), and based on the GEOWARN researchers' expertise on historical eruptive behavior of dormant volcanoes.

The GEOWARN data types have been structured accordingly and grouped into main information layers. Different schemas of attribute data related to the geographic representation (points, lines, polygons, raster layers) were analyzed and optimized in order to meet the following criteria:

- Provision of a better representation of data to enhance optimal information retrieval and enable designs of complex query and analysis scenarios;
- Diminution of data redundancy;
- Establishment of a good platform for analysis and correlation for the highly heterogeneous data;
- Support the data for the modular web-based atlas information system.

The general database archive composition is shown in Fig. 3. Three main parts can be distinguished: *attribute data*, *geometric vector and raster data layers*, and *cartographic data*. These are complemented by supplementary data consisting of descriptions, audiovisual material, field orientation sketches, literature references, links, and others.

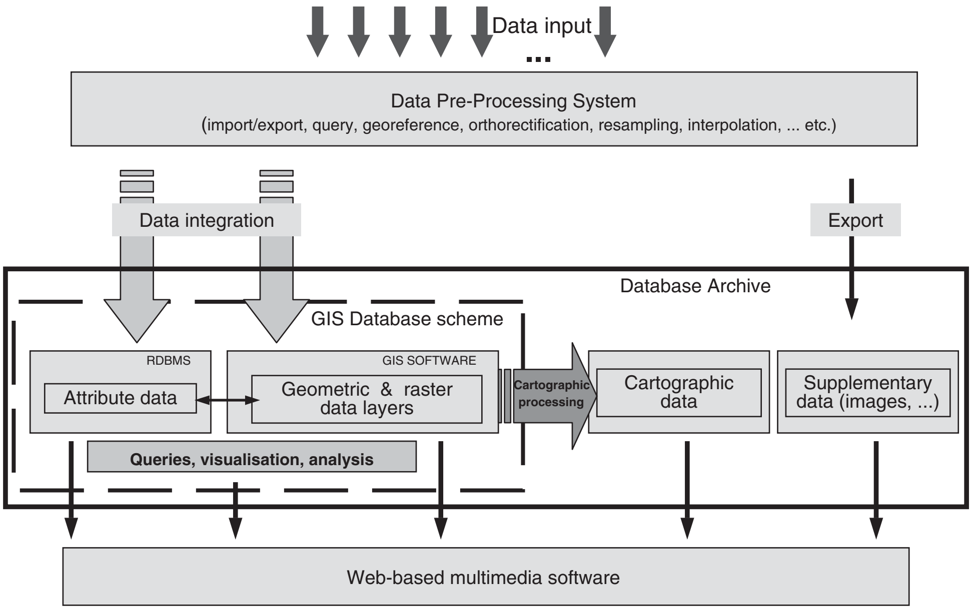

Fig. 3. Overview on data-flow and data-organization system.

2.3. The layers

A simplified version of the database layers and its content for the Kos–Yali–Nisyros–Tilos volcanic field is shown in Table 1. The information is divided into several groups. Each group of data is composed of one or several layers and optional additional data.

The *Topography* group contains topographical features as class layers, such as contour lines, roads, buildings, churches, etc. *Land-use* consists of a single polygon layer and a simple related attribute table describing the land-use characteristics. The *digital elevation models* (DEM) group local and regional models of different resolutions. The DEM for Kos, Yali, and Tilos islands were acquired using the topographical paper maps of a scale of 1:50,000 of the Hellenic Military Topographic service. For Nisyros island, a 2 m cell size DEM was produced using paper maps of the same source of scale 1:5000. The procedure of deriving the land DEM is described by Vassilopoulou et al. (2002). The regional DEM including the bathymetry data was produced by the National Center of Marine Research of Greece after several data acquisition cruises during the year 2000.

The *Geology* group comprises the geological maps of the studied area. *Volcanological structure* regroups simple lithological units, tectonic structural features (faults, cracks, fissures), fissures with fumarolic or effusive phenomena, eroded fissures, and the crater rims. They are modeled by polygons and lines with an attached attribute table. Tectonic features of the regional Kos–Yali–Nisyros–Tilos volcanic field and Nisyros island, together with the lithologic units, are represented within the *Tectonic* group. *Neotectonic* data, based on the regional tectonic map, regroups morphotectonic features (landslides, rock-falls, debris) and active tectonic features (active faults, cracks, and others).

Seismic data are represented by three distinct layers of information: position of the local seismic stations during the project period (2000–2002), hypocenters of a magnitude $M<4.0$ registered during the project period (2000–2002), and historical hypocenters (1911–2003) of important regional earthquakes with magnitudes $M>3.0$.

Gravity and magnetic data are both structured in a similar way: a point layer relates to a table where their coordinates are specified, the date and time, and the corresponding gravity or magnetic value registered at each station. The raster grid data-sets derived by interpolation from the above mentioned layers of points, representing Bouguer anomaly and magnetic data, respectively, are also stored in the database.

Earth's *Density* was derived from Bouguer gravity data constraining the density values by the registered *Vp* velocities as well as using the Nafe–Drake curves for sediments and the Birch empirical functions for the crust and the upper mantle (Makris et al., 2001). It contains three groups of information: the three-dimensional density model, a set of equal velocity surfaces as grids characterizing the interpreted limits between the various rock type units, and the interpreted density cross-sections.

Table 1
Simplified version of database schema content for Nisyros–Kos–Tilos (Greece) volcanic area (main layers)

	Group of data	Characteristics represented	Details
1	Topography	Topographical map	
2	Land-use	The land-use map	
3	Digital elevation models	Digital elevation models—regional and local	
4	Geology (*Geology & Volcanology*)	Geological maps of the areas of interest	
		Sea floor geological map	
		Geological cross-sections	
5	Volcanological structure	Fumarolic fissures, flow structure features, crater rims	
6	Tectonic	Lithologic units, tectonic features	
7	Neotectonic	Morphotectonic features (landslides, rock-falls, debris), active tectonic features (active fault, cracks, …)	
8	Seismic	Position of seismic stations	
		Regional hypocenters of $M<4.0$ (link to seismic stations)	
		Historical hypocentres $M \geqslant 4.0$	
9	Gravity	Location of the gravimetric stations + measurement points on land and sea	
		Grid of interpolated gravity	
10	Density	Three-dimensional voxel density cube—not in GIS (model output)	ASCII file
		Surfaces, delineating the rock types (equal velocity values) interpolated from the model output	
		Cross-sections of density model	
11	Magnetic	Location of the magnetic stations + measurement points on land and sea	
		Grid of interpolated magnetic values	
12	Velocity model	Cross-sections of velocity model	
13	Tomography	Three-dimensional voxel tomography cube—not in GIS (model output)	ASCII file
		Surfaces, delineating rock types (equal velocity values)	
		Cross-sections of tomographic model	
14	Technological data	Ship tracks, shooting points, active seismic stations (land, sea)	
15	Degassing process	CO_2 flux, heat flux, soil temperature—measured and processed	
16	Geochemistry	Geochemical measurement points (geothermal wells, springs, gas emissions, …)	
17	GPS	Location of the GPS stations—link to measured and computed displacements	
18	Thermal	Ground temperatures—points (used in thermal images calibration)	
		LANDSAT and ASTER thermal images and surface temperature differences derived from LANDSAT	
19	Interferometric	Interferograms	ERDAS raster dataset
20	Satellite image	Satellite image—orthorectified	IKONOS—1 m resolution
21	Weather	Weather parameters measurements	

Geometric features and attribute table.
Point features and attribute scheme.
Point features and attribute table.
Line features and images for each cross-section.
Line features and attribute table.
Grids (raster data)—various resolutions.
Geometric features and attribute scheme.

The seismic *Velocity model* is represented by various cross-sections (images) linked to a layer of lines that follow the surface trace directions of the cross-sections. The tomographic data is represented within the group of layers called *Tomography*. Even though it is not directly accessed by the GIS software, the derived tomographic three-dimensional model cube is also a part of the database. Surfaces of equal velocity (horizontal and vertical cross-sections) can automatically be derived as a set of grids, for instance, representing the interpreted limits between the various geological units (e.g. soft sediments, magmatic rocks, etc.). Interpreted tomographic cross-sections are also represented as images, linked to a layer of surface traces.

Technological data includes the seismic station locations on land and on the seafloor (ocean bottom seismographs), as well as the shooting points and ship tracks for the active seismicity experiments. This group provides information about the geophysical campaigns performed within the Kos–Yali–Nisyros–Tilos volcanic field in 1997 and 2000 as part of the GEOWARN project.

Degassing process refers to data resulting from the study of diffuse degassing at the southern Lakki plain (within the Nisyros caldera), and Stephanos hydothermal crater in particular. The main goals of the study of diffuse degassing processes in hydrothermal areas are both the mapping of the process and the computation of the amounts of gas and energy released. The diffuse degassing measurements at Stephanos crater were performed during several field campaigns between 1997 and 2003. Each campaign consisted of the direct measurement of CO_2 flux by the accumulation chamber method (Chiodini et al., 1998), heat flux (conducting plate method (Geowarn, 2003)), and soil temperature in about 80–100 temporary measuring stations regularly arranged in a rectangular grid of 20 m cell width. Systematic CO_2 flux and soil temperature measurements covering the southern Lakki plain were performed during 1997–2003. About 2900 measuring sites consistently covered the area. A Sequential Gaussian simulation was applied to soil flux data (gas and heat) and soil temperature data, respectively (Brombach et al., 2001). Modeling the degassing process affecting the Lakki plain was performed in order to derive a detailed map of CO_2 soil degassing of this area. The resulting grid was integrated into the spatial database. At Stephanos crater, several grids were derived, each of them corresponding to one measurement campaign (nine campaigns during 1997–2003).

Geochemistry is a group of layers representing almost all point features with time-dependent geochemical information: fumaroles, springs, geothermal wells, and wells. Each type of feature has its layer, and the point features are linked to an attribute scheme. The attribute scheme of each entity differs slightly from each other. In Fig. 4, the scheme for geothermal springs is shown as an example. *Geothermal springs* is the main table where the scheme is linked to the geographical location of the point in the GIS software. The relationships "*one to one*" and "*one to many*" between the *Geothermal springs* table and the connected tables are defined using the same indicator. As shown in Fig. 4, the table *Geothermal springs* contains information concerning the geographical position (coordinates), type of represented entity, name (or official names), system of codes (used by several experts in order to identify the entity), altitude, locality (description in words), and remarks. The local geology of a geochemical sampling site is described within the *Geology* table. Note that rock chemistry is not included in the *Geochemistry* group since it contains data of static nature with respect to time scales of the monitoring activities and is therefore included in the *Geology* table. The *Sample* table is designated for registering individual water or gas samples. The *Parameters* table contains time-dependent data series for various physical parameters (temperature, pH, and others) and chemical composition parameters (including isotope data). The number of geochemical parameters is relatively large compared to the physical ones due to their extensive analytical data, although the number of entries (samples) is smaller. Among the geochemical parameters, gaseous samples and aqueous samples differ slightly in terms of their list of parameters; similarly, well parameters differ slightly from spring parameters.

GPS represents geodetic measurements using *Global Positioning System* with horizontal (X, Y) and altitude (Z) data. The main reference layer of points is made up of GPS station locations from the first establishment of the network (June 1997). Two tables are related to this table, both following a "*one to many*" relationship. The first one contains horizontal (X, Y) and altitude measurements at various campaign dates, and the second table contains horizontal, azimuthal and vertical displacements between different campaigns. Related estimates of horizontal and vertical standard deviations of each set of values are attached as well.

The *Thermal* group contains three sets of raster grids representing the thermal images acquired by the LANDSAT satellite system, the grids of surface temperature differences between the satellite passes (derived from LANDSAT 7 ETM), and the thermal images recorded by the ASTER satellite system. Both sets of thermal grids (LANDSAT and ASTER) were acquired at different dates (day and night time), orthorectified, and corrected for atmospheric influences. In addition, all satellite thermal images were corrected by measuring soil temperatures at specific points and various depths (2, 4, 7, and 10 cm) at the time of the satellite overpass.

The images resulting from the application of interferometric synthetic aperture radar (InSAR) are part of the *Interferometric* group. This technique was applied to study the regional deformation of the island in conjunction with GPS measurements and morphological corrections using the orthorectified DEM. Two interferograms of Nisyros island are currently in the database. They cover the 1996–1999 and the 1999–2000 time periods.

The *satellite image* layer contains a satellite image of Nisyros island with 1 m resolution. The image taken by the IKONOS satellite was orthorectified using the before

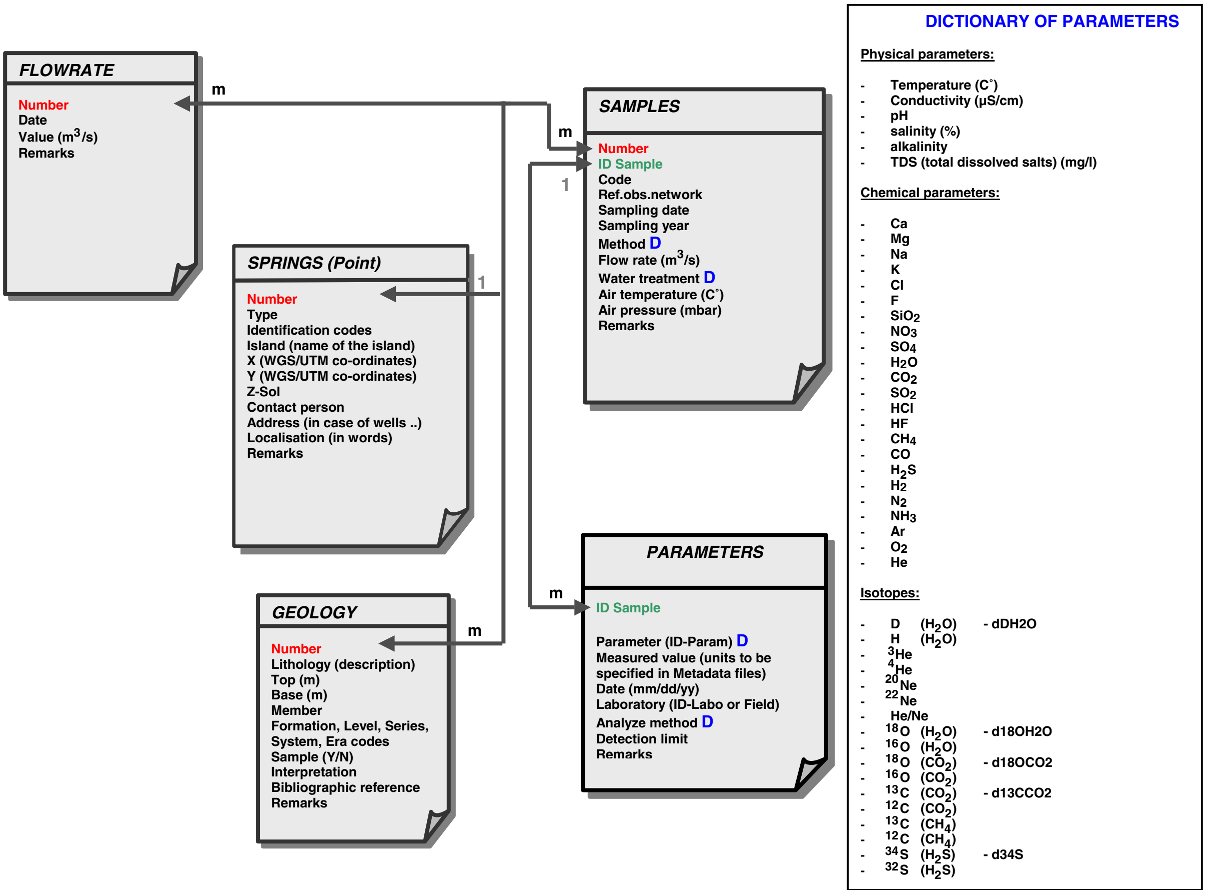

Fig. 4. Simplified version of attribute data schema for *Geothermal springs*.

mentioned 2 m cell size DEM. The entire orthorectification procedure has been described in Vassilopoulou et al. (2002).

Meteorological data are embodied within the *Weather* group. The only deployed weather station, represented as a point, is linked to tables where time-dependent data is registered. The collected weather parameters are air temperature, humidity, atmospheric pressure, wind speed, and a brief weather description. The acquired data cover the GEOWARN project duration (2000–2003).

2.4. Technical aspects: data types, coordinates, metadata, and software

After the database schema has been developed and its layers have been defined, it has to be optimized. A thorough analysis of the existing, expected and incoming data types and formats, as well as data quantity and quality, is an important consideration to ensure an optimal data representation in a volcanological database.

To compare and correlate spatial data-sets, the entire set of data for a particular volcanic field must use a single coordinate system. In the case of the "GEOWARN early warning system", the national Hellenic reference system (HGRS 87) was used for the pilot site in Greece.

One concern in the database design was the inevitable simplification of data-sets. This is necessary in order to achieve maximum information retrieval, while attempting not to lose data resolution or precision. The inclusion of error estimations for some time-series data was thus necessary to allow for the distinction between artifacts, noise, and "real" deviations from background data trends that may represent a change in subsurface processes.

A useful method for metadata generation is to follow widely accepted standards. For the described data-sets, we adopted the US Federal Geographic Committee's Content Standard for Digital Geospatial Metadata (FGDC). The chosen GIS software offers tools to comfortably handle metadata using this standard. This standard was customized according to the individual projects needs and requirements.

As a software solution, ArcGIS-Arc/Info^{TM} 8.1. (Zeiler, 1999) embedding MS Access^{TM} (Microsoft) was considered satisfactory for expert-level GIS operability of the database. The database itself can easily be transferred to other database systems (e.g. Oracle^{TM}). MS Access was chosen simply for its wide distribution and low cost. It soon appeared necessary to combine the main GIS package (GIS expert software and the access—Relational Database Management System) with complementary software and to develop new data exchange interfaces (Hurni et al., 2004). This arises from the broad requirements of general user skills, uses, and needs encountered in volcano observatories.

3. Examples of visualization, and spatial analysis

Spatial analysis is feasible once the database is established. The needs and knowledge of volcano monitoring activities define the types of query, visualization and data analysis tools required. Much of this depends on the monitoring tasks and technical capabilities of volcano observatories. However, personnel, access, usage and knowledge base to design, program, customize and operate query strategies and tools on large relational databases in an GIS environment is to date still a rare occurrence. GIS technology is still used mainly to generate maps.

3.1. Crustal structure and tomography

In the GEOWARN project, scientific query interfaces were designed and implemented following different query scenarios. These query scenarios are currently used for deductions from the data sets and for the purpose of visualization. For example, various analyses of the DEM, of seismic data represented by the locations of the hypocenters, and of the three-dimensional tomography were done using the ArcScene^{TM} module (ArcGIS^{TM} software package). As a result, the relation between the calculated hypocenters and the tomographic model of the underground has been generated (Fig. 5). It gives an overview of the greater Yali–Nisyros volcanic field represented by the DEM (view to north, Kos island in the background), the subsurface crustal structure (iso-velocity surfaces of unconsolidated volcanoclastic sediments, the deeper metamorphic rock formations, and magmatic intrusive bodies), and the earthquake hypocenters registered during 2001 with a magnitude <4. Clearly, both the tomographic results and the earthquake hypocenters testify geodynamic activity concentrated underneath Nisyros island.

Similar query interfaces allowing for data manipulation, analysis and visualization are

- earthquake hypocenter queries in time and space (3.2),
- a grid analysis tool for diffuse soil degassing and heat flux data (3.3),
- and query interfaces for analyzing geochemical data (3.4).

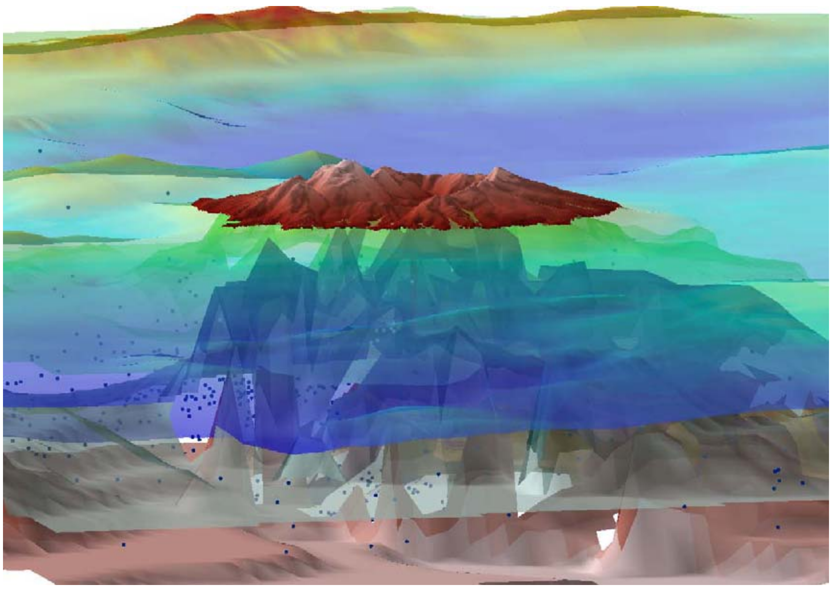

Fig. 5. Visual correlation between calculated hypocenters and interpreted limits between various geological strata resulting from tomographic model.

3.2. Earthquake hypocenters in time and space

A tool was developed for queries of earthquake hypocenters in time and space. Used in the ArcScene™ module, it allows temporal and spatial (x, y, and depth) dependent queries on point features. The tool is specifically designed to assist the analysis of earthquake hypocenters. However, it also allows 3D time-dependent animations. The script operates in the background by sequentially selecting and then displaying the points using a customizable time-step (day, hour).

3.3. Grids of the temperature, diffuse soil degassing, and heat flux

To achieve a better representation for grids of the temperature, diffuse soil degassing, and heat flux datasets, several interpolation procedures were tested. One example is given in Fig. 6. It shows an approximate image of the apparent CO_2 flux distribution of the southern part of the Nisyros caldera. The resulting multi-dimensional grid represents the CO_2 flux values as heights and the temperatures as colors. The orthorectified satellite image of Nisyros Island is overlaid on the DEM and serves as a spatial reference. Temperature or CO_2 flux values can be queried simply by selecting any point on the grid with the cursor.

3.4. Time series of physical and chemical monitored parameters

Time series consisting of physical and chemical parameters related to fumaroles, springs, geothermal wells, and wells can easily be retrieved, visualized, statistically treated, and displayed on charts.

Query interfaces for analyzing geochemical data were programmed using the Visual Basic and SQL programming languages as well as the Arc/Object™ library (Object-Oriented modules library, by ESRI). These query tools complete and combine the existing GIS package functions. The tools were designed to query, display, calculate time-dependent statistics, and show graphs of the physical and chemical parameters related to volcanic point features such as springs and fumaroles. Fig. 7 shows the H_2S variation measured during August 02, 1997 and January 02, 2002 at a fumarole coded as PP9N ("Polyvotes Micros" hydrothermal crater). Minimum, maximum, mean, and the standard deviation for the selected period is automatically computed and displayed. These tools can be used to process and display time series data related to other geometric entities (line or polygon) representing other features (faults, fractures, etc). For instance, if separate overlapping consecutive grids of diffuse degassing campaigns are considered, a time series of individual CO_2 flux

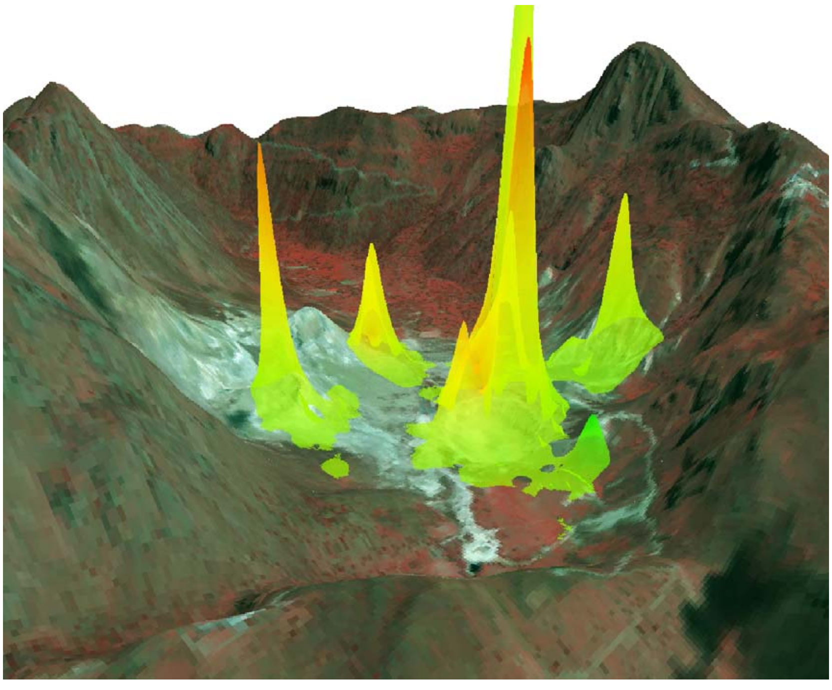

Fig. 6. Three-dimensional representation of exuded CO_2 flux distribution in Nisyros caldera. Heights represent modeled CO_2 grid flux values and colors represent temperature.

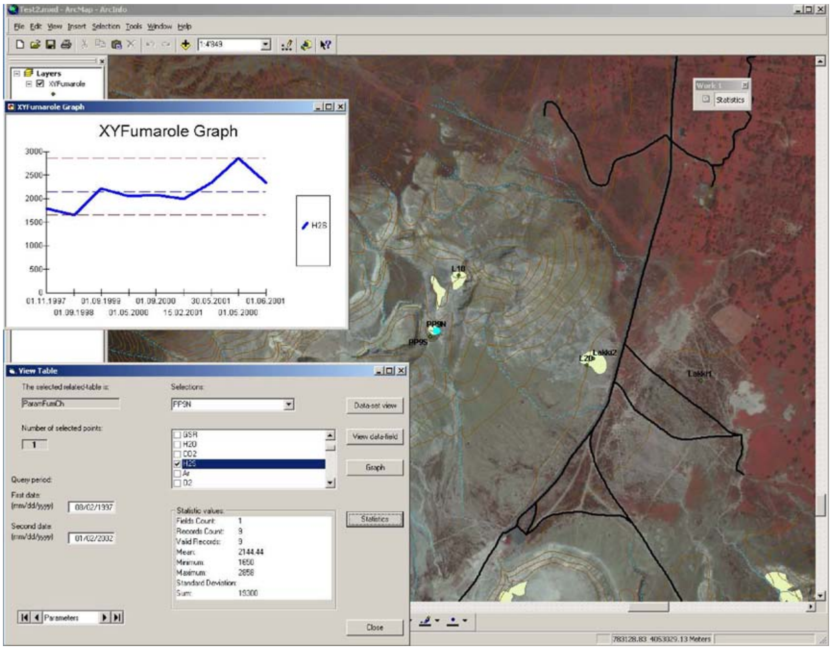

Fig. 7. Spatial database query menu for fumaroles chemical parameters.

values can be computed at any given point location within the areal coverage of these grids.

3.5. Hazard assessment

Quantification of volcanic and related hazards can easily be derived. The slope stability map (Fig. 8) demonstrates a complex example, which has been derived following an overlay and indexing method. The method combines the classified slopes, the geotechnical behavior of lava flows and unconsolidated pyroclastic rocks as well as steep cliffs of loose rock material in order to delineate zones of fragile stability.

Power lines, streets and settlements may show an increased vulnerability due to a highly exposed position in a valley that would serve as the transport bed for a rock fall event, as could be triggered by increased local earthquake activity.

4. Discussion

The following chapter is devoted to the problems that have arisen during the three-year GEOWARN project in particular, during the design of the GIS database handling complex data provided by all partners of different scientific fields and from different European countries. In addition, a new development has been undertaken, the programming of user-friendly, web-based multimedia software. The design and programming of these interfaces required continuous communication, the use and understanding of a common "scientific" language, and the full understanding of the entire GEOWARN work and its final goals among volcanologists, geophysicists, geochemists, cartographic designers, GIS specialists, and informatic engineers.

4.1. DEM of volcanic landscapes

Any volcanic environment shows major differences in morphology. The volcanic landscape exhibits various landforms created by a variety of eruptive scenarios and any subsequent erosional processes. These processes generate specific landforms that have to be reproduced with accuracy by the DEM. As a consequence, the operator creating the DEM of a volcanic landscape has to understand the geomorphology of a volcanic environment to be able to interpret singularities, heights, depressions, steep escarpments and fractures that could appear to the unwary operator. Vents, collapsed flanks, domes, necks, spines, lava and pyroclastic flows, ash and pumice deposits generated during eruptive phases, as well as craters and large calderas and their erosional products, could appear as DEM errors for an unskilled operator. To better discriminate the volcanic landscape singularities from possible modeling errors, a careful examination of the DEM versus volcanic and other geomorphological features is necessary. Furthermore, a good knowledge of the specific volcanic field, careful field examinations, and an interpretation of existing

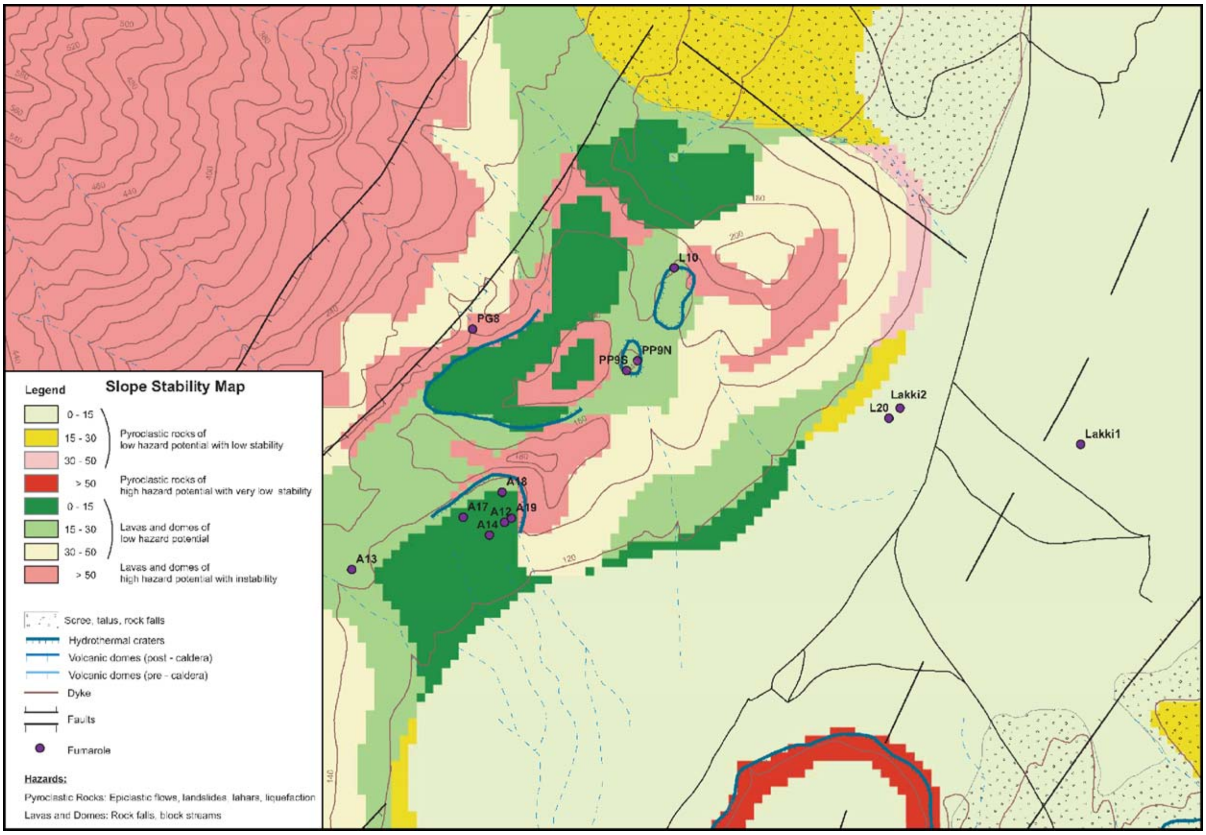

Fig. 8. Slope stability map of Nisyros island derived by performing an overlay and index method on spatial database (as a combination of GIS based functions).

geological maps are essential prior to the creation of a DEM.

4.2. Data modeling

A data model represents a methodical approach to classify information and their relationships. A geographic data model represents the real GIS world in order to create maps, perform queries, and support analysis. It is the basis for modeling the system behavior describing how the various features of the landscape interact with each other.

Within the GEOWARN project, it was necessary to generate an appropriate way to explain data-modeling issues to all scientific experts. Because of the myriad of volcanological, geophysical, geodetic, and geochemical monitoring procedures, this task helped in finding a proper common language necessary for optimizing the data representation.

Finding an optimal spatial and temporal database representation for various phenomena is essential. The solution to this task is not obvious, when dealing with complex features like volcanic fumaroles or thermal springs. Fumaroles, vents from which volcanic gases (like sulfur vapor) escape, can occur along small cracks or long fissures. At the land surface, they show a frequent displacement in time, because soil fills some of the vents while others open at the same time. Scientists are sampling the fumaroles belonging to the same field but coding differently various superficial soil holes. Following their experience, they will identify easily the samples belonging to the corresponding location. Representing this within a spatial database needs a clear understanding of the phenomena and of the field, as well as the sampling procedures and measured parameters of various research teams.

4.3. Visualization of seismic data and test tomographic models

Data visualization allows surveying data quality and avoids unfitting between data delivery and database capture. To recognize data errors, data visualization has to include time and spatial data query facilities. For data related to the location of hypocenters of earthquakes, a three-dimensional visualization within the GIS package

(ArcScene) offered a good understanding of the seismic phenomena and avoided in several cases, error propagation. The visualization procedure enabled the three-dimensional hypocentres to be observed from various angles, simultaneously with the geology, tomography, gravity, and magnetic models.

5. Conclusions

The GEOWARN GIS database offers capabilities for data modeling as well as for other volcanic studies, such as

- *Data verification and validation,* essential for accurate and precise data representation. Using an advanced database supported by GIS, these operations can be done in a simple way. For example, anomalies in chemical time-series data for fumaroles, springs, and geothermal wells can be inspected on graphs as a result of a query.
- *Automatic data treatment* is required before input to any process-based model and for data to be stored from continuous data streams. Because of the huge amount of work required to prepare the data used by various modeling procedures, a GIS-supported database is absolutely essential.
- *Maps of various parameters* can be generated. Paper and screen maps, as well as other graphical spatial screen representations (e.g. four-dimensional-animations of data correlations) can be created starting from existing point data using statistical procedures (including geostatistics) supported by the GIS software. Anomalies indicating unrest in volcanic behavior can be detected using these maps.
- *Correlations among parameters* can be detected and displayed using programmed interfaces or already existing GIS software procedures. For instance, geochemical parameters, lithology, morphotectonic features, and hypocenters distribution can be compared.
- Using the entire set of spatial data and having the described tools available "at a mouse click", the user is able to have a *complete view of the entire data-set*.

The database described in this paper is an integral part of the GEOWARN project, a pilot study of geospatial data management of dormant volcanoes. It still has certain limitations, which were considered in the previous sections. Changes, updates, or further developments of the schema are expected to be incorporated in the future. Furthermore, experts using only a Relational Database Management System (RDBMS) in the absence of a GIS tool can handle the attribute data.

Starting from this schema, new developments have been undertaken. One of them consists of web-based cartographic multimedia software having GIS tools, designed for spatio-temporal volcanological data analysis (interactive maps, stations, and time-dependent data-series; Hurni et al., 2004). This "GEOWARN software" accesses the described database.

6. Outlook

A comprehensive geo-spatial database concept for data management of dormant volcanoes is still lacking in the daily operations in many observatories. Such a concept should be the very basis for any analysis and visualization efforts that help observatory scientists to extract the most out of their data in times of crisis, and for scientific work for the purpose of expanding the body of scientific process knowledge. Efforts are currently under way by IAVCEI to accelerate the process of implementing such improvements in individual observatories (the "bottom-up" approach) by creating a world-wide standard for a database structure of volcanic unrest (Venezky et al., 2002).

The volcanological geo-spatial database presented here gives volcanologists a modern and versatile research tool. Query, visualization, and analysis tools such as the ones presented here are useful for other observatories. Furthermore, observatories facing a volcanic crisis can easily store, share, visualize, correlate, and analyze various sets of monitoring data in space and time. GEOWARN represents an important step toward more efficient integrated monitoring and hazard assessment procedures for potentially active volcanoes.

Acknowledgments

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Web Based Information System for Natural Hazard Analysis in an Alpine Valley

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Abstract

A platform for geospatial hazard and risk information system, comprising graphical and numerical geospatial data, aerial and satellite images, georeferenced thematic data, and real time monitoring feeds is being developed by the Research Network on Natural Hazards at ETH Zurich (HazNETH). It will allow researchers to build efficient systems for handling, pre-processing, and analysing the existing large and variable datasets from different natural hazard phenomena as well as different natural environments in the Swiss region. The final product will be a geospatial hazard information system.

Three main steps will be followed in order to create this information system: the spatial database development, an integrated hazard procedure design, and a web enabled data query and visualisation tool set. The geospatial database including the entire set of natural hazards phenomena occurring in an alpine valley will offer a platform to study existing hazard assessment methods and will allow the analysis and combination of various hazard parameters in relationship to phenomena. The final application based on the concept of Atlas Information Systems (AIS), will be used as an additional tool for risk and emergency assessment as well as for planning and decision making purposes.

1 Introduction

Switzerland has always been exposed to a wide variety of natural hazards happening most frequently in its alpine valleys (Fig.1). Recent events, such as those which occurred in Canton Wallis in October 2000 and included floods, debris flows and slope instabilities, or avalanches in February 1999, led to substantial loss of life and damage to property, infrastructure, cultural heritage and environment. Thus the need for an integrated natural hazard management and sustainable hazard prevention culture became obvious. Methods were developed and improved to identify areas affected by natural hazards, and parameters allowing quantifying static and dynamic impacts on structures in these areas were defined.

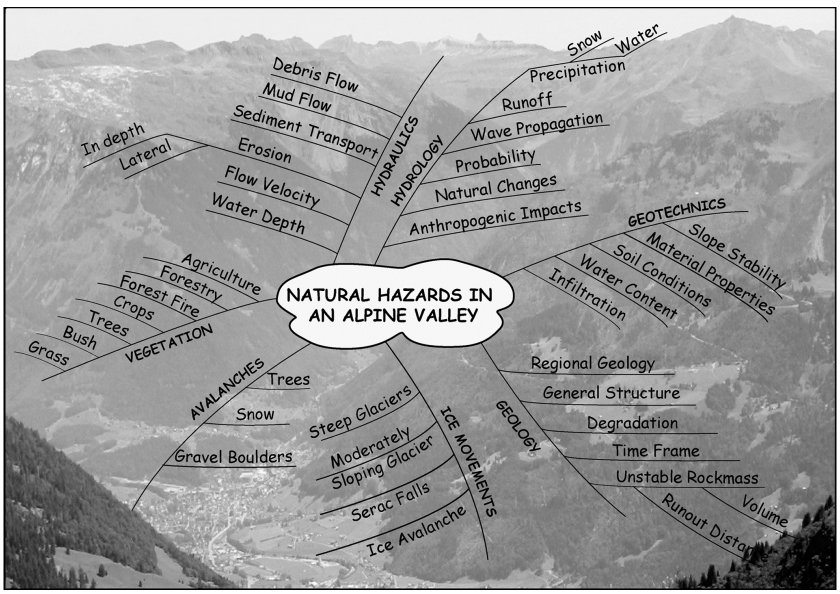

Fig. 1 *A synthesis of different phenomena acting as natural hazards in an alpine valley*

HazNETH is the Research Network on Natural Hazards at ETH Zurich and combines the expertise of several partner institutes: Atmospheric Physics, Climatology, Hydrology, Hydraulic Engineering, Water Management, Risk Engineering, Construction Engineering, Forest Engineering, Engineering Geology, Geotechnics, Seismology, Geodynamics, Geodesy, Cartography, Environmental Social Sciences, and Economics. HazNETH provides a platform for trans-disciplinary projects focusing on natural hazard research. It contributes to the improvement of methods and tools for integral risk management as a base for sustainable development.

The HazNETH project intends to develop a web browser enabled geospatial hazard information system (Fig. 2), which allows the project partners to share and analyse their datasets (HazTool). Apart from standard GIS functionalities, the system will provide expert analysis tools which are tailored specifically to the needs of interdisciplinary hazard research. Technically the system will be implemented as a multi-tier architecture: Internet client, application server with web server and spatial engine, and spatially enabled database.

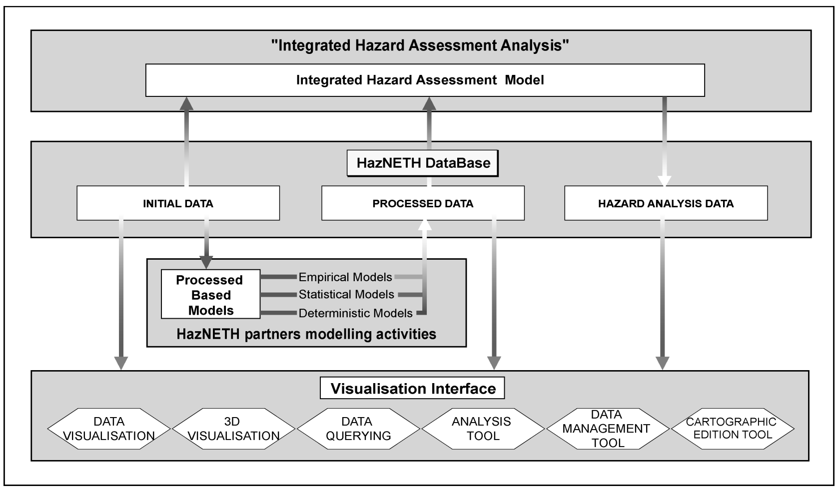

Fig. 2. The general scheme of the HazTool system

Apart from scientists, who are experts in their field, HazTool should also be used by decision makers such as emergency organizations, public authorities, and politicians. This requires a very flexible graphical user interface which lives up to the needs of the various user groups and allows the administrator to set different levels of access to the information. Experience with information systems or GIS expertise should not be a prerequisite for using HazTool as long the user is adept in the field of hazard research or management. It is the concept of the Atlas Information System (AIS), explained in Sect. 2.3, which will guide the design of such an "intuitive" user interface. Analysis results will be depicted in interactive two and three dimensional presentations and in time series, which allow the user to visually grasp correlations between different types of information.

Building on the comprehensive information in the HazTool database, the project partners will be able to evaluate existing hazard assessment methods, to improve them, or to even discover new methods.

2 Geospatial System for Data Management, Modelling, Visualisation, and Analysis (HazTool)

The conception and development of a web based information system for natural hazard analysis is carried out at the Institute of Cartography of the Swiss Federal Institute of Technology in Zurich (ETHZ). It is based on research in the following three areas:

1. The design of a database concept as a basis for analysis and natural hazard assessment method deduction (Sect. 2.1).
2. The development of integrated natural hazard assessment methods and data modelling tools (Sect. 2.2).
3. The creation of specific hazard analysis tools for interdisciplinary research as well as for specific research needs of particular partners (Sect. 2.3).

The following paragraphs describe the research goals and tasks that have to be completed in the above named research areas. The significance of the performed research for the development of HazTool is highlighted and the resulting technical implementation concept of HazTool (Sect. 2.4) is described.

2.1 Database Concept Design

Intensive cooperation between the project partners is a prerequisite for designing a common research platform. This implies that each partner contributes his datasets and knowledge to identify research foci. For this purpose each HazNETH partner delegated one or more responsible persons who discussed the natural hazards to be considered as relevant for Switzerland, as well as each partner’s research interests and suggestions on how to map hazard related phenomena in a database. The parameters relevant to monitor each natural hazard phenomenon were identified and grouped thematically and known relationships between phenomena were documented.

Information gathered for natural hazards research is complex. Apart from managing very large interrelated datasets of different scale and spatial extent, important issues of combining hazards and their effects have to be solved. A well thought-out database concept and implementation will provide the basis for deriving new hazard assessment methods from intrinsic interactions between the studied hazards. Methods of quantifying hazard parameters as well as the uncertainty of such methods and of the datasets themselves have to be taken into account when designing the database concept.

2.1.1 Data Collection on Three Spatial Scales

Depending on the spatial extent and local distribution of natural hazard phenomena three spatial scales of data collection and analysis were identified (Fig. 3):

- General Level: Switzerland (country)
- Regional Level: Wallis (river basin)
- Local Level: (alpine valley)

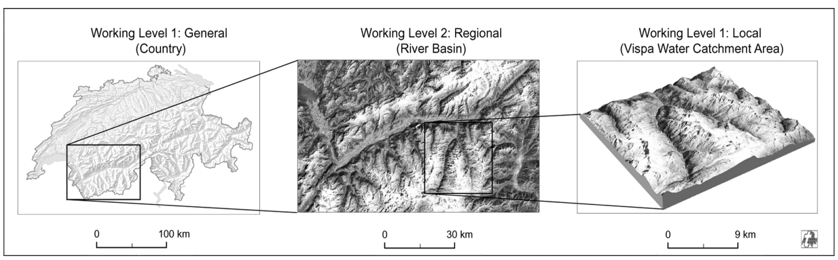

Fig. 3. Different spatial scales of data collection and analysis

The Local level (alpine valley) is targeting natural hazard phenomena occurring at a local level including landslides, torrent streams, debris flows, glaciers hazard events, etc. The datasets for this level were generally sampled at a higher resolution than for the other two levels.

The Regional Level datasets were collected for an entire hydrological system, a river basin, which roughly corresponds to the administrative boundaries of Swiss Canton Wallis plus the areas that are not part of Canton Wallis but belong to the river basin. The research focus on the regional level is directed towards natural hazards that concern the whole river basin (e.g. floods). The resolution of the collected datasets is generally lower than at the local level.

The General (country) level covers the administrative boundaries of Switzerland and to some extent the neighbouring countries taking into account that natural phenomena do not respect manmade administrative boundaries. Phenomena like earthquakes or other various tectonic phenomena are observed and analysed on such a scale.

2.1.2 Dataset Description

The information collected in the HazNETH project consists in geological, hydrological, geomorphologic, soil, climate, land use, and anthropogenic parameters and their geometry. Topological, photogrammetric, and geological information acquired from other organisations (e.g. SwissTopo, Natural Hazard Office of Canton Wallis) complement the datasets used with HazTool. The database concept requires these datasets to be organised thematically.

The datasets will be available to the project partners at different stages of processing: raw data, processed data, and project generated hazard data. Raw data is obtained through scientific measurements; processed data is received when applying different calibration and modelling procedures (process based, statistical, or empirical) of phenomena analysis to raw data. This step will be chiefly performed by each project partner with their specific modelling software. The treated datasets will then be made available to the other HazNETH partners in the database. The project generated hazard data regroups the results (maps or other output types) obtained through applying various hazard quantification methods. This group of datasets may be persistently stored and not generated by HazTool on-the-fly for reasons of system performance or lack of functionality integration into the system. At the current stage the raw data was structured and has been processed to some extent.

2.1.3 Data Models

In order to set up the database several data models were analysed. The task was to design a data model that takes into account the special features of natural hazards of Switzerland, while permitting to direct the research focus at the beginning of the project on alpine valleys. This was a logical consequence of the completeness and detail of available datasets of the local research area (Vispertal including Saastal und Mattertal). It was also decided to direct research attention during the first two years of project duration primarily on the phenomena of torrent streams and debris flow.

Experience gathered during a similar project carried out at the Institute of Cartography of ETH Zurich (the GEOWARN project, Hurni et al. 2004) influenced the design of the database concept. Two other data models constituted sources of inspiration for the design process: ArcHydro data model developed by ESRI (Maidment 2002) for managing surface water resources and HYGES (Gogu et al. 2001) developed by University of Liege for managing groundwater resources.

The ESRI ArcHydro Data Model is used to restructure the base surface hydrology data to study torrent streams and debris flow phenomena. Using the ArcHydro data model with ESRI ArcGIS, it is possible to extract different themes from hydrological data (Maidment 2002): *Network (*showing pathways and waterflow), *Drainage* (drainage areas and stream lines), *Channel* (three dimensional representations of river and channel shapes) and *Hydrography* (hydrographic features as found on topographic maps).

The ESRI ArcHydro Data Model has to be customized to the needs of the HazNETH project. Significant modifications are the adoption of a river cross section database scheme of the Swiss Federal Office for Water and Geology, the addition of a *Sedimentology* layer representing sediment volumes showing a potential to be eroded, relevant characteristics of *soil composition* (describing the soil layers, the ground covering, and the grain size distribution), and the addition of the *Ground covering layer* storing parameters like land roughness and erosion threshold.

2.2 Development of Integrated Natural Hazard Assessment Methods

Another research area deals with studying qualitative and quantitative hazard assessment for interrelated phenomena. The focus resides also with torrent streams and debris flows including related hazards such as soil and rock mass movements, and flood hazards. The main objective is to develop the scientific framework to derive new methods for integrated assessment of natural hazards in alpine valleys. Furthermore, a method of analyzing the input data uncertainty as well as the sensibility of spatial analysis reflected in hazard assessment procedures will be developed. Further details concerning this research area will be described in a different paper.

2.3 Web Based Information System for Natural Hazard Analysis

In order to create appropriate hazard analysis tools, an initial step was to organise several bilateral interviews and surveys with the various HazNETH partners. The following list describes the characteristics of the user groups identified during the interviews:

- The HazNETH partners: mostly experienced scientists with good GIS knowledge; their main interest is to combine their own information with the partners' information; they need access to all datasets with unlimited download/upload possibilities.
- The "Section dangers naturels" (Natural Hazard Office of Canton Wallis) and "Section des routes et des cours d'eau" (Division of Roads and Rivers of Canton Wallis): field specialists who work with the local council and natural hazards engineering companies for risk assessment; one of their main interest is to consult the HazTool system in order to manage their building planning permissions; they need access to all datasets with visualisation/download permissions.
- Guest users: interested persons who will only be granted limited visualisation permissions.

Based on the aforementioned discussions with the project partners, general objectives and priorities for the system were defined. The needs of the different user groups with none to expert experience in using computer systems need to be satisfied. Therefore, an easy to manipulate user interface should be designed to facilitate access to information, visualisation and to the use of analysis tools. The concept of the Atlas Information Systems (AIS) is suitable to guide the design of such a user-friendly system since AIS are state of the art for visualising and analysing predefined thematic collections of spatial data. They can be defined as "computerized geographic information systems related to a certain area or theme in conjunction with a given purpose – with an additional narrative faculty, in which maps play a dominant role" (Ormeling 1995, Van Elzakker 1993). The major difference to established Geographical Information Systems (GIS) is their ease of use and their cartographic quality.

Two other system priorities are on-the-fly creation of high quality web maps and integration of real-time data. Additional optional objectives are three dimensional modelling and cross-section/volume visualisation of phenomena, as well as the ability to support modelling of standard decision chains of users (agencies, offices, administrations, etc). This will help to strengthen decision support systems in the field of natural hazards. The interoperability of the data, metadata, and web-services should be guaranteed through the implementation of standards (OGC and ISO).

Based on theses objectives, a set of specific natural hazard analysis tools for the HazTool system was identified, supplemented by standard GIS tools. A typical tool set could be composed by:

- panning and adaptive zooming tools on the map,
- map scaling tool,
- caption legend display,
- information queries on attributes and metadata,
- distance measurement,
- buffer zone tool,
- specific hazard queries combining interdisciplinary datasets,
- drill-tool that displays all natural hazards information available for a user specified point or surface,
- user account for saving temporarily the user defined map and settings,
- map layout and printing,
- a contextual help enabling the non-expert user to quickly understand the hang the different functionalities.

Nowadays, more and more unpleasant web based information systems are found on the Internet. Many do not respect basic cartographic rules and are therefore unattractive, unfriendly and sometimes incorrect. Visualisation with the HazTool system will therefore be guided strongly by aspects of cartographic quality and graphical semiology.

2.4 Technical Implementation Concept of HazTool

With regard to the project objectives and expectations, the following decisions (Fig. 4) were taken when considering different technical implementation alternatives:

Dynamic map content, geodata, and hazard analysis services will be delivered via the web using ESRI ArcIMS. This software provides a highly scalable framework for geodata visualisation, analysis, and publishing which meets HazNETH’s needs. Furthermore it supports layers, database management, client-side information entry, and geospatial information sharing. The choice of this product over an open source product or another commercial system was made along the following criteria: most of the

HazNETH partners currently work with ESRI products, are therefore familiar with the software, and store their geodata in the corresponding formats. Through ETH Zurich the HazNETH partners have access to a campus licence for ESRI ArcIMS, ESRI ArcSDE, and ESRI ArcGIS products, as well as to customer support. No additional financial investment is necessary to use these products. The possibility of developing natural hazard custom applications, as well as the good reputation of the product, and its ease of use and administration made the ESRI software more attractive.

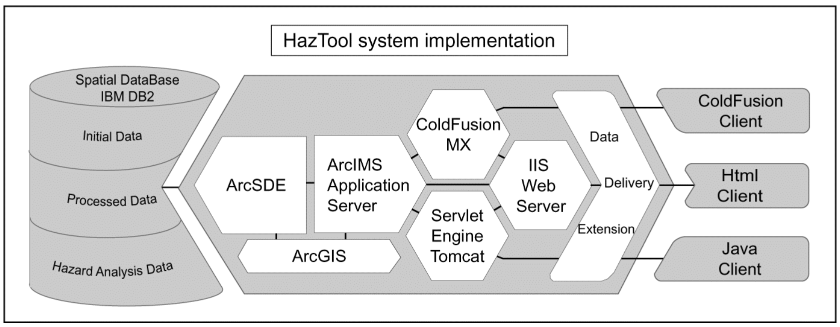

Fig. 4 *HazTool system implementation*

Complementary to ArcIMS, a special engine is needed to access and index geodata: ArcSDE is an ESRI server software product used to access massively large, multi-user geographic databases. Its primary roles are to provide a suite of services that enhance data management performance, but also to offer configuration flexibility, and to provide a spatial extension to the geodata.

As database management software IBM DB2® Universal Database™ with Spatial Extender was selected. This powerful multi-user geographic database was chosen according to its high performance, its capacity to store extremely large data volumes, and its compatibility with ArcSDE. Under the IBM Scholars license agreement, the database can be used free of charge for non-profit research.

In order to enable users to easily select, export, and deliver data in multiple formats and projections HazTool uses the ArcIMS Data Delivery extension. This tool allows users to upload/download geodata in 20 different spatial formats corresponding to industry standards and to project features to a variety of projections.

Each client technology proposed for ArcIMS has its respecting advantages and problems. To achieve maximum user-friendliness a benchmark will be realized in order to chose the best solution considering flexibility, performance, cartographic quality, and plug-in download necessity. At the moment, the planned client solution will probably be based on the ColdFusionServer© and SVG technologies.

3 Conclusion

Potential damage in Switzerland constantly increases because man moves into areas that are more exposed to natural hazards. The described research will provide a knowledge base and network with an easy-to-use web based client software for scientists, civil protection, and politicians when considering natural hazard prevention and protection.

The final software product will be easily adaptable to the purposes of federal and cantonal government agencies concerned with Swiss geotechnical and risk inventories, hazard assessment and disaster relief, or cantonal environmental offices. The software may eventually be made available to international and foreign national agencies, such as UNEP (United Nations Environment Program), or through Swiss foreign aid and disaster relief agencies.

This project is not only relevant for Switzerland and other countries of the European alpine region. Its results can also be transferred mountainous areas in general where similar problems with natural hazards are experienced (e.g. the Himalayas and the Andes).

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