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HABILITATION THESIS

TEZĂ DE ABILITARE

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Abstract

This document resumes the scientific research activity, teaching initiatives, and the future professional plans of Dr. Constantin Radu Gogu. The thesis is organized in three parts. Part A mainly describes the scientific achievements of Dr Gogu during his professional carrier focusing mainly the time period following his PhD thesis defense. Briefly his academic and professional realizations are further mentioned. Part B gives a brief overview on Dr Gogu self proposed future developments of scientific, academic, and professional carrier. Part C regroups the scientific and technical references.

The scientific achievements are structured in four research topics as follows: Urban Groundwater Modeling, Groundwater Vulnerability, Geosciences Databases, and Hydrogeological Data Scientific Instruments.

After presenting the current state of urban groundwater modeling theoretical aspects, are explained distinct modeling problems of the interaction between groundwater and the sewer networks (in Bucharest). A description, of an extensive experimental and modeling study (Barcelona, Spain) on the aquifer system behavior during a subway tunnel execution, follows.

Groundwater vulnerability assessment techniques are discussed in the second chapter. It is given an updated overview of the current vulnerability assessments methods. Then, a comparative study on vulnerability mapping results is presented. Five different methods were applied on a slightly karstified area located in Condroz region (Belgium). The last part of this chapter presents a sensitivity analysis study to assess uncertainty of vulnerability maps. The scientific challenges identified by Gogu and Dassargues (*2000a*) are still valid today. Removing the empirical character of the vulnerability assessment will eliminate the existing lacks and drawbacks of the nowadays used methods.

Spatial databases developed for geosciences are presented in the third chapter. Two geoscience fields are followed: Hydrogeology and Natural hazards. Starting from the experience achieved during the hydrogeological geospatial database design of the Walloon Region (Belgium), the author presents an evolved scheme of the hydrogeological geospatial database developed for the aquifers located in the deltaic sediments of Barcelona region and in the alluvial sedimentary media of Bucharest area. Prototypes of hydrogeological maps were designed between 1999 and 2000 for the Walloon region on the basis of the above mentioned hydrogeological geospatial database. Since then, four teams of three universities are working for the hydrogeological mapping program of the Walloon Region.Geospatial databases developments for natural hazards were elaborated for two geosciences research fields: Volcanic systems and Alpine valleys. The European large scale research project called *Geo-spatial warning systems, Nisyros volcano, Greece (GEOWARN)* offered the framework of developing a geo-

spatial data management system for potentially active volcanoes. As mentioned by the president of World Volcanic Observatories in Science revue (Vol 299/2003 - *Annex 1*), the system gave “an unusually good integration of different kinds of data and an ability to look at them together in space and time”. The system has combined digital three-dimensional maps with the powerful data-processing tools of Geographic Information Systems. For alpine valleys, the geospatial database (2003–2005 at ETH Zurich) of a web based information system for natural hazard analysis has been designed. It has been applied on Vispa valley (near Matterhorn) in the Wallis Canton of Switzerland. A parallel work has been dedicated to an extensive study of remote sensing techniques for landslides, specifically an analysis of their potential contribution to geo-spatial systems for hazard assessment in mountainous environments.

The last chapter presents distinct instruments of managing and analyzing hydrogeological data. For Bucharest City an integrated software platform for groundwater geospatial data management is currently developed under the framework of a national research project (*www.simpa.utcb.ro*). It regroups a set of instruments for 3D geological and hydrogeological analysis, developed for aquifers located in alluvial and deltaic sedimentary media and a Hydrogeochemical analysis software package (developed initially for the Catalan Water Agency, Barcelona). The second main section describes a geospatial Decision Support System for groundwater artificial recharge based on alternative sources of water. It has been developed under the FP6 European research project called *GABARDINE* (*www.gabardine-fp6.org/home.aspx*).

Academic and professional achievements are also pointed out. The organization and coordination since 2011 of the Groundwater Engineering Research Centre - CCIAS (*www.ccias.utcb.ro*) is one of them. The centre research activity concentrates on the characterization of permeable media by means of hydraulic and hydrochemical data and on the human impact on groundwater. CCIAS coordinates or is an active key partner in several national and European research projects.

In order to share the geospatial database analysis knowledge on volcano monitoring systems, achieved during GEOWARN project, Dr. Gogu collaborated with the World Organization of Volcano Observatories. Between 1998 and 2000 Dr. Gogu has been invited systematically to bring his expertise in the frame of COST-A620 European project “Vulnerability and risk mapping for the protection of carbonate (karst) aquifers". He was the initiator and the coordinator of the first Postgraduate school in Geographical Information Systems in Romania. Organized between 1994 and 2000 in the Technical University of Civil Engineering (Bucharest), the course system offered Diploma/Master of Sciences title in GIS. It was developed in the frame of UNIGIS universities network (*www.unigis.org*).

Dr. Gogu reviewed scientific manuscripts for different scientific papers submitted to Journal of Environmental Management (Elsevier), Advances in Water Resources, Water Resources Management, Hydrogeology Journal (Springer), Groundwater (Blackwell).

Rezumat

Această teză sistematizează activitatea de cercetare științifică, intțiativele didactice și planurile profesionale ale domnului Dr. Constantin Radu Gogu. Teza este organizată în trei părti. Prima parte descrie realizările științifice ale domnului Gogu, punând accent pe perioada ulterioară oferirii titlului de doctor în științe inginerești aplicate. Urmează o mențiune succintă a realizărilor academice și profesionale. Partea B prezintă o vedere de ansambu asupra planurilor de evoluție și dezvoltare a propriei cariere profesionale, stiințifice și academice. Partea C regrupează referințele bibliografice asociate conținutului primelor două părți. Realizările științifice sunt structurate în patru subiecte de cercetare: Modelarea apei subterane în medii urbane, Vulnerabilitatea apelor subterane, Baze de date dezvoltate pentru științele pământului și Instrumente științifice pentru analiza datelor hidrogeologice.

Primul capitol este dedicat apelor subterane din zonele urbane și a interacțiunii acestora cu infrastructura urbană. După prezentarea stadiului actual ale aspectelor teoretice privind modelarea apei subterane din medii urbane, sunt explicate probleme ale modelării interacțiunii dintre apa subterană și rețelele de canalizare (din București). În continuare urmează o descriere a unui studiu experimental și de modelare a comportamentului unui sistem acvifer în timpul execuției unui tunel de metrou (Barcelona, Spania).

În al doilea capitol sunt discutate tehnicile de evaluare a vulnerabilității apelor subterane. În primul rând este prezentată o vedere de ansamblu actualizată asupra metodelor existente de evaluare a vulnerabilității acviferelor. Urmează prezentarea unui studiu comparativ între hărți de vulnerabilitate obținute prin cinci metode diferite. Acestea au fost aplicate pe o zonă cu un grad mic de carstificare localizată în regiunea Condroz (Belgia). Ultima parte a acestui capitol, descrie o analiză de senzitivitate în vederea evaluării incertitudinii hărților de vulnerabilitate. Provocările științifice identificate de Gogu și Dassargues (*2000a*) sunt în continuare valabile. Eliminarea caracterului empiric al evaluării vulnerabilității acviferelor va elimina lipsurile și defectele metodelor utilizate în prezent.

Al treilea capitol prezintă baze de date spațiale dezvoltate în două domenii: hidrogeologie și hazarde naturale. Plecând de la experiența acumulată în timpul proiectării bazei de date hidrogeologice geospațiale pentru Regiunea Valonă (Belgia), autorul descrie o schemă evoluată a acestei baze de date dezvoltată pentru acviferele cantonate în sedimentele deltaice din regiunea orașului Barcelona. Pe baza structurii de date spațiale anterior menționată, în perioada 1999 -2000, au fost proiectate hărțile hidrogeologice prototip pentru Regiunea Valonă. De atunci, în cadrul unui proiect al Regiunii Valone, patru echipe din trei universități dezvoltă hărțile hidrogeologice ale acestei regiuni.

Pentru hazarde naturale, bazele de date geospațiale au fost dezvoltate pentru două domenii: Sisteme vulcanice și Văi alpine. Proiectul european de cercetare intitulat *„Sistem de avertizare geospațial, Vulcanul Nisyros, Grecia (GEOWARN)”* a oferit cadrul de dezvoltare al unui sistem de gestiune și analiză pentru datele geospațiale a vulcanilor potențial activi. Așa cum a fost menționat de președintele Asociației Internaționale a Observatoarelor Vulcanice în revista Science (Vol 299/2003 - *Anexa 1*), sistemul oferă “o integrare neobișnuit de bună a diverselor tipuri de date și posibilitatea ca acestea să poată fi privite împreună în spațiu și timp”. Sistemul combină hărți tridimensionale digitale cu instrumentele de procesare și analiză spațială. Pentru văile alpine a fost proiectată o baza de date geospațială (2003 – 2005 la Universitatea Politehnică ETH Zurich) a unui sistem pentru analiza hazardelor alpine bazat pe tehnologii web. Sistemul a fost aplicat pe valea Vispa (lângă Matterhorn) în cantonul Wallis al Elveției. În paralel a fost realizat un studiu privind aplicarea tehnicilor de teledetecție pentru alunecările de teren. S-a analizat contribuția potențială ale acestora la sistemele geospațiale de analiză a hazardelor naturale din regiunile muntoase.

Ultimul capitol prezintă instrumente de gestiune și analiză a datelor hidrogeologice. Pentru municipiul București este dezvoltată în prezent o platformă software pentru managementul datelor spațiale privind apele subterane (*www.simpa.utcb.ro*). Aceasta regrupează un set de instrumente pentru analiza geologică și hidrogeologică 3D precum și un set de analiză a datelor hidrogeochimice (dezvoltat inițial pentru Agenția Catalană de Apă, Barcelona). A doua secțiune a capitolului descrie un Sistem Suport de Decizie pentru sistemele de realimentare artificială a acviferelor bazate pe surse alternative de apă. Acest sistem a fost dezvoltat în cadrul proiectului de cercetare *GABARDINE* (*www.gabardine-fp6.org/home.aspx*) al Programului European Cadru 6 (FP6).

În cadrul acestei teze sunt menționate și realizările academice și profesionale ale d-lui Gogu. Una dintre acestea este inființarea, organizarea și coordonarea Centrului de Cercetare Ingineria Apelor Subterane (*www.ccias.utcb.ro*). Activitatea de cercetare a centrului este axată pe caracterizarea mediilor permeabile în raport cu proprietățile hidraulice și hidrochimice precum și pe analiza impactului uman asupra apei subterane. Centrul coordonează și este implicat în câteva proiecte de cercetare naționale și europene.

În vederea prezentării cunoștiințelor privind analiza și structurarea datelor spațiale rezultate din sistemele de monitoring ale vulcanilor, acumulate de-a lungul proiectului GEOWARN, dl. Gogu a colaborat cu Asociația Internaționala a Observatoarelor Vulcanice. Între anii 1998 și 2000 dl. Gogu a fost invitat în mod sistematic în cadrul proiectului european COST-A620 “Cartografierea vulnerabilității și a riscului în vederea protecției acviferelor carbonatate (carstice)". Dl Gogu a fost inițiatorul și coordonatorul primei școli postuniversitare de Sisteme Informatice Geografice din Romania. Dezvoltată în cadrul rețelei de universități UNIGIS (*www.unigis.org*), aceasta a fost organizată între anii 1994 și 2000 în cadrul Universitarii Tehnice de Construcții București, oferind Diplomă de Studii Aprofundate.

Dl. Gogu a realizat recenzii ale unor articole pentru următoarele reviste: Journal of Environmental Management (Elsevier), Advances in Water Resources, Water Resources Management, Hydrogeology Journal (Springer), Groundwater (Blackwell).

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Introduction

This document resumes the scientific research activity, teaching initiatives, and the future professional plans of Dr. Constantin Radu Gogu. The thesis is organized in three parts. Part A mainly describes the scientific achievements of Dr Gogu during his professional carrier focusing mainly the time period following his PhD thesis defense. Briefly his academic and professional realizations are further mentioned. Part B gives a brief overview on Dr Gogu self proposed future developments of scientific, academic, and professional carrier. Part C regroups the scientific and technical references mentioned in the first two parts. A separate volume containing references for the entire activity is attached as Annex of this thesis.

The scientific achievements presented in Part A are structured in four distinct research topics as follows: Urban groundwater modelling, Groundwater vulnerability, Geosciences databases, and Hydrogeological data scientific instruments.

The first chapter of Part A focuses on urban groundwater modelling studies. This experience came by coordinating and working in several research projects conducted in the Technical University of Barcelona (Spain) and in the Technical University of Civil Engineering of Bucharest (Romania). The chapter begins with the current state of urban groundwater modeling theoretical aspects. Then, the quantitative interaction modeling problems, studied in an ongoing research project (*www.simpa.utcb.ro*), between groundwater and a sewer network segment in Bucharest are presented.

The need of the sewer system rehabilitation in Bucharest initiated a study of the interaction between groundwater and the sewer network. Recent conclusions show that the sewer network acts mainly like a drainage system for the groundwater. The groundwater infiltration in the sewer conduits can cause the decrease of the groundwater level leading to structures instability problems as well as to the increase flow-rates of the sewer system. The last one affects seriously the wastewater treatment plants efficiency. The sewer network leakage cause groundwater pollution and locally could increase the groundwater level triggering buildings instability or other urban operational problems. A description of an extensive experimental and modeling study (El Prat de Llobregat - Barcelona, Spain) on the aquifer system behavior during a subway tunnel execution follows.

Groundwater vulnerability assessment techniques are discussed in the second chapter. An updated overview of the current vulnerability assessments methods is given. Then, a comparative study on vulnerability mapping results is presented. Five different methods were applied on a slightly karstified area located in Condroz region (Belgium). The last part of this chapter presents a sensitivity analysis study to assess uncertainty of vulnerability maps. The chapter underlines the fact that removing the empirical character of the vulnerability assessment will eliminate the existing lacks and drawbacks of the nowadays used methods. The scientific challenges identified by Gogu and Dassargues (*2000a*) are still valid today. Aquifer vulnerability assessment using a process based methodology complying with the physics of groundwater flow and contaminant transport still represents a research challenge.

Spatial databases developed for geosciences are presented in the third chapter. Two geoscience fields are followed: Hydrogeology and Natural hazards. Starting from the experience achieved with the hydrogeological geospatial database design of the Walloon Region (Belgium), the author presents further an evolved scheme of the hydrogeological geospatial database. It has been developed for the aquifers located in the deltaic sediments of Barcelona region and in the alluvial sedimentary media of Bucharest area. Prototypes of hydrogeological maps were designed between 1999 and 2000 for the Walloon region (Belgium) on the basis of the above mentioned hydrogeological geospatial database. Since then, four teams of three universities are working for the hydrogeological mapping program of the Walloon Region.

Geospatial databases developments for natural hazards were elaborated for two geosciences research fields: Volcanic systems and Alpine valleys. The European large scale research project called *Geo-spatial warning systems, Nisyros volcano, Greece (GEOWARN)* offered the framework of developing a geo-spatial data management system for potentially active volcanoes. As mentioned by the president of World Volcanic Observatories in Science revue (Vol 299/2003 - Annex 1), the system gave “an unusually good integration of different kinds of data and an ability to look at them together in space and time”. The system has combined digital three-dimensional maps with the powerful data-processing tools of Geographic Information Systems used by surveyors and other field specialists to create a template that monitoring data can be fed into and displayed. For alpine valleys, the geospatial database design of a web based information system for natural hazard analysis has been set-up for Vispa valley (near Matterhorn) in Canton Wallis. The work was performed between 2003 and 2005 within the Research Network on Natural Hazards at ETH Zurich (HazNETH). A parallel work has been dedicated to an extensive study of remote sensing techniques for landslides, specifically an analysis of their potential contribution to geo-spatial systems for hazard assessment in mountainous environments.

The last chapter presents distinct instruments of managing and analyzing hydrogeological data. For Bucharest City (Romania) an integrated software platform for groundwater geospatial data management is currently developed under the framework of a national research project (*www.simpa.utcb.ro*). Regrouping a consistent set of instruments, it benefits from the scientific experience achieved in distinct research projects developed in different European countries.

Starting from an accurate and very detailed geological description, one set of instruments allows representing 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.

The groundwater quality survey can be made by using monitoring and analysis tools that are able to manipulate time-series large datasets showing a spatial reference. Data correlation with the spatial distribution of the hydrogeological structures is compulsory. Within the urban environment the problem show a larger complexity because of the infrastructure interaction. The section Groundwater analysis and data management systems regroups 3D geological and hydrogeological analysis instruments developed for aquifers located in alluvial and deltaic sedimentary media and a Hydrogeochemical analysis software platform developed for the Catalan Water Agency (Barcelona, Spain). The second main section describes a geospatial Decision Support System for groundwater artificial recharge based on alternative sources of water. It has been developed under the FP6 European research project called Groundwater artificial recharge based on alternative sources of water: advanced integrated technologies and management (*www.gabardine-fp6.org/home.aspx*).

Academic and professional achievements are pointed out in the last section of part A. The organization and the coordination since 2011 of the Groundwater Engineering Research Centre (CCIAS) in the Technical University of Civil Engineering (*www.ccias.utcb.ro*), is one of them. The centre has about 15 members and its research activity concentrates on the characterization of permeable media by means of hydraulic and hydrochemical data and of the human impact on groundwater. CCIAS is currently coordinating or represent an active key partner in several national or European research projects as Sedimentary media modeling platform for groundwater management in urban areas (*www.utcb.simpa.ro*) or the FP7 project Tailored Improvement of Brownfield Regeneration in Europe *(www.timbre-project.eu*).

It worth to be mentioned also the initiation and the coordination of the first Postgraduate course in Geographical Information Systems in Romania (GIS). Organized between 1994 and 2000, the course system offered Diploma and Master of Sciences title in GIS. It was developed in collaboration with Manchester Metropolitan University in the frame of UNIGIS (Manchester Metropolitan University, University of Salzburg, Free University of Amsterdam, University of Salford, and University of Huddersfield) international universities network (*www.unigis.org*).

In order to share the geospatial database analysis knowledge on volcano monitoring systems, achieved during GEOWARN project, Dr Gogu has been invited in 2002 by the United states Geological Survey and World Organization of Volcano Observatories as invited speaker at the "2nd Workshop World Organization of Volcano Observatories"2002, USGS Menlo Park, California, USA. Between 1998 and 2000 Dr. Gogu has been invited systematically to bring his expertise in the frame of COST-A620

European project - “Vulnerability and risk mapping for the protection of carbonate (karst) aquifers". He reviewed scientific manuscripts for different scientific papers submitted to Journal of Environmental Management (Elsevier), Advances in Water Resources (Elsevier), Water Resources Management (Elsevier), Hydrogeology Journal (Springer), Groundwater (Blackwell).

Starting from the research, academic and professional experience gained over about 22 years in various academic institutions of different countries as Romania, Belgium, Switzerland, Spain and Greece, and overview on Dr. Gogu future professional objectives is given by part B. There are essentially based on his last three years activity centered on the new established Groundwater Engineering Research Centre (CCIAS) of the Technical University of Civil Engineering. In this sense the consolidation of the CCIAS team, working in groundwater research topics that covers different knowledge areas (hydrogeology, geology, hydrology, structures and foundations, hydraulics, geographic informational system, informatics, mathematics, chemistry, biology), will be a main concern. Scientific research activity will focus mainly on urban groundwater modeling, hydrogeological data management and on groundwater resources protection by improving the vulnerability assessment methodologies and their implementation. The scientific research directions will be performed by outlining the following actions:

- improving the geological models generation techniques by combining the stratigraphic analysis concepts with those of hydrogeological modeling;
- improve the hydraulic characterization of underground structures in relationship to groundwater;
- the development of a hydrogeological qualitative and quantitative information management framework in relationship to urban infrastructure (water supply, sewer system, subway lines, foundations, etc);
- the development of hydrogeological and geological data models needed for the spatial data infrastructure (INSPIRE);
- developing and applying groundwater protection strategies.

PART A

SECTION I - RESEARCH ACHIVEMENTS

1. Urban groundwater modeling

In urban areas, due to the strong impact of urbanization and industrialization on groundwater, an improved management of this resource is essential. Nowadays a reliable management of the water resources can be performed by means of mathematical modelling. A synthesis of a large literature review is presented in the following chapter. It focuses on different mathematical modelling aspects of the groundwater flow in urban environments and offers an overview of the urban groundwater quantitative problems, associated phenomena, and their modelling solutions. Its content treats distinct aspects encountered in Bucharest. It is proposed a global conceptual schema of an interactive system to manage the groundwater data for distinct modelling activities at a city scale level.

1.1. Groundwater flow modeling aspects in urban environment

Urban areas are a focus of increasing conflict with regard to water use and water protection. Half of the world's population and about 73% of Europeans live in cities. In Europe, numerous urban areas are located in 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 (*Gogu et al. 2011*) due to their high permeability, storage and management ability, interaction with surface water and others. In Europe and in the Mediterranean region urban aquifers contribute with more than 40% as water supply source *(Wolf et al., 2006)*.

Urban groundwater resources management practices cover the following three directions.

(1) Common tasks consisting in:
- understanding and quantifying the hydrological system behaviour;
- assign suitable urban activities to appropriate areas;
- define the possible secondary water uses concerning the current water quality and its possible evolution;
- minimize the quantitative and qualitative impacts on urban infrastructures (subway, sewer systems, parking lots, basements, etc.);

(2) Assess the local groundwater behaviour in relationship to building foundations, to underground structures, and to the associated geotechnical works (during execution as well as during service);

(3) Particularly for Bucharest it has to be mentioned that even the constructive processes of the new subway lineal underground works are well known, they show some problems in the designing phase due to the geological location. Most of these lineal works could show significant problems associated to the groundwater seepage during the construction phase and to the missing of the detailed level of knowledge regarding the underground heterogeneities.

These problems take place particularly in highly heterogeneous permeable media, associated to high permeability contrasts or to high vertical hydraulic gradients such as those existing in sedimentary media. Thus, the acquired knowledge related to the underground (geology, hydrogeology, etc.) is insufficient to make an accurate characterization. This is especially critical during the building phase, where the works can be affected by unforeseen events or processes. It is for this reason that in most cases the project solutions do not specify possible unpredictable changes in: the geology and nature of the ground, water intake and mechanical problems associated to the hydraulic gradients towards excavation. These cases may even suggest a significant extra cost. On the other hand, the strong drainage that is actually taking place and that is sometimes associated to the habitual building methods can cause a significant impact on the aquifers. This aspect should be actually minimized in most of civil works.

Nowadays a reliable management of the water resources in urban areas can be performed by using mathematical modeling (*Gogu et al. 2010*). Models can provide accurate results if they correctly reproduce the hydrological processes. Concerning groundwater, it is well-known that sedimentary media are normally highly heterogeneous (*Gogu et al. 2011*), which is a paradox as it leads to simplified models based on the homogeneity of large zones characterizing the medium. Tools and methodologies should allow the representation in three dimensions of the geological record heterogeneity and its spatial distribution as well as the interaction of groundwater with the urban infrastructure (water supply and sewer systems, drainage systems of basements, subway network, parking lots, etc.).

Groundwater flow modelling of sedimentary aquifers represents a tool used to:

- Quantitatively assess the groundwater behaviour; necessary for the management of groundwater operation, environment protection, structures stability, geotechnical work (estimation the groundwater level in relationship to underground structure and infrastructure design), infrastructure networks rehabilitation (sewer) and others;
- Study the groundwater quality and the contaminant transport phenomena.

From the quantitative point of view, urban hydrogeological systems are subjects of the following stresses to be analysed:

- Groundwater discharges, triggering a decrease of the groundwater level (infiltrations into tunnels, drains, effluent lined canals);
- Groundwater recharges, source of the groundwater level increase (losses from the water supply network, leaks from the sewage system, influent lined canals);

- Barriers, causing differential fluctuations of the groundwater level (tunnels, large diameter sewer conduits, large foundations, underground structures, cut-off walls);
- Pathways for groundwater flow causing preferential informal horizontal or vertical flow paths for groundwater. Such effect can be *(Preene and Brassington 2003)* temporary (e.g. investigation and dewatering boreholes) or permanent (e.g. granular bedding for pipelines, open excavation with their associated draining system).

This research direction provides a global description of the groundwater flow modelling aspects applied for urban environments, as well as a literature review of the currently used methods to quantify the effects of distinct factors affecting the groundwater flow system in urban areas. Considering Bucharest city as study area, a conceptualization of the effects quantification of these factors is given.

Groundwater flow as part of the urban water cycle

An urban water system owns a multitude of components focusing on the drinking water supply, wastewater management, protection against floods, as well as surface and groundwater management. This system contains also components dealing with the protection and maintenance of the ecosystems located upstream and downstream of an urban area as well as in its boundaries. These urban system components show a strong interaction (Figure 1-1). The positive or negative consequences of an urban water system could be analyzed only by an accurate monitoring and analysis integrated system.

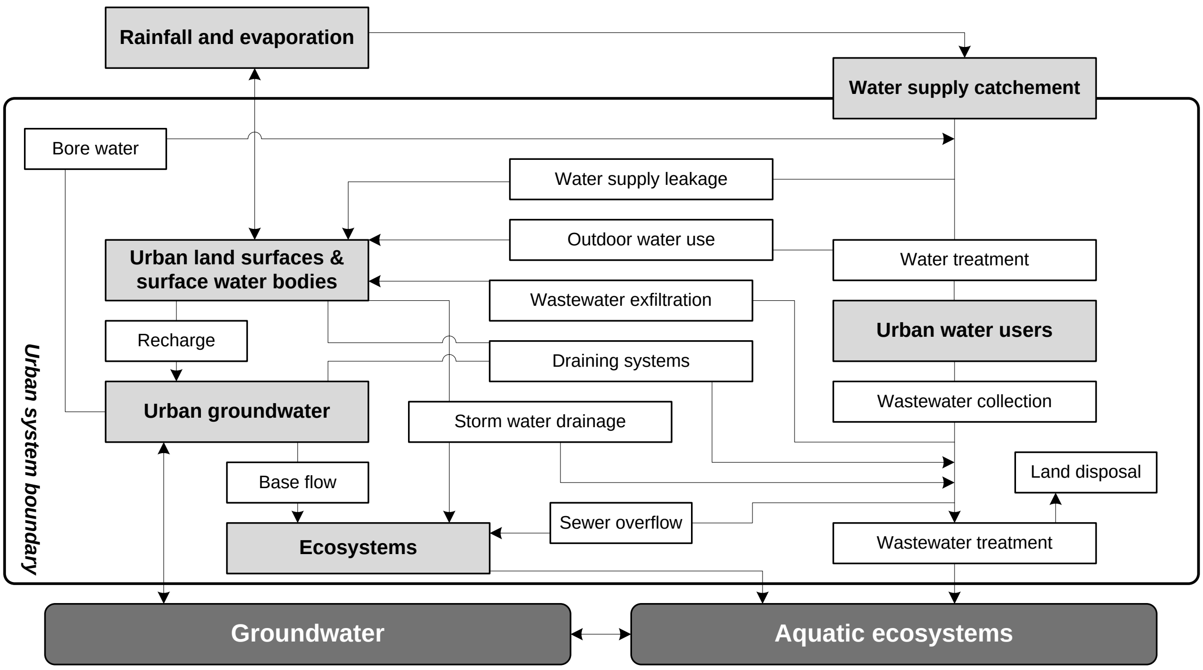


Figure 1-1 Interaction between urban water system components

Acting like a source or a sink, urban groundwater interacts with the other urban water systems. This interaction may be on purpose or not. Groundwater artificial recharge or abstraction for water supply represents planned interactions. Leaking pipes or sewer conduits draining the groundwater are undeliberate actions.

Water supply networks usually recharge groundwater with the exception of maintenance periods, when they can drain the groundwater if the conduit is located in the aquifer. The interaction of sewers with groundwater can occur in both directions. If the wastewater or stormwater level in the sewer is higher that the groundwater level, the conduit will recharge the groundwater through cracks and faults. In this case, results a contamination of the aquifer. If it is lower it can act like a drain for the aquifer, increasing the water volume that arrives at the treatment plant.

The interaction between the groundwater and the other urban water system components has to be integrated in a coherent concept. However, a performant integrated urban water management system implies continuous monitoring and management activities. This could be achieved only by an institutional collaboration between the operators, agencies, administrations and water regulators in charge of distinct elements of this system. Furthermore, is required an active interaction of the universities and research centres.

Within the urban expansion of the Bucharest surrounding, urban aglomerrations (Buftea, Otopeni, Voluntari, Chitila, Măgurele, Bragadiru, Popeşti-Leordeni, Pantelimon), the drinking water supply increases continuously. As mentioned by the Water Framework Directive (*2000/60/EC*) and by the Integrated Water Resources Management principles *(UN-Water, 2008)* the water should be managed within natural hydrological units - the river basin, lake basin or aquifer. Generally speaking, the town shape and its extension potential severely depend on the hydrological surfaces of the river basins. However, Ilfov county communities show different particularities related to the spatial development and the evolving potential due to the atypical way this territorial community area has been dimensioned, organized, and stated. From the functional point of view, the Ilfov county communities do not show a networking structure. The building area growth surrounding Bucharest is determined by the main roads and not by the river basins or by the aquifer systems disposal. However the urbanization process modifies the river basins natural behavior and generates a parallel hydrological cycle. The city development generates new type of surfaces, most of them impervious. The water supply and sewer networks are artificial water cycle systems that interact with the natural hydrological cycle. The runoff modification due to urban enlargement, the water resources contamination due to wastewater discharge as well as the fragile hydro systems overload during the droughty years represent urbanization effects.

The middle of Bucharest city is crossed almost entirely by a large sewer gallery. This is located under the artificial river bed of the Dambovita River. This gallery *(Regional Agency for the Environment Protection of Bucharest - Romania, 2010*) is fed by 12 main sewer conduits and 11 channels collecting waste water and storm water of Bucharest and of neighboring urban communities: Pantelimon, Voluntari, Dobroieşti, Chiajna, Chitila, Popeşti – Leordeni, Buftea, Mogoşoaia. The sewer system works efficiently if the rainfall does not exeed 30 l/m^2. The collected wastewater flow rate shows a 24 hours variation between 15 m^3/s and 22.5 m^3/s (without counting storm water). During rainy days it can increase to160 m^3/s. A strong interaction between the sewer system and the groundwater has been highlighted showing both leakage or draining areas.

Overview on different urban case studies

Some specific problems that can be met when dealing with urban groundwater, they have been reported in different case studies and can be organized as follows:

- *Hydrological cycle disturbance*: as a direct consequence of the land-use change, the natural hydrological cycle is disrupted. Recharge to the aquifer system is considerably modified. This is mainly due to the continuously decreasing contribution of water infiltration from rainfall and of the increasing water inputs form different urban sources. These could be leakage from the Water Supply Network (WSN) and from the Sewer System (SS). Such problems were reported for Barcelona (Spain) where leakages from WSN and SS became the main groundwater recharge source *(Vázquez-Suné and Sanchez-Vila, 1999),* Doncaster (UK) with 30-40% of groundwater recharge from the SS losses *(Rueedi et al., 2009),* San Luis Potosi (Mexico) where the shallow aquifer recharge is about 74% of the WSN losses *(Martinez et al., 2010),* and others.
- *Groundwater level fluctuation*: an artificial increase or decrease of the groundwater level due introduction, modification, or elimination of different urban water cycle components that can disturb a given flow state. The rise of water table can lead to flooding the underground works (e.g. cellars, basements, tunnels, etc.), to increase the groundwater infiltration into sewers, and to increase the development costs for infrastructure works (associated with the necessity of dewatering, draining or waterproofing measures). Many case studies pointed out this kind of problems. As for example, in Barcelona (Spain) *(Vázquez-Suné and Sanchez-Vila, 1999),* mentioned that in recent years an increase of groundwater levels was observed after a record of minimum historical levels during 1960-1980. This happened due to an economic expansion of the city when many buildings were constructed. At that time the uppermost aquifer layer levels recovery has not been suspected. This led to construction practices neglecting the waterproofing measures and a decade later this became the main reason for underground

infrastructure seepage (that can lead to serious structural damages). Water-table rise with seasonal formation of water ponds (during winter) was reported in urban area of Kuwait city *(Al-Rashed and Sherif, 2001)*. This problem was attributed to over irrigation practices of private gardens and public green areas along with the losses of WSN and SS.

- *Groundwater quality deterioration*: leakage from SS represents an important source of groundwater pollution with substances such as nitrates, nitrite, phosphorous, chloride, boron, bacteriological contamination and others. Important contributions of groundwater recharge from SS losses have been reported in many case studies as for example Doncaster (UK) with 30-40% *(Rueedi et al., 2009)*, Rastatt (Germany) with 5-12% *(Wolf et al., 2006)*, and San Luis Potosi (Mexico) with 11% *(Martinez et al., 2010)*. These quantities reflect directly the magnitude of the groundwater quality deterioration induced by this urban contamination source. For coastal cities, the groundwater quality can also be affected by seawater intrusion that could be induced by the decrease of the groundwater level to negative values (below sea level), usually associated with excessive groundwater abstraction. Examples have been highlighted by *(Vázquez-Suné and Sanchez-Vila, 1999)*, for Barcelona city during 1960s (due to the increase of the industrial activities), and by *(Nakayama et al., 2007)* for Tokyo (Japan).

Aspects of groundwater flow modelling

The first step in mathematical modelling is the conceptualization of the physical system that needs to be modelled. This consists in the choice of different factors and assumptions regarding the aquifer system (type, configuration, and spatial variation describing parameters), the dimensionality of the problem (2D or 3D), the boundary conditions, and the origins of recharges and discharges. The next step is the mathematical expression of the groundwater flow. And so, the flow modelling of a hydrogeological system will lead to the resolution of the governing groundwater flow equation for saturated porous media given in 3D Cartesian coordinates system by:

$$\frac{\partial}{\partial x}\left(bK_{xx}\frac{dh}{dx}\right)+\frac{\partial}{\partial y}\left(bK_{yy}\frac{dh}{dy}\right)+\frac{\partial}{\partial z}\left(bK_{zz}\frac{dh}{dz}\right)=b\,S_s\frac{\partial h}{\partial t}+Q \qquad (1\text{-}1)$$

Where, b is the aquifer saturated thickness [L], h is the hydraulic head [L], K_{ij} hydraulic conductivity tensor [L/T], S_s aquifer specific storage [L^{-1}], t time [T], $Q=Q(x,y,z,t)$ volume flux per unit area (positive for recharge and negative for discharge) representing source and sink terms [L/T].

To solve this equation, numerical methods such as finite element method (FEM) or finite difference method (FDM) are used. By classifying the different terms of this equation into input parameters (like hydraulic conductivity) and output results (hydraulic head), this problem can be solved in two ways:

1. *Direct approach*: mathematically depends on the parameter to determine the output. This approach requires a non-automated calibration of the model (via trial-and-error technique) by varying the different parameters in order to obtain better but not necessarily best results. The non-automated calibration is time consuming and as consequence it sometimes reduces the focus on the validity of the conceptual model itself;
2. *Inverse approach*: it uses an optimization procedure to find the parameter when the output is given *(Poeter and Hill, 1997)*. In this approach, the model calibration is automated and ensures the best possible result for a given conceptual model. As consequence it increases the focus on the validity of the conceptual model.

To support distinct modelling activities at a scale level of a city, a complex interactive system to manage the groundwater data could be set-up. This can be done by using a combined interdisciplinary approach involving geology, hydrology, hydrogeology, geography, geotechnical engineering, and computer sciences. A global conceptual schema in this respect is given in Figure 1-2.

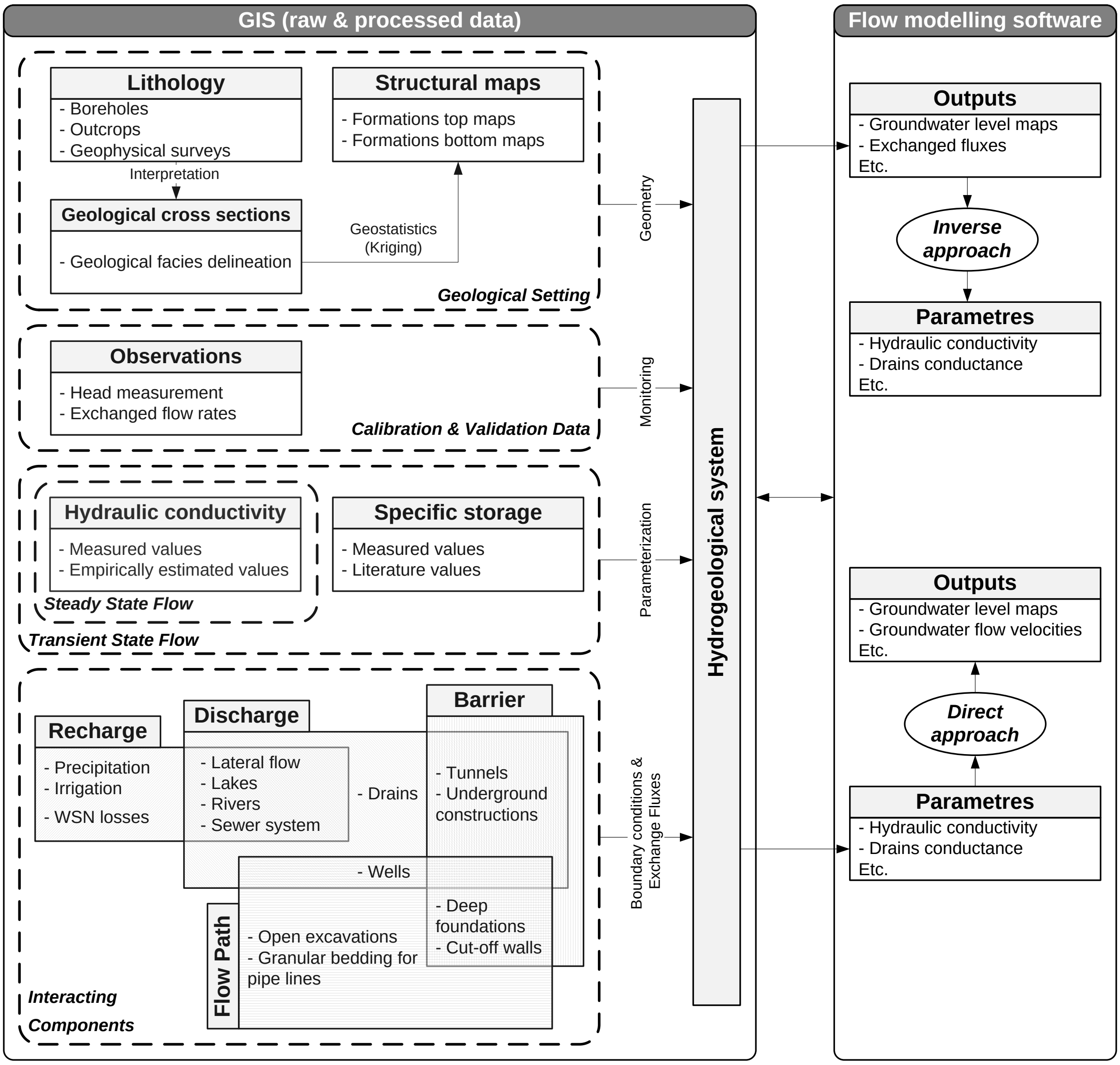


Fig. 1-2 Global conceptual schema for flow modelling in urban environments

Quantification methods of Urban Groundwater Recharge Sources

In urban regions the main groundwater recharge sources are: precipitation, rivers, surface channel seepage, irrigations, sewers leakage, water supply system losses, and artificial recharge. Table 1-1 gives a summary of some methods that can be used for the quantification of the recharge sources typically encountered in urban areas.

Table 1-1 Quantification methods review for specific urban groundwater recharge source

Source	Reference	Quantification	Parameters	Observation
Sewers Leakage	Torricelli equation *(Rutsch, 2006)*	$Q = \mu \times A \times \sqrt{2 \times g \times h}$	Q: discharge rate; μ: coefficient of outflow; A: area of the outlet; h: water level; g: gravitational acceleration.	
	Darcy's law *(Rutsch, 2006)*	$Q = A_{leak} \times K_f \frac{\Delta h}{\Delta s}$	Q: discharge rate; A_{leak}: leakage area of the pipe; K_f: soil hydraulic conductivity; Δs: depth of soil column; Δh: difference between the sewer water level and the aquifer water level [m].	
	(Rushton and Tomlinson, 1979)	$Q = K_1(e^{K_2 \times \Delta h} - 1); For\ \Delta h \geq 0$	Q: specific flow between river and aquifer per unit length of the river [$m^3.m^{-1}.s^{-1}$]; K_1: constant representing streambed leakage coefficient [$m.s^{-1}$], K_2: constant; Δh: difference in the water level between the river and the aquifer [m].	
	Leakage factor approach *(Rauch and Stegner, 1994) - (Gustafsson, 2000)*	$Q = (H_{gw} - H_{Sewer}) \times A_{Sewer} \times C$	Q: discharge rate; H_{gw}: groundwater level; H_{Sewer}: water level in sewer; A_{Sewer}: sewer surface to which waste water is exposed to; C: leakage coefficient.	It can also be used to estimate the discharge taking A_{Sewer}: sewer surface to which groundwater is exposed to;
	(Wolf, et al., 2007)	$Q = \left(K_{LowFlow} WPR_{LowFlow} I_{LowFlow} \alpha + K_{HighFlow} WPR_{HighFlow} I_{HighFlow} (1 - \alpha)\right) A_{Leak} AGW$	Q: discharge rate; α: ratio between ***dry weather*** and ***storm weather*** flow; $K_{LowFlow}$ ($K_{HighFlow}$)[m/s] hydraulic conductivity of the clogging layer during dry (storm) weather flow; A_{Leak} [m^2] total area of the open sewer defect/soil interface in the catchment; $WPR_{LowFlow}$ ($WPR_{HighFlow}$) wet perimeter ratio during dry (storm) weather flow; $I_{LowFlow}$ ($I_{HighFlow}$) hydraulic gradient across the clogging layer during dry (storm) weather conditions; AGW proportion of sewer conduits length above the groundwater table.	In order to use this equation, it is necessary to determine probability distribution function for each of the seven input parameters.
Water supply network (WSN) losses	*(Lerner, 1990)*	10 to 50% of supply. Rates of 100-300 mm/yr		
	1D areal recharge	Arial recharge using percolation modelling using 1D flow model		Uniform areal recharge distribution estimated from the total losses from WSN in the correspondent area
	3D punctual recharge	Punctual recharge using percolation modelling using 3D flow model.		Non uniform recharge for punctual localized with quantified rates leaks from the WSN.
Surface channel seepage	*(Kumar)*	$Losses[m^3/s/millon\ m] = 1.83Q^{0.56}$	Q [m^3/s]: discharge carried by the channel.	Lined channel in Punjab (India).
	U.S. Bureau of Reclamation	(1) Clay and clay loam=1.50; (2) Sandy loam=2.4; (3) Sandy and gravely soil=8.03; (4) Concrete lining=1.20	Losses given in [m^3/s/million m^2 of wetted area]	
	(GWREC, 2009)	(1) Unlined canals in normal soil with some clay content along with sand=1.8 to 2.5; (2) Unlined canals in sandy soil with some silt content=3.0 to 3.5; (3) Lined canals and canals in hard rock areas =20% of the above values for unlined canals	Losses given in [m^3/s/million m^2 of wetted area]	

Since the exchange flow direction between the aquifer system and the sewer conduit depends on the hydraulic gradient between them, the exchange can be from the sewer to the aquifer or in the opposite direction. Estimating the infiltration/exfiltration rate into/from the principal sewer using the leakage factor approach *(Rauch and Stegner, 1994; Gustafsson, 2000)*, the following technique is proposed:

In order to estimate the infiltration/exfiltration rate into/from the sewer conduit, one can discretize it into a finite number N of elements (see figure 1-3). This can be done considering that the parameters of an adapted form of Darcy's law (leakage approach) are constant at the scale of each element.

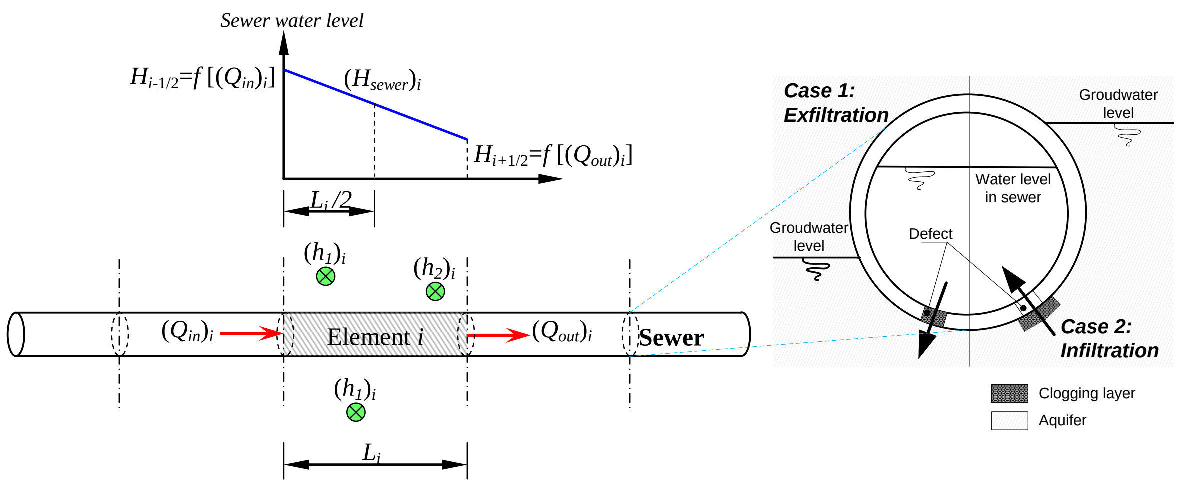


Fig. 1- 3 Sewer conduit discretization

It is considered that for M elements of the global set of N elements, the following data are known:

- The input flow rate $(Q_{in})_i$ and the output flow rate $(Q_{out})_i$ for the element i from the set of the M elements;
- The groundwater level around the conduit estimated from a set of hydraulic head measurements in a set of j wells/piezometres.

Knowing this data will lead to the direct calculation of:

- The exfiltration or infiltration flow rate by:

$$\left(Q_{infiltration}\right)_i = (Q_{out})_i - (Q_{in})_i \tag{1-2}$$

- The sewer hydraulic head ($(H_{Sewer})_i$), estimated at the mid length of the sewer element i; the variation of the hydraulic head along the sewer element is supposed to be linear and its values at the element extremities can be estimated since the flow rates at this points ($(Q_{in})_i$ and $(Q_{out})_i$) and the sewer geometry is known;

- The sewer conduit surface exposed to the groundwater $(A_{sewer})_i$ estimated at the mid length of the sewer element *i*;
- The exfiltration coefficient for the element *i* (C_i).

Once the values of the infiltration/exfiltration coefficient for the *M* elements set are known, one can identify the presence of an eventual pattern between this variable and other parameters. This pattern might be used to further estimate this coefficient for the rest of the elements of the global set of *N* elements.

Quantification methods of urban groundwater discharge sources

Apart the sewer system that could work as a recharge source as well as a discharge one, the main groundwater sinks are: infiltration into underground cavities (tunnels, subway stations, parking lots, building, building foundations, etc.), drains, and others. Table 1-2 gives a summary of some methods that can be used for the quantification of the discharge sinks encountered in urban areas.

Table 1-2 Review of quantification methods for specific urban groundwater discharge sinks

Sink	Reference	Quantification	Parameters	Observation
Tunnel/Drain	*(Goodman et al., 1965)*	$Q = \frac{2 \times \pi \times K \times h}{2.3 \times \log(2h/r)}$	*Q*: flow rate into the tunnel; *K*: hydraulic conductivity of the rock; *h*: elevation of the water table above the tunnel; *r*: tunnel radius;	Steady state
	(Goodman et al., 1965)	$Q(t) = \sqrt{\frac{8C}{3} K \times h^3 \times S_y \times t}$	*Q*: flow rate into the tunnel; S_y: specific yield; *C*: constant. According to the theory of Dupuit-Forchheimer, *C* = 0.5.	Transient state
	(Perrochet, 2005)	$Q(t) = \frac{2\pi K L s_0}{\ln\left(1 + \sqrt{\frac{\pi K t}{S_s r_0^2}}\right)}$	*Q*: flow rate into the tunnel; *K*: aquifer hydraulic conductivity, *t*: time, r_0: tunnel radius, s_0: the specific drawdown at the tunnel, S_s: specific storage coefficient; *L*: tunnel length over which a permeable zone is encountered	It can also be used to estimate the discharge flow rate into a horizontal drain.

The interaction between the aquifers system and the subway tunnels is another important topic. In addition to the presented methods the discharge into tunnels can be quantified using the same technique as presented for the sewer conduit by taking the hydraulic head in the tunnel equal to zero. The obtained values can be evaluated if compared to the admissible infiltration rates indicated by the construction design criteria for tunnel sealing and waterproofing. For the Bucharest subway construction elements the following admissible values were taken *(Sebesan and Voinescu, 2010):*

- *stations and galleries max. 1,0 l/s *km;*
- *tunnels max. 2.0 l/s * km.*

One can accept that these values can be exceeded due to aging degradation of the sealing and waterproofing.

Discussions and Conclusions

The study of the urban hydrogeological systems requires a good knowledge of the aquifer system and its interaction with the urban infrastructure. This is quite complex and various tools to describe and to assess the effect of each component (mathematical model, analytic, or empirical methods) are still necessary.

Starting from some urban groundwater aspects, this section outlines specific modelling problems reported in different case studies, as the typical urban factors interacting with groundwater.

This research direction presents a global conceptual schema of an interactive system to manage groundwater data for distinct modelling activities at a city scale level. This uses a combined interdisciplinary approach involving geology, hydrology, hydrogeology, geography, geotechnical engineering, and computer sciences.

A summary of methods useful for the quantification of the recharge sources encountered in urban areas is provided. This focuses mainly surface channel seepage, sewers leakage, and water supply system losses. A technique is proposed for the estimation of the infiltration/exfiltration sewer rate using the leakage factor approach. This is based on the hydraulic gradient of the exchange flow direction between the aquifer system and the sewer conduit.

Apart the sewer system that could work as a recharge source as well as a discharge one, this section presents a summary of some methods that can be used for the quantification of the discharge sinks encountered in urban areas.

1.2. Quantitative assessment of the groundwater-sewer network interaction

The groundwater management in urban areas has to take account each possible and relevant phenomena that could arise from the complex interaction between subsurface water, surface water, and urban infrastructure. In Bucharest, the need of the sewer system rehabilitation initiated a study of the interaction between groundwater and the sewer network. Recent conclusions show that the sewer network acts mainly like a drainage system for the groundwater. However, it could be easily proven that several sewer segments located mainly in the unsaturated zone contaminate the groundwater by leakage. The groundwater infiltration in the sewer conduits can cause the decrease of the groundwater level leading to structures instability problems as well as to the increase the sewer system flow-rate. This last one affects seriously the wastewater treatment plants efficiency. The sewer network leakage generates groundwater pollution and locally could increase the groundwater level triggering buildings instability or other urban operational problems. The current study, developed within the research project "Sedimentary media modelling platform for groundwater management in urban areas, SIMPA" (*www.simpa.utcb.ro*), focuses on the consequences of sealing a part of the sewer system to eliminate groundwater-sewer conduits interaction. Doing this the existing groundwater behavior disturbance appears which may lead to serious consequences. In this framework are presented the analysis results of a groundwater flow model used to quantify the interaction between the groundwater and the sewer network.

Introduction

The integrity of the sewer systems is crucial to guarantee the transfer of wastewater from domestic, commercial and industrial users to treatment plants with no infiltration or exfiltration phenomena during this process. Groundwater infiltration into sewer systems has an important impact on treatment plants efficiency, while wastewater exfiltration is prejudicial to ground and to surface water quality.

Leakage of the sewer system represents a major source of groundwater pollution by means of nitrates, nitrite, phosphorous, chloride, boron, bacteriological contamination and others. Important contributions of the groundwater recharge from the sewer system losses have been reported in many case studies as for example Doncaster (UK) with 30-40% *(Rueedi et al., 2009)*, Rastatt (Germany) with 5-12% *(Wolf et al., 2006)*, and San Luis Potosi (Mexico) with 11% *(Martinez et al., 2010)*.

In the literature two contradictory viewpoints concerning the amount and the impact of exfiltration can be found:

1) The global environmental impact of exfiltration from sewers is insignificant due to negligible exfiltrated volumes, biodegradation, and pollutants adsorption during their pass through the soil. It has been argued that despite some extreme, exceptional loss cases, there is little evidence that sewer leakage endangers groundwater resources at a large scale (*Dohmann et al., 1999*; *Fenz, 2003).*

2) Exfiltrating sewers can be a major source of groundwater contamination *(Hornef, 1983; Bishop et al., 1998).* Nevertheless, many studies acknowledge that the associated impact is strongly variable *(Eiswirth and Hotzl, 1997; Ellis and Revitt, 2002; Klinger et al., 2005)* in both time and space.

The present section treats the interaction between urban groundwater and urban infrastructures. The focus is on the sewer system. The case study is a pilot zone of Bucharest city. The problem is approached from a quantitative point of view by mathematical modeling of the groundwater flow.

For the studied zone, the urban water cycle (Figure 1-4) elements are: water supply network exfiltration, sewer system leakeage or draining effects, a drainage gallery (located along the main sewer conduit) interaction with the aquifer, subway tunnels in relationship to groundwater, and the Morii Lake equipped with an earth made dam and a screen wall. Also, through the studied zone flows a lined river (Dambovita River).

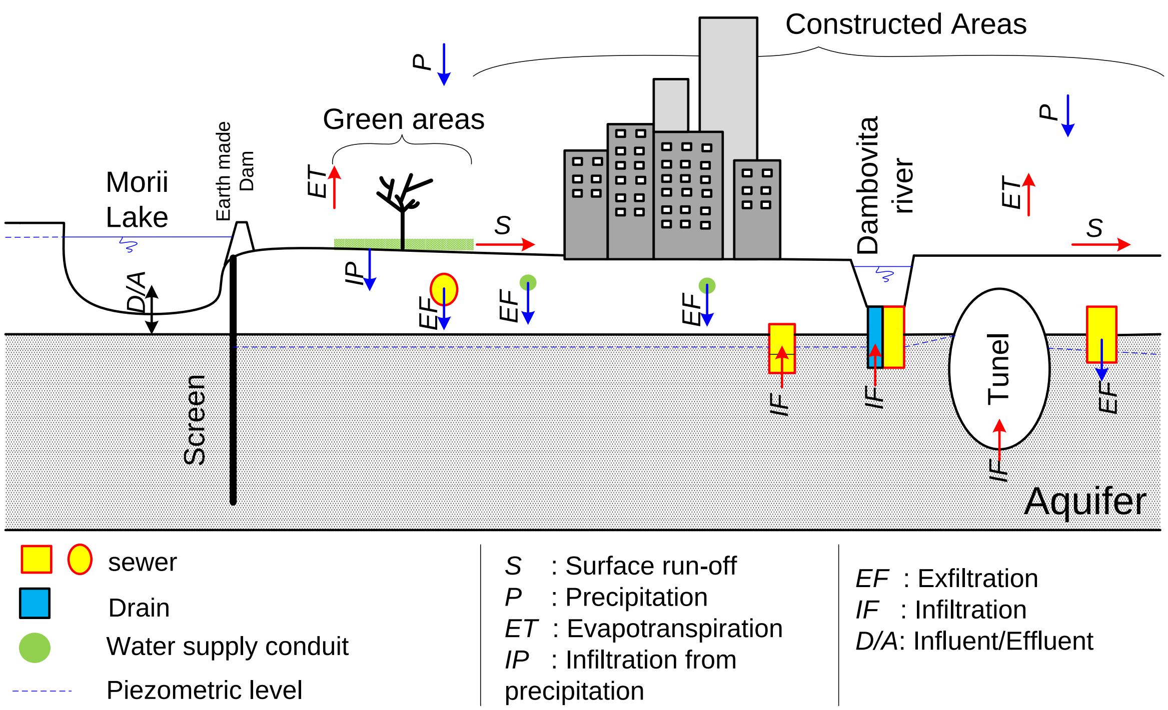


Figure 1-4 Urban water cycle of the study zone

The study zone

A pilot zone in the West region of Bucharest city, downstream Morii Lake, has been chosen. It is an urban area of about 9 km^2 (Figure 1-5). In the south east, the study area is delimited by a line representing future subway tunnels (currently in the design phase).

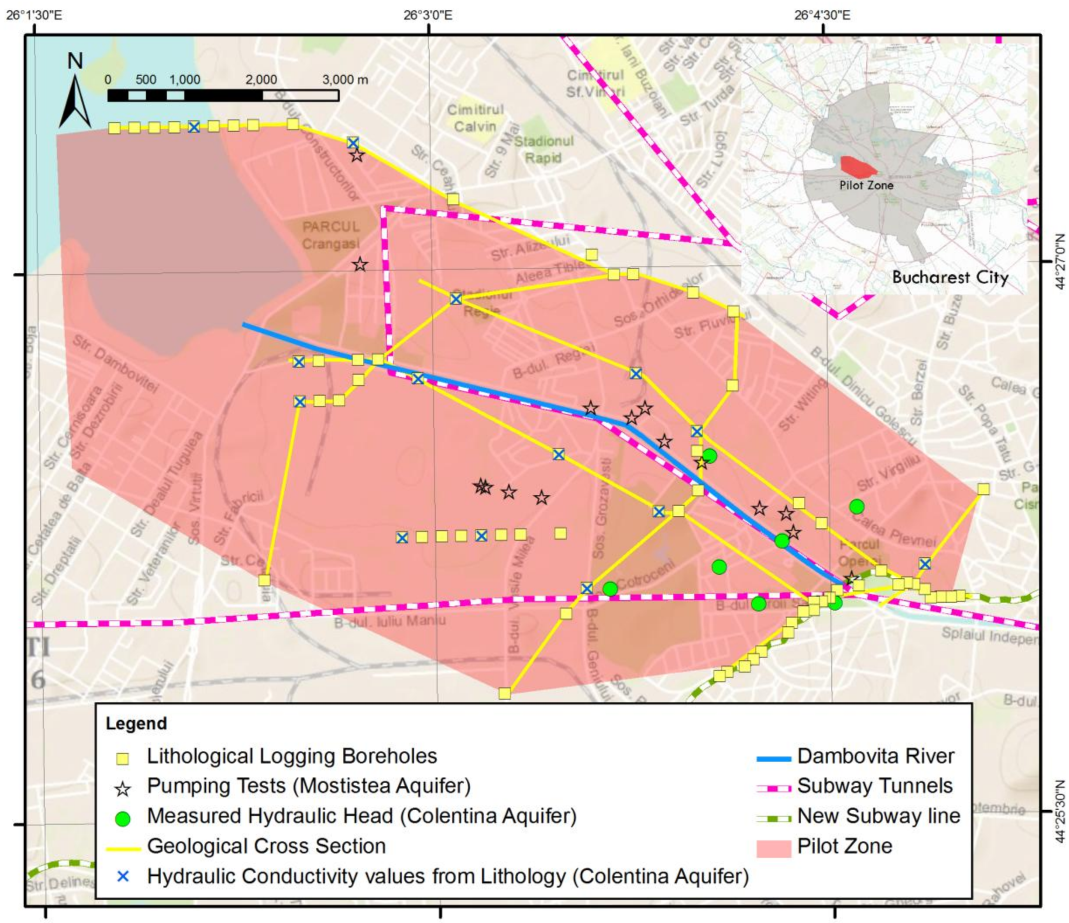


Figure 1-5 Map of the study zone and the spatial distribution of the data

Geological conditions

The lowest porous media aquifer system called "Fratesti strata" (*Liteanu, 1952*) is placed in the Tertiary deposits of the Upper Pleistocene and of Lower Pleistocene. It behaves as a confined multilayered aquifer and can be found at depth between 150 m and 200 m. A sequence of marl and clay layers with slim sandy intercalations overlays the "Fratesti strata". In the Bucharest area its thickness decreases from north to south from about 150 m to 40 m. 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. This upper aquifer stratum, of these quaternary formations, called “Colentina gravels” is made of gravels and sands. This unconfined aquifer layer 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 m to 10 m depth. The aquifer thickness is between 3 m 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 called “Intermediary deposits” is located between the “Mostistea sands” and the “Colentina gravels”.

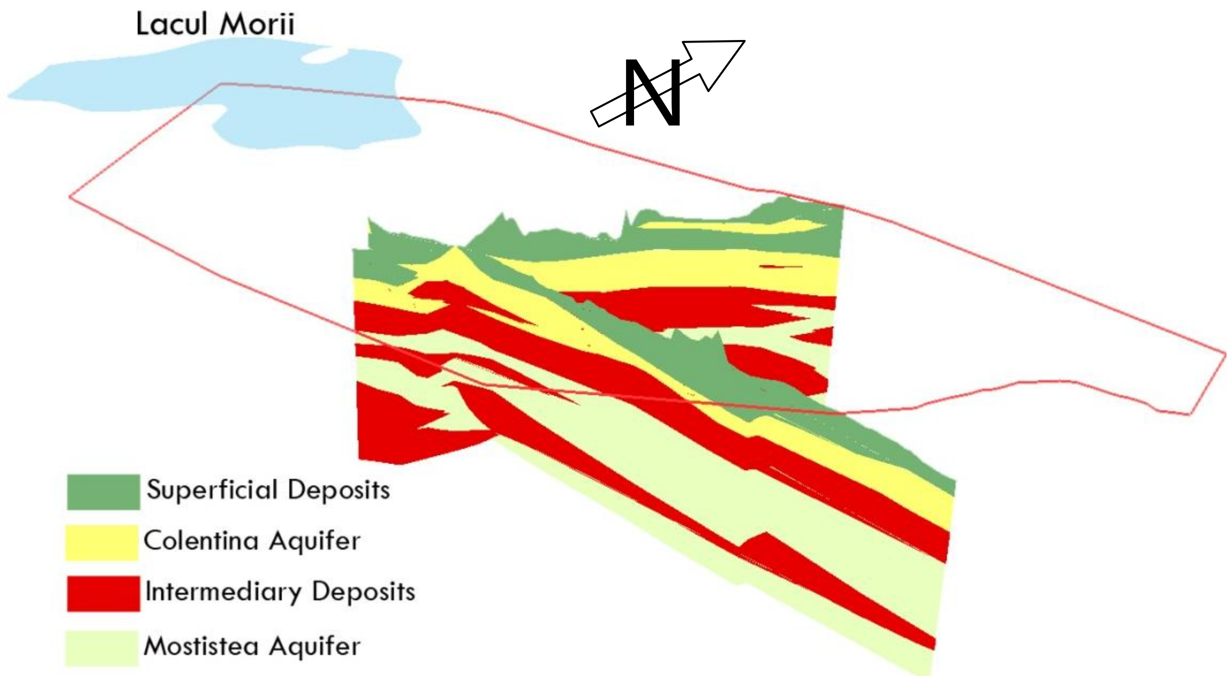


Figure 1-6 3D geological cross-sections in the study zone

Hydrological and hydrogeological settings

Modelling the urban water cycle requires the quantification of the effect of each urban water cycle element (natural or humane made) on groundwater. These interacting components can act as a recharge source, a discharge sink, or a flow barrier.

Morii Lake, with a surface of about 2.2 km^2 representing a reservoir of 15x 10^6 m^3 is located at about 3 km from the centre of Bucharest. The lake is equipped with an earth man-made dam with a screen wall. This screen wall, made of cement-bentonite, has about 23 m depth and 0.6 m thickness. It is located on the northern to north-western contour of the lake *(Popescu & Lăzărescu, 1988).* The water level in the lake was used as a specified head boundary condition for the hydrogeological flow model. A similar boundary condition was set-up by applying the hydraulic head measurements of the boreholes located along the line of the future subway tunnel.

Groundwater recharge from precipitation was estimated by using Soil Conservation Service (SCS) model *(United States Department of Agriculture, 1954).* The following values of recharge rates were given function of the land-use: **i)** 1.3 mm/day for areas covered up to 50% with vegetation, **ii)** 1.6 mm/day for areas covered up to 70% with vegetation and trees, and **iii)** 0.4 mm/day for areas covered by buildings, concrete works, and similar.

The main sewer collector system (made of 2 parallell sewer galleries and a groundwater drainage gallerie) is located under the lined Dambovita River having a segment of 3.3 km length in the study zone (between Morii Lake and Eroilor Bridge). According to a technical study elaborated by the water supply operator ApaNova Bucuresti (ANB) in 2009, the drain constructed along the main sewer collector system discharge groundwater with a total rate of 0.22 m^3/s. This observed value was used in the groundwater flow model calibration.

The study zone is crossed by subway tunnels (as shown by Figure 1-5) representing segments of two subway lines: Magistrala 1 (M1) and Magistrala 3 (M3). These tunnels act on groundwater like **i)** drains, when considering the infiltrating groundwater and as **ii)** horizontal flow barriers, by obstructing totally or partially the natural flow conditions. This second behavior feature leads to a differential fluctuation of the groundwater level around the tunnel. Considering the total measured groundwater infiltration rate into the entire subway tunnels network of Bucharest city (estimated by ANB in 2009 to be of about 0.2 m^3/s), it was possible to obtain observation values (assuming a uniform linear distribution of the total infiltrated rate) when modelling the drain effect of the tunnels. These values were used for the calibration of the groundwater flow model.

The estimation of the groundwater recharge coming from the water supply network was done by considering a uniform areal distribution of the total leakage rate. This total loss was estimated (according to a technical study of ANB in 2009) to be about 2.5 m^3/s (representing about 29% of the total water supply production of Bucharest city). Thus a 1.2 mm/day groundwater recharge rate corresponding to this source was adopted for the hydrogeological model.

Since the effects of the sewer system depend on sewer conduits positions in the aquifer system, some of the sewer conduits were modelled as drains (to represent the infiltration phenomena) when others were modeled as recharge sources (to represent the exfiltration phenomena).

Hydrogeological model

The modeled aquifer system structure (first two aquifer layers Colentina and Mostistea separated by the Intermediary deposits aquitard) use an accurate 3D geological model. This relies on 8 geological cross-sections interpreted using lithological logging of 73 boreholes. The spatial distribution of the cross-sections and boreholes is given by Figure 1-5. Two cross-sections integrated in the 3D geological model are illustrated in Figure 1-6.

A pseudo-3D steady state groundwater flow model using MODFLOW software (Environmental Modelling Software-Inc.) was elaborated. The model provides a better understanding of groundwater flow in urban area of Bucharest city, with a focus on the interaction with the sewer system.

In order to preassess a type of behaviour (as drain or as recharge source) of a given sewer conduit segment, there is a need to localize the zones where the sewer segment is located in the aquifer and where is located above the aquifer. This was initially obtained by intersecting the 3D geological model with the 3D sewer network representation. This procedure allowed the classification of the sewer system into zones function of the conduits location: sewer conduits crossing the Colentina aquifer and sewer conduits located above this aquifer (results are represented in Figure 1-7). The sewer conduits crossing the aquifer were modelled with two elements: a drain and a recharge source. In this case, the sewer behaviour (infiltration or exfiltration) was defined function of the predominant effect of these elements resulted from the model calibration. For the zones with sewer conduits located above the aquifer, the draining effect of is null and thus only the recharge source component was used.

The spatial parameterization of the modelled aquifer system was done in terms of horizontal hydraulic conductivity for the two aquifer layers (Colentina and Mostistea) and vertical hydraulic conductivity for the aquitard (Intermediary deposits). The spatial distribution of these parameters was obtained using the pilot-points method. The punctual values of the considered parameters were obtained from pumping tests (in 15 wells) for the Mostistea aquifer, and estimated by using the lithological description for the Colentina aquifer. The spatial distribution of the used data is given in Figure 1-5. Finally, the model was calibrated against piezometrical head data using inverse optimization.

Results

The calibrated model shows clearly a disturbance of the natural groundwater flow caused by the interaction with urban infrastructures. As presented in Figure 1-7, the flow direction in the upper aquifer is toward the central zone where is located the drainage gallery of the main sewer collector. Also, the changes of the flow direction and velocities in vicinity of the subway tunnels emphases their barrier effect on the groundwater flow.

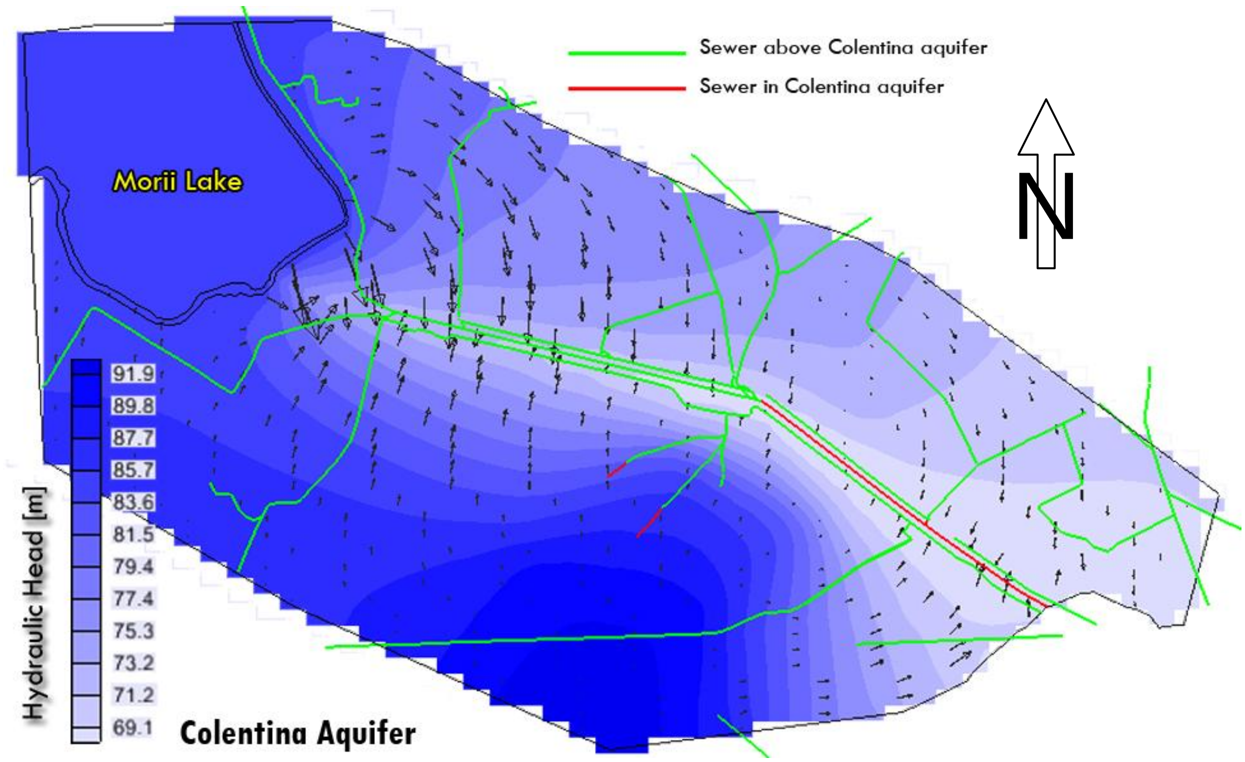


Figure 1-7 Hydraulic head and flow directions of the modeled Colentina aquifer layer

Furthermore, it was found that Morii Lake drains the upper aquifer in its southern part and feeds the same aquifer in its northern part.

The model results indicate also that the sewer conduits located in the Colentina aquifer layer have a drainage effect showing that they are feeded by groundwater. The rest of the sewer conduits show a recharge source effect and thus exfiltrations are present for these conduits.

The spatial distribution of the horizontal hydraulic conductivity for the Colentina aquifer issued after the model calibration is given in Figure 1-8.

The flow budget of the study zone indicates that about 40% of groundwater recharge comes from the losses of the water supply network, while more than 2% comes from the leaky sewer conduits and about 10% from precipitation.

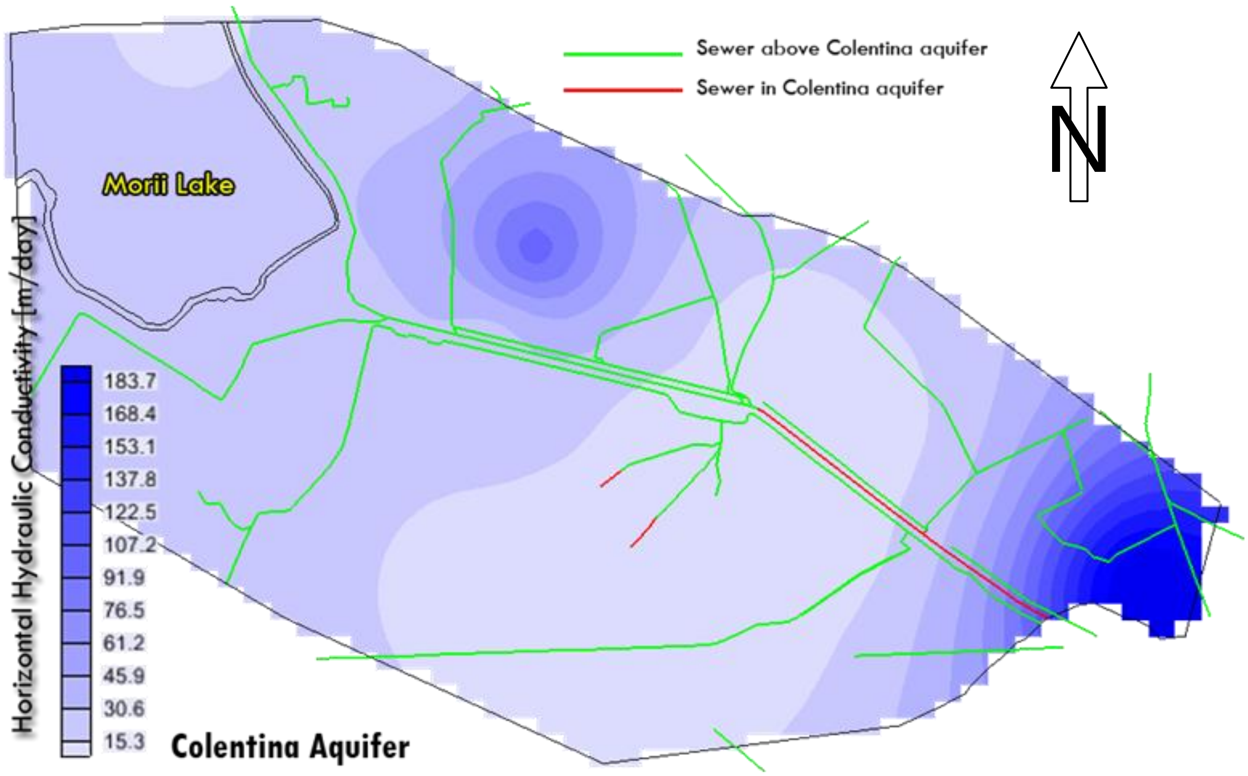


Figure 1-8 The spatial distribution map of the hydraulic conductivity of the modeled Colentina aquifer layer

Conclusions

The two-layers groundwater flow model simulating the Colentina and Mostistea overlaid sedimentary relies on a 3D geological model made by using 8 accurate geological cross-sections of the studied domain. The model set-up and its calibration are done by using pumping tests data, groundwater hydraulic heads, and water levels measured in the sewer system. The advantage of using a groundwater flow model when quantifying the exchange with the sewer system lies on the possibility of computing the leakage rate from sewer system. This is not the case when using the dry weather flow method because it provides an equivalent response of the system resulting from the sum of every infiltration and leakage rates. Thus only the predominant component will be pointed out: either the infiltration or the leakage rate.

The obtained model is part of a larger ongoing national research project (*www.simpa.utcb.ro*). These first results show that it can be further improved in order to simulate the sewer system rehabilitation effect on groundwater. It will allow the design of different solutions in order to finally prevent urban disturbances.

The conducted study shows clearly the important impact of urbanization on groundwater:

(a) Water cycle disturbance, since about 42% of groundwater recharge comes from the leakage of the water supply network and of the sewer system;

(b) Groundwater level fluctuation induced by barrier-like effect component (subway tunnels, screen wall, etc.);

(c) The groundwater quality deterioration is very probable since the exfiltrated sewage water is an important source of pollutants such as nitrates, chloride and bacteriological contamination.

The obtained model can be used to simulate the sewer system rehabilitation effect on groundwater and thus will allow the design of different solutions in order to finally prevent urban disturbances.

1.3. Integrated study for tunneling development in sedimentary media

An extensive experimental and modeling study (El Prat de Llobregat - Barcelona, Spain), on the aquifer system behavior during a subway tunnel execution, has been developed within a research project collaboration established between the Technical University of Catalonia (Barcelona, Spain) and the Spanish FCC (*www.fcc.es*) infrastructure development company. The study has been conducted between 2008 and 2009. In this project, four directions were followed (*Gogu et al. 2008*): the first one consisted in geological, geotechnical, and hydrogeological data collection, during an extensive geological and geotechnical field measurements campaign, developed in a pilot area in the urban environment before, during, and after the excavation of a subway tunnel; the second direction consisted in the design and development of a platform for temporal and 3D spatial data management and visualization; the third direction was the development of a hydrogeological model simulating the behavior of the aquifer system (*Monfort et al. 2008*); and the fourth direction is a correlation study of the recorded parameters using the excavation machine (TBM type EPB), during the tunnel execution, with the parameters resulted from the field measurements campaign. In the following section two of the four analyzed directions are presented.

<u>*Data acquisition*</u>

A pilot area was selected along the L9 subway line (Figure 1-9) in El Prat de Llobregat (suburb of Barcelona city) located between the emergency shaft - exit 3B and the metro station Sant Cosme of El Prat de Llobregat.

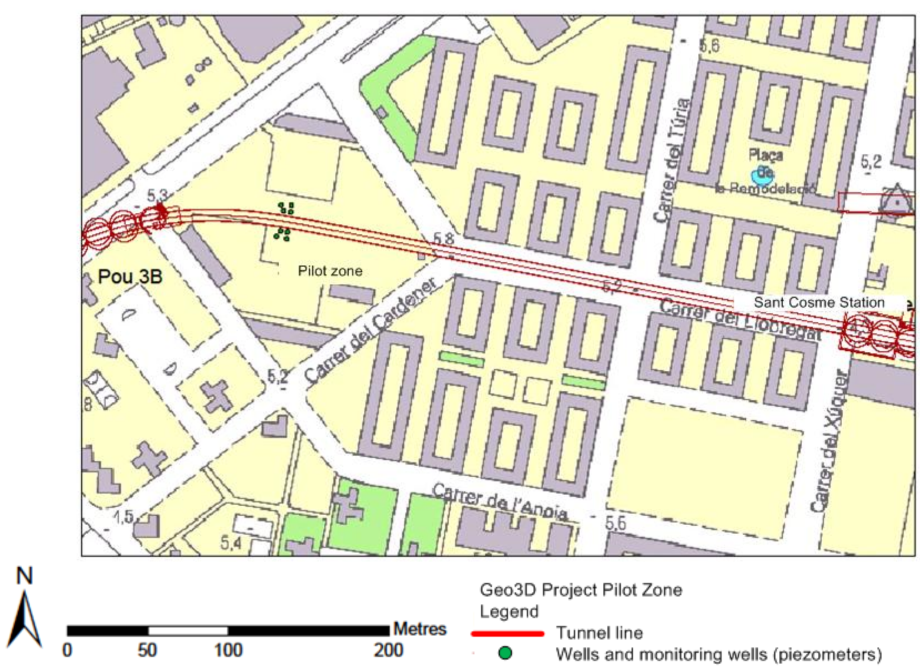


Figure 1-9 The study area in Sant Cosme district (El Prat de Llobregat, Barcelona)

Figure 1-10 Location of the wells and piezometers in the study area.

Geological studies

Methodology

Six monitoring wells (piezometers) and two wells used for hydraulic tests were constructed in the study area, their location being symmetrical to the tunnel axis (Figure1-10). The monitoring wells (piezometers) were drilled in continuous mechanical logging, thus sampling was possible.

The piezometers were drilled at three different depths (Table 1-4), having their screens at three different intervals, thus being possible to track the water table variations in three distinct geological formations.

Table 1-4 Altitudes, depths, and screen location for the wells and piezometers in the pilot area.

	Altitude (m)	**Depth (m)**	**Altitude of the screen position (m)**	**Distance from the tunnel axis (m)**
Well 1	5.50	30	Slotted until -24.5	8
Well 2	5.50	30	Slotted until -24.5	8
Piez-1	5.31	30	between -20 and -24	8
Piez -2	5.50	30	between -20 and -24	8
Piez -3	5.465	15	between -4.5 and -8.5	12
Piez -4	5.42	20	between -7.5 and -12.5	13
Piez -5	5.34	20	between -9.5 and -13.5	13
Piez -6	5.335	15	between -4.5 and -8.5	12

The deepest piezometers (PA1 and PA2) were drilled at depths of 25 meters. In the pilot area the subway axis reaches the depth of 13.5 meters. Given the fact that the tunnel diameter is 9.2 meters, it is located at altitudes between -8.8 and -18.2 meters (*Reference: Mediteranean Sea level*).

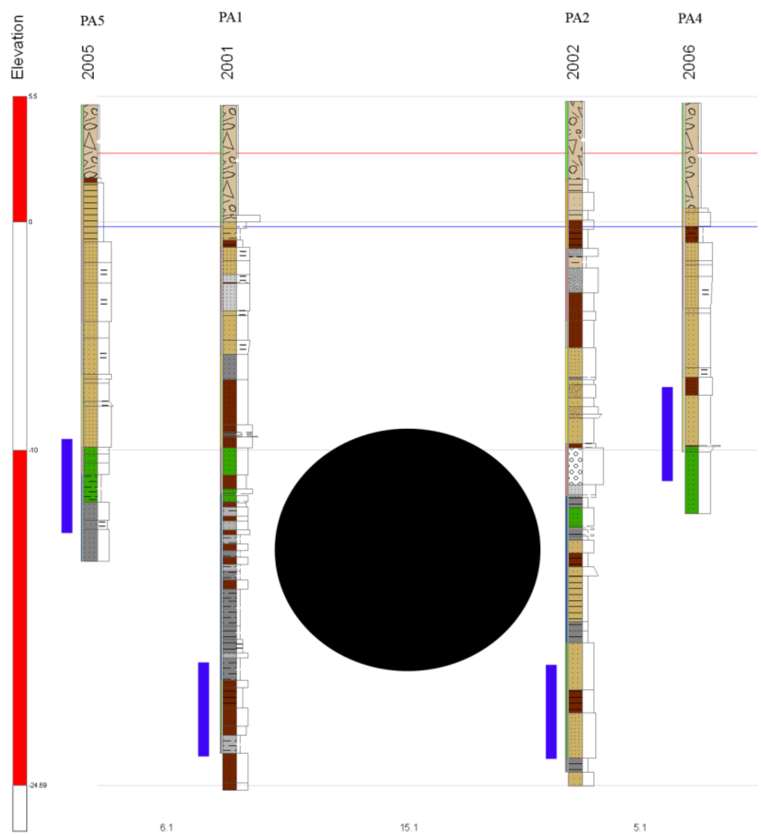


Figure 1-11 Tunnel cross-sections with four lithological columns. (*The tunnel cross-section in the pilot area is marked by the black filled circle. The location of the screens is marked in blue*.)

The deltaic material, resulted after the geological survey, has been divided into three main units: (1) Sediments of the deltaic plain; (2) Detritic sediments of the frontal delta; (3) Pro-deltaic sediments

1. Deltaic plain

Deltaic sediments of the main geological unit consist mostly of brown-gray clays with intercalations of sand and very fine sand. This unit presents thicknesses between 2 and 3 meters and varies function of the thickness of the superficial layers corresponding to the anthropic deposits. In the studied area these deposits are located between 3-5 meters and 6-6.5 meters depths.

2. Frontal Delta

The second unit is characterized by a succession of facies consisting of silty fine sand to coarse sand with some gravel crossings, alternating with fine sand with a clayey matrix. This unit is located just after the previous described unit. They are separated by a stratigraphic discontinuity. Together, these geologic materials correspond to the frontal delta sediments where beach and fluvial channels environments are distinguishable. The thickness of this unit varies between 9-11 meters and can be found at a depth of about 17 meters. From the hydrogeological point of view they belong to the shallow aquifer.

3. Pro-deltaic

The last geological unit consists of fine-grained deltaic sediments composed mainly of clay and sandy silt sediments. It is characterized by alternations of clayey mud that becomes sandy. From the hydrogeological point of view this unit represents an aquitard. The granulometry of the sands, that form the superficial deposits, is higher than the one found in the lower deposits.

Hydraulic tests and modeling

Four pumping and tracer tests were performed in the study area, two of them before starting the excavation of the tunnel and two after the tunnel was finished. For each test only one of the wells was used for pumping. The approximate duration of these tests was about seven days. The water was pumped at a flow-rate varying between 5 l/s and 4 l/s, although in one of the pumping tests the flow-rate value was 3 l/s.

In all the pumping tests three tracer substances were injected in different monitoring wells (piezometers), always injecting a tracer in the piezometer with the smallest depth located on the other side of the tunnel. The tracer substances were injected once the piezometric head was stabilized, at a day and a half after the pumping was finished. The used tracers were Rhodamin, Fluorescein, Eosin, NaCl, NaI, and NaBr.

The pumping tests were simulated using the finite element software TRANSIN IV *(Alcolea et al 2004)*. The objective of the modeling was to have a good approximation of the hydraulic parameters of the geological materials. At this point, the tunnel presence was not taken into account.

Starting from the initial geological description, first results obtained through a detailed geological analysis and boreholes logging were incorporated. A conceptual hydrogeological model for 6 layers has been obtained. Out of this, the numerical model was defined for the 6 layers together with 5 one-dimensional elements, located between the layers (Figure 1-12), allowing the vertical water flow.

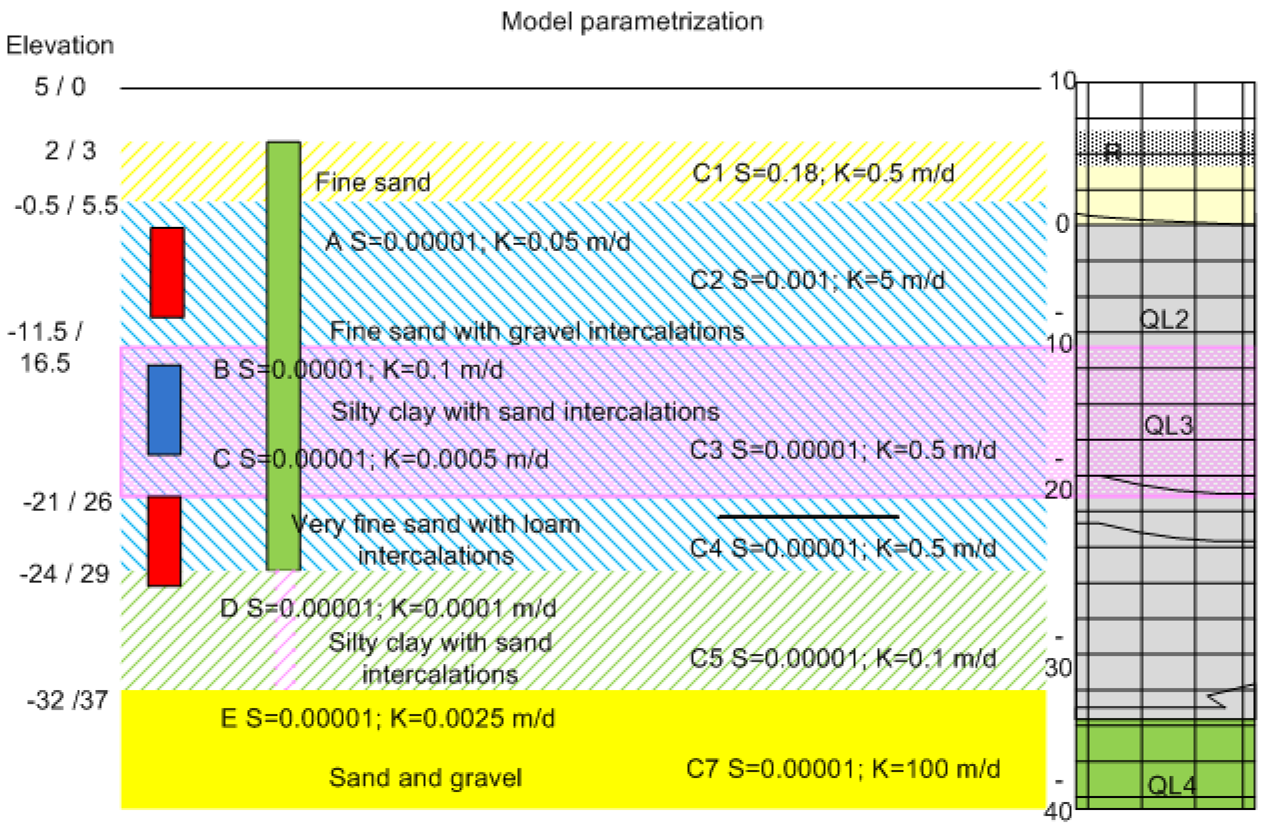


Figure 1-12 Flow model parameterization using TRANSIN IV. (*In pink the subway line is represented.)*

The model is a square area of 2000 x 2000 m, the study area being located in the centre of this model. The mesh of the model was made so that in the area of the boreholes the cell size dimensions are about 0.5 to 1 m (Figure 1-13).

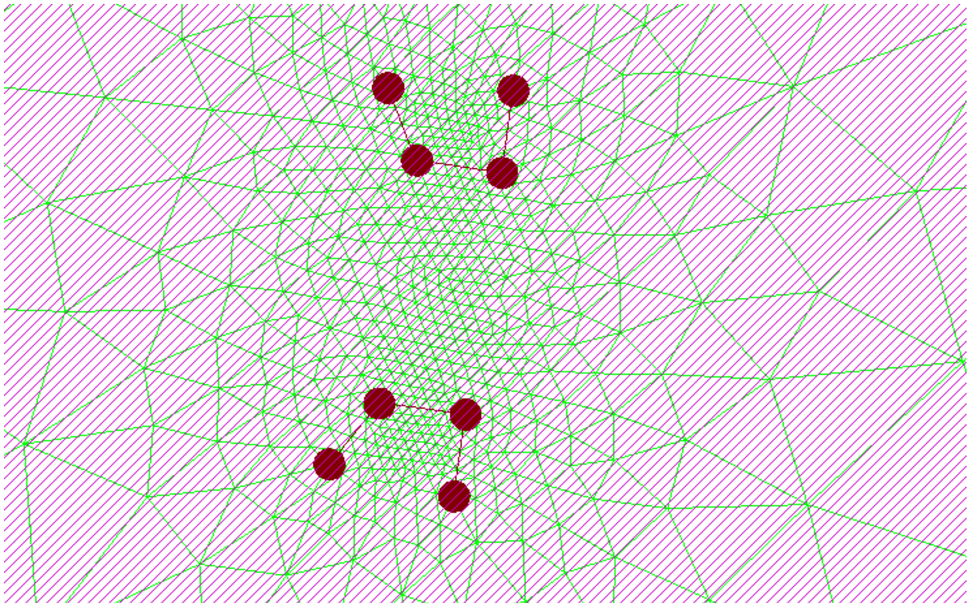


Figure 1-13 View of the finite elements mesh for the boreholes area in the pilot zone

The model results show a general good correspondence between the measured and the computed values. The first two tests, performed before the beginning of the tunnel excavation, are in good correlation with the measured aquifer parameters variation. The exception is made by the monitoring wells PA1 and PA2 (Figure 1-14) where the observed water levels recovery is higher than expected.

After the first two tests, the tunnel was excavated. This effect has not been considered by the model. Later, for the third and the fourth pumping tests, the calibration strongly depended on the drilled depth of the piezometers. The simulation continues correctly for the two shallow piezometers PA3 and PA6. As these points are situated at a higher elevation than the tunnel elevation, there has been not observed any effect produced by the tunnel. In return, for the piezometers located at depths equal to the tunnel depth (PA2, PA4, and PA5) as well as for the two wells, the effect of the tunnel was observed. When the observation point is on the same side with the pumped well, variations in measured and computed water levels are in a very good correspondence. In return, if the observation point is located on the other side of the tunnel, the simulated values for the water levels are lower than the observed ones. This means that the tunnel has a major impact on groundwater by reducing the aquifer hydraulic conductivity at this level.

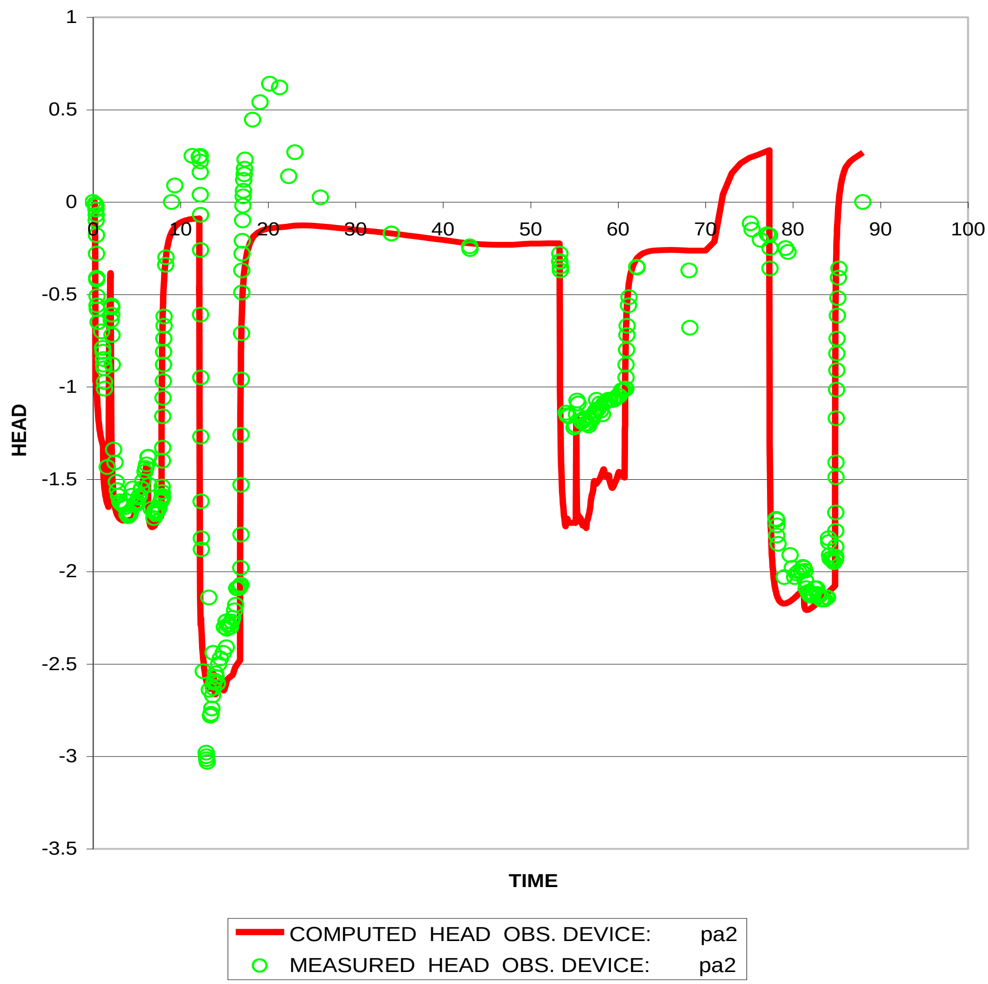


Figure 1-14 Comparative variation between the measured and the computed values for the PA2 piezometer

Parametres of the Tunelling Borring Machine-TBM

Various parameters were measured while the TBM passed through the pilot area. The hydraulic heads were measured at intervals of 10 minutes for the wells and the monitoring wells (piezometres), where automated level sensors have been also installed. The results consisted in very detailed records of water level variations (considered necessary to follow the advance rate of the tunnel) in six different points.

On the other side, from the TBM's cabin all the TBM recorded parameter values were provided. Average values for each parameter correlated with the excavated ring were extracted. In addition, for each ring the starting and the finishing excavation time was obtained (the initial and the final time for the ring set-up and the time the machine stops). In the same time, soil samples were collected for each ring, on which granulometric analysis were performed.

Starting from the piezometric head measurements and the comparison of these with the TBM's cycles as well as with positioning of the machine in relationship to the studied area, the followings can be mentioned:

The piezometric heads values in the monitoring wells, located at a higher level (PA3 and PA6) as well as for those located at the tunnel elevation (PA4 and PA5) measured at each of the TBM's cycles (excavation and mortar injection phases), show an increase of the groundwater levels that sometimes reachs 50 cm height (Figure 1-15). The peaks of the graphic do not always correspond to the same point of the cycle, but usually occur at the end of the cycle. It must be mentioned that the measurements performed with a time step of 10 minutes do not allow the observation of the entire water level fluctuation. The levels return to the original state immediately when the machine stops. Function of the time-step duration between the measurements, the level fluctuation can be more or less pronounced. Another influencing factor is the distance between the monitoring wells and the frontside of the TBM. As the TBM gets closer to the pilot area, the magnitude of the water level rise increases, while as the TBM is moving away the magnitude of the water level rise is decreasing. However, the maximum levels have been recorded in PA5, when the front side of the TBM has surpassed the section with about 9 meters. It should be noted that in PA4 the water level rise trend has been respected, although without having the sudden peaks corresponding to each cycle of the TBM.

This results show that during the excavation of the tunnel, the TBM transmits a stress in the ground that produces an increase of the piezometric head. In addition to the stress produced by the TBM, it must be taken into consideration the mortar injection operation (in the empty space between tunnel rings and the surrounding soil). This injection could explain why the highest level is not observed when the front side of the TBM is located between the monitoring wells (piezometers), but only after the TBM moved forward several meters. The mortar is usually injected at a distance of 3 - 4 rings behind the front of the TBM.

A distinctive behavior of the groundwater levels has been observed for the PA1 and PA2 piezometers (Figure 1-16). Being drilled deeper, the screens are located at a lower elevation than the tunnel bottom. Starting from a certain point, a sudden decrease of the piezometric head has been observed for these monitoring wells (piezometres). This is explained by the void that appears and means that the tunnel causes a decrease of the general vertical stress that generates a relaxation of the interstitial pressure.

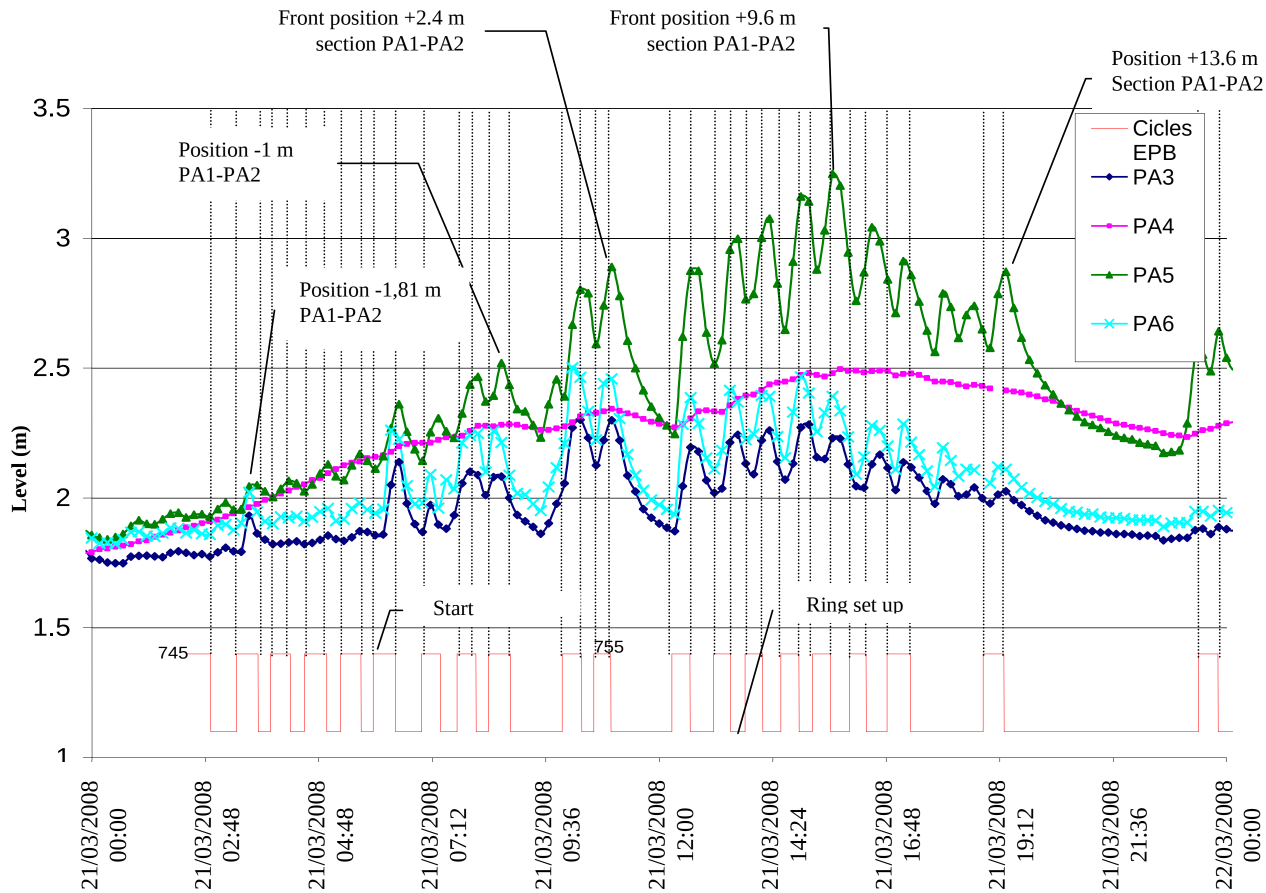


Figure 1-15 Piezometric head fluctuation in PA3, PA4, PA5 and PA6

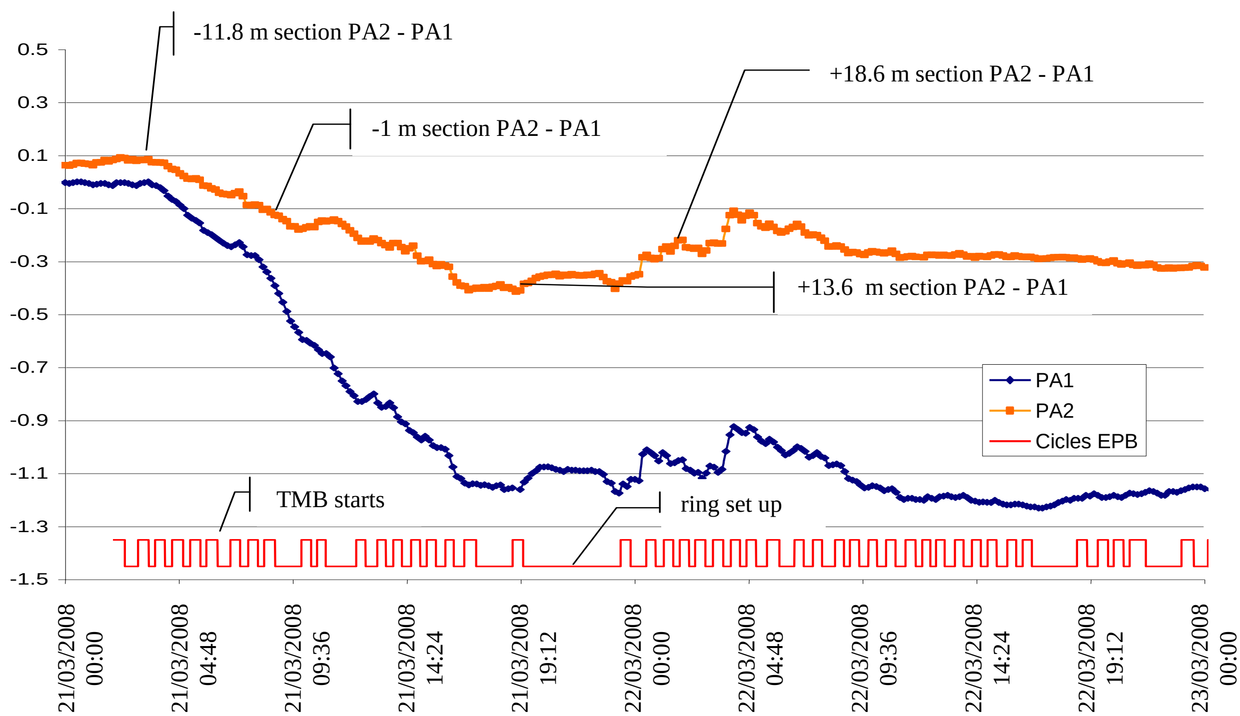


Figure 1-16 Piezometric head fluctuation in PA1 and PA2 during the TBM passage

2. Groundwater vulnerability

2.1. Groundwater vulnerability concepts and assessment methods

Vulnerability mapping is one of the tools used to establish protective measures for groundwater bodies. Vulnerability to pollution maps is instrument for taking preventive or corrective measures with respect to land use to protect groundwater. Their objective is to subdivide the land by establishing categories according to the natural capacity of the environment to protect groundwater. These maps are designed to protect the water body and not the water collection point (*COST 65, 1995*). It is necessary to distinguish between resource and source protection although both concepts are closely related to each other (it is impossible to protect the source without protecting the resource). Therefore, **COST 620** proposed to distinguish between two types of intrinsic vulnerability maps: ones describing the vulnerability of the source and the others the vulnerability of the resource (*Zwahlen, 2004*).

Groundwater vulnerability is the aquifer susceptibility to contamination as a result of the impact of human activity at the land surface (*Foster, 1987*). This concept is based on the assumption that the physical environment provides a natural protection to groundwater (*Vrba and Zaporozec, 1994*). These authors stress that vulnerability is a relative property, dimensionless, and difficult to measure. It is possible to distinguish between two main concepts related to vulnerability. Intrinsic vulnerability is the susceptibility of groundwater to pollution generated by human activity in terms of geological and hydrogeological characteristics of an area, but regardless of the nature of the contaminants. Specific vulnerability is the susceptibility of groundwater contamination with a certain pollutant or group of pollutants according to their characteristics and their relationships with the components of the intrinsic vulnerability (*Zwahlen, 2004*).

The **COST 620** (Vulnerability and risk mapping for the protection of carbonate aquifers) action has been an important milestone in the vulnerability assessment of carbonate aquifers. Carbonate aquifers deserve special attention, because they are a worldwide major resource for water supply and stand out as being especially vulnerable to contamination. This is in general due to the lack of protective cover, concentration of flow in the epikarst and in swalowholes as preferential infiltration pathways causing the contaminants to quickly reach groundwater and to travel long distances at high speed due to the presence of karst conduits.

The concept of groundwater vulnerability is based on a proposed conceptual model of “origin-pathway-target” type as shown in Figure 2-1. The origin corresponds to the place where the contaminant infiltration occurs. The flow path that follows to reach the groundwater describes the pathway, and the target represents the water table (*Daly et al., 2002, Zwahlen, 2004*). Cost A620 action proposes a conceptual framework that considers four factors for vulnerability mapping: surface layers (O factor), flow concentration (factor C) and precipitation regime (P factor) to assess the vulnerability of the resource and karst development (K factor) for the source (*Daly et al., 2002, Zwahlen, 2004*).

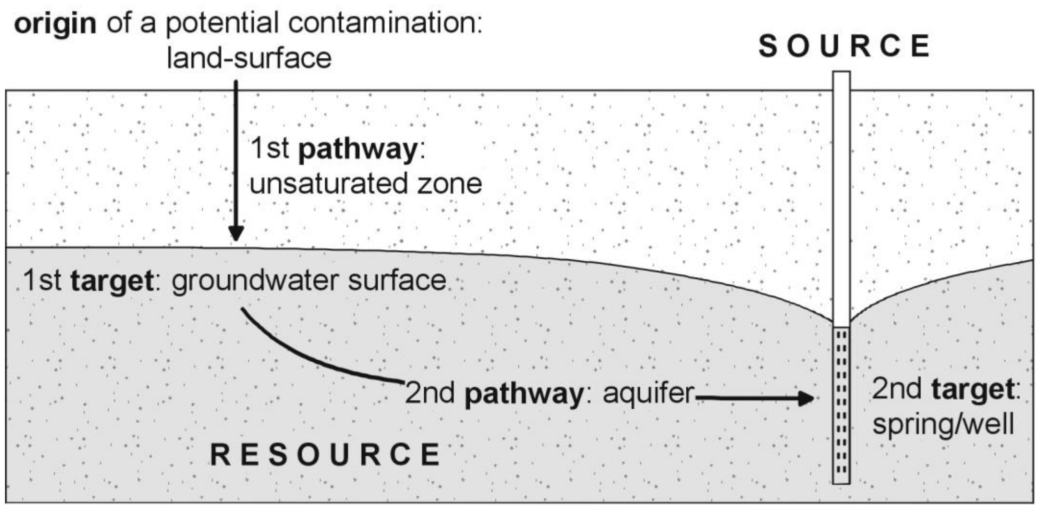


Figure 2-1 Conceptual model of "origin-pathway-target" type (modified from *Daly et al., 2002*)

The assessment of vulnerability to contamination can be classified into three groups:

1. **Cartographic models.** They are based on a combination of maps of various parameters (lithology, soil, thickness of the unsaturated zone, etc.). Three sub-groups could be identified (*Gogu and Dassargues, 2000a*):
    a. <u>*Complex hydrogeological methods*</u> (HCS). These types of methods involve a qualitative assessment. To do this, one should first determine the hydrogeological, hydrological and morphological conditions corresponding to each class on a vulnerability scale. Then, the selected study area is analyzed and divided according to established criteria. Generally, the obtained maps are overlapped to obtain a proper result. These methods are used to assess vulnerability at a medium-large scale.
    b. <u>*Parametric systems*</u>*:*
        i. Matrix systems methods (MS). These methods consider a few representative parameters of the study area. To obtain a quantified level of vulnerability is necessary to combine these parameters following different approaches that involve research in specific sites.

   ii. Indexed systems methods (RS). These methods provide a fixed range of values for each parameter considered necessary in the vulnerability assessment. The sum of the ratios of each of the parameters is obtained by overlaying them. The final numerical value is divided into several classes expressing different levels of vulnerability.

  c. *<u>Methods involving weighting and quantification of parameters</u>* (PCSM). These methods use the same procedure as indexed systems methods and also use weighting indices to differentiate the relative importance between the various parameters.
  d. *<u>Analytic index based relations</u>*. They are based on the mathematical description of the hydrological and hydrogeological processes.

2. **Simulation models.** They include the use of equations simulating the contaminant transport processes.
3. **Statistical models.** They are based on a variable that depends on the concentration of a contaminant or the likelihood of contamination.

Over the years, there have been developed several methods to evaluate the intrinsic vulnerability to contamination. Some well known methods (developed in the eighties and nineties) are: **GOD** method (*Foster, 1987*), **DRASTIC** (*Aller et al., 1987*), **AVI** method (*Van Stempvoort et al., 1993*), **SINTACS** (*Civita, 1994*), **ISIS** method (*Civita and De Regibus, 1995*), and **EPIK** (*Doerfliger, 1996*). The most widely used method is **DRASTIC**, usually applied for porous media. This method has undergone multiple modifications including, among others, adapting it for use in carbonate aquifers. For carbonate media, a very well known method is **EPIK** although in recent years its use has been relegated due to the apparition of new methods, like **RISKE** method (*Petelet et al., 2000*), **RISK** method (*Doerfliger et al., 2004; Doerfliger, 2005*) and **PaPRIKa** (*Doerfliger and Plagnes, 2009*).

In the last decade, several specific methods for assessing vulnerability in karstic aquifers have been developed. One of them was **PI** method (*Goldscheider et al., 2000*). Following the rationale and conceptual framework based on the **COST 620** action several methods came out like the **Slovenian approximation** (*Ravbar and Goldscheider, 2007*), **PaPRIKa** (*Doerfliger and Plagnes, 2009*) or the method **COP + K** (*Andreo et al., 2008a*) by including a new factor **K** (Karst saturated zone) in the **COP** method (*Way et al., 2006a*).

It should be noted that the characterization of vulnerability is a qualitative and not a quantitative approach, so the methods of intrinsic vulnerability assessment are a subjective component that can influence the outcome. These methods are applied to different scales to determine the potential for contamination of groundwater. They are not standardized and therefore cannot provide a single assessment of the vulnerability. The differences between the vulnerability maps of the different used methods reflect the specific procedures for identification of system parameters and their weighting and classification.

Referring to these assessments is necessary to point out that at the end of the ’90, the COST Action 620 generated an increased number of methods to assess the vulnerability of aquifers. However, the scientific challenges identified by Gogu and Dassargues *(2000a)* are still valid today. Currently there are two methods that attempt to move away from empiricism provided by most of the methods of vulnerability assessment analysis. One is the **VULK** method, developed at the Hydrogeology Center of Neuchâtel *(Jeanin et al., 2001*) and a new method called **APSU** (protection of aquifers based on the sensitivity of the vulnerability) created at the University of Liege (*Popescu et al., 2010*). Both methods are based on the same criteria for assessing vulnerability to contamination of aquifers.

The **VULK** method has been developed to simulate the mass transport of a conservative contaminant that enters the aquifer at a given point. The model is an analytical solution of advection-dispersion type to simulate the transport of a stable non-reactive flow transient. The lapse between the release of the pollutant and the discharge point is divided into several subsystems: soil, groundwater, unsaturated zone (karstified or not) and karstified saturated zone.

Another concept has been defined by the **APSU** method (*Popescu et al., 2010*) as it combines two aspects, the assessment of the likelihood of contaminants reaching groundwater and its potential impact on their quality. The first of them is considered by combining the evaluation of direct infiltration of water and contaminant discharge point (Direct Potential Dangerosity) and posterior lateral infiltration (Lateral Potential Dangerosity). This combination is called by the authors Land Surface Dangerosity and represents the infiltration capacity of water and contaminants based on properties of the different existing land uses.

The second aspect considered in this method takes into account the attenuation capacity of aquifer and unsaturated zone (Underground attenuation capacity). The first one is evaluated using an advection-dispersion equation without taking into account the phenomena related to sorption and degradation processes. Attenuation capacity of the unsaturated zone is characterized in terms of vertical leaching phenomenon. The overall result is expected in each cell defined in the study area based on three parameters: the first contaminant to reach the goal, the duration of the pollution and the reduction of the concentration.

Analyzing the **APSU** method, one observes the following simplifications:

- The coefficient of runoff (representing the fraction of water that does not infiltrate the soil) was taken function of the land-use (forests, pastures, agriculture or bare soils), the slope and the soil texture (sands, silts, clays). The used values of this coefficient were adapted from Ebener *(2000)*.
- The effect of contaminant dilution due to the additional water recharge, coming from precipitation and feeding the cells laterally, has not been considered.

Concerning the first simplification, one can say that the water infiltration into soil has to take into account also the water content of the soil column through which the infiltration process takes place (described by the water content variation in depth). This is a major factor (time dependent) controlling the infiltration and consequently the runoff. Function of the considered time scale, one can consider a constant value of the infiltration or runoff coefficient for a given situation (described by the three parameters considered originally in the infiltration/runoff model). More precise quantifications of the infiltration into soil can be obtained using Richards' equation *(Richards, 1931)* or using simplified methods such as *(Green & Ampt, 1911)*. Such models require a larger amount of data and extensive computations.

Concerning the second simplification, the consideration of the contaminant dilution due to the additional amount of rainfall water feeding through lateral inflow will increase the effect of attenuation, and so will reduce the lateral potential dangerosity (defined by the authors).

2.2. Comparison between vulnerability assessment techniques

2.2.1. Application to the Néblon river basin (Belgium)

Study frame and hydrogeologic context

Vulnerability methods can be evaluated by comparing vulnerability map outputs. The use of a large number of parameters in vulnerability assessment allows one to describe complex hydrogeological settings. This usually requires a substantial effort in getting the input data. In order to reduce error propagation, these data must have a certain level of accuracy. For developing easily applicable methods, one solution is to reduce the number of parameters. Unfortunately the methods using fewer parameters present serious difficulties for adaptation to different geological contexts.

In order to evaluate their capacity for delineating groundwater vulnerability in the limestone aquifers of the Walloon Region (Belgium), several vulnerability assessment methods have been considered *(Gogu 2001, Gogu et al. 2003)*. Five methods were selected for this study: **EPIK** (*Doerfliger and Zwahlen 1997*), **DRASTIC** (*Aller et al. 1987*), **German method** (*von Hoyer and Söfner 1998*), **GOD** (*Foster 1987*), and **ISIS** (*Civita and De Regibus 1995*). DRASTIC and GOD represent classic approaches in vulnerability assessment. ISIS is a development based on DRASTIC, SINTACS (*Civita 1994*), and GOD, where the authors give more importance to the recharge effect. EPIK and German method are procedures developed in Europe for geologic contexts existing respectively in Switzerland and in Germany. A consistent description of these methods is provided by Gogu (*2001*).The analysis was conducted using the raster data model within a Geographical Information System (GIS) software package (ESRI).

The chosen test area is located in the Condroz region (Belgium). Geologically it is situated in the eastern part of the synclinorium of Dinant. It represents a part of the Néblon river basin and is situated at about 30 km south of Liège (Figure 2-2).The area includes several villages: Ouffet, Bende, Ama, Oneu, Ocquier, and Bonsin.

The hydrologic basin covers about 65 km^2 and represents an important hydrogeological potential. The aquifer is exploited for supplying water for Liège city and for the surrounded villages. It provides a daily yield of about 28.000 m^3.

Because of its high hydrogeological potential and its geological heterogeneity, this aquifer has been the subject of previous investigations. Several campaigns of data collection consisting in geomorphological observations, geophysics, pumping and tracer tests as well as their interpretation and modelling, have been performed in the scope of different scientific reports. Several MSc thesis and a PhD thesis contributed also to the study of this aquifer. This already collected information played an important role in choosing this site. Chronologically, this area was the target of several studies to analyse the groundwater reservoir structure (CILE, LGIH, INIEX 1986 and 1989; and LGIH 1995 b), to investigate the karstic aquifer hydrodynamics *(Meus 1993)*, as well as to delineate a first guess for protection zones around the water supply system through numerical modelling *(Dassargues and Derouane 1997)*. A prototype study (LGIH 2000) of a hydrogeological map (Modave-Clavier) was undertaken on this area. All these studies allowed a vast synthesis concerning the nature and the geometry of the geological strata, the hydrological and hydrogeological limits of the basin, faults, lineaments and fractured zones, the piezometric heads evolution, the hydrological water balance, hydrogeochemical analyses, and the determination of groundwater media physical parameters (hydraulic conductivity, storage coefficient, effective porosity, and others).

Geomorphology and Geology

The Néblon basin is a part of the Devonian-Carboniferous folded formations of the south-eastern edge of the Dinant synclinorium that crosses Belgium from West to East.

Typical alternation of shales and sandstone anticline crest (Upper Devonian or Famennian) and calcareous syncline depressions (Lower Carboniferous or Dinantian) are found. They contain several carbonate aquifers locally interconnected through sandstone layers. The relief in the Néblon basin is cut by a well developed river network.

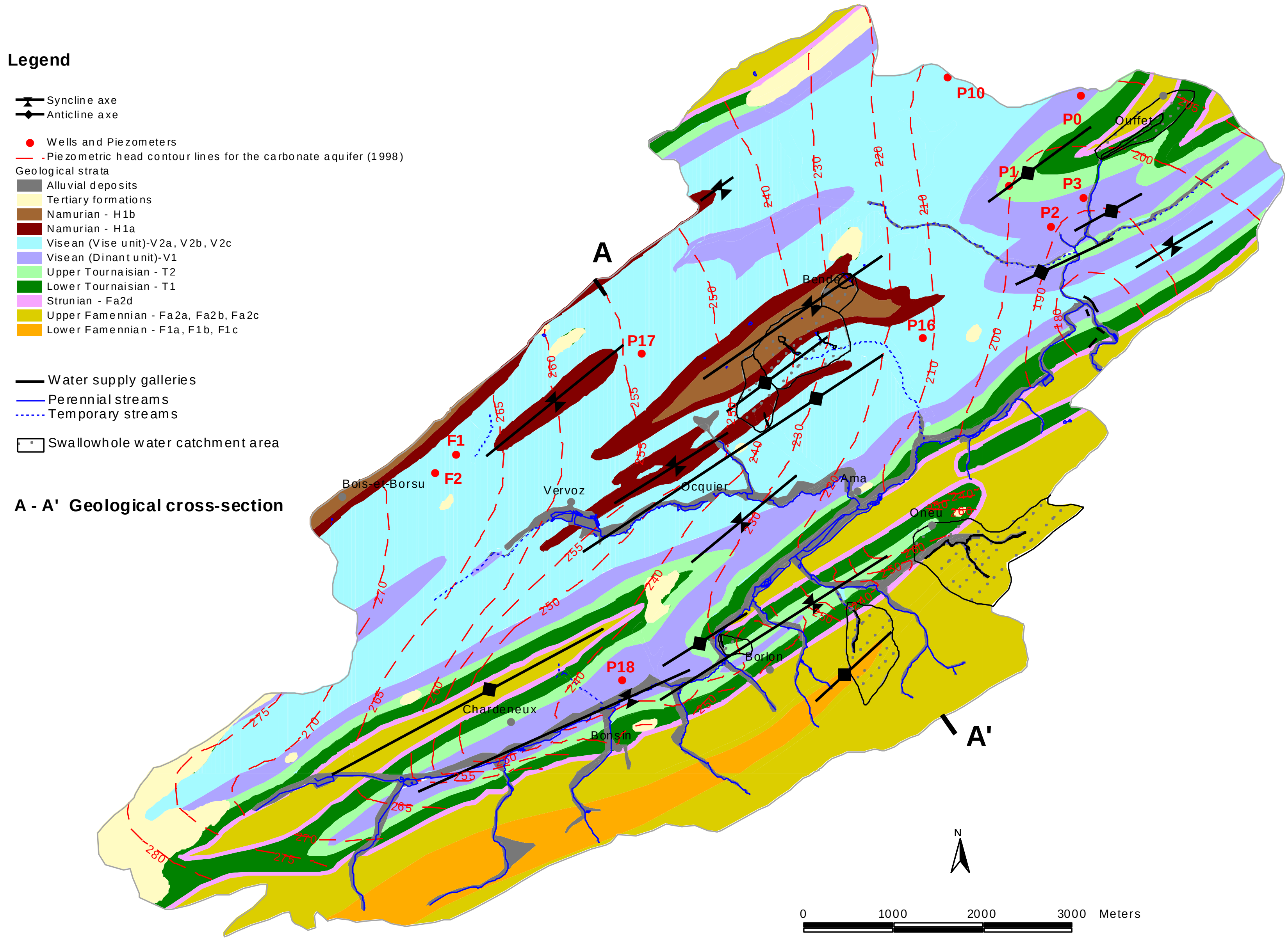


Figure 2-2 Geology and hydrogeology of the study area *(Gogu 2001)*

The tributary streams of the Néblon River are flowing transversely to the general West-East geological structure (Figure 2-2). 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 are ending in swallowholes. Several temporary and losing streams as well as other diffuse losses can be observed in the area. Locally, ancient paleokarst was filled by Tertiary sandy-clay sediments. Generally, the region is covered by a loess formation with about 2 to 4 m of thickness.

Hydrogeology and karstic features

The Néblon basin aquifers are located in the Tournaisian and Visean limestone, in the Famennian fractured sandstone, and in the Namurian silty-sandstone. The main aquifer of the basin is made of the Tournaisian and Visean limestone. The aquifer is highly fissured, presenting locally clear signs of karstification. The Visean is generally made of purer limestone than the Tournaisian, and it is easily karstified.

The Néblon River is generally draining the main aquifer. The natural outflows of the aquifer are diffuse discharges and point sources along the Néblon River. They are exploited by the CILE Water Company via four collecting galleries. The galleries are located in order to drain the natural outlets of the hydrogeological basin on the both sides of the Néblon River.

The Famennian sandstone represents another exploitable aquifer mainly in the weathered zones but also in strongly fissured zones. Connection with the limestone aquifer (Figure 2-2) is done predominantly by several springs raising upstream the Strunian shale band or probably through presumed strong fissured zones.

The silty-sandstone Namurian formations of Bois-et-Borsu and Bende synclinals (Figure 2-2) act like small perched aquifers. These aquifers have a very weak storage capacity, and are exploited only for agricultural purposes by few local wells with production. It is supposed that the shale of the lower Namurian insures a relative imperviousness of the Namurian synclinals in depth.

Several karstic features can be identified in the Neblon basin, the most significant being dry valleys, swallowholes and resurgences, sinkholes (dolines). The high flow-rates recorded at the springs are presumed to indicate that karstic conduits are active. On (Figure 2-2), swallowholes and diffuses losses are located. Among them, three major swallowholes were identified: Bois de Marsée, Bende, and Oneu. Tracers injected in the swallowhole of Bois de Marsée, have been recovered in two of the galleries. This clearly indicates very quick flow in karstic conduits (*Meus 1993*). The tracers times arrivals were lower than 50 h. That corresponds to a velocity of 73 m×h^{-1}. Such velocities confirm that some particular zones are affected by karstification. Several dry valleys can be observed in the area (Figure 2-2). Only very few undeveloped karstic caves are noticed along the Néblon cliffs as well as a small sinkhole South of Ouffet. During rainy periods the bottom parts of these dry valleys become small tributary streams.

The hydrogeological limits of the Néblon basin show spatial and temporal variations. In the southern part, an impervious boundary can be considered in the Famennian shale. The northern and eastern limits are mainly situated in the Visean limestone, where hydrogeological limits are not corresponding to hydrological ones. Also in the western part, groundwater transfers from the West are indicated by water-balance studies.

The few goundwater level measurements do not allow a complete understanding of the aquifer behaviour. However, considerable variations of the hydraulic heads were observed (5 m to 40 m). A piezometric map portraying a groundwater low levels period, was designed for 1998 (Figure 2-2).This piezometric map clearly indicates a general groundwater flow to the East. A stronger depression in the Néblon River valley is also shown.

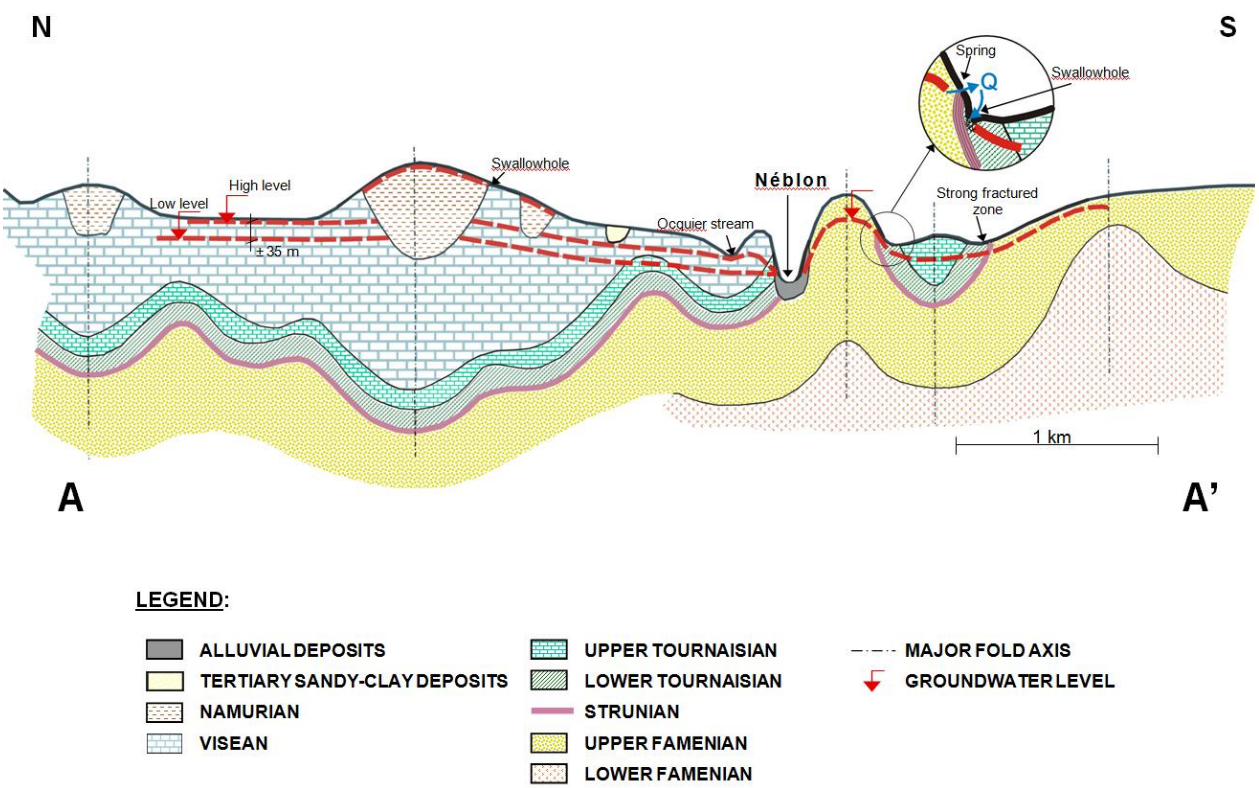


Figure 2-3 Schematic geological and hydrogeological cross-section *(Gogu 2001)*

The karstified aquifer and the Tertiary deposits filling the paleokarst pockets are supposed to keep a good groundwater communication. A clear relationship between the karstic aquifer and the surface river network was pointed out. In different river sectors, the water feeds the aquifer through the river bed. These observations pointed out the danger of water-supply galleries contamination by the river. *Di Clemente & Laurent (1986)*, observed an identical chemical composition of groundwater and similar temporal variation of groundwater conductivity, pH, and ionic content at the Vervoz springs feeding the Ocquier stream and in the galleries. These observations pointed out possible links between the Néblon River and the galleries. The depth of the Namurian synclines made of shale and sandstone is not known. They are considered as allowing deep groundwater communication within the underlying limestone aquifer (Figure 2-3) as confirmed by water-balance results (*Di Clemente & Laurent 1986, Dassargues & Derouane 1997*).

Methodology

The study was conducted in an area of 64.70 km^2 (Figure 2-2). For the five applied methods, quantification of the parameters was done in parallel, in order to be consistent for further analysis. Evaluation of the vulnerability methods parameters was done by considering possible relationship between them. The needed data processing steps for obtaining reliable results were the followings: (1) a careful analysis of the existing raw and treated data, (2) a quality control of the data, (3) a study of possible correlations between the hydrogeological parameters, and finally the (4) hydrogeological interpretation of each parameter of each method.

Short overview on technical aspects in vulnerability analysis

It is not beyond the scope of this section to describe GIS terms definitions (*De Mers, 1997*), types of geographical modelling and their achievement, aspects of data capturing, used GIS functions, procedures, operations, spatial manipulation issues and possible errors.

A brief description of the most important steps in vulnerability parameter estimation is needed. However, in this section 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 Figure 2-4.

Mostly, data come from the geological map of Belgium, the map of karstic features *(De Boyer et al. 1996)*, a prototype of the hydrogeological map *(Hallet et al. 2000)*, various local and regional hydrogeological studies, topographic map of Belgium, soils map of Belgium, the digital numerical model of Belgium and the land use map (*source: National Geographical Institute of Belgium*). These data were then completed by a campaign of field tests consisting in: geophysical prospecting (electrical sounding and profiling, seismic soundings), piezometric measurements, pumping tests, tracer tests, field observation (geomorphology, rock quarries, springs), river flow-rates data (gauging stations), short auger holes interpretation, identifying and mapping the rock outcrops, rock quarries, and new karstic features (not mentioned before). The digital numerical model (DTM) of the region was used for slope computations needed for some of the methods. The piezometric map of the existing hydrogeological map *(Hallet et al. 2000)* was completed with data obtained in the distinct field measurement campaign. Then, by subtraction, a map of 'depth to water table' for the karstic aquifer was drawn.

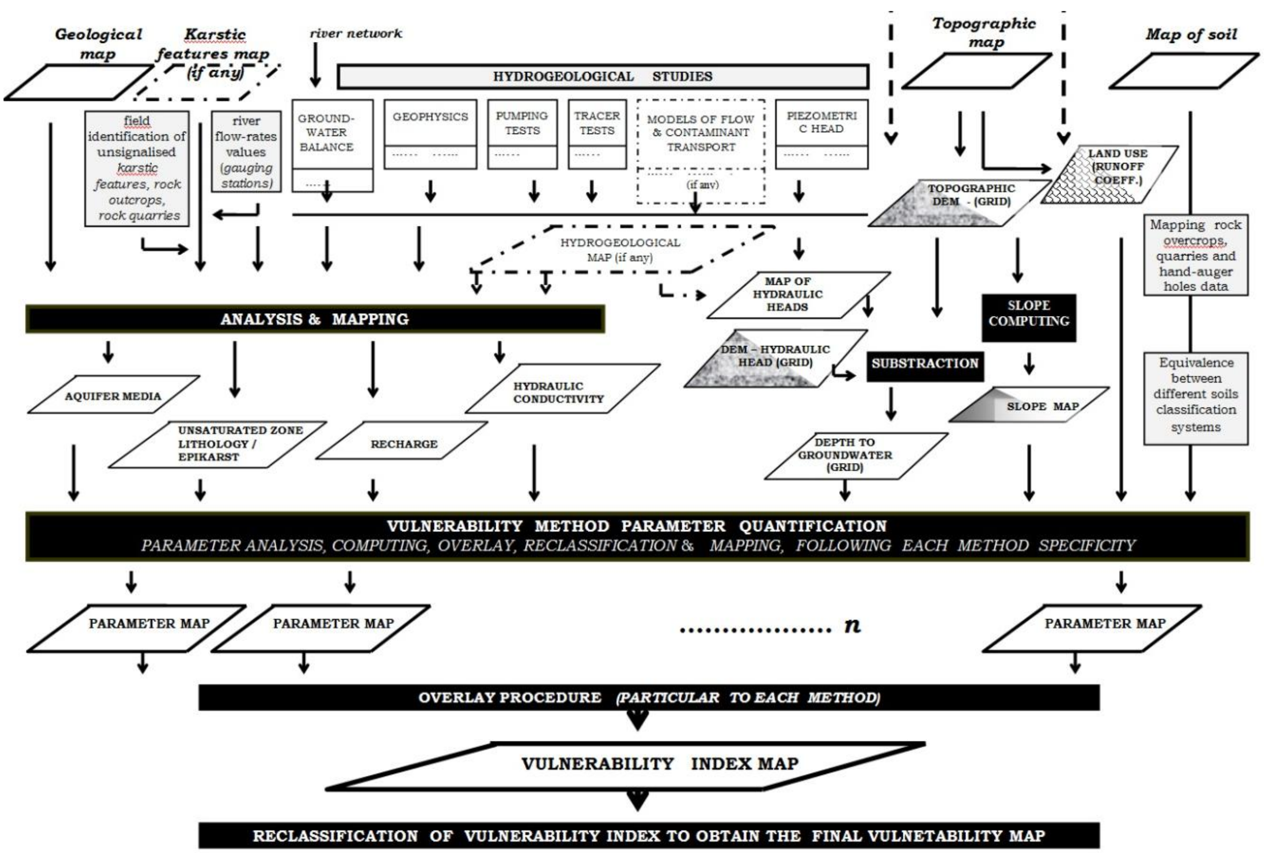


Figure 2-4 Main steps in groundwater vulnerability assessment for Neblon aquifer *(Gogu 2001)*

The existing map of soils represented the basic information for obtaining the map of soil parameters. Additional information concerning soil thickness, rock outcrops and quarries, was obtained during an extensive field work campaign.

Results

Analyzing and comparing results from such different methods can be performed in different ways. As each method has its own system for defining and regrouping final classes of vulnerability, a first way for comparing results consists in taking the point of view of a 'blind' user of the methods. According to the classification system prescribed in each of the methods, results are found in terms of high, moderate and low vulnerability zones. Then, the user can check, for example, if high vulnerability zones are mapped in the same areas and if there are some large discrepancies between results from one method to the others. If a more quantified comparison is to be made, a regrouping in three common classes is needed: let's propose high, moderate and low vulnerability. Respective percentages of high, moderate and low vulnerability zones found by each method can be compared from one map to another. This direct approach will be applied here below.

However, knowing that intrinsic vulnerability is only a relative concept, this last approach can be judged statistically and mathematically inconsistent. Another way for comparing results would consist in redefining the final vulnerability classes taking into account that the values of the vulnerability index follow in each study area a normal statistical law. Then defining percentiles, vulnerability classes can be found: taking a percentile 33, would lead, for example, to the definition of the three vulnerability classes (low, moderate and high). However, even if this last method is more statistically consistent for comparing results in one study area, from the hydrogeological point of view it is difficult to accept that a same zone will be given another final vulnerability depending if it was included within a map or another.

Comparison between intrinsic vulnerability maps

As previously mentioned, a classical comparison is made here below. For the classic DRASTIC method, the zones of very high and high vulnerability cover about 5 % of the study area (Figure 2-5). According to EPIK, the zones of high and very high vulnerability cover 8.5 %. The very high and high vulnerability zones for the other three methods, correspond to more than a half of the study area.

A general similarity between GOD, ISIS, and the German method can be observed. The German method is outlining the most extended zones with high and very high vulnerable areas (high 48 % and very high 34 %). The ISIS method provides 63 % of high vulnerable areas.

In general the limestone aquifer is characterized as high or very high vulnerable. Only in the DRASTIC method it takes moderate vulnerability. In the German method and in the GOD method vulnerability maps, the difference between high and very high vulnerability is largely influenced by the depth to groundwater table. Furthermore, these two methods use the depth to groundwater table as a direct multiplier for the other parameters. The ISIS method is using differently (than the other methods) the depth to groundwater table parameter. Unfortunately this procedure, used by ISIS, is smoothing the vulnerability index results. It clearly appears that in DRASTIC vulnerability map, the introduction of depth to the groundwater table creates the distinction between the moderate vulnerability and the high vulnerability (Figure 2-5) zones.

Karst features are not always pointed out as high or very high vulnerable zones. For example for the GOD method, the small diffuse swallowhole of Bende and the swallowholes and resurgences located near Ouffet are considered respectively as low and moderate vulnerable. The streams feeding the swallowholes are considered as high vulnerable zones by EPIK, by the German method, and by GOD. ISIS and DRASTIC methods consider these zones partly high vulnerable, partly moderate vulnerable. Except ISIS, the dry valleys and the sinkholes were characterised by all methods as being more vulnerable than the rest of the limestone.

Temporary streams are springing from the Namurian terrains and are feeding directly swallowholes when arriving in limestones (Figure 2-2).

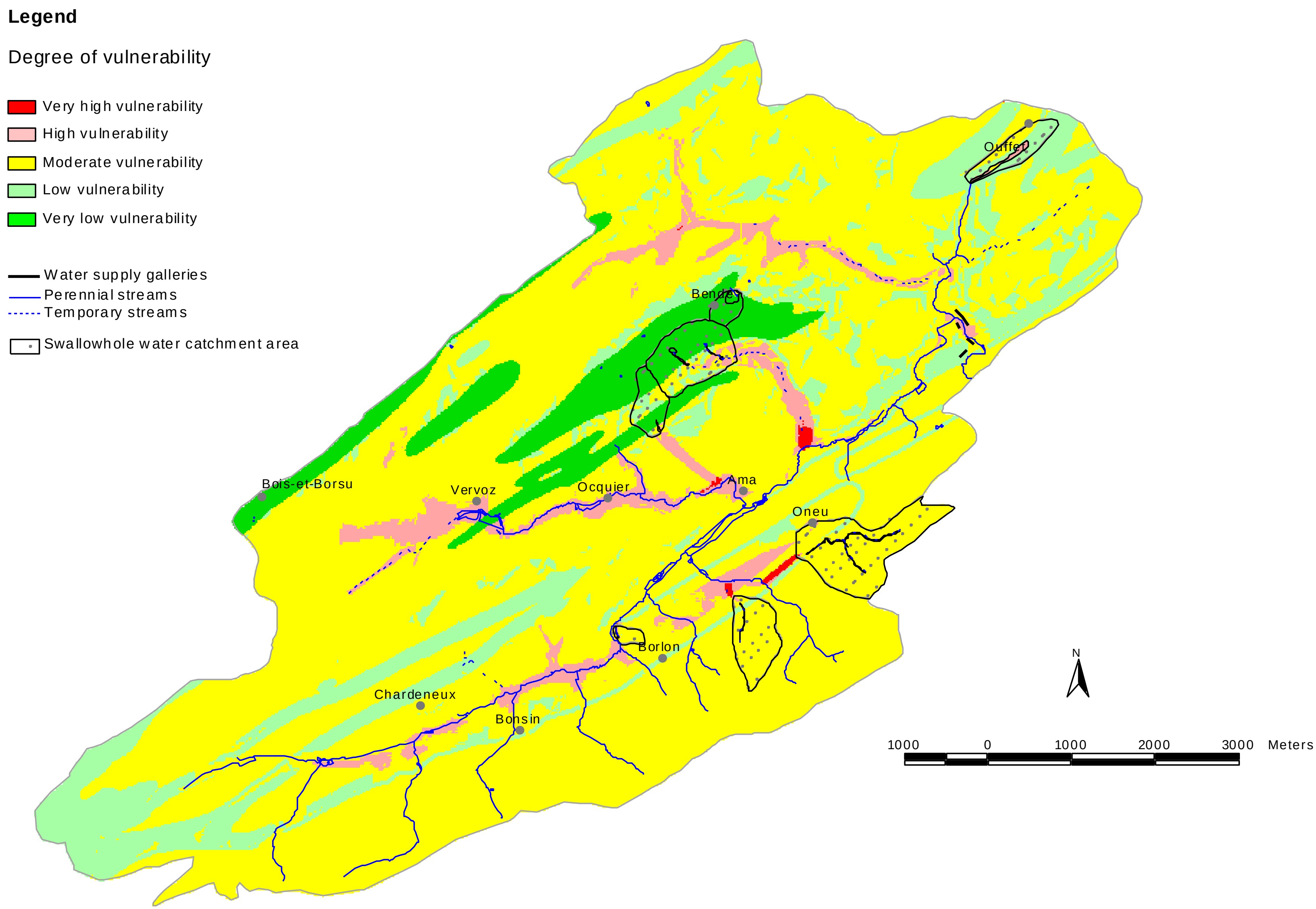


Figure 2-5 Final vulnerability map using DRASTIC method and the commonly used final classes of vulnerability

EPIK is the only method that considers these temporary small stream-basins as moderate vulnerable zones. The other four methods consider them as low vulnerable zones. These methods are not outlining specifically, the karstic environment. This delicate issue is derived from the vulnerability concept scheme used by these four methods: only vertical permeability is considered. In consequence these methods are neglecting the potential contamination that comes by the streams and bypassing the soil and the unsaturated zone.

A similar problem is observed for the small Vervoz Lake that overlies the limestone as well as the Namurian formations. All the methods except EPIK, consider as low vulnerable the part corresponding to the Namurian formations and as high or very high vulnerable the parts of the lake lying on the limestone. The Lower Tournaisian is mostly characterised with a moderate or high vulnerability. The Strunian bands appear with a moderate or low vulnerability. A particularity of the ISIS method is the use of the land-use parameter as a multiplier factor for all other parameters.

Regrouped classes of vulnerability

For comparison, regrouping the classes of vulnerability was done for each vulnerability map, outlining three main categories: high (including the high, very high, and extreme vulnerability), moderate vulnerability (the same class for all five methods), and low vulnerability (including low and very low vulnerability). Results are shown in Figure 2-6.

All the five methods designated areas corresponding to the Namurian formations as low vulnerable. The German method shows the most extended area of high vulnerability, with 83 %. The DRASTIC results are more balanced with 73 % of the area with a moderate vulnerability and 22 % with a low vulnerability.

For this basin, these regrouped classes of vulnerability indicate two main trends in the vulnerability assessment: (a) the German method, the GOD method, and the ISIS method consider the study area as being dominantly high vulnerable; (b) the DRASTIC method and the EPIK method moderate vulnerable 73 % and 92 %. These results show a high discrepancy between the methods.

Conclusions

A larger discussion of the obtained results is provided by Gogu et al *(2003)* and by Gogu *(2001)*. Describing the results of vulnerability assessment using the five methods, some comments can be deduced:

(a) according to the German, GOD, and ISIS methods (Figure 2-6) more than a half of the study zone is vulnerable;
(b) according to the DRASTIC and EPIK methods most of the study area is moderate vulnerable;
(c) all the five methods give a low vulnerability to the areas corresponding to the Namurian formations;
(d) except for the GOD vulnerability map and partially for the German method, the Famenian sandstone is less vulnerable than the limestone aquifer;
(e) the Strunian bands are considered moderate or low vulnerable for all the methods;
(f) the Lower Tournaisian is mostly assessed with a moderate or a high vulnerability;
(g) the Tertiary sandy-clay deposits are generally assessed as low vulnerable except for the GOD and ISIS methods.

Suiting a high or very high vulnerability degree, the karstified zones are apparently properly evaluated by the presented methods with exception for GOD and in a smaller measure for ISIS. The EPIK method better outlined the karstic features than the other four methods.

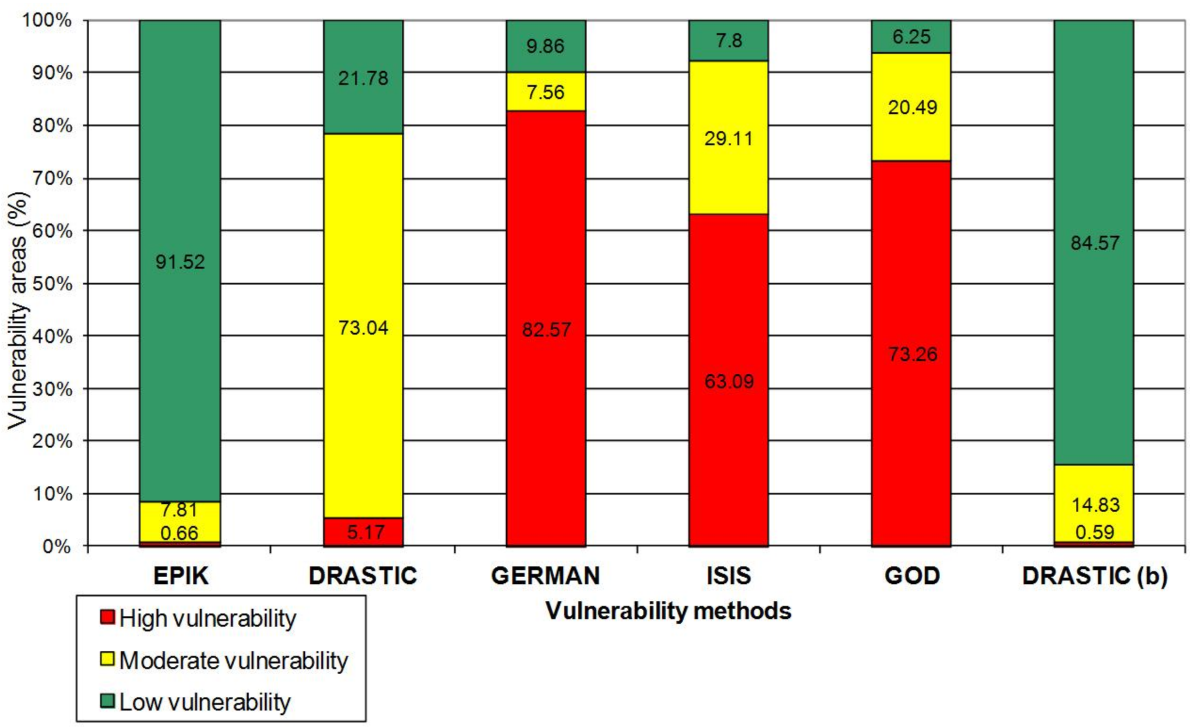


Figure 2-6 Comparison between the regrouped classes of vulnerability as defined by the applied methods (*Gogu 2001*)

All the vulnerability methods are taking into account directly or indirectly the vertical permeability. However, most of them are neglecting possible contamination coming directly from the streams, feeding directly the aquifer.

In the EPIK method, the assumption consisting in relating a steeper slope to a higher degree of vulnerability is not realistic when open valleys and fissure matrix are predominant. On the contrary, it is valid within drainage basins of karstic features. Another concern is the fact that the relative high vulnerability of karstic systems is not related to other types of aquifers in the EPIK method. As the fundamental concept of vulnerability is a relative concept (*Gogu & Dassargues 2000a*), ignoring other lithogical and hydrogeological conditions lead to less contrasted results than awaited.

These conclusions should open new research directions in the procedures of the parameter quantification and weighting. It shows clearly the need for more flexible and more physically-based methods. To be more reliable, the vulnerability mapping techniques must be adapted in the future. For example, the recharge of the aquifer seems to be one of the most significant parameters in vulnerability assessment. In all the five methods this parameter is explicitly or implicitly taken into account. Results in vulnerability assessment can be influenced and improved if the recharge parameter becomes a spatially variable data and if a 'concentration of flow' factor is distinguished (*Daly et al., 2001*).

Too many classes of vulnerability are physically useless: it is the case of the extreme vulnerability class defined within the ISIS method. In this study, even if a karstic aquifer was analysed, the extreme vulnerability class is not present. In consequence, defining four classes of vulnerability appears to be a more reasonable choice. It fully satisfies the needs and the resulted maps are easily understood and manipulated.

Until now, the choice among vulnerability methods remained a subjective decision of the hydrogeologist. Additionally, all the methods are to some extent flexible in the process of parameter quantification. As underlined by Aller et al. *(1987)*, the vulnerability methods have to be used as screening tools. They cannot replace the professional expertise and field works needed for more quantified answers. The choice of parameter rating must be based on extended studies of the hydrogeological conditions. The so-called vulnerability "rapid assessments" performed by untrained operators may conduct to serious errors. The only way to reflect the reality in the aquifers vulnerability results is to merge adequately all the existing studies related to geology, hydrogeology, hydrology, soil topography, climate, and land-use.

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.

2.3. Uncertainty of vulnerability maps. Sensitivity analysis applied to a small karstic aquifer

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 *(Gogu and Dassargues 2000 b)*.

A part of 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 sensivity 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. This analysis represents a technique of investigation for the vulnerability map uncertainty and allows a correct judging of the parameters role 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.

2.3.1. 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 to the France - Belgium border. Locations are shown in Figure 2-7.

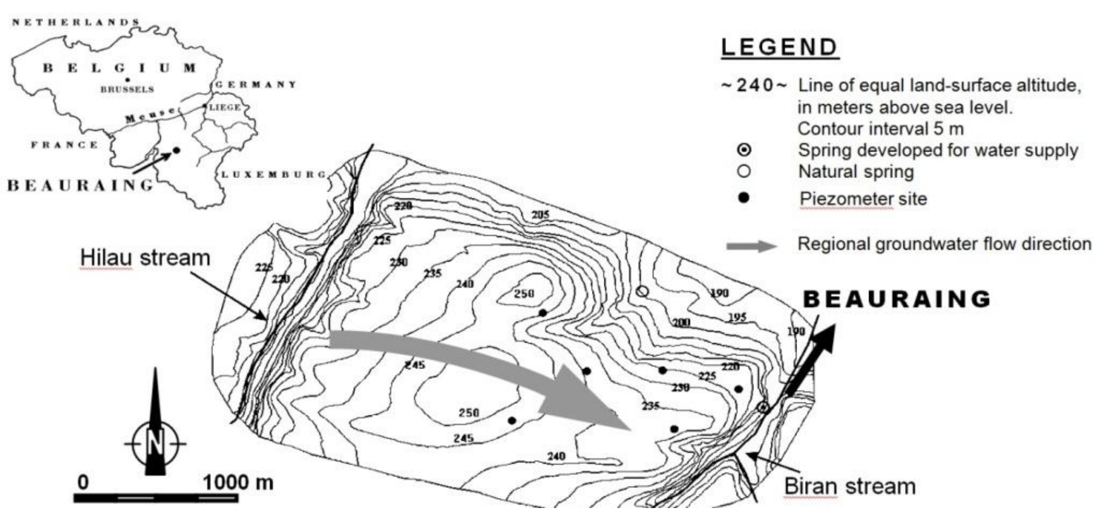


Figure 2-7 Location of the study area, near Beauraing, Belgium

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 2-8.

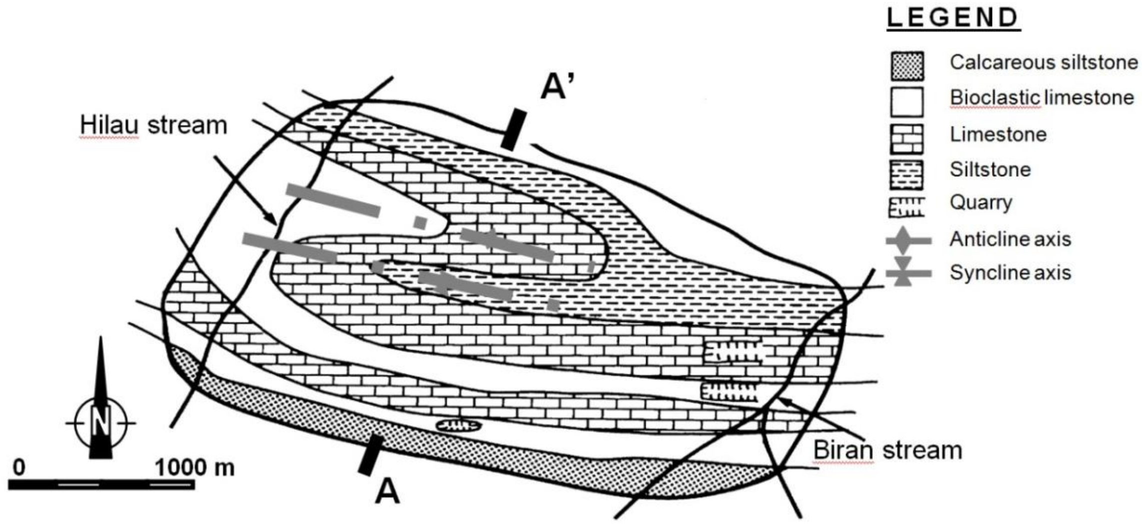


Figure 2-8 Geology of the study area (it shows structure as well as lithology)

The siltstone bands act as impermeable boundaries for the limestone aquifer. A geological cross-section can be seen in Figure 2-9**.** 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 (*LGIH 1997 a*).

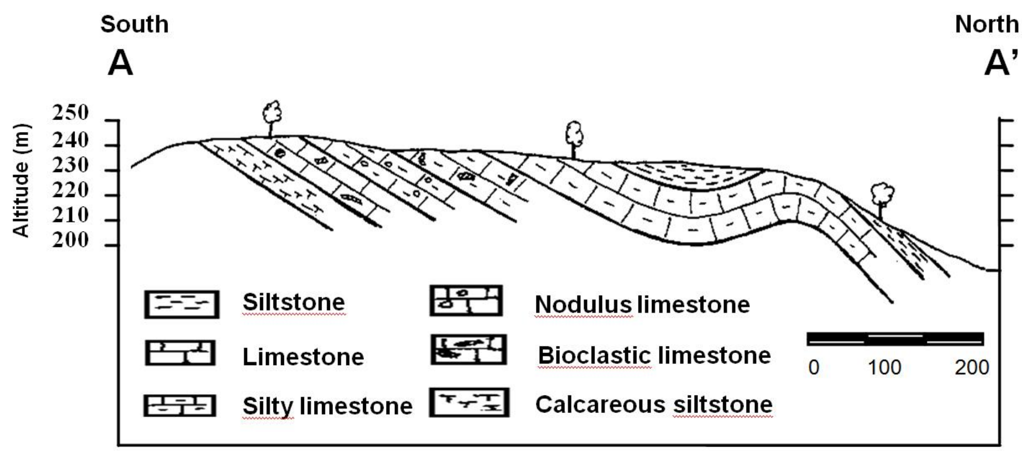


Figure 2-9 Geological cross-section on the study area

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 piezometric levels indicate that the depth to the water table ranges from 18-40 m. Regional studies (*LGIH 1997 a*) 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) 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 (*LGIH 1997 a*).

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.

2.3.2. Map of intrinsic vulnerability

In order to map aquifer intrinsic vulnerability for the study area, a raster-based Geographical Information System software (IDRISI) was used. The *Epikarst* (*E*) parameter was determined using morpho-structural analysis on aerial photos and 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 soils map of 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 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 quarry where 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 (Figure 2-10). 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 equation, the four parameter maps were overlaid cell by cell to produce a “vulnerability index map”. For the study area, calculated values of 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.

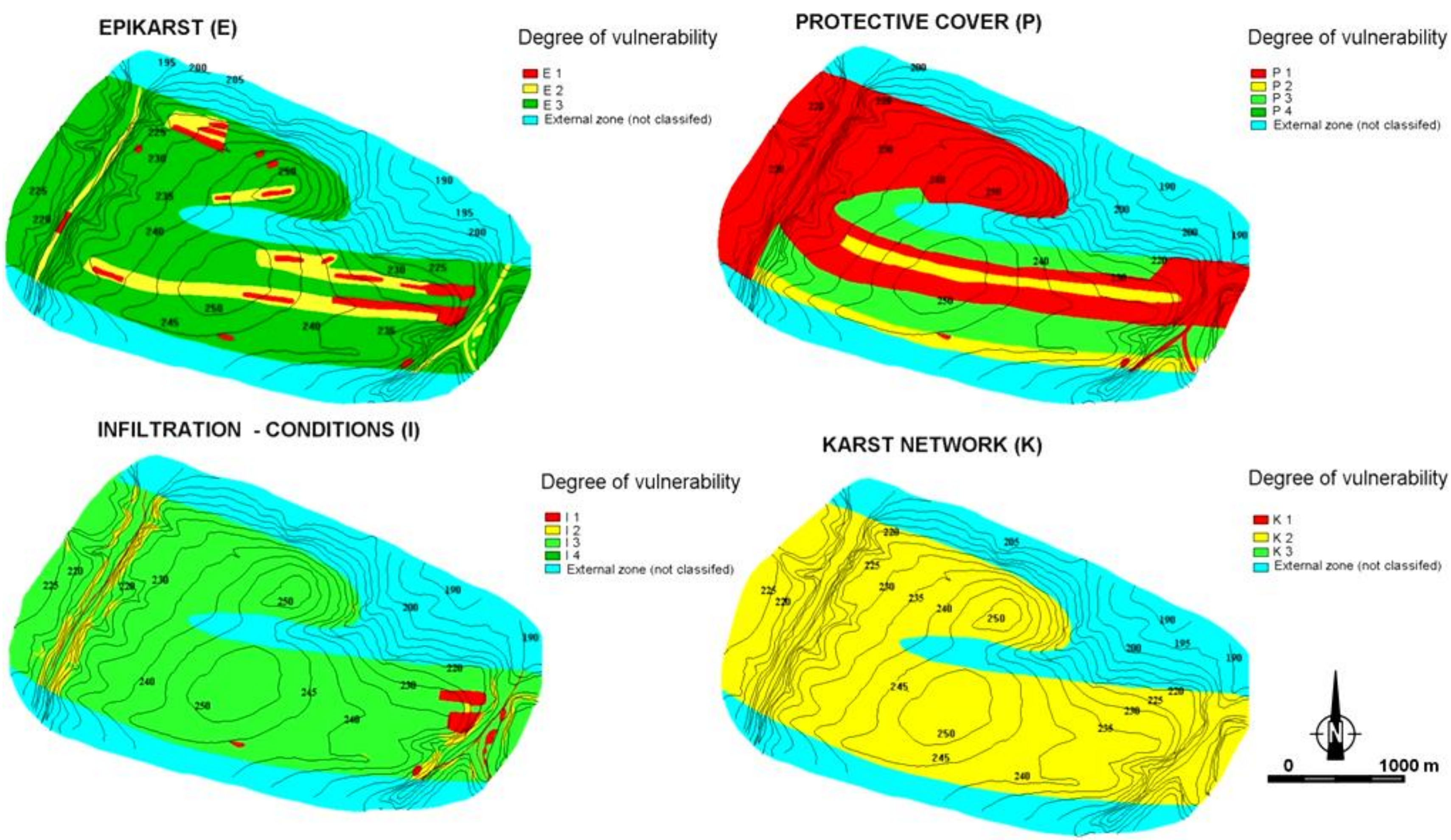


Figure 2-10 Parameter maps (E, P, I, and K) estimated for the Beauraing study area

The final vulnerability map is shown in Figure 2-11.

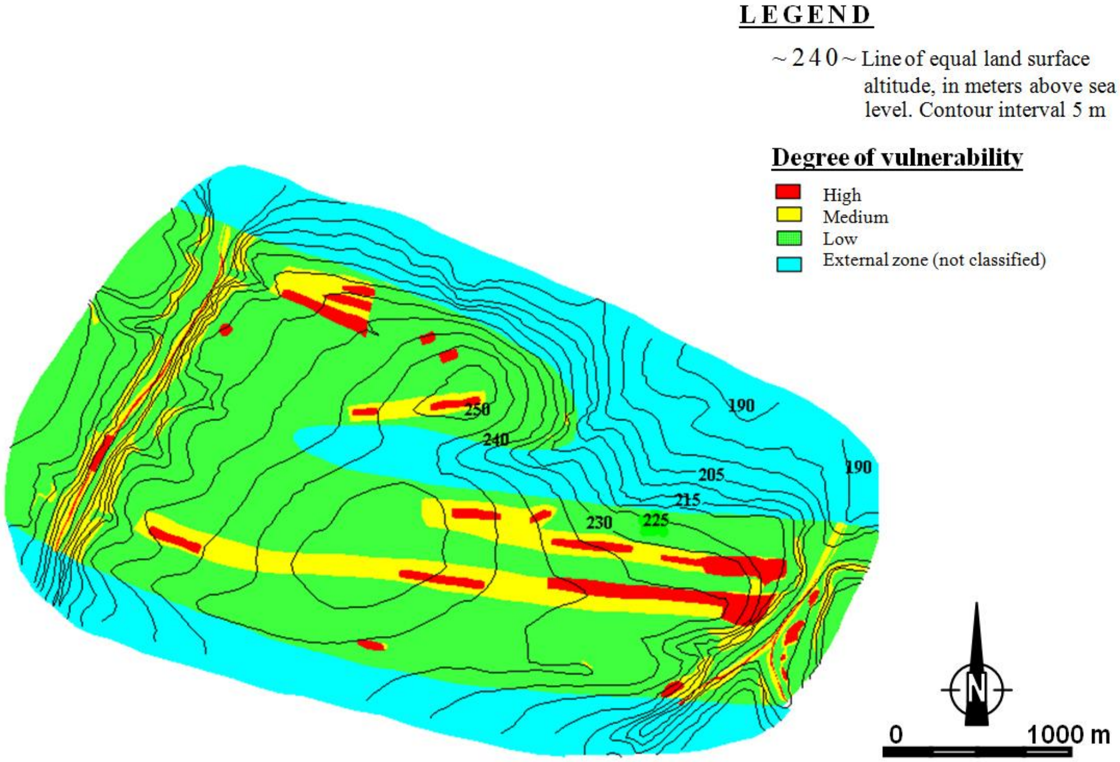


Figure 2-11 Vulnerability map of the study area Beauraing site, based on the EPIK method

A comparison of the four parameter maps (Figure 2-10) to the final vulnerability map (Figure 2-11) indicates that the *epikarst* parameter (*E*) plays a major role in delineating the high vulnerability zones. The *conditions of infiltration* (*I*) also have a noticeable contribution. Parameters *E* and *I* both play an important role in determining medium vulnerability zones.

2.3.3. Review of the theory of geographical sensitivity analysis

In general terms, geographical sensitivity analysis concepts (*Lodwick et al. 1990*) were developed for understanding how perturbations or errors on the input parameters of a geographical analysis can change the output map. Imposing perturbations on the input and computing resultant variations (using an overlay-based operation) can indicate which are more sensitive subareas (group of cells having the same attribute value or polygons) of the output map. It indicates where most attention must be paid in the input data, in order to obtain reliable conclusions from the output maps. This kind of analysis of errors and sensitivities for attribute values associated to subareas mapped units, assumes that the delineation of the subareas is correct.

Mathematical formulation

Two definitions are given, representing concepts used in GIS operations. A *primary map* represents a map of a physical property (i.e. geologic, hydrogeologic, land-use) that is going to be studied. A *rank map* is a map having numerical attributes and represent mathematical relations or measurements of the attributes connected with to one or more maps. In consequence the *rank maps* can be derived from *primary* maps or other *rank maps*. In aquifer vulnerability assessment the rank maps are the *parameter* maps.

For example, in Figure 2-12, there are two primary maps: the *Depth to water* map and *Aquifer media* map. Data existing on the both maps are captured and encoded, and respective *rank maps* can be generated. In Figure 2-12 the rank maps are grids, each of them made by 4 cells. The *Aquifer media* map was classified using values that are ranging from 0 to 10. The *Depth to water* map has been rated with classes of 10 m from 0 to 100 m (0 – the depth to water is between 0 and 10 m; 10 – the depth to the water is greater that 100 m).

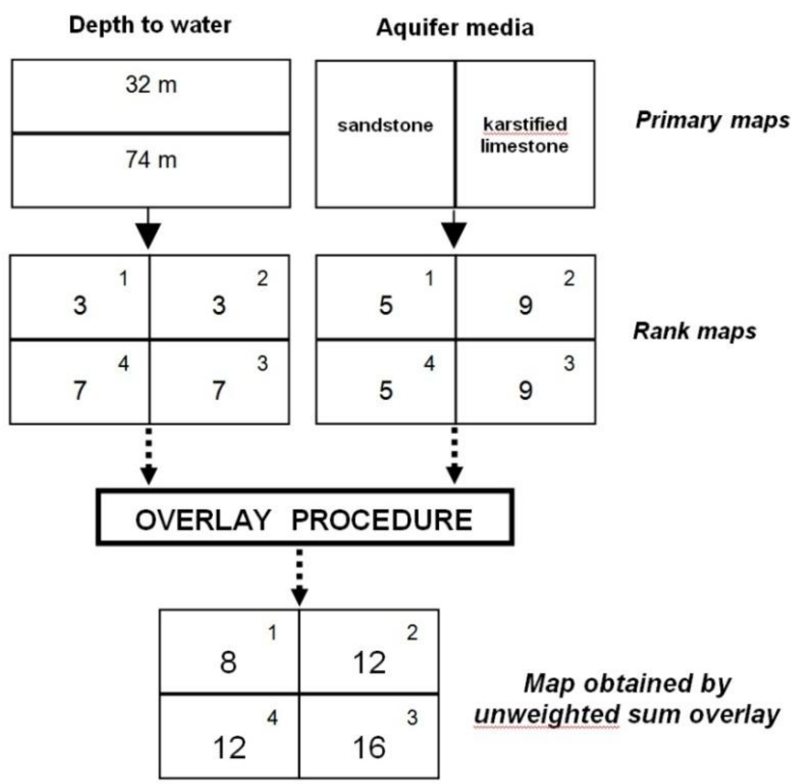


Figure 2-12 Steps in the examining the sensitivity analysis technique applied for an unweighted sum overlay procedure

The mathematical representation of a geographical analysis that combines and transform attributes of several inputs maps into an output map (in the mentioned case, *unweighted overlay*) can be defined as a function whose domain is a set of vectors of input map attributes and whose range is the resultant attribute:

$$r_c = P\,(\mathbf{a_{ci}}) \qquad (2\text{-}1)$$

where:

P – geographical procedure (example: the formula of the vulnerability index V_i);

$\mathbf{a_{ci}} = (a_{c1}, a_{c2}, \ldots, a_{cN})^T$ – the vector of input attributes (example: the parameter maps);

N – the number of input maps corresponding to the c^{th} subarea (group of cells or polygons);

$\boldsymbol{r_c}$ – the resultant attribute of the c^{th} subarea (group of cells or polygons) of the output maps (in the vulnerability assessment represents the vulnerability index V_i);

c – subarea (group of cells or polygons) of the resultant map.

Considering the example presented in Figure 2-12**,** the equation (2-1) can be rewritten as follows:

resultant map1 map2 weights

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} 8 \\ 12 \\ 16 \\ 12 \end{bmatrix} = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \\ a_{41} \end{bmatrix} \begin{bmatrix} a_{12} \\ a_{22} \\ a_{32} \\ a_{42} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \end{bmatrix} = \begin{bmatrix} 3 & 5 \\ 3 & 9 \\ 7 & 9 \\ 7 & 5 \end{bmatrix} \times \begin{bmatrix} 1 \\ 1 \end{bmatrix} \qquad (2\text{-}2)$$

As a function, the geographical analysis representing the overlay map can be written as:

$$\mathbf{r} = \mathbf{A} \cdot \mathbf{w} \qquad (2\text{-}3)$$

where:

A – the matrix of attributes whose columns correspond to the attribute values of one map and whose rows are the attributes corresponding to one subarea, as in equation (2-2).

$\mathbf{w} = (1,1)^T$- the vector representing the weights (as the overlay procedure is unweighted, the weights are equal to 1)

Following equation (2-1), the *geographical sensitivity analysis* is the study of the variations in r_c caused by variations or errors in the vector of input attributes $\mathbf{a_c}$ and modalities of measuring these variations.

In consequence, the geographical sensitivity analysis is using imposed variations on the input attribute vector $\mathbf{a_c}$ in order to determine the corresponding resultant r_c using the function or the set of instructions P.

Geographical suitability analysis

The notion of *geographical suitability analysis* will be described *(Gogu and Dassargues 2000 b)*, in order to understand its need in vulnerability assessment. The following notations are necessary:

N – the number of primary or rank maps used in the analysis

C(N) – the number of subareas (polygons or groups of cells) having the same attribute value after the overlay operation between the N maps

$\boldsymbol{a_{cn}}$ – the attribute from rank map $1 \leq n \leq N$ contained in the c^{th} subarea $1 \leq c \leq C(N)$ of the intersected overaly map

$\boldsymbol{A} = (a_{cn})$ - the $C(N)\times N$ matrix of attributes corresponding to the $C(N)$ subareas of the N maps

$\boldsymbol{w_n}$ – the weighting given to the n^{th} rank map

A *geographical suitability analysis* generates attributes for the c^{th} subarea of the resultant (attribute) map as a mathematical function of $\mathbf{w} = (w_1, \ldots, w_N)^T$ representing weights and $\mathbf{a_c} = (a_{c1}, a_{c2}, \ldots, a_{cN})^T$ representing input attributes, in the following way:

$$r_c = \begin{cases} P(a_{c1},\ldots,a_{cN}, w_1,\ldots,w_N) \\ P(\mathrm{a}_c, \mathrm{w}) \end{cases} \qquad (2\text{-}4)$$

and

$$\mathbf{r} = (r_1, r_2, \ldots, r_{C(N)})^T = P\,(\mathbf{A},\mathbf{w}) \qquad (2\text{-}5)$$

Using geographical sensitivity analysis, the *weighted sum of intersection overlay* could be studied from a more general perspective of equation 1-5.

The weighted sum overlay is represented by:

$$r_c = P\,(a_c,w) = \Sigma_n\, a_{cn}\cdot w_n, \qquad \text{for } 1 \leq c \leq C(N) \qquad (2\text{-}6)$$

Equation (1.6) identifies *overlay suitability* and the associated map is called *overlay* map. It is assumed that for equation (3.6) the attributes are interval or ratio data types, since multiplication is involved.

Continuing the example presented Figure 2-12 it can be considered that that a vulnerability assessment method implies only two parameters: *Depth to water* map and *Aquifer media* map. As described above, the grid based *rank* maps are generated. The weighting system is controlled by the w_n in equation 2-6.

Applying an unweighted sum overlay (the equation 2-6 with $w_1 = w_2 = 1$) to the rank maps, the resultant overlay suitability map (*Map obtained by unweighted sum overlay*) is obtained.

The cells values of the resulted map are written in Figure 2-12. If the depth to water of the bottom cell from the *Depth to water* map is 75 m instead of 74 m (a 1% difference), its value on the corresponding *rank map* would be a rating of 8 (if rounding 7.5 to 8). The effect of this error in the suitability analyse equation (2-5) is that cells 3 and 4 of the overlay operation take values 17 and 13 instead of 16 and 12. This means a 6.25% difference for the cell 3 and a 8.33% difference for cell 4. In conclusion, it can be said that cell 3 is more sensitive to errors than cell 4.

Measures of geographical sensitivity

Numerous defined types of *sensitivities* related to geographical operations can be found in the literature. However, sensitivities more directly related to the suitability analyses are *metric sensitivities* and *weight sensitivities*. *Metric sensitivities* are the variations that arise when different functions in equation (2-1) are used in the determination of the suitability (vulnerability index determination) analysis. *Weight sensitivities* are variations that occur with respect to perturbations of weight associated with overlay suitability. The *weight sensitivities* are divided in *layer sensitivities* and *scale sensitivities*. *Layer sensitivities* are variations in the resultant map that are due to removing any one or a group of maps in a suitability analysis. This corresponds to taking weight perturbations that are equal in magnitude but the negative of ones given for the maps that are to be removed. For N maps, there are $2^N - 2$ possible ways to perform the analysis. *Scale sensitivities* are variations that arise from different scale ranges, used in rating schemes for rank maps (if setting rating $w_1 = 2$, this corresponds to a perturbation of 100%, that is equivalent to making the rank scale for the depth to water map to take values between 0 and 20 instead of a 0 to 10 interval).

Starting from these ideas, Lodwick et al. *(1990)* define several measures of geographical sensitivity that concern the variations over the entire set of subareas *C(N)*. *Map removal sensitivity measures* and *attribute sensitivity measures* are those used in the sensitivity analysis performed for the EPIK method on the Beauraing aquifer.

2.3.4.. Parameter sensitivity analysis

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. The general flow-chart of the procedure is presented in Figure 2-13.

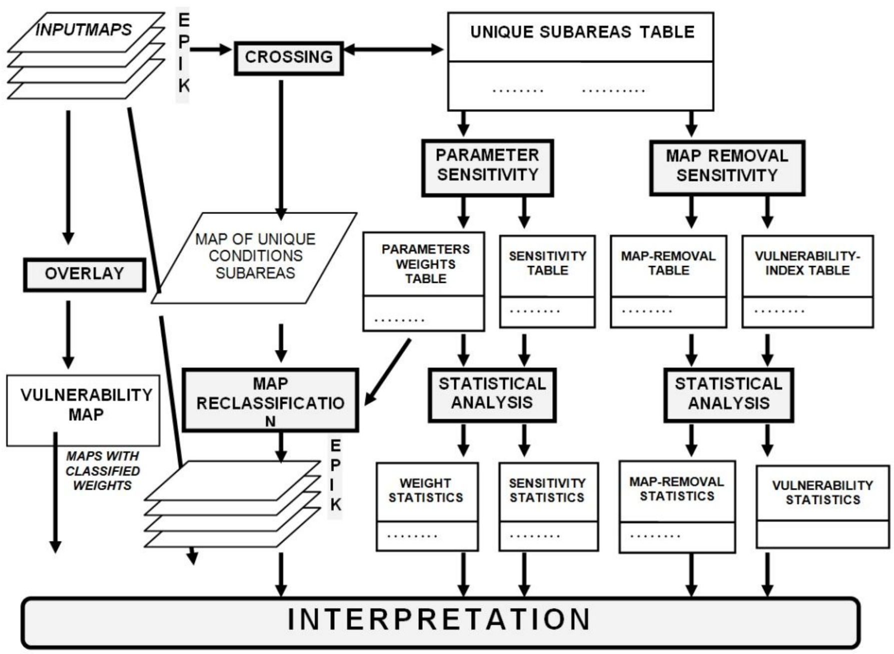


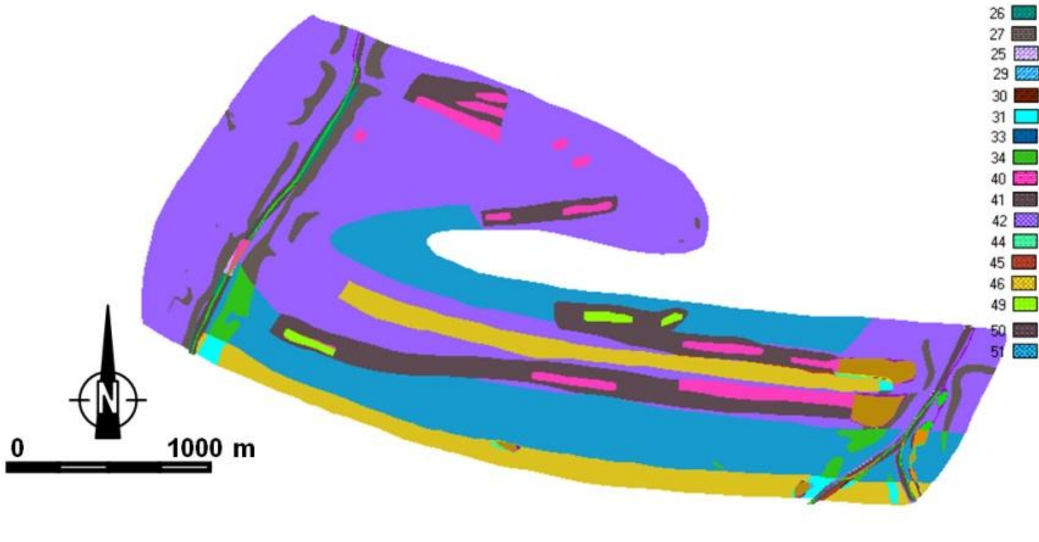
Figure 2-13 Procedure for applying sensitivity analysis *(Gogu and Dassargues 2000 b)*

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. The statistical values are further mapped and discussed.

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 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 macro-language 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. The resulted "unique conditions subareas" map and table are illustrated in Figure 2-14.



	E	P	I	K	Vul.
12	1	1	1	2	11
13	3	1	1	2	17
14	4	1	1	2	20
16	1	2	1	2	12
17	3	2	1	2	18
18	4	2	1	2	21
20	3	3	1	2	19
21	4	3	1	2	22
26	1	1	2	2	14
27	3	1	2	2	20
25	4	1	2	2	23
29	1	2	2	2	15
30	3	2	2	2	21
31	4	2	2	2	24
33	3	3	2	2	22
34	4	3	2	2	25
40	1	1	3	2	17
41	3	1	3	2	23
42	4	1	3	2	26
44	1	2	3	2	18
45	3	2	3	2	24
46	4	2	3	2	27
49	1	3	3	2	19
50	3	3	3	2	25
51	4	3	3	2	28

Figure 2-14 Unique conditions subarea map and table *(Gogu 2001)*

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 (Table 2-1) indicate that the relative influence on the final vulnerability index is: **E > I > K > P**

Table 2-1 Statistic balance on the effect of one parameter map removal

Parameter	Average – Parameter value (rating and weight)	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value(%)
V_i	20.00 (P= 0)	4.65	21.00	11.00	28.00
$V_i – E/f$	15.95	3.57	16.00	10.67	21.33
$V_i – P/f$	24.05	6.24	25.33	13.33	33.33
$V_i – I/f$	18.87	5.19	20.00	10.67	25.33
$V_i – K/f$	21.54	6.20	22.00	9.33	32.00

$\overline{V_i} = 20.00$ (Calculated average of vulnerability index), f = 4/3 (re-scaling factor)

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

$$S_{Xi} = \left| \frac{V_i}{N} - \frac{V_{Xi}}{n} \right| \qquad (2\text{-}7)$$

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 expression (2-7) 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 (4 maps);

n = number of maps used in perturbed suitability (3 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 2-2, 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.

Table 2-2 Statistics on sensitivity to the 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

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

$$VX_i = \frac{V_i - V_{Xi}}{V_i} \cdot 100 \qquad 1 \le i \le 22 \qquad (2\text{-}8)$$

where:

VX = variation index of the removal parameter *X* (E, P, I, or K);

V_i = vulnerability index computed using expression (2.8.) 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 (Table 2-3) is positive for parameters E (*VE*) and I (*VI*) and negative for P (*VP*) and K (*VK*). Because the whole analysed area is 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).

Table 2-3 Statistics on variation index

Parameter	Average–Parameter value (rating and weight)	Standard deviation (%)	Median (%)	Minimum value (%)	Maximum value (%)
VE	18.66	18.25	23.81	-12.28	46.67
VP	-19.87	6.19	-20.63	-28.21	-2.56
VI	6.42	14.95	3.90	-15.15	37.25
VK	-5.21	7.74	-7.30	-14.29	15.15

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:

$$W_{Xi} = \frac{X_{Ri} \cdot X_{wi}}{V_i} \cdot 100 \qquad (2\text{-}9)$$

where:

$\boldsymbol{X_{Ri}}$ *and* $\boldsymbol{X_{wi}}$ =are, respectively, the rating values and the weights for the parameter *X* assigned in the subarea *i*

$\boldsymbol{V_i}$ = is the vulnerability index as computed in expression (2-7) 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 condition subareas was reclassified according to the attribute values of effective weight for each parameter. Statistical results of effective weights are shown in Table 2-4.

Table 2-4 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

Then, the effective weights expressed in percentage were mapped according to classes defined every 5%. The effective weights maps are illustrated in Figure 2-15.

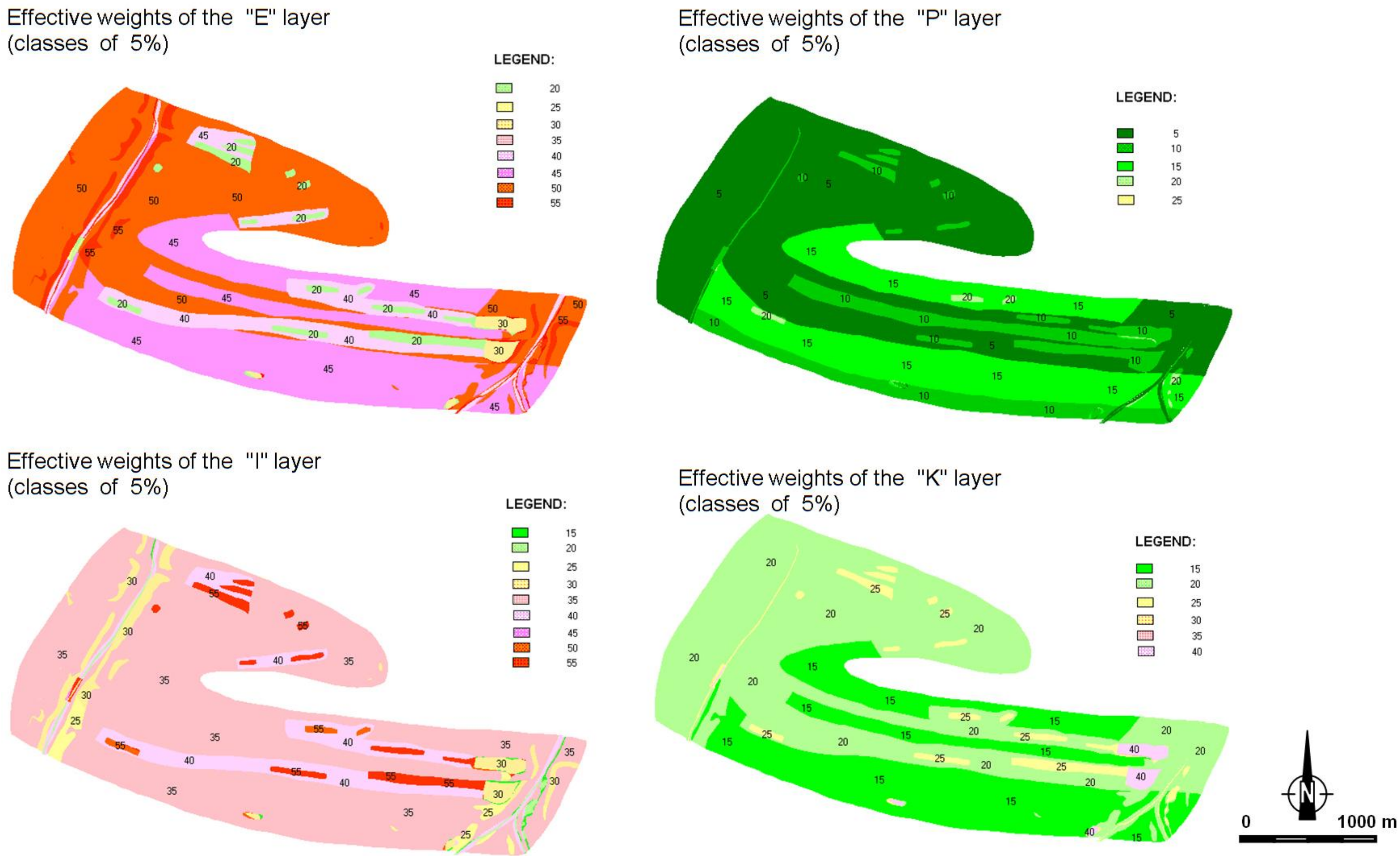


Figure 2-15 Maps with the effective weight distribution calculated for each parameter (E, P, I, and K)

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* illustrated on Figure 2-13) the final vulnerability map (Figure 2-14), and the maps representing the effective weights (Figure 2-15) used in each subarea.

Statistical analysis of the sensitivity of the effective-weight parameters shown in indicates that the *Epikars*t 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 (Figure 2-15) shows that all the effective-weight maps are strongly dependent on the value of the *Epikarst* parameter. Also, significant variations of the effective weight distribution exist, depending on values of I and P parameters. 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 ratings and on the theoretical weights chosen in equation 2-7. 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 equation 2-7 can be considered in order to reduce or increase the importance of a parameter in the vulnerability index determination.

Conclusions

The 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 *(Gogu and Dassargues 2000 b).*

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 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.

3. Geosciences spatial databases

3.1. Hydrogeology

3.1.1. Hydrogeological databases design

3.1.1.1. Hydrogeological spatial database, support for vulnerability assessment and groundwater numerical modeling in the Walloon region (Belgium)

Introduction

The use of the Geographical Information Systems (GIS) has grown constantly in groundwater management and research. GIS are 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, which are available or under development, could further support the requirements of process-based approaches. Actually, groundwater studies cannot be anymore performed without Geographical Information Systems.

A GIS managed hydrogeological database (*Gogu et al. 2001*) in order to support data used in vulnerability assessments techniques and numerical modelling for groundwater flow and contaminant transport studies has been developed. The database has the hydrogeological specificity of the Walloon region, Belgium (*Annex 19*) environment. The design of the coupling between the database and process-based numerical models was also done. 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 schemas have lead to the conclusion to design the schema of a new hydrogeological spatial database. There is a need for an advanced structure to be used for different environmental studies and consulting activities as well as research and modelling. Design has to address: (i) data management, processing and analysis as well as hydrogeological map production; (ii) numerical modelling as well as overlay and index techniques used in aquifer vulnerability assessment; (iii) support for water authorities' decision making process.

GIS and hydrogeology

Data and databases representation

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

Use of point automatic collecting systems for some of the physical and chemical parameters is more and more used. Remote sensing techniques to assess parameters related to soil, unsaturated zone, geomorphology, and climate, are increasingly used. Techniques for hydrogeological parameters measurement (sampling, monitoring of piezometric heads and flow rates, geophysical techniques) show a continuous progress. All these data need to be managed and this can be done in databases and particularly in GIS databases.

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

Assembling groundwater models and GIS

Geographic data processing can be seen as a subfield of data processing in general. There is a clear distinction between geographical data processing and process-based modeling. In order to create a digital version of the real geographic form or pattern, geographical features and attributes have to be modeled. For understanding and prediction behavior, process-based modeling uses the equations describing the physical or biochemical processes which are to be simulated. Between these two forms of modeling useful relationships can be established.

Most of GIS can easily accomplish overlay and index operations, but cannot perform the process-based groundwater modeling 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 if the use of GIS does not enhance the applicability of the process-based models, it can reduce drastically the time needed for data analysis, 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 zone and with rivers are also addressed. In these models, the equations based on the physical processes are solved.

Modeling groundwater flow and contaminant transport in aquifers represent 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, involved in the constitutive laws describing the simulated processes, creates a huge data volume. Managing this data can be done only through GIS.

Data used in groundwater modeling can be divided into four categories: (i) the aquifer system stress-factors, (ii) the aquifer system and strata geometry, (iii) the hydrogeological parameters of the simulated process, (iv) the main measured variables.

Stress-factors for groundwater flow can be: effective recharge, pumping volumes, water surface flow exchanges, etc. In contaminant transport modeling, the input and output contaminant mass flows can be mentioned. These stress-factors are imposed to the model through the “boundary” conditions or “source/sink” terms.

Good aquifer system geometry can be determined using geological information (maps and cross-sections), topographical maps, contour maps of the upper and lower limits for the aquifer strata and aquitards.

Initial guess for the distributed values and spatial distributions of the hydrogeological parameters (hydraulic conductivity, storage coefficient, dispersivity, etc.) have to be done using raw data and interpretation. Of course, the interpretation is based on the good knowledge of the aquifer geology and hydrogeology. Maps and vertical cross-sections representing the hydrogeological parameter values spatial variation are used. For a flow problem the main measured variable is the piezometric head and for a contaminant transport problem, 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. In describing how links can be organized between models and GIS, three techniques could be used: loose coupling, tight coupling, and embedded coupling.

Loose coupling is defined when the GIS and the model represent distinct software packages and the data transfer is made through input/output model pre-defined 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.

When a model is created using the GIS programming language or when a simple GIS is assimilated by a complex modeling 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.

Application of GIS data processing for groundwater numerical modelling

A good opportunity for developing the hydrogeological database was given by the study of the climate changes impact on the hydrological cycle at the basin scale, within the Belgian research project "Integrated modeling of the hydrological cycle in relation to global climate change" (CG/DD/08). The modeled system involves the simulation of quantitative interactions between river, soil, and groundwater. Three different process-based models were coupled to simulate the water flow in each of the three media: soil, river, and groundwater (Figure 3-1). The groundwater models are using finite element or finite difference software.

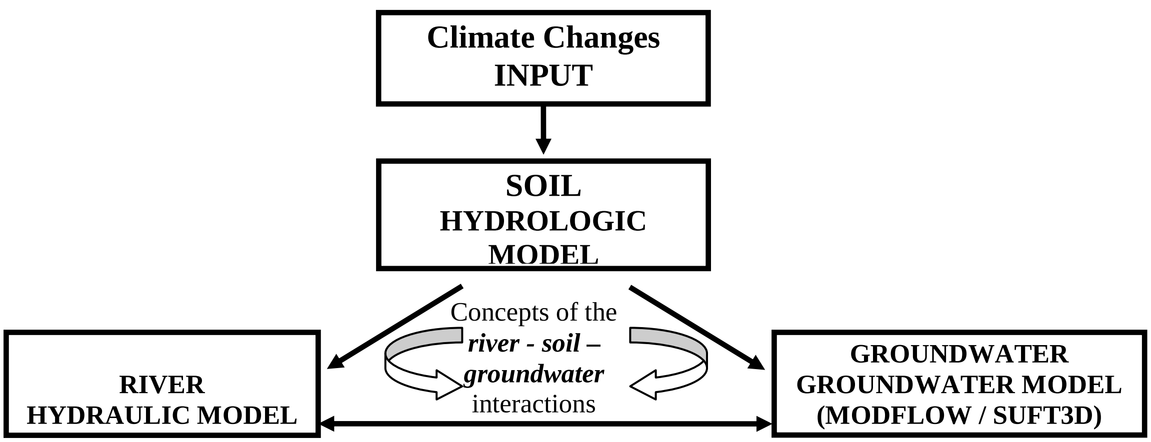


Figure 3-1 The general frame of integrating the hydrogeological database, as support for study the impact of the climate changes in the hydrological cycle at the "small" basins scale (***Gogu et al. 2001***)

For application, five hydrogeological basins were chosen (Figure 3-2) for their contrasted hydrogeological characteristics: Gette (sands and chalk), Geer (chalk), Hoyoux (limestones and sandstones), Orneaux (sands and limestones), Ourthe (fissured shale bedrock).

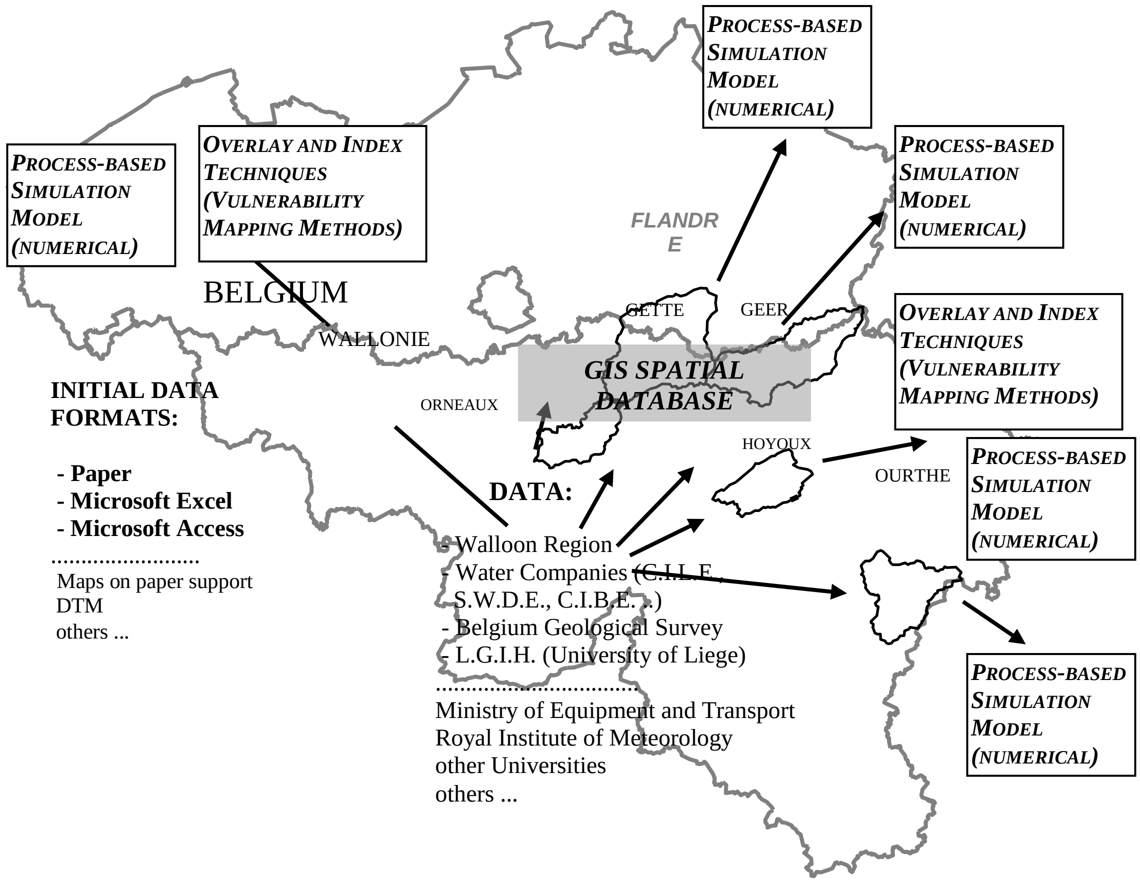


Figure 3-2 Applications of the hydrogeological database (*Gogu et al. 2001*) and analysed hydrogeological basins location (Geer, Gette, Hoyoux-Neblon, Orneaux, Ourthe)

<u>*An advanced approach for managing hydrogeological data: the HYGES database schema*</u>

Accepting that every field hydrogeologist, modeller, or regulator must have strength in data management, the purpose of developing the hydrogeological database concept (called HYGES) was to integrate main data and information the hydrogeologist needs. The objectives for the final database were: (i) to provide an organised schema for capturing, storing, editing, and displaying geographically referenced hydrological data and information, (ii) to process and analyse spatial distributed data, (iii) to properly support aquifer vulnerability assessments, (iv) to easily provide values for numerical models parameters and variables, (v) to create hydrogeological maps.

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

<u>Technical aspects in the HYGES database construction</u>

An important consideration in database construction is data analysis. Accurate studies 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 services, research offices, and many others. In this case the main data providers were 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 distinct sources showed strong dissimilarities in data type, in quality and in quantity as well as in storage media. All the data were analyzed for import to a single system. Data that could appear redundant had to be specified in the database schema to avoid loss of information. Such decisions were based on: (i) exploitation schedules, (ii) data registration formats, (iii) uncertainty of existing data (measures and registration), and (iv) insufficiency in data registration system.

Depending on 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 was the case where flow rate registrations related to several wells were available, without distinguishing the exploitation schedule of each well. There, a field containing wells sharing the same flow rate value had to be specified.

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

After structuring the spatial database schema, hydrological and hydrogeological data coming from Ministry of Walloon region, SWDE, CILE, and elsewhere, were introduced into a GIS project using Arc/Info (ESRI) and Access (Microsoft). This solution was chosen after analyzing the software platforms used by different hydrological and hydrogeological research teams, Belgian regulators, water companies and authorities, in order to ensure compatibility in future data exchange operation.

In the first step, the information has been collected for the following hydrogeological entities: wells and wells systems, piezometers, drains, water supply galleries, quarries and mines exploited for water. For this features the following characteristics were mainly introduced: location in Belgian Lambert coordinates, address, altitudes, depth, local aquifer information and owners. Almost 30 years (1947 – 1999) of time dependent data have been encoded: piezometric heads, annual and monthly exploitation flow rates. Quality data represented by 147 water quality parameters determined on 2316 groundwater samples are now registered in the database. The information is completed with digital geological maps (geology, strata elevation), land-use maps, zones of hydrogeological protection and others.

The HYGES database schema description

Data and information being specific to geomorphologic, geologic, and hydrological conditions have been divided in two parts: primary and secondary data.

Primary data section (Figure 3-3) contains layers of general environmental information (such as topography, geological maps, maps of soils), hydrological and hydrogeological raw data or data undergoing an initial minor pre-treatment as well as information related to hydrogeological investigation and exploitation means (wells, piezometers, drains, mines, quarries) and land use maps. Secondary data consist of derived primary data after being treated in different ways (maps of piezometric head, hydraulic conductivity maps, vulnerability maps, etc.).

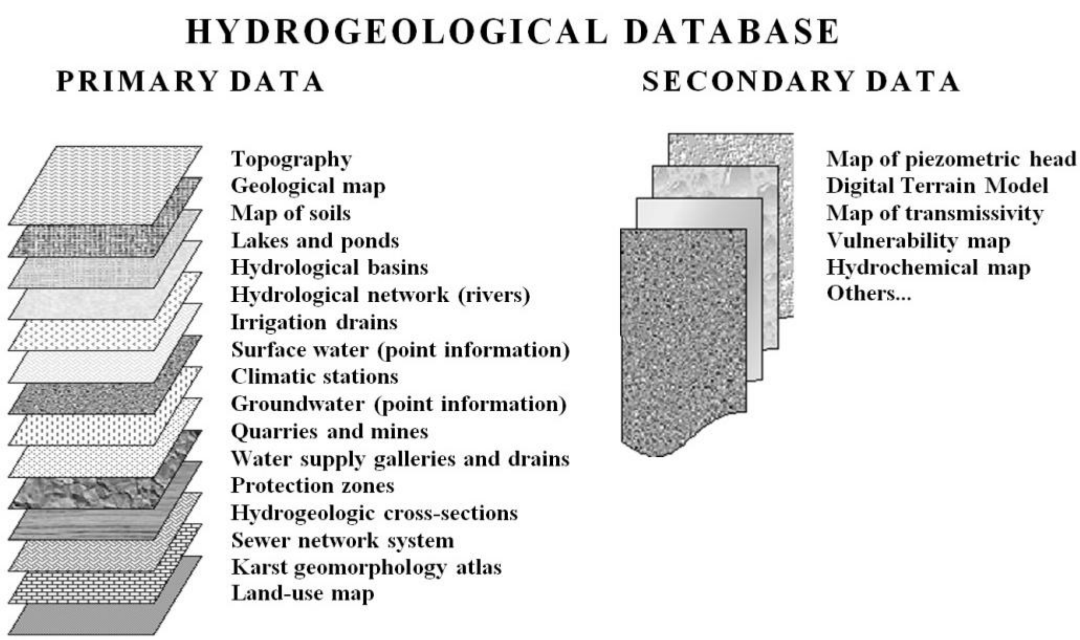


Figure 3-3 The general database schema, dividing the required hydrogeological information into "Primary data" and "Secondary data" ***(Gogu et al. 2001)***

The primary database composition is shown in Table 3-1.

Table 3-1 Primary hydrogeological database layers

N°	Groups Of Layers	No Of Layers	Name Of Layer (Coverage)	Characteristics Represented	Geometry	Item - Id Info File	Main Table Dbms	Link Column Rdbms
1	*Topography*	1	Topo	*Land Elevation – Contour Isolines*	*Arc*	Topo-Id	-	-
2	*Geological Map*	1	*Geol*	Geological Formations	*Polygon*	-	-	-
3	Map Of Soils	1	Soils	*Soils*	*Polygon*	-	-	-
4	*Surface Water-Tables*	1	Hydro	*Surface Waters (Lakes,Ponds)*	*Polygon*	*Hydro-Id*	Hydro	Number
5	*Hydrological Basins*	1	Basin	*Hydrological Basin*	*Polygon*	*Basin-Id*	Basin	Number
6	Hydrological Network	1	River	*Rivers, Interactions - Aquifers*	*Arc*	River-Id	River	Number
7	Irrigation Drains	1	Drain	*Irrigation Drains (Unexploited)*	*Arc*	Drain-Id	Drain	Number
8	Surface Water *(Point)*	1	Gauging	*Quantitative Measurement Sections*	*Point*	*Surface-Id*	Surface	Number
			Quality	*Qualitative Measurement Sections*	*Point*			
			Spring	*Springs*	*Point*			
			Exps	*Exploited Springs*	*Point*			
			Swr	*Swallowholes And Resurgences*	*Point*			
			Udrain	*Irrigation Drains (Unexploited)*	*Point*			
9	Climatic Stations	1	Climate	*Climatic Measurement Stations*	*Point*	Climate-Id	Climate	Number
10	Groundwater *(Point)*	1	Wells	Wells, Piezometers	*Point*	*Grwater-Id*	Groundwater	Number
			Gallery	*Water Supply Galleries And Drains*	*Point*			
			Cmh	*Quarries, Mines – Hydrogeological Information*	*Point*			
			Ump	*Unknown Points Of Measurement*	*Point*			
			Borh	*Geological Boreholes (Drilling)*	*Point*			
11	Quarries And Mines	1	Cm	*Quarries, Mines – Description*	*Polygon*	Cm-Id	Cm	Number
12	Water-Supply Galleries And Drains	1		*Water Supply Galleries And Drains*	*Arc*	Gallery-Id	Gallery	Number

13	Protection Zones	1	Pzones	*Protection Zones*	*Polygon*	Zones-Id	Zones	Number
14	Hydrogeologic Cross-Sections	1	Section	*Hydrogeologic Cross-Sections*	Arc	Sect-Id		
15	Sewer Network System	1	Sew	*Sewer Network System*	*Arc*	Sew-Id	-	-
16	Karst Atlas	1	Karst	*Karst Geomorphology*	-	-	-	-
17	Land-Use Map (3 Layers)	1	Sit	*Topographical Map*	-	-	-	-
		1	Com	*Communes*	*Polygon*	-	-	-
		1	Prov	*Provinces*	*Polygon*	-	-	-

Information has been divided into several groups of layers:

- Topography
- Geological Map
- Map of Soils
- Surface water tables (lakes, ponds)
- Hydrological basins
- Hydrological network
- Irrigation drains
- Surface water points
- Climatic stations
- Groundwater points
- Quarries and Mines
- Water supply galleries and drains
- Protection Zones
- Hydrogeologic cross-sections
- Sewer network system
- Karst (carbonate rocks) geomorphology atlas
- Land-use plan

As described in Table 3-1 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 the characteristics of the database link are specified in the same figure.

Topography is represented by contour isolines. 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 has been applied for 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 has been classified into two main layers depending on the relative position to the ground surface: “Surface water points” and “Groundwater points”.

“Surface water points” information layer

The information layer “Surface water points” contains: rivers gauging information, water quality sampling data, irrigation drains point data, springs, exploited springs, and swallowhole and resurgence hydrogeologic characteristics.

The attribute schema of this layer (Figure 3-5) contains several related tables. *Surface* is the main table where using a relation “one to one”, the schema is linked to the geographical location of the point in the GIS software. The linkage is done through the unique item called “Number”. The relationships “one to one” and “one to many” between the *Surface* table and the derived tables are defined using the same item. The *Water levels* and *Description (Gauging station)* tables contain river cross-sections characteristics. *Geology* and *Aquifer* are tables needed to describe the environmental conditions of springs, exploited springs, surface drains (irrigation), and karst features. The *Type (Swallowhole/Ressurgen-ce)* table is specific to the karst features.

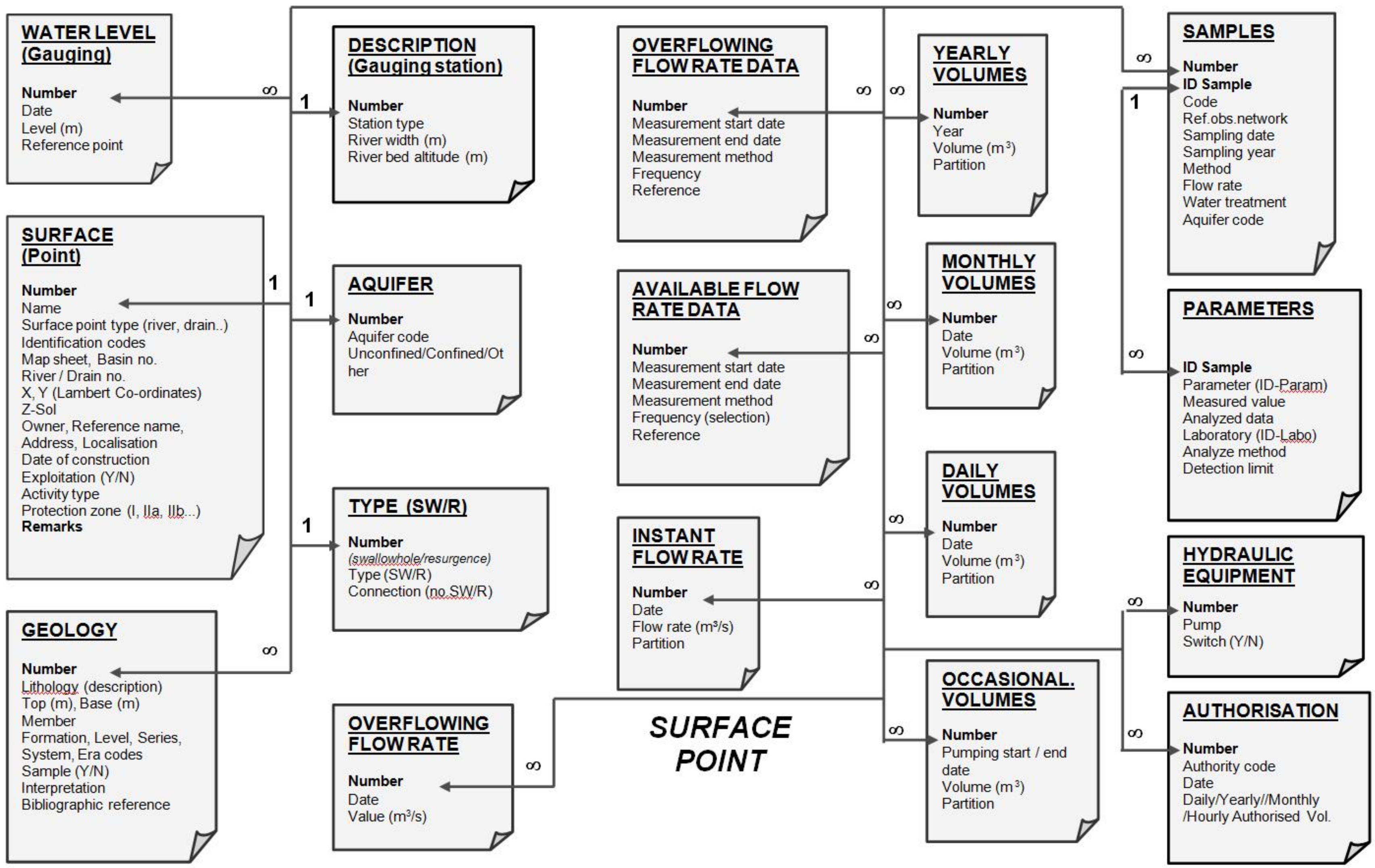


Figure 3-5 Attribute data schema simplified version for "Surface water points" layer (rivers gauging information, water quality sampling, irrigation drains point data, springs, exploited springs, swallowholes and resurgences hydrogeologic characteristics)

As it could be seen in the Figure 3-5 six tables of flow rates data have been introduced. Two of them, *Overflowing flow-rate* and *Overflowing flow-rate data* are available only for the exploited springs. Specific data for the exploited 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 *Samples* and *Parameters* tables.

The "Groundwater points" attribute schema

The "Groundwater points" layer is registered in the database with a more extended attribute schema. This layer regroups the following entities: wells, traditional hand-dug wells and simple piezometers, galleries and gallery wells, rock quarries and mines hydrogeologic point information, and boreholes. The main table linked to the layer points is *Groundwater*. The relationships between tables are made using the unique layer item also called "Number".

As can be seen in Figure 3-6 the table *Groundwater* contains information concerning the geographical position (coordinates, address), type of represented entity (well, traditional well, borehole, gallery well, piezometer), 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 belong to, and others).

Data containing the lithology and stratigraphy can be found in the *Geology* table. Each stratum a borehole is penetrating 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) can be found in the tables: *Borehole diameter*, *Borehole execution*, *Borehole treatment*, *Borehole samples*, and *Reference*. Information related to the tests conducted in the boreholes (well logging …) are stored in the table *Tests*. Data related to wells technical characteristics and equipment are in the tables: *Hydraulic equipment* and *Equipment*. The table *Equipment* is used to store information relating to the completion of wells.

Aquifer table is used to store information that describes the penetration of aquifer strata by wells. The code of the aquifer (placed in a Dictionary of terms), the punctual confined/unconfined conditions as well the location of the screens are stored here.

The piezometric head values are stored in *Piezometry* table. Seven tables representing diverse kinds of flow rates measurements are present. Two of them contain specific data for galleries and drains (Figure 3-6).

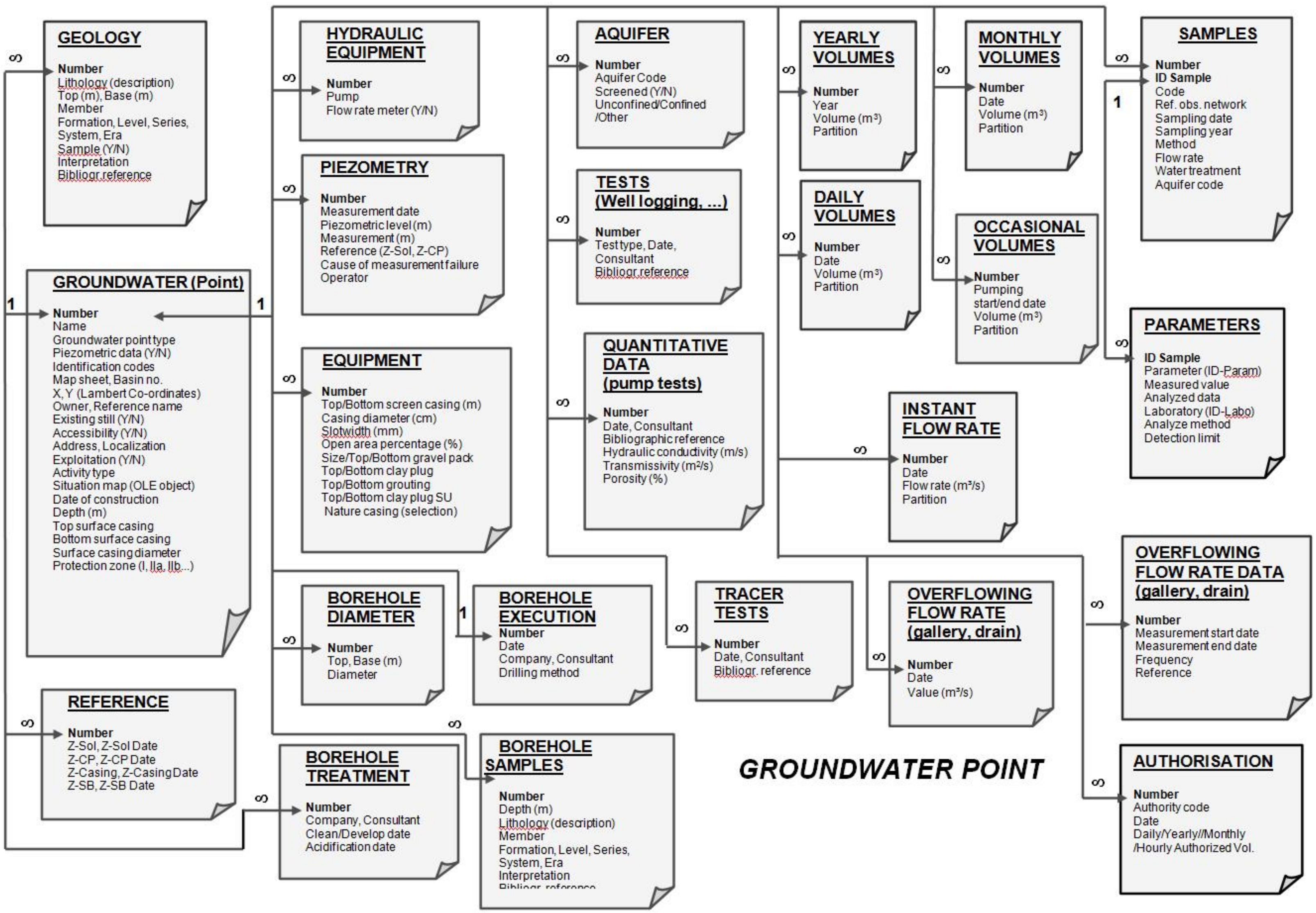


Figure 3-6 Attribute data schema simplified version for "Groundwater points" layer (wells, traditional wells and simple piezometers, galleries and gallery wells, rock quarries and mines hydrogeologic punctual information, and boreholes).

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 could be 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 (Dictionary of terms) and it's respective value, the date the analysis was done, the analysis type, and it's limit of detection. Also the name of the laboratory and its coordinates are introduced here in a dictionary of terms.

Hydrogeological tests information 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 (m/s), transmissivity (m^2/s), and porosity (%) parameters associated to a bibliographic reference are also stored here.

A table containing the authorised volumes of exploited water for each well (approved by regulators) completes the schema. The *Authorisation* table represents a good reference for the environmental impact studies and other different hydrogeologic investigations.

"Climatic stations" were represented as a separate layer of points having also an attached attribute schema. More simple attribute schemas are developed also for "Hydrological network" (line), "Surface water-tables" (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 could be done once the database was established. Maps representing database attribute queries (time and space dependent parameter values) could be created. Simple statistics related to hydrogeological entities can be displayed on the screen or printed on paper support maps. Contour maps of piezometric heads can be generated (Figure 3-7) using the optimised grid of interpolated piezometric levels. Geostatistic procedures (i.e. kriging) complete the analysis. A small part of the tools needed to achieve the objectives are already implemented in the base software package but most of them need good knowledge of GIS techniques, database philosophy, and targeted programming using specific programming languages.

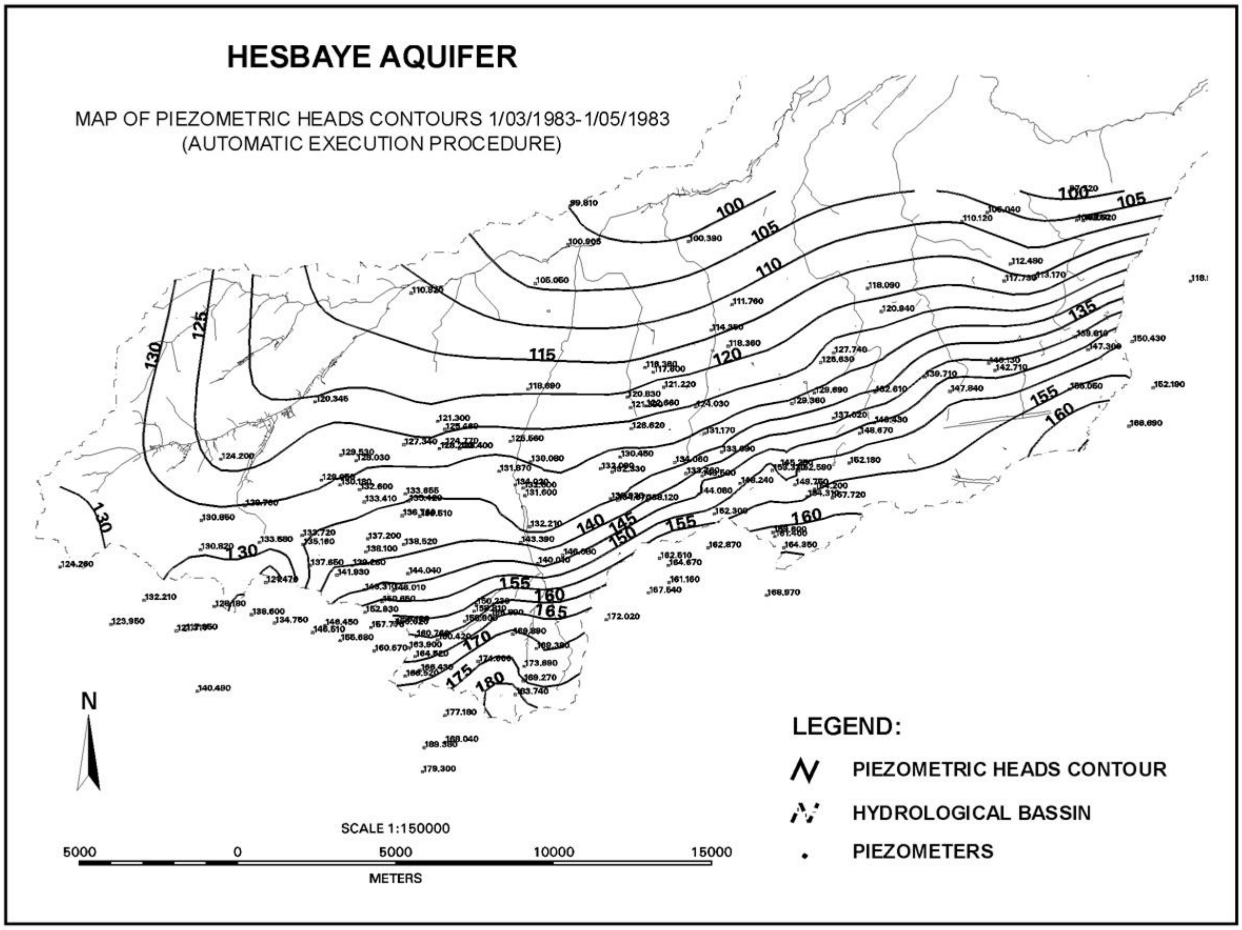


Figure 3-7 A result of the generating procedure for obtaining contour maps of piezometric heads

<u>*Some conclusions and further developments*</u>

This hydrogeological GIS database offers facilities for hydrogeological modelling as well as for other hydrogeological studies.

Data verification and validation is essential. Using an advanced database supported by GIS, this operation could be done in a simple way. Possible piezometric data anomalies could be observed directly on the generated piezometric head maps. *Automatic data treatment* is required before input to the numerical model. Because of the huge work in the preparation of the data used in the process-based models, the GIS database is essential.

Global view on the hydrogeological data can be obtained using the generated maps. Piezometric heads maps, maps of exploited flow rates, maps of statistical data, show very clearly the data distribution and allow a clear view of conditions of the aquifer behaviour and stress factors. *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 exploitation can be detected using these maps. The vertical variability of the hydrogeologic parameters (hydraulic conductivity, porosity) that have a great influence on the aquifer exploitation conditions also can be analyzed.

Correlations between groundwater hydrochemical parameters, aquifer depth, lithology and the landuse can be done using the recorded data and statistical procedures already implemented in the GIS software. *Aquifer vulnerability studies can be performed* using the existing spatial database. New procedures for physically significant quantification of the parameters can be developed using this hydrogeologic database. From this point of view, coupling GIS to process-based numerical models with applications in groundwater phenomena as well as in the unsaturated zone will represent one of the most interesting steps in the hydrogeological research for the near future.

In the year 2000 the database schema has been implemented at Department of Natural Resources and Environment - Ministry of the Walloon Region *(Annex 18)*. This database is still used as the “reference” by various universities involved in groundwater research programs.

3.1.1.2. Urban groundwater spatial database (Barcelona, Spain)

Between 2006 and 2009 a geospatial database has been developed for Barcelona city region (*Gogu et al. 2010*) to support hydrogeological studies. The database scheme has been designed having in mind the existing hydrogeological model of Barcelona (*Vázquez-Suñé, 2006*) and has an Object-Oriented approach. It assures interoperable data exchanges between different project actors and is easily extensible once its structure is unambiguously described.

An important step in the database development process was the design of a conceptual model of the required information. A large spectrum of data was identified, as many related domains are concerned: geography, geology, hydrology, hydrogeology, meteorology, water engineering, land management and others. Also, existing projects and data models were explored in order to identify possible interactions and contributions. Furthermore, the proposed conceptual model and its implementation in the geospatial database should be conformant with internationally accepted norms and specifications.

The architecture of the hydrogeological database follows 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 Organisation for Standardisation (ISO), which enables, for instance, an easy transposition and translation between real-world objects and informatics objects.

Several existing patterns or already implemented data models have been explored as follows:

- The Australian National Groundwater Data Transfer Standard, (*1999*);
- HYGES hydrogeological database: University of Liège expertise (*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 Laguage (*Lake, 2005*);
- GeoSciML – a generic Geoscience Mark-up Language (*Sen and Duffy, 2005*).
- Groundwater Model: ESRI, Strassberg Ph.D. dissertation (*Strassberg, 2005*);
- XMML (eXploration and Mining Markup Language): as a GML application schema (*Cox, 2001; XMML, 2006*);

Starting from these models it has been considered necessary to prepare a new, more complete and exhaustive model of extended hydrogeological information (Figure 3-8) that has to match better the particularities of sedimentary media groundwater. The main components of the hydrogeological database are Abstract feature classes, Regional data package, Hydrogeology, Hydrography, Drainage features, and Observations and Measurements. Abstract feature classes are defined as parent classes for other concrete classes. They allow to establish a basis for the classification of hydrogeology, hydrography, drainage, artificial recharge and other features. The Regional data package stores information about different regional data grouped within the "Aquifer properties" and "General data" sub-packages. Hydrogeology regroups groundwater bodies and established groundwater protected zones, as well as tracer, pumping, and geophysical test areas. Hydrography contains spatial information about rivers, rivers segments, lakes and their segments, costal and transitional waters. Drainage features show the classification of sub-basins, river basins, and river basins districts. Groundwater features regroups information about wells, boreholes, springs, groundwater monitoring stations, and boreholes interpreted lithology. In Observations and Measurements package are stored and managed primary data as well as interpreted results from hydrogeological and geophysical tests.

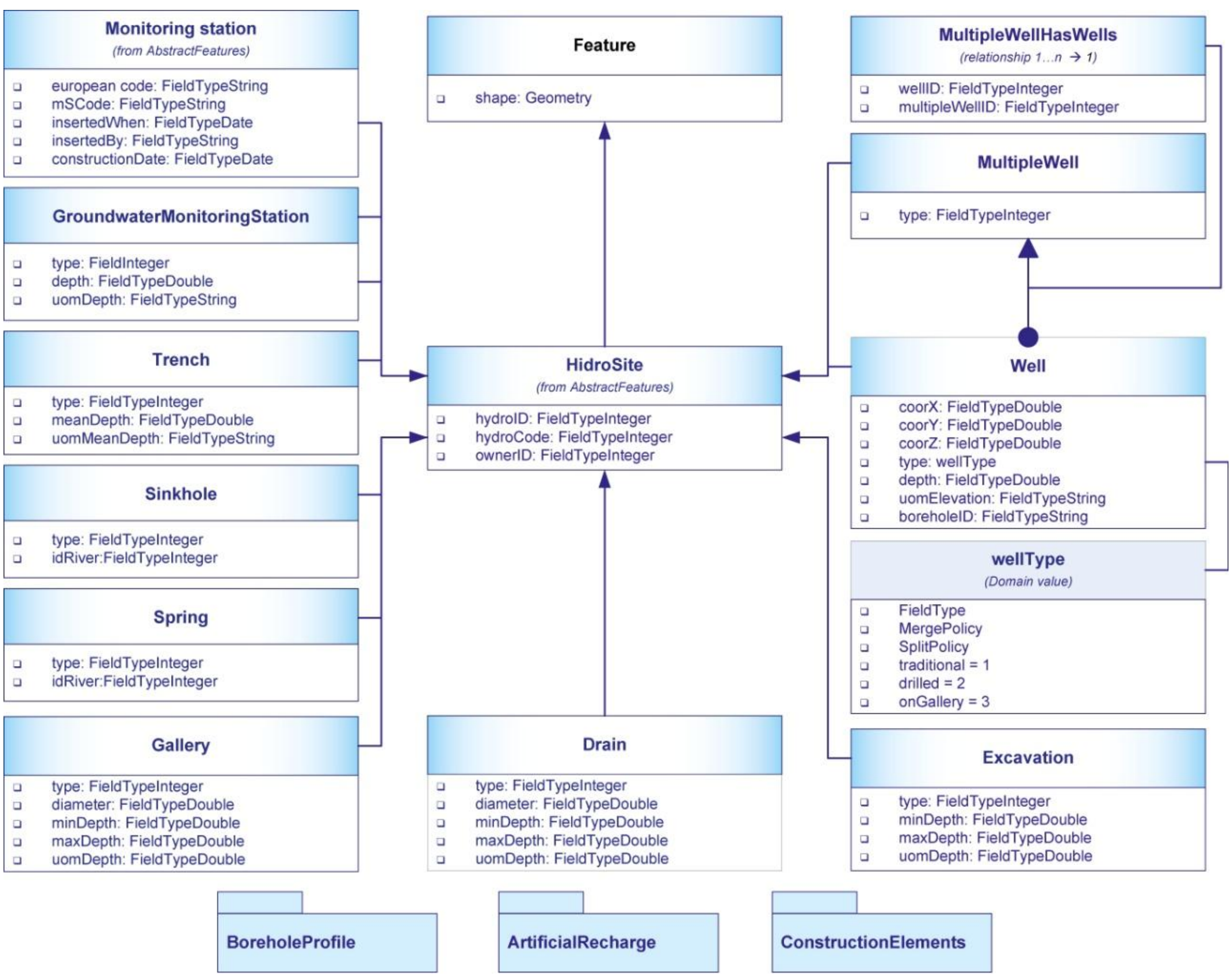


Figure 3-8 Overview on the hydrogeological database scheme

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 in separate tables. They could be easily queried and represented in a stratigraphic column.

3.1.2. Prototype design of hydrogeological maps in Walloon region (Belgium)

"A picture speaks more than a thousand words and a map more than a thousand pictures" said Vrba and Zaporozec (*2004*). As consequence maps are an indispensable tool for water scientists and professionals. They support data documentation and hydrogeological data description. Starting from the schema presented at 3.1.1.1. a large scale project started and still continue nowadays (*Bouezmani et al., 2006*). In 1999 a pilot project *(Annex 18)* was set up and prototypes of the first hydrogeological maps for the Walloon *(Annex 9 on CD)* region have been dressed. Since then four teams from three universities are working for the hydrogeological mapping program of the Walloon Region (Belgium).

The hydrogeological maps *(Annex 19 on CD)* are structured as follows:

- a main hydrogeological map (scale 1: 25,000) showing the main layers as topography, geology (litho-stratigraphical formations grouped in hydro-geological units), hydrographic network, position of wells, galleries, drains, protected areas, karstic features, springs, hydraulic heads contour lines, groundwater flow directions, and others;
- geological and hydrogeological cross-sections showing the hydrogeological units and the hydraulic head;
- a table showing the correspondence between geological formations and hydogeological units described as aquifers (high hydraulic conductivity values), aquitards (medium hydraulic conductivity values), and aquicludes (low hydraulic conductivity values) on a lithological basis;
- thematic maps scale 1:50,000 showing specific information as the confined or the unconfined nature of the hydrogeological units, top and bottom of the aquifer strata, annually exploited volumes, well logging, pumping and tracer tests, hydrochemical analysis and others;

Explanatory booklets accompany each hydrogeological map containing geographical, geological and hydrogeological aspects of the mapped region. Specific hydrogeological issues are also focused as for example karstic features, hydrochemical parameters, water extraction protected areas, and others.

3.1.2.1. The hydrogeological map prototype of Waremme - Momalle area (Belgium)

The hydrogeological map (*Annex 19*) is based on an entire set of available data (geological, hydrogeological and hydro-chemical) offered by different institutions. It aims to give information about the spatial extent, the geometry and the hydrodynamic and the hydro chemical characteristics of the aquifer formations in order to offer support for quantitative and qualitative water resources management tasks.By a deliberate choice, the map wants to avoid any outrageous information overlapping that would reduce the readability. For this purpose, beside the main map, three thematic maps, with hydrogeological cross sections and a lithostratigraphic array are presented.

<u>*Introduction*</u>

The Waremme-Momalle region is situated north-west of Liège (Figure 3-9). The main groundwater resource in this region is the Hesbaye aquifer. The boundaries are: the Meuse river in South and Est, the Méhaigne basin in West; to the North it is drained by Geer river then it extends under the tertiary covers.

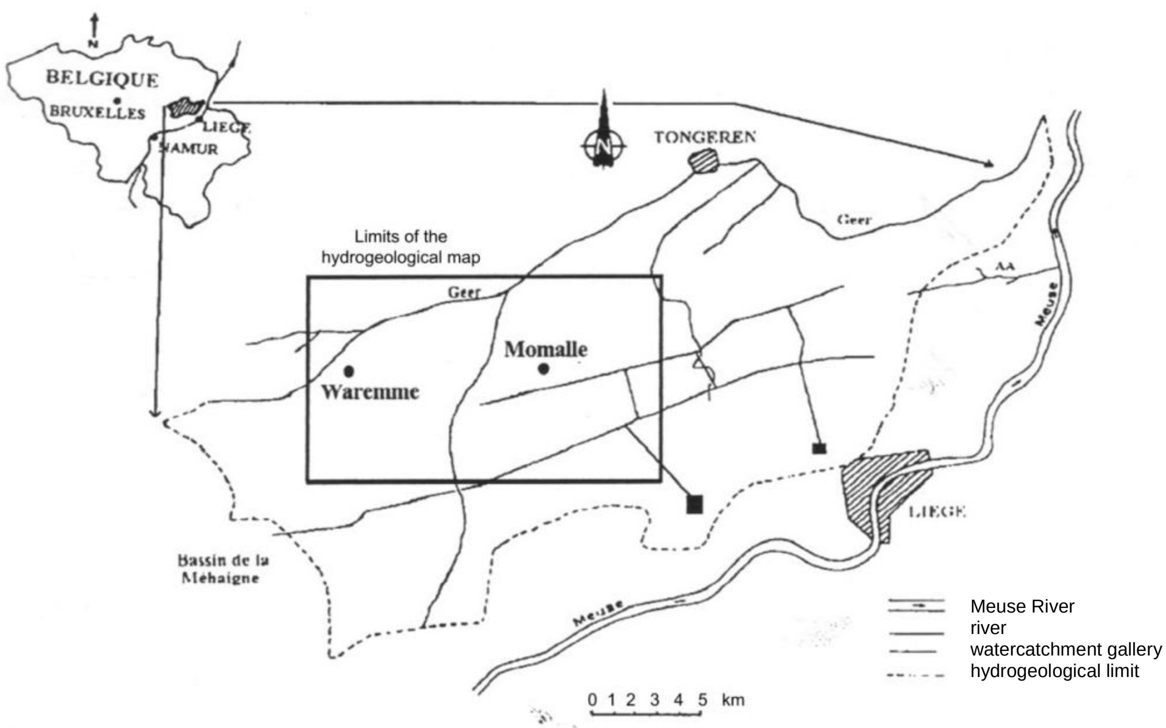


Figure 3-9 The location of the Waremme – Momalle hydrogeological map.

The Hesbaye aquifer is located in the porous and fissured media of the existing Cretaceous chalk. The chalk is characterized by a very high porosity, conferring a good storage capacity. The presence of fissures guaranties an efficient drainage of the water. It is a highly important aquifer that assures between 60000 and 80000 m^3/day water for the city of Liège (Campagnie Intercommunal de Distribution d’Eau – CILE), Waremme (Société Wallonne de Distribution d'Eau – SWDE) and for the municipalities of the Hesbaye plateau (CILE and SWDE).

Geographical and geomorphological context

The region is situated in the Hesbaye plateau (Belgium) that shows a topographic surface that gently slopes towards N-NW. The range of altitudes is between 180 m at SE and 100 m at NE. About 93% of the region belongs to the River Geer water catchment area. On the North side about 6% of its area is drained by a series of streams belonging to the River Gette basin and about 1% (South-East extremities) is drained towards the River Meuse.

Apart from the Geer, the main draining flow axis is SW-NE and the active hydrographic network is sparse. The three main components are:

- The Yerne River, with the flow direction SSW-NNE and whose upstream valley ravine of Limont drains the groundwater over an area of nearly 1 km. In its middle part, the river is situated above the groundwater table;
- The Roua River is flowing towards the North in the direction of the River Geer. In the upper stream of its course the river is supplied by surface runoff of the regions Fexhe-le-Haut-Clocher, Kemexhe and Crisnee;
- The Figgelbeek River belongs to the Basin of the Gette River and flows towards North.

This very low surface drainage density, justifying the term of dry Hesbaye, is in direct relation with the subsoil permeability and the groundwater depth.

The numerous dry valleys of the major flow directions, S-N, SW-NE and SE-NW, define a fossil hydrographic network, leading to a typical relief, representing a succession of ridges and broadly rounded depressions, often with symmetrical slopes.

These dry valleys are progressively deepening towards North, finally arriving to the Geer River. They have mainly a periglacial origin, however some of them must have more recent causes, such as slow the dissolution of chalk. These valleys correspond to areas of high permeability, thus constituting preferential flow paths that can lead to significant drawdowns of the piezometric head.

Methodology used for the hydrogeological map development.

The Hesbaye aquifer has been exploited for over a century by various water companies, thus a high number of geological, hydrogeological and hydro-chemical data are available. The data availability represented one of the criteria that have led to the selection of the Warreme-Momalle region for the development of the prototype hydrogeological map.

The hydrogeological map description (Annex 19 on CD)

The hydrogeological map consists in:

- The main hydrogeological map (1:25 000) giving information on different aquifer formations, the shape of the aquifer, the location of surface water supply systems, and others;
- A map (1:50 000) with the location of groundwater supply systems;
- A map (1:75 000) with contourlines for the top and bottom of the main aquifer formation;
- A map (1:75 000) to place:
    - The locations of available hydro-chemical data and locations of different performed tests (pumping, tracer, borehole logging);
    - Areas where the aquifer is unconfined, semi-confined and confined;
    - The extent of the vulnerable area of the Crétacé de Hesbaye;
- one hydrogeological cross-section;
- one lithostratigraphical table.

3.1.2.2. The hydrogeological map prototype of Modave-Clavier area (Belgium)

The hydrogeological map (*Annex 19*) is based on the existing geological, hydrogeological and hydro-chemical data available offered by various organizations. It aims to give information about the spatial extent, the geometry, and the hydrodynamic and hydro-chemical characteristics of the aquifer formations to offer support for quantitative and qualitative water resources management tasks.

Introduction

The Modave – Clavier region is situated at about 10 kilometers south of Huy town. The main aquifer formation in this area is located within the Carboniferous limestone of the eastern part of the Dinant synclinorium (Figure 3-10). It is an aquifer of primary importance, exploited by various water distribution companies. Its limestone formations assure about 97 000 m^3/day of water for the surrounding communities and for the cities of Bruxelles and Liège.

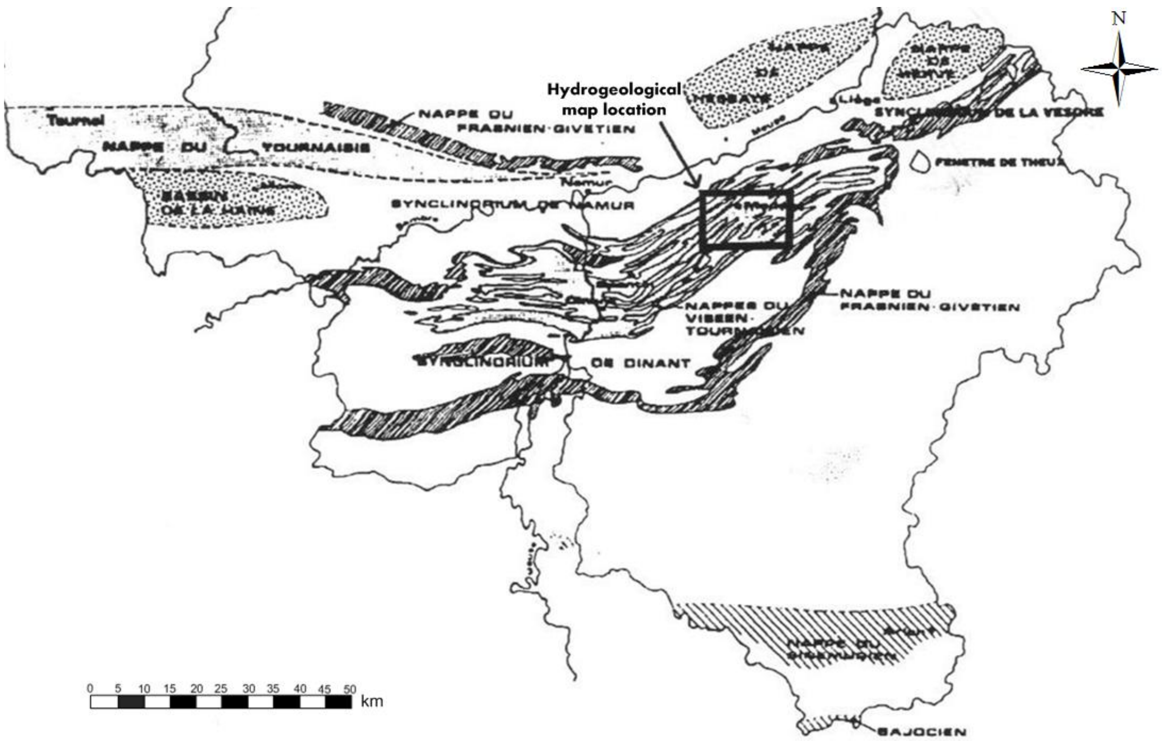


Figure 3-10 The location of the Modave - Clavier hydrogeological map

Geographical and geomorphological context

The area covered by this map is part of Condroz region. Its bedrock is formed by Devonian – Carboniferous strata belonging to the eastern part of Dinant Basin. Condroz is an ancient plateau that is characterized by alternating topographic ridges and depressions oriented from North-East towards South-West. The ridges are generally composed by schists and Famenian formation sandstone as well as depressions of carboniferous limestone (Pailhe valley, Vyle valley,). Locally, this landscape is cut by a hydrographic network from West to East (Hoyoux valley).

The four distinct watersheds are:

- The Hoyoux Basin, covering about 70% (111.7 km^2) of the area, whose waters flow northward toward Meuse;
- The Néblon Basin, draining 28% (45.3 km^2) of the area eastward, towards the valley of the Ourthe;
- The Anthines Basin, located in the North-East, having a small extent (2.24 km^2, 1.4 % of the area) draining toward East in direction of Ourthe;
- The Ourthe Basin, located in the South-East (0.75 km^2, 0.3 % of the area).

The hydrogeological map

The hydrogeological map consists in:

- A hydrogeological map (1/25 000) giving information on different aquifer formations, the shape of the aquifer, the location of water inlets, and others;
- A map (1/50 000) with the location of water catchment areas;
    - The sites where hydro-chemical data are available and the sites where different hydrogeological tests (pumping, tracer, borehole logging, …) were performed;
    - The investigated sites using geophysical measurements;
- Hydrogeological cross section;
- Lithostratigraphical table.

3.2. Natural hazards

3.2.1. Data management of volcanic systems: Nysiros (Greece) and Campi Flegrei (Italy)

Introduction

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

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 (Figure 3-11). 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 10MA 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.

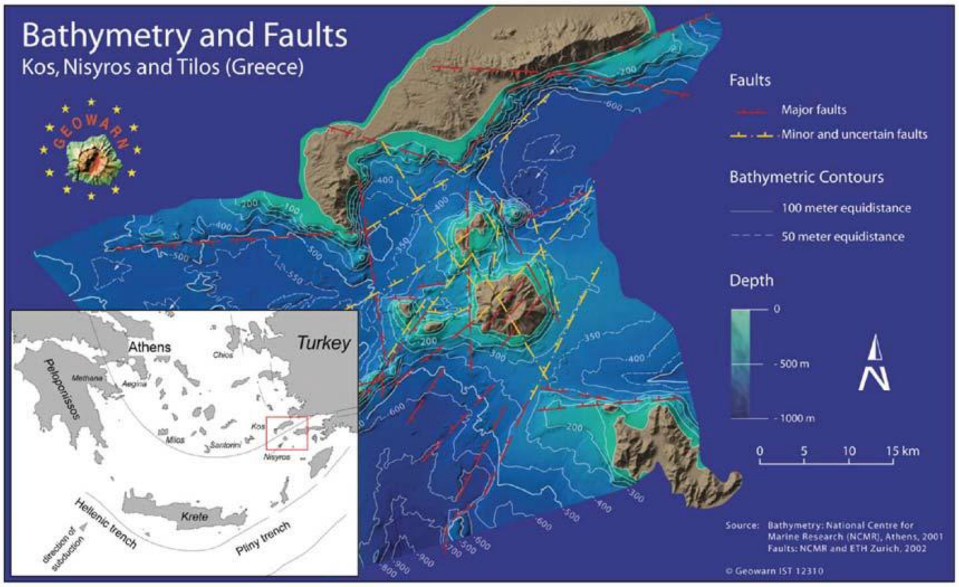


Figure 3-11 Nisyros Island and Kos–Nisyros–Tilos volcanic area

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 (Figure 3-12).

Figure 3-12 Stephanos crater, Nisyros caldera

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 N-NW 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 10km depth, damaging 30 houses in Mandraki.

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.

The GEOWARN geo-spatial database concept

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 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.

The geo-spatial database design

The GIS database developed in this study (*Gogu et al. 2006*) 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 Figure 3-13. 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.

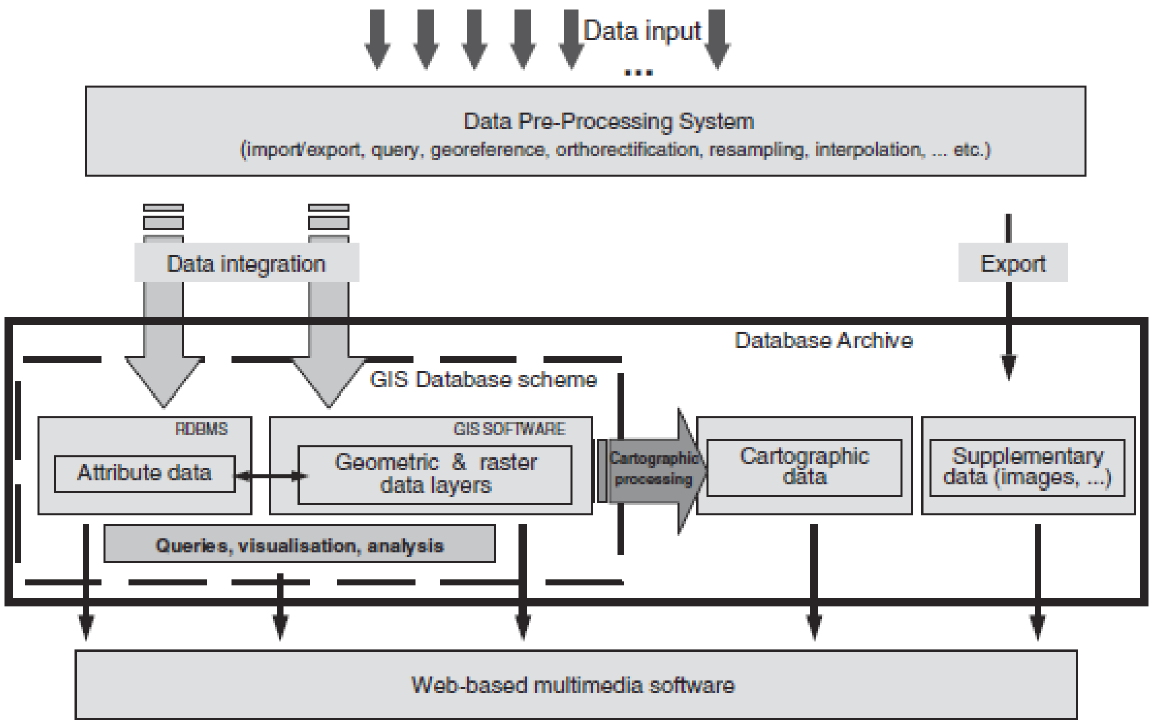


Figure 3-13 Overview on data-flow and data-organization system (*Gogu et al. 2006*)

The layers

A simplified version of the database layers and its content for the Kos–Yali–Nisyros Tilos volcanic field is shown in Table 3-1 (*Gogu et al. 2006*). 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 2m 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 Mo 4.0 registered during the project period (2000–2002), and historical hypocenters (1911–2003) of important regional earthquakes with magnitudes M43:0.

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 3-1 Simplified version of database schema (*Gogu et al. 2006*) content for Nisyros–Kos–Tilos (Greece) volcanic area

	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 20m 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 Figure 3-14, 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 Figure 3-14, 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.

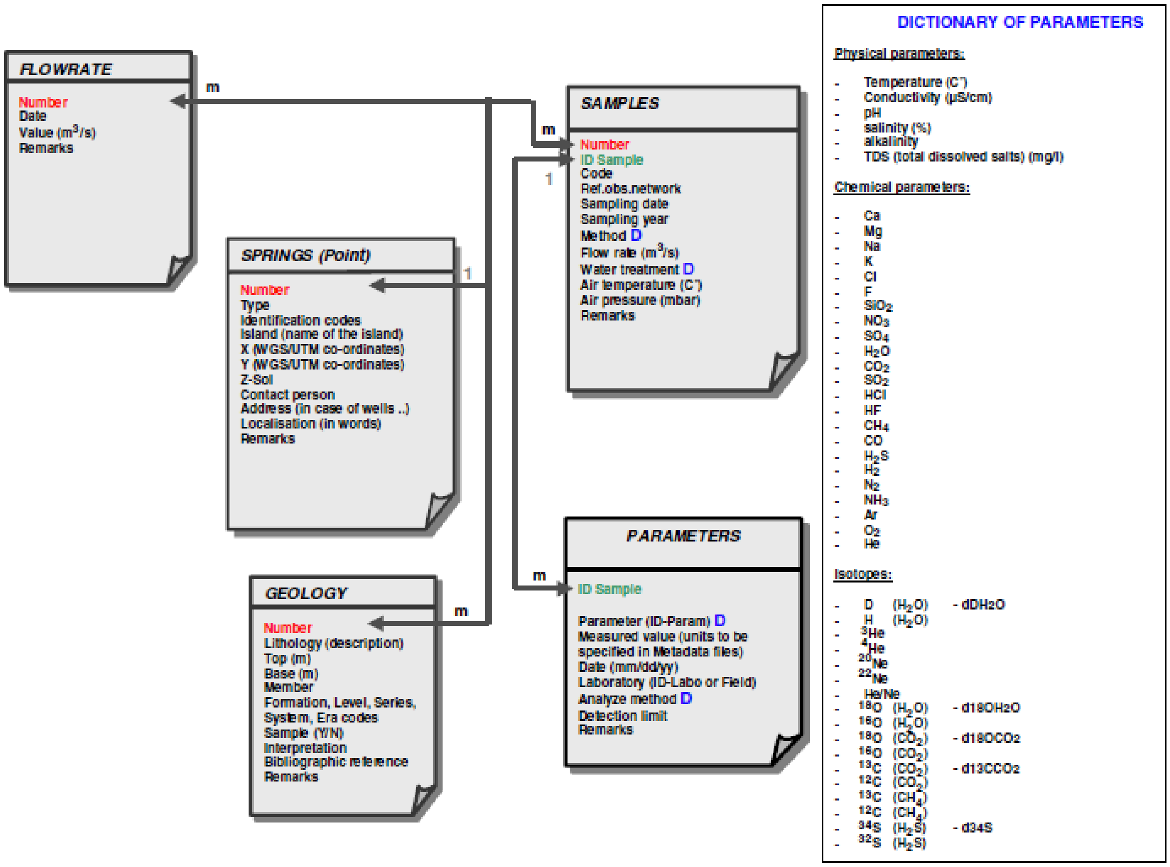


Figure 3-14 Simplified version of attribute data schema for Geothermal springs (*Gogu et al. 2006*)

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 1m resolution. The image taken by the IKONOS satellite was orthorectified using the before mentioned 2m 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).

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 a GIS environment is to date still a rare occurrence. GIS technology is still used mainly to generate maps.

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 ArcSceneTM module (ArcGISTM software package). As a result, the relation between the calculated hypocenters and the tomographic model of the underground has been generated (Figure 3-15). 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 (isovelocity 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.

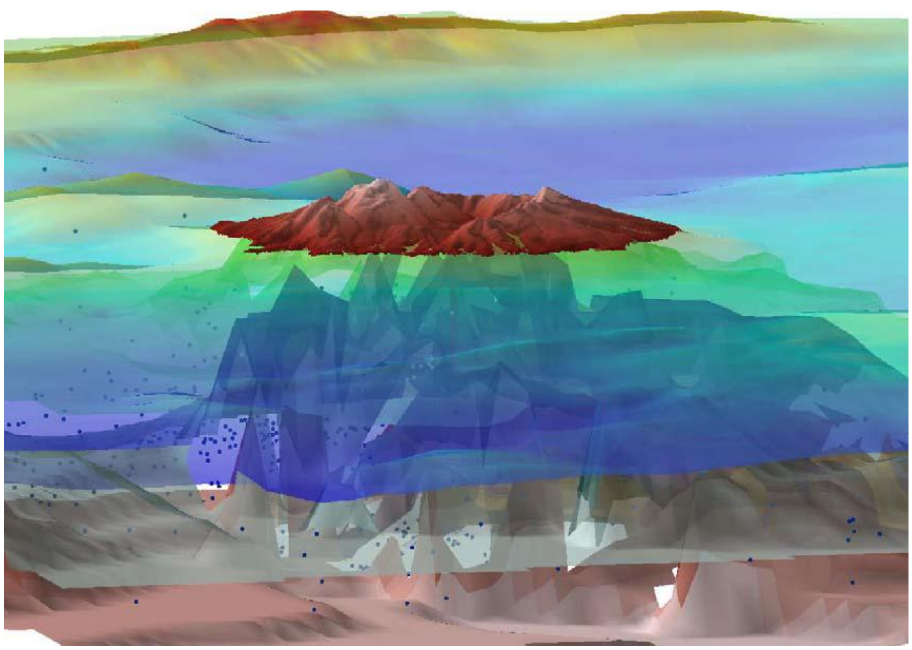


Figure 3-15 Visual correlation between calculated hypocenters and interpreted limits between various geological strata resulting from tomographic model

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

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

Earthquake hypocenters in time and space

A tool was developed for queries of earthquake hypocenters in time and space. Used in the ArcSceneTM 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).

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 Figure 3-16. 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.

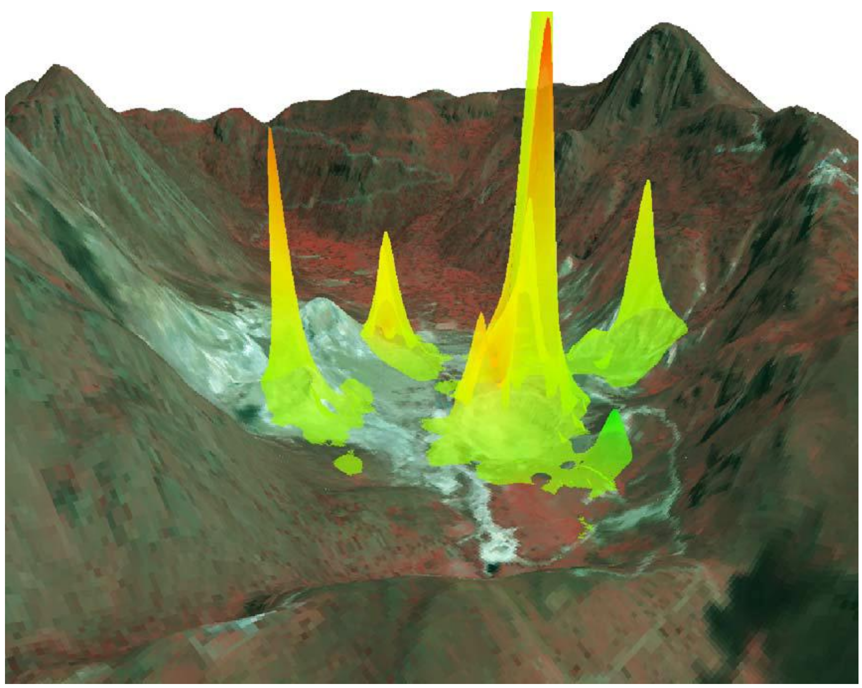


Figure 3-16 Three-dimensional representation of exuded CO2 flux distribution in Nisyros caldera. Heights represent modeled CO2 grid flux values and colors represent temperature.

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/ObjectTM 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 showgraphs of the physical and chemical parameters related to volcanic point features such as springs and fumaroles. Figure 3-17 shows the H2S 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 values can be computed at any given point location within the areal coverage of these grids.

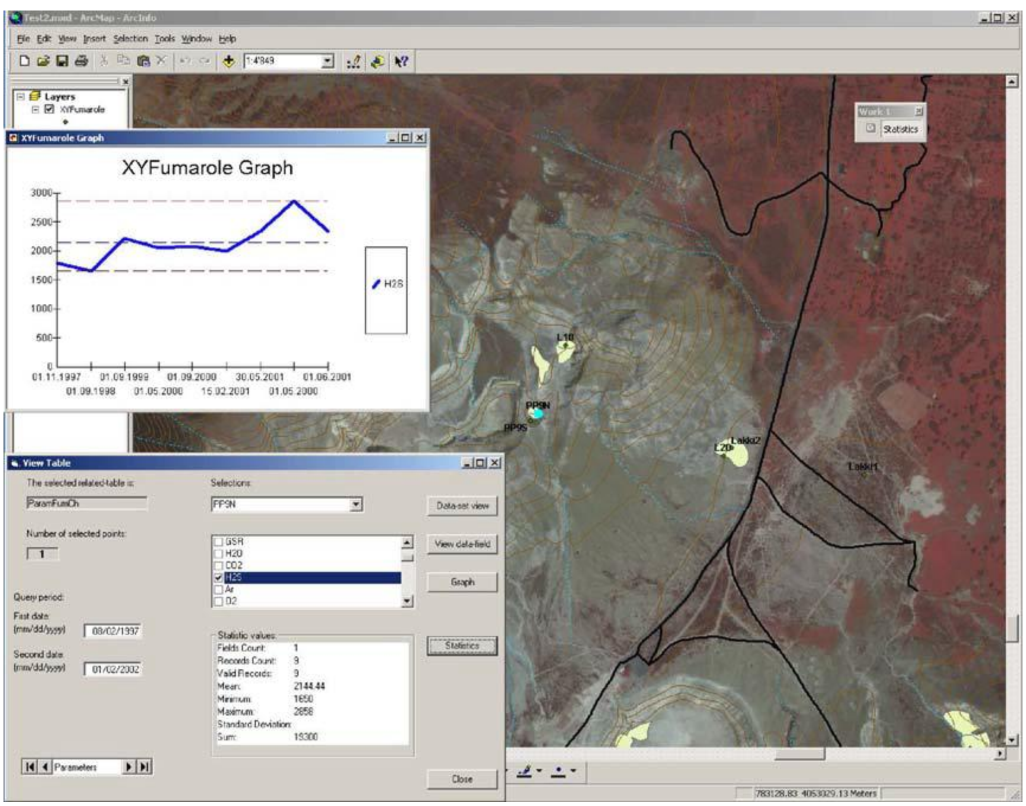


Figure 3-17 Spatial database query menu for fumaroles chemical parameters

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.

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 threedimensional hypocentres to be observed from various angles, simultaneously with the geology, tomography, gravity, and magnetic models.

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 section is an integral part of the GEOWARN project, a pilot study of geospatial data management of dormant volcanoes. Changes, updates, or further developments of the schema are expected to be incorporated in the future. Starting from this schema, new developments have been undertaken.

3.2.2. Geospatial systems for hazard assessment in mountainous environments

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. Systematically 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 has being developed under HazNETH (the Network for Natural Hazards at ETH Zurich). HazNETH is a consortium of research groups studying natural hazards and risk in different departments with combined expertise in Atmospheric physics, Climatology, Hydrology, Hydraulics engineering, Water management, Risk engineering, Construction engineering, Forest engineering, Engineering geology, Geotechnics, Seismology, Geodynamics, Geodesy, Cartography, Photogrammetry and Remote Sensing, Environmental social sciences and Economics.

3.2.2.1. Geospatial systems for hazard assessment studies (Vispa valley, Switzerland)

Switzerland has always been exposed to a wide variety of natural hazards happening most frequently in its alpine valleys (Figure 3-17).

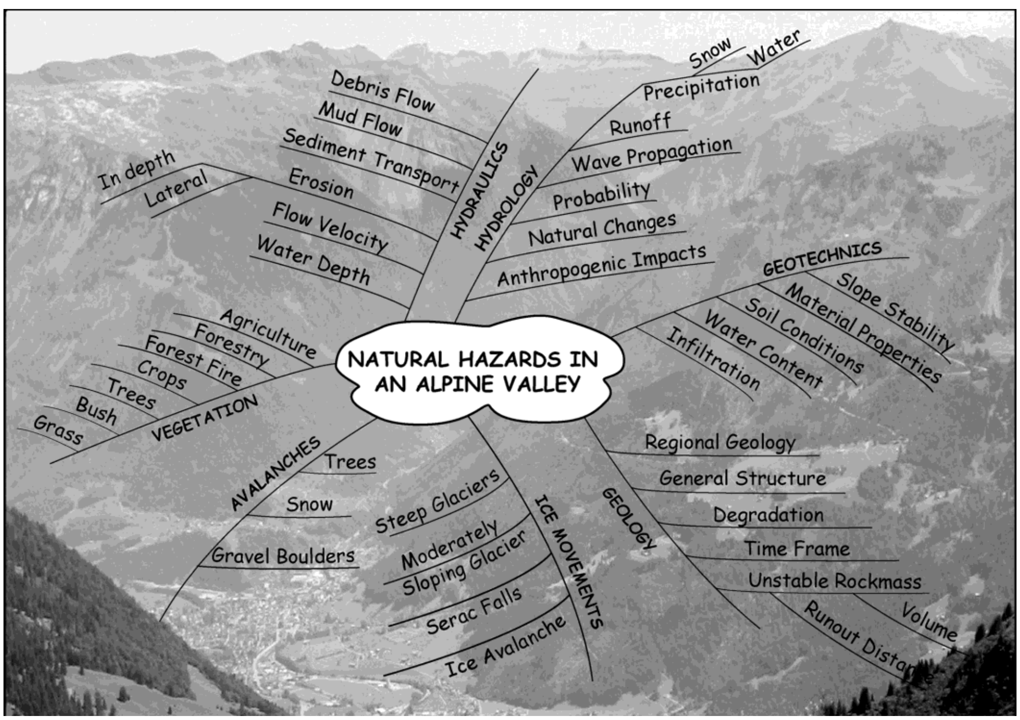


Figure 3-17 A synthesis of different phenomena acting as natural hazards in an alpine valley

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.

A geospatial hazard information system (Figure 3-18), which allows the project partners to share and analyze their datasets (*HazTool*), has been designed (*Gogu et al. 2005*). Apart from standard GIS functionalities, the system provides expert analysis tools which are tailored specifically to the needs of interdisciplinary hazard research. Technically the system has been implemented as a multi-tier architecture: Internet client, application server with web server and spatial engine, and spatially enabled database.

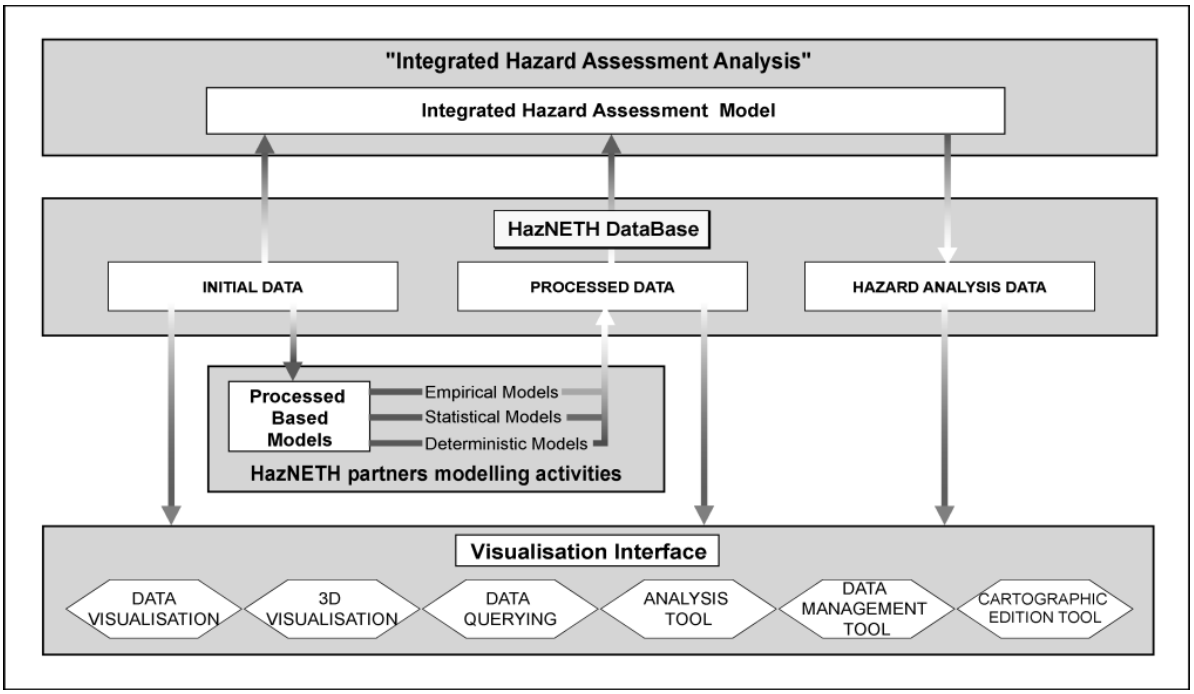


Figure 3-18 The general scheme of the HazTool system

Apart from scientists, experts in their field, HazTool has been designed to 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.

<u>*Geospatial System for Data Management, Modelling, Visualisation, and Analysis (HazTool)*</u>

The conception and development of a web based information system for natural hazard analysis has been carried out at the Institute of Cartography of the Swiss Federal Institute of Technology in Zurich (ETHZ). It was 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;
2. The development of integrated natural hazard assessment methods and data modeling tools;
3. The creation of specific hazard analysis tools for interdisciplinary research as well as for specific research needs of particular partners.

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. 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 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.

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 (Figure 3-19):

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

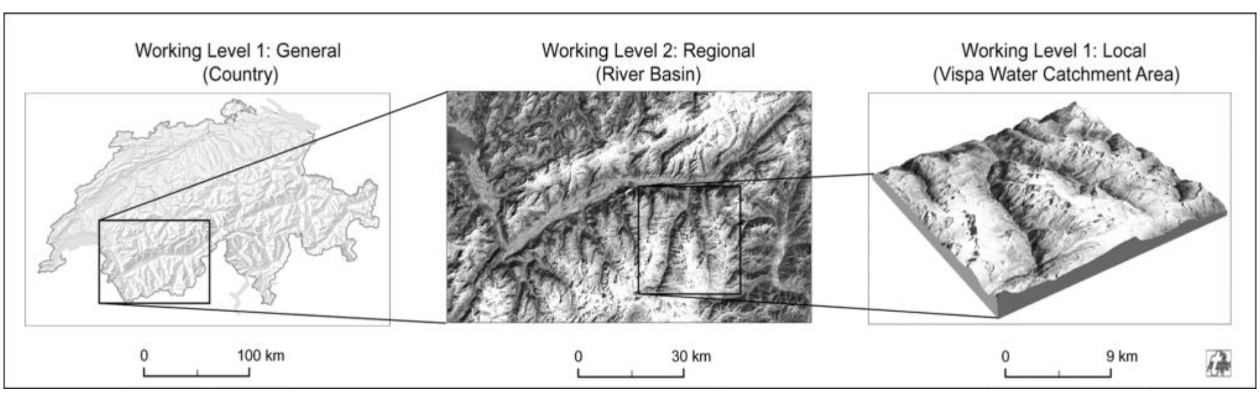


Figure 3-19 Different spatial scales of data collection and analysis

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.

Dataset Description

The collected information 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 organized thematically.

The datasets were 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 modeling procedures (process based, statistical, or empirical) of phenomena analysis to raw data. This step is performed by each project partner with their specific modeling software.

Data Models

In order to set up the database several data models were analyzed. 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, *Gogu et al. 2006*) 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.

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 was to develop the scientific framework to derive new methods for integrated assessment of natural hazards in alpine valleys.

Web Based Information System for Natural Hazard Analysis

In order to create appropriate hazard analysis tools, an initial step was to organize 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 visualization 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, visualization 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 visualizing and analyzing 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 were on-the-fly creation of high quality web maps and integration of real-time data. Additional optional objectives were three dimensional modeling and cross-section/volume visualization of phenomena, as well as the ability to support modeling of standard decision chains of users (agencies, offices, administrations, etc). This help to strengthen decision support systems in the field of natural hazards. The interoperability of the data, metadata, and web-services were guaranteed through the implementation of standards (OGC and ISO).

3.2.2.2. Remote sensing of landslides and debris flows for hazard assessment

Given the HazNETH database design (*Gogu et al., 2005*) contemplates the detection and mapping of diagnostic features from remote sensors (e.g. ground, air and space borne) the research work (*Metternicht et al. 2005*) offers an overview on the use of remote sensing data in landslides studies and 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. Because 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 section presents and discusses 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. The entire research work has been largely described by Metternicht et al. *(2005)*.

<u>*Introduction*</u>

As mentioned previously, a new concept and expert-tool for natural hazard assessment based on an integrated web-based database/GIS structure has been developed. 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 and 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 and van Steijn, 2003; Lin et al., 2002*).

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 research discuss previous applications of remote sensing to landslide mapping task , summarises techniques that exploit the optical, IR and microwave regions of the spectrum for monitoring landslide activities and finally establishes the link between remote detection and mapping of landslide diagnostic features, including monitoring activities, and their application to spatial analysis and modeling 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, the research work 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 are highlighted 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.

Integrating Remote Sensing and GIS for a geo-spatial hazard information system: Conceptual framework for database design

The concept of integrated hazard assessment analysis (Figure 3-20) 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 (Figure 3-20). 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.

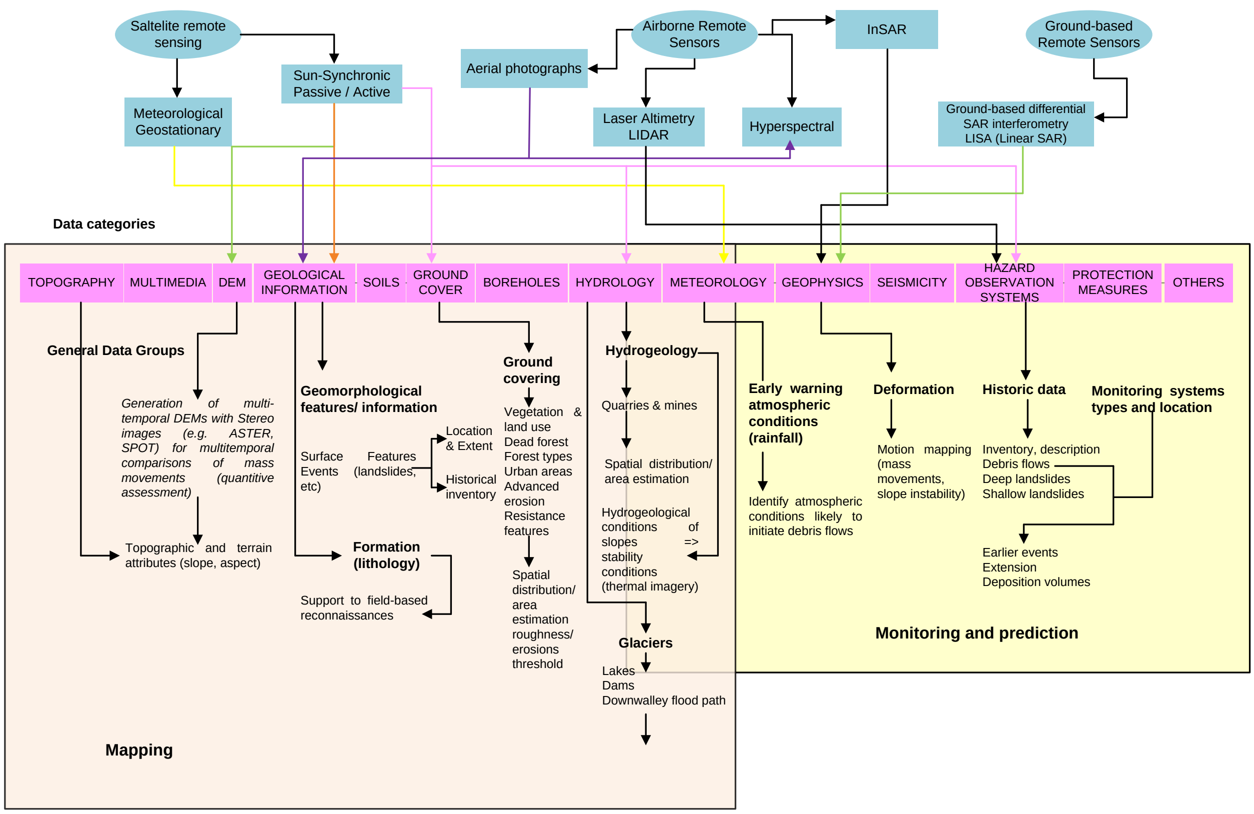


Figure 3-20 Contribution of remote sensing techniques to the HazNETH project (modified after *Metternicht et al. 2005*).

Taking into account the findings in terms of possibilities and limitations of satellite and airborne remote sensors used in previous studies, 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 Figure 3-20, 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 follows:

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 by Metternicht et al. *(2005)*. 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 sqkm). This level 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, *(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 and van Steijn, 2003*) adopt this type of rainfall as the main triggering factor.

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.

Level 3: deals with detailed investigations, at a large scale (1:15,000 and larger) of debris flow hazard potential areas 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.

Conclusions

Results from different projects with the focus 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 analyzing the spatiotemporal 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 exists. 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.

Carrara et al. (1991) suggest that multi-temporal thermal infrared imagery may be useful for detecting the hydrogeological conditions of slopes as a parameter for determining slope stability conditions. 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.

It is also 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. 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.

4. Hydrogeological data scientific instruments

4.1. Groundwater analysis and data management systems

4.1.1. Groundwater management platform for urban areas (SIMPA)

Introduction

Due to the large amount of civil work projects and investigation studies, large quantities of geo-data are produced for the urban areas. These data are usually redundant and spread between different institutions or private companies. Time consuming operations like data processing and information harmonisation represents the main reason to systematically avoid the re-use of data. The urban groundwater data shows the same complex situation due to the fact that the urban elements like underground structures (subway lines, deep foundations, underground parkings, and others), urban infrastructure networks (sewer systems, water supply networks, heating conduits, etc), drainage systems, surface water works and others shows a continuous modification. Due to the rapid evolution of technology in the past few years, transferring large amounts of information through internet has now become a feasible solution for sharing geoscience data. Furthermore, standard data transfer instruments have been developed. They allow easily updating and sharing through internet large geospatial databases between different institutions that do not necessarily use the same database structure. For Bucharest City (Romania) an integrated platform for groundwater geospatial data management is developed under the framework of a national research project.

Platform architecture

The software platform architecture is based on three components (Figure 4-1). The first component and the core of the platform is the hydrogeological geospatial database (*Gogu et al. 2011*) and the geospatial server application. The design of the database follows an object-orientated paradigm and is easily extensible. A large spectrum of data is stored in the database (geology, hydrogeology, topography, urban infrastructure, etc). The geospatial database is connected to the desktop platform application and to the geospatial server, so data management and data publishing it is easily made. The geospatial server application (Figure 4-2) allows the communication between the client side application (geoportal), the geospatial database and the desktop platform component.

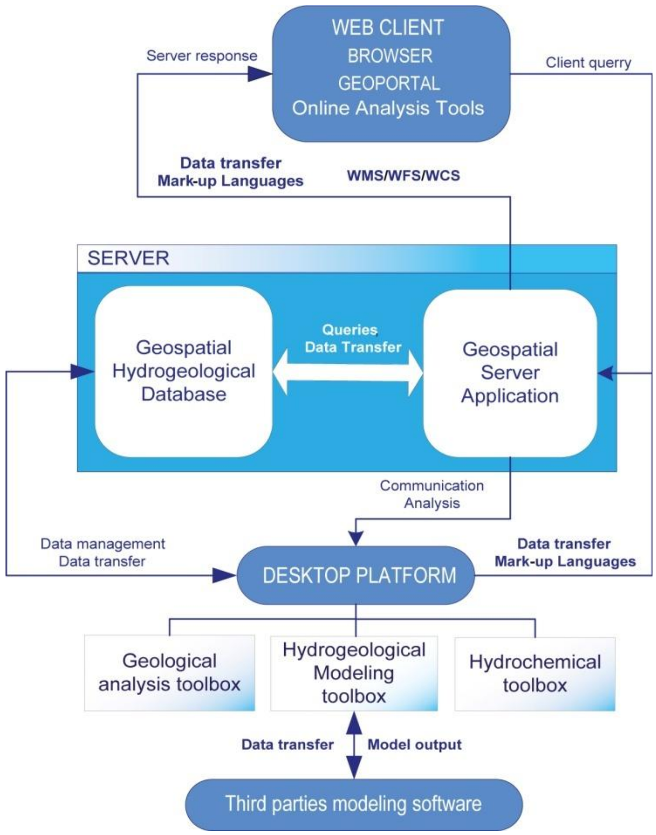


Figure 4 -1 Software platform architecture

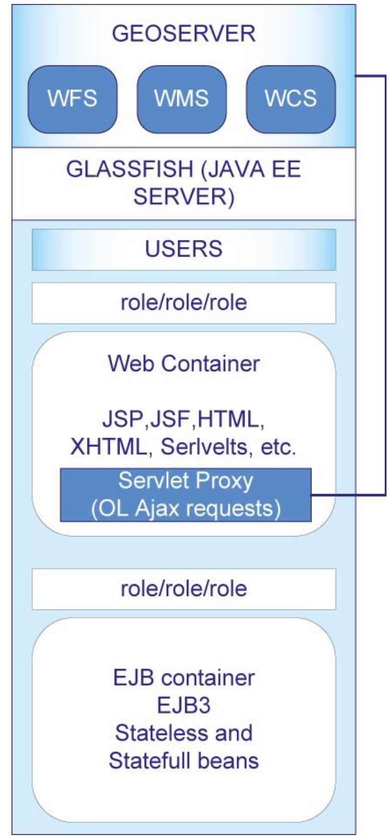


Figure 4 -2 Server side application

Communication is standardized through a series of services (WMS-Web Map Service, WFS-Web Feature Service, WCS-Web Coverage Service) and mark-up languages (GML-Geographic Mark-Up Language, GWML-GroundWater ML, GeoSciML-GeoScience ML, CityML-City ML). The second component is the client side, a geoportal application capable to publish hydrogeological data and to make preliminary analysis (statistic, buffer, intersections) and geospatial queries.

The geoportal service offers the possibility of querying a dataset from the spatial database. The query is coded in a standard mark-up language and send to the server to be processed by the local application. After the validation of the query the results are send back to the user to be displayed by the geoportal.

The last and the most developed component is the desktop platform. The desktop platform is designed to be used by specialists and researchers. The platform is developed under a GIS framework (ArcGIS). The main tasks are: (1) geospatial data management and (2) modelling and analysis of different urban groundwater scenarios. Therefore under the ArcGIS framework a series of toolboxes are developed (geological analysis, hydrogeological modelling toolbox, hydrochemical toolbox). Because of the plug-in GIS framework new toolboxes can be added, depending on specific needs.

The geological toolbox allows the specialist to manage litology, geophysical, and petrological data. Analysis such as: borehole diagram, geological cross-sections, defining hydrogeological units, can be easily made and exported in 2D and in 3D environment (geological fence diagram). The toolbox also allows the user to have a preliminary interpretation of the hydraulic conductivity based on geological settings (lithology, sorting, grain size, matrix).

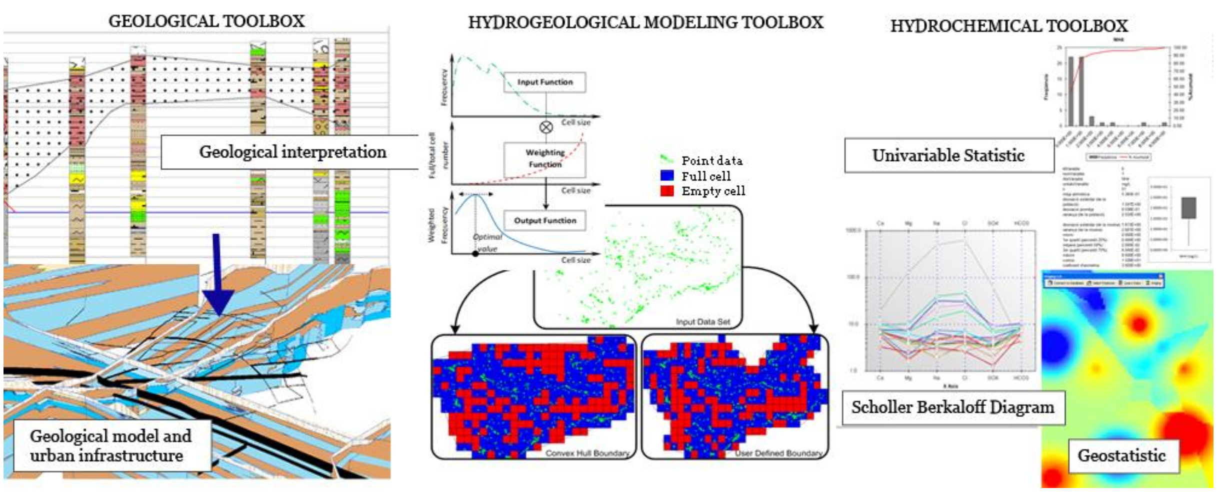


Figure 4-3 Software platform toolboxes

The hydrochemical toolbox performs a series of hydrochemical analysis for groundwater quality data: hydrochemical parameter statistics (univariable, bivariable, analysis), geostatistics (using GSLib library), general chemical diagrams, charts and maps (Stiff Map, Wilcox diagram, Ionic Balance, Piper Diagram) and a series of parameter orientated maps.

The third toolbox is an interface between the platform and other third parties software (such as GMS - Groundwater Modelling System). Data from the geospatial database are exported to the modelling software and the outputs of model can be imported back to the platform. Beside the communication capabilities, the toolbox can generate an optimal cell-size modelling grid on the basis of the hydrogeological data spatial distribution. Starting from the discontinued point data (distributed randomly, uniformly, or clustery over a spatial domain), the algorithm is developed to find the optimal cell size by increasing the number of cells containing at least one data point.

4.1.2. Sedimentary media analysis instruments

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 Robin et al. 2005, Ross et al. 2005, Wycisc et al. 2009.

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 et Park, 2004*).

This section 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 modeling, 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 modeling.

These technologies were applied to some studies in urbanized areas such as Barcelona, Spain (*Escorcia 2010*, *Riera 201, Velasco et al. 2011*) and Bucharest, Romania (*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 in order to illustrate an application of the presented tools and methodologies.

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 Geographical Information Systems (GIS). 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.

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 by 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 by using:
- Different modeling 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 by using tools that enable us to:

- Calculate hydraulic properties from the stored data.
- Import/export of hydraulic conductivity spatial distribution

5) Facility of interaction with external software such as:

- Geostatistic software such as SGEMS (*http://sgems.sourceforge.net/*) or GSLIB (*www.gslib.com*)
- Groundwater modeling packages such as TRANSIN (*Medina and Carrera 2003*)
- Pre-processor package to generate 3D finite element mesh such as GID (*www.gid.cimne.upc.es*).

6) Post-processing by using:

- Maps, diagrams or queries in a GIS environment.

Analysis software platform.

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

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) (Figure 4- 4).

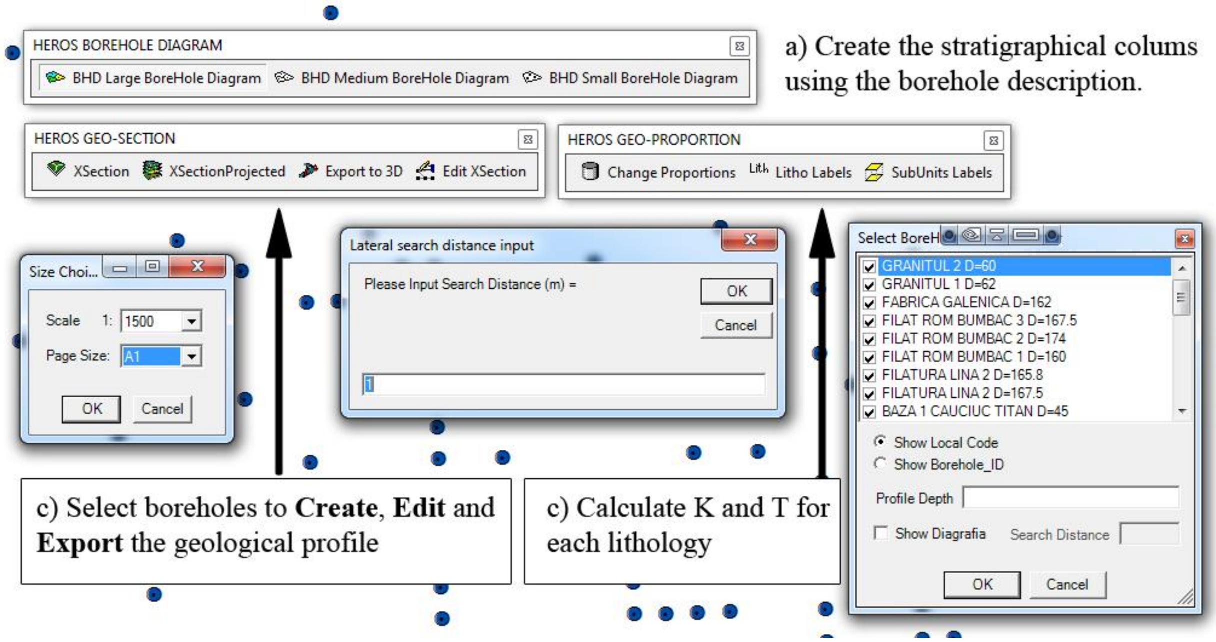


Figure 4-4 Toolbars, developed as an extension of ArcGIS (ESRI), of the three main sets of instruments created to facilitate the detailed stratigraphic analysis and the estimation of the sedimentary media hydraulic conductivity initial values: a) Borehole diagram instruments; b) Stratigraphic cross-sections; c) Tools for hydraulic conductivity initial estimation.

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 opt to attach information of geophysical in situ tests such as diagraphies. Figure 4-5 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.

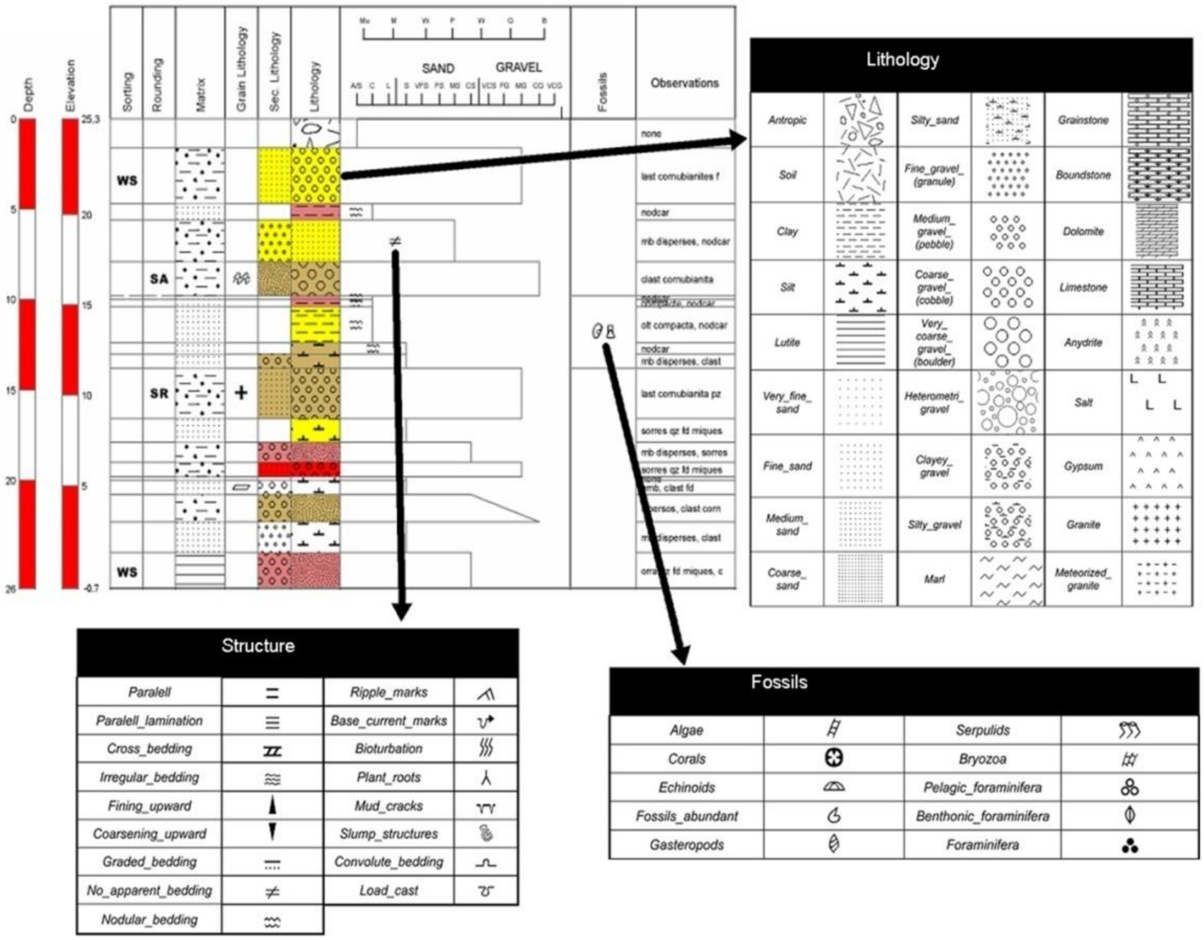


Figure 4-5 Scheme showing the representation of the petrological characteristics for sediments in terms of textural (sediment size, sorting, roundness, matrix support), lithological, colour, and other properties in a stratigraphic column obtained by using the tool *Borehole Diagram*.

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 example of a query resulting in a borehole diagram format is shown in Figure 4-6.

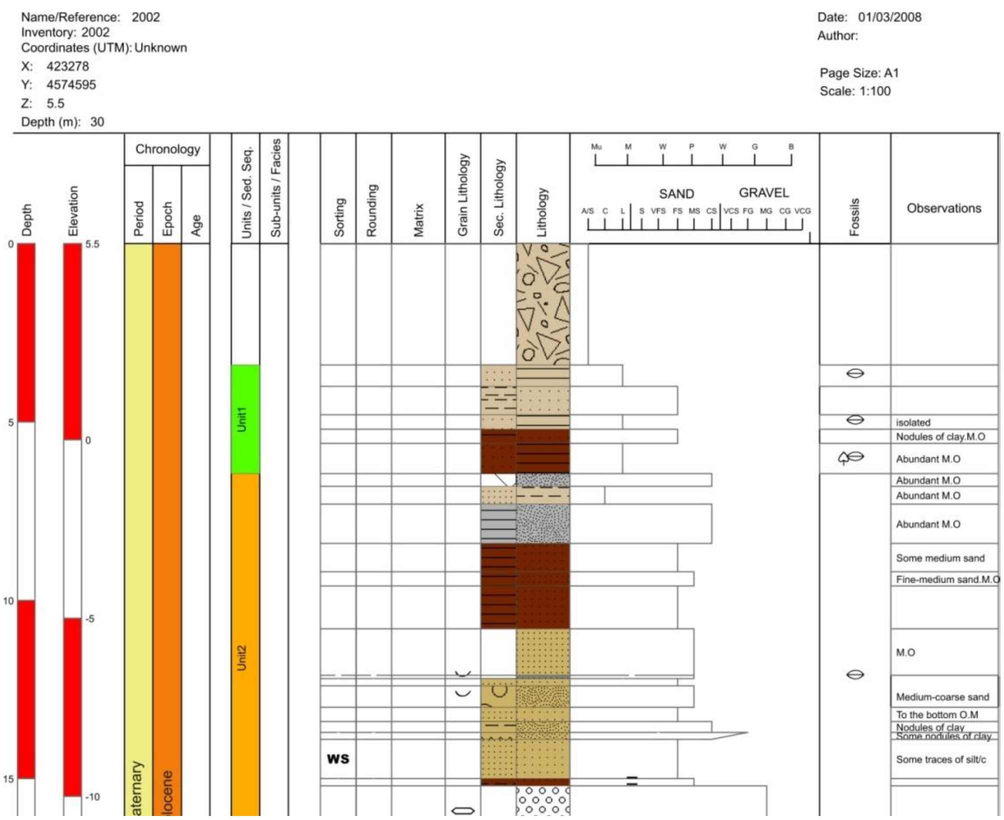


Figure 4-6 Result of the Borehole diagram query procedure. The lithology is defined by three components: Lithology (main litholgy), secondary lithology and matrix. The proportion between the secondary and the main lithology is represented by the column labelled as Proportion, where W=with (same proportion of main and secondary lithology), F=frequent, S= Some and T=traces.

<u>*Stratigraphic cross-section correlation tool*</u>

This instrument facilitates the process of stratigraphic well correlation, in this way improving the geological interpretation of the sedimentary media. This set of tools starts from the creation of a geological profile (Figure 4-7) 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.

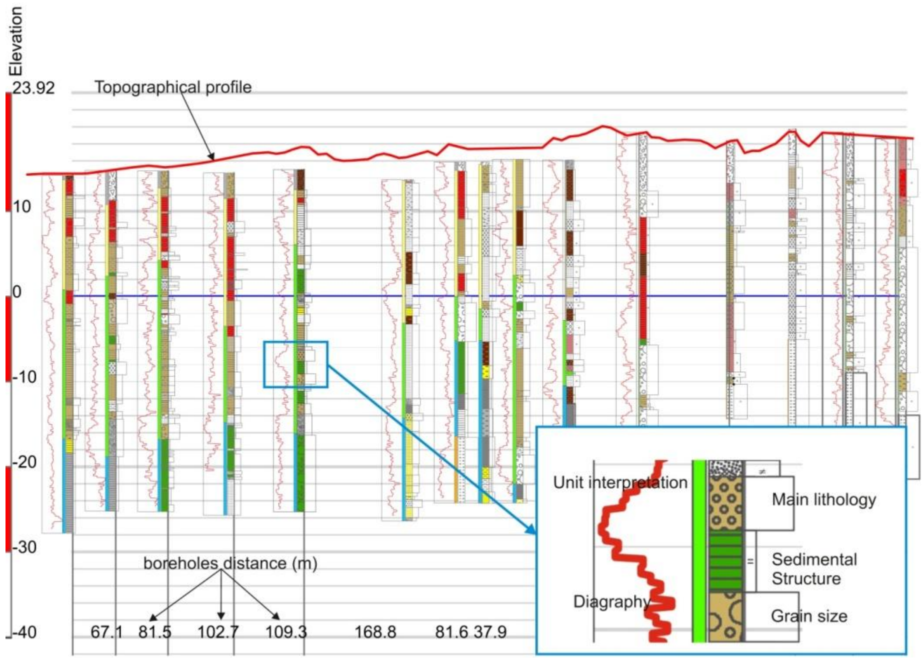


Figure 4-7 Scheme showing the geological profile generated by displaying the boreholes lithological columns and together with the related stratigraphic subunits and diagraphies.

Thus, an interactive analysis environment (Figure 4-8) is created for a subsequent set of instruments. The user is able to analyze and to vectorize on screen the existing stratigraphic elements by 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.

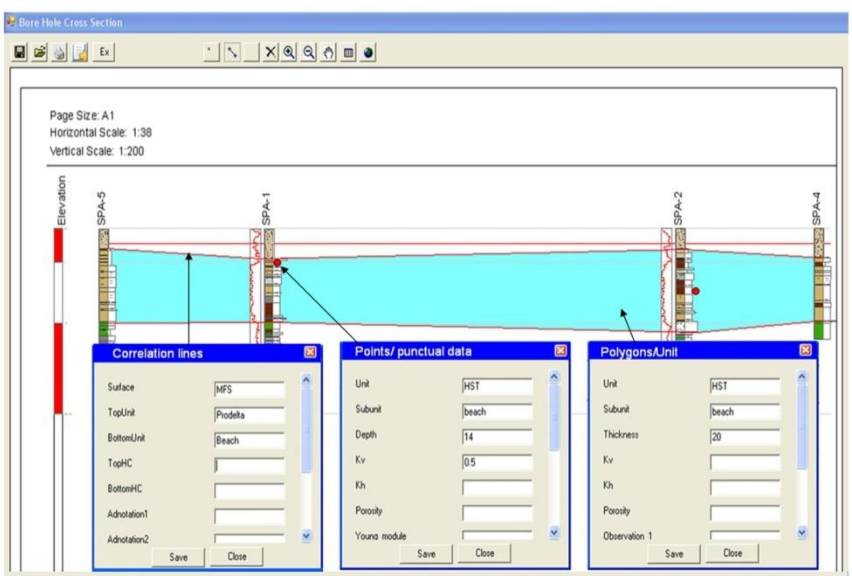


Figure 4-8 The stratigraphic working environment (the geologists draw their sections based on different borehole-log correlation techniques).

Although a cross-section is a 2D representation, the geological features defined by the user can be exported to a 3D environment via 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 (Figure 4-9).

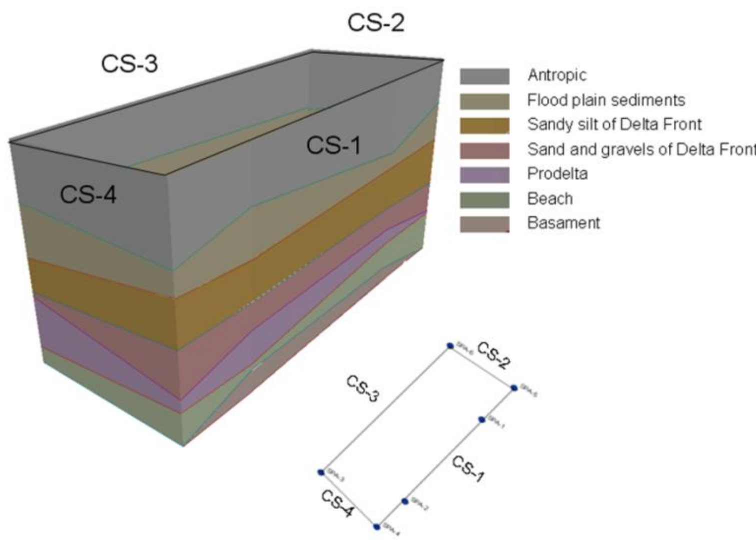


Figure 4-9 Fence diagram showing the obtained stratigraphic information visualized within a 3D environment

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.

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 et al. 2009).* Accordingly, several steps were undertaken to quantify the hydraulic conductivity on the basis of grain size distribution.

Hydraulic conductivity can be computed automatically for each lithological interval defined in the boreholes or for the user defined hydrogeological units by using a set of tools. This was based on the existing lithological descriptions using empirical formulas. Each lithology listed in the database is associated with hydraulic conductivity values obtained from the literature (*http://wwhypda.org/, Freeze and Cherry 1979, Custodio and Llamas 1983*). 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 (Figure 4 -10) can be calculated for each interval of the borehole, taking into account the hydraulic conductivity values assigned to each lithology (function off the grain size distribution). The approach adopted for the calculation of hydraulic conductivity was based on the traditional calculation methods of hydrologically equivalent horizontal and vertical conductivity (*Custodio and Llamas*, *1983*).

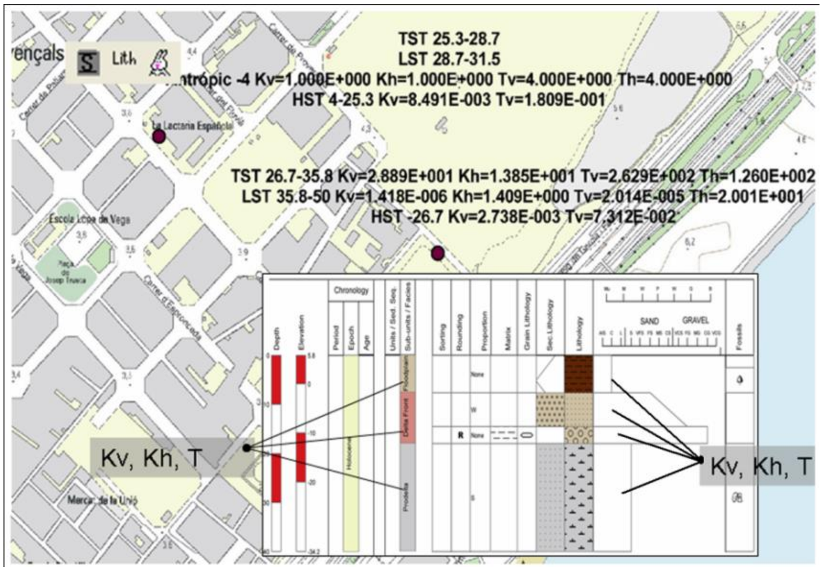


Figure 4-10 Tool for the hydraulic conductivity initial estimation

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

<u>*The Bèsos river Delta application*</u>

One application of the software platform is discussed in Velasco et al (2010). It consists in a case study concerning the geological and the subsequently hydrogelogical characterization of the Besòs river delta located on the NW Mediterranean coast, in Barcelona (Spain). Due to its location, partially in the city of Barcelona, the region suffered an extended urbanization process. As a result, most of the previous existing rocky and sedimentary outcrops have disappeared. However, the recent increase of several new geological, hydrogeological, and civil engineering works that provided a huge amount of new data, initiated an optimal moment to createa geological model integrating a database made of 372 boreholes. The described instruments were used for the interpretation of the borehole information, for the creation of the geological profiles, and finally to obtain a 3D geological model.

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

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

Thirteen geological cross-sections (Figure. 4-11) have been used to build the deltaic 3D geological model. They were obtained through borehole correlation. The borehole core information has been previously interpreted by identifying key stratigraphic subdivisions chosen on the basis of the progradational-retrogradational or coarsening-fining upwards patterns, observed on the marine and transitional sediments. Thus, two sequences were identified on the Besòs river delta. These are bounded at the base by erosional surfaces representing periods of subaerial erosion. The lower stratigraphic unit located in between two erosional surfaces is mostly continental. The uppermost sequence develops the entire range of deltaic system facies belts (from subaerial to submarine). Three key surfaces have been defined: basal sequence boundary (SB), a transgressive surface (TS), and a maximum flooding surface (MFS). The lower sequence can be attributed to the Pleistocene, whereas a Holocene age is considered for the upper sequence.

Figure 4-11 The location of the geological cross-sections used to develop the 3D geological model.

An accurate positioning of these contact surfaces and sequences on the borehole logs is essential to define the distribution of the sedimentary bodies. These are made of genetically related facies associations, displaying different petrophysic properties such as porosity and hydraulic conductivity.

A sketch of the obtained geological model is represented as a fence diagram in Figure 4-12. The model developed by using the described GIS analysis instruments was used to build-up a complete 3D geological model or can be exported to a numerical preprocessor to create a 3D hydrogeological model. To do this, GID software (*www.gid.cimne.upc.es*) developed by *CIMNE Center* (Technical University of Barcelona) has been chosen as preprocessor to generate the 3D finite element mesh needed for groundwater modelling.

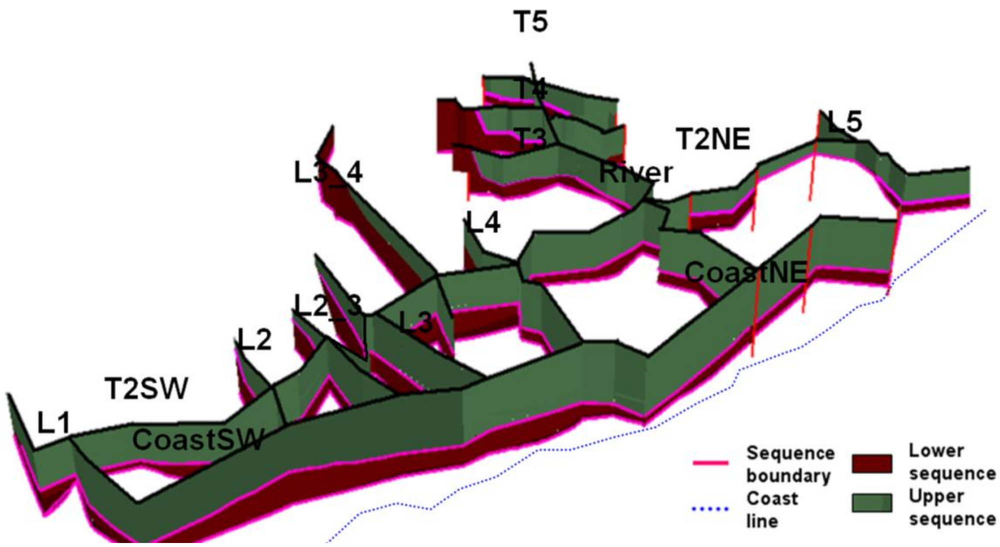


Figure 4-12 The Besòs river delta geological model represented as a fence diagram.

<u>*Discussion*</u>

The final target for the performed work focuses especially the characterisation of groundwater, as well as the dynamics of water systems and their distribution in space. In this sense, the presented set of instruments represents a working environment to integrate the 3D sedimentary media spatial distribution of the different hydraulic parameters, in the regular hydrogeology modelling methodologies. This help improving the conceptual model to build-up a hydrogeological model.

The developed database structure allows storing data for most of the hydrogeological studies. 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.

Using the spatial database eases data integration concerning land-use, infrastructure, and environmental aspects. The relationship between the groundwater and the main urban contaminant factors (sewerage system, water supply network, etc) as well as the interaction of the groundwater with the main civil works (subway tunnels, building large basements crossings, underground parkings, etc) can be shown and studied. Nowadays there is an increased concern which focuses on searching how to integrate efficiently the great volume that continuously accumulates information on the geology and land. This aspect that is crucial for an urban environment can be solved only by building a bridge between science and application. This allows studying in a more realistic manner several problems, particularly in improving the geological and hydrogeological knowledge of urban areas.

Conclusions

The design of the described instruments is following the geologist classical way of working to characterize a study area. Even the main goal of the described instruments was to improve sedimentary media groundwater modelling, the field of application can be easily enlarged. The analysis of geotechnical aspects of various ground and underground infrastructure objectives together with other kinds of geological or environmental studies represent another direct uses of the 3D geological software platform.

The objectives of the presented work are mainly targeting the development of 3D geological characterization methods in sedimentary media, to support the development of hydraulic parametrization techniques for hydrogeological modelling. These techniques are seen in terms of petrophysic properties parametrization and other similar concepts (e.g. facies), application of deterministic and stochastic techniques to define the properties of sedimentary bodies in 3D, and definition of limits and connectivity between sedimentary bodies.

An essential achievement of the presented tools is represented by the hydrogeological spatial database scheme developed behind (*Gogu et al. 2011*). The possibility of querying and visualising high detailed information at various scales represents a reliable background for geological analysis. This is further used as a 3D analysis environment to generate 3D models.

4.1.3. Hydrochemical analysis toolbox

Introduction

Groundwater quality in urban areas is strongly influenced by anthropogenic factors. Collection, organization, and interpretation of data defining the water quality requires a concentrated effort from the government agencies, water service companies, drilling companies and water utilities operating administrations. Detailed knowledge of the qualitative characteristics of an aquifer may lead to a proper and sustainable management of water resources. As before described in this chapter, a software platform was developed to facilitate the development of 3D geological models for sedimentary environments. The platform is composed of a geospatial database and distinct sets of instruments. One of them, called QUIMET, is dedicated to the management and the analysis of groundwater quality parameters. This instrument developed for analysing and visualizing the distribution of groundwater quality parameters, was designed on the basis of data corresponding to the region of Barcelona City, Lobregat River Delta, and Besos River Delta (Barcelona, Spain). Query analysis tools search in the database and allow the geospatial data integration with time series of physical-chemical parameters.

The spatial distribution of qualitative data has a start point in the location of wells, piezometers, and boreholes. Data collected from these wells and boreholes is organized in quantitative and qualitative hydrological data. For the above mentioned region, the application manages over 1300 spatial points (representing wells, piezometers, and boreholes) in which there are over 350 physico-chemical parameters measured over last the 50 years in laboratory or on field.

The hydrogeological geospatial database

A general description of the hydrogeological database has been made previously in Chapter 3. Regarding qualitative hydrogeological data analysis, the database allows a series of queries based on spatial and temporal criteria, on the distribution of geochemical parameters measured in distinct control points. The database scheme is centred on the table that contains the points representing the spatial location of boreholes, wells, and piezometers. This table is related to other tables containing the type of parameters (over 350 geochemical parameters), field campaigns, samples, type of units, measured parameters, owning entities, etc.

Analysis and data visualization tools for groundwater quality

The toolbox for managing groundwater quality data is a modular application that allows analysis and visualization of data through specific hydrochemistry diagrams generated by spatial and temporal queries, statistical analysis, and geo-statistical analysis. This set of instruments build in a GIS environment was developed using VB.net (Visual Studio, Microsoft) using ArcObjects libraries (ESRI).

The main concept links to the need of simplifying operations for the water agencies operators. These operations consist in the import, export, query, viewing, and analysing large data sets of water quality. Simplifying these operations lead naturally to save time and resources.

Main operations, as listed in Figure 4-13, create a workflow that simplifies the work within an institution that manages water resources. The structured information of a database can be distributed and may have different access levels. This helps to define scenarios of query processing, enables the use of geographical information systems (GIS) data, and facilitates the creation of reports and maps.

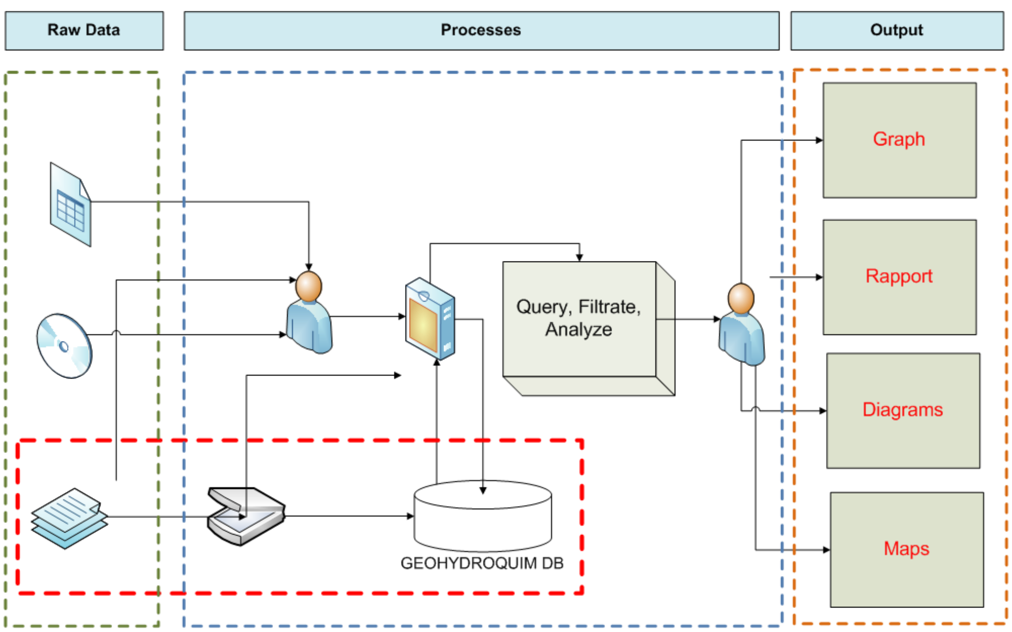


Figure 4-13 QUIMET instruments workflow

The Scholler-Berkaloff Semi-Logarithmic Diagram

A first tool is the automatic generation of the Schoeller - Berkaloff semi-logarithmic diagram - *(Escuder et al, 2009)*. This consists of six logarithmic scales corresponding to major ions as: (1) cations: Ca +, Mg +, Na + and (2) anions: Cl-, SO4 -, HCO3 -. The values of the dominant ions are specified in milliequivalents on a logarithmic scale. Following a spatial selection on the screen, the user can select one or more wells.

In the case of a well selection, the selected values correspond to anions and cations of several samples of water taken from the well. In the next step, these values are displayed on the screen according to the Schoeller - Berkaloff semi-logarithmic diagram (Figure 4-14).

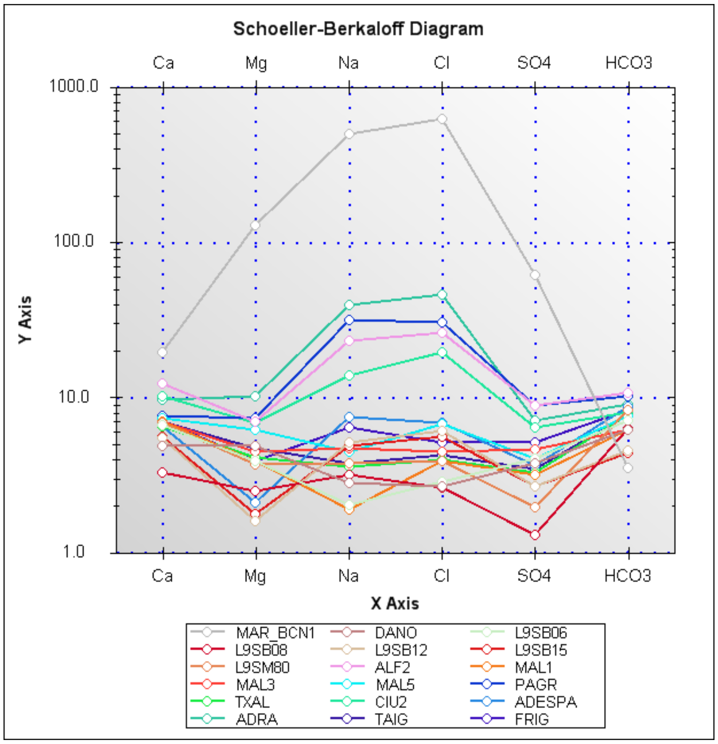


Figure 4-14 The Scholler-Berkaloff Semi-Logarithmic Diagram

Sodium Adsorption Ratio (SAR) – The Wilcox Diagram

The SAR index (the Adsorption of sodium) is an indicator generally used in evaluating the sodium-induced threat to groundwater. SAR index formula is:

$$SAR = \frac{[Na^{+}]}{\sqrt{\frac{1}{2}([Ca^{2+}]+[Mg^{2+}])}} \qquad (4\text{-}1)$$

The Wilcox diagram (Figure 4-15) joins the calculated values of the SAR index with the electric conductivity (CE) measured in microsiemens per centimeter and represent them on a logarithmic scale. With the help of the Wilcox diagram the excess of sodium in groundwater can be established. The diagram (Figure 4-15) shows the variation of the SAR index (on the Y axis) depending on the electric conductivity (on the X axis). The diagram is generated for each groundwater sample taken at a certain date.

The Wilcox diagram has the following parts:

Electric conductivity (μs/cm):

- C1: low (0 - 249)
- C2: medium (250 - 749)
- C3: high (750 - 2249)
- C4: very high (2250 - 5000)

SAR index values:

- S1: low
- S2: medium
- S3: high
- S4: very high

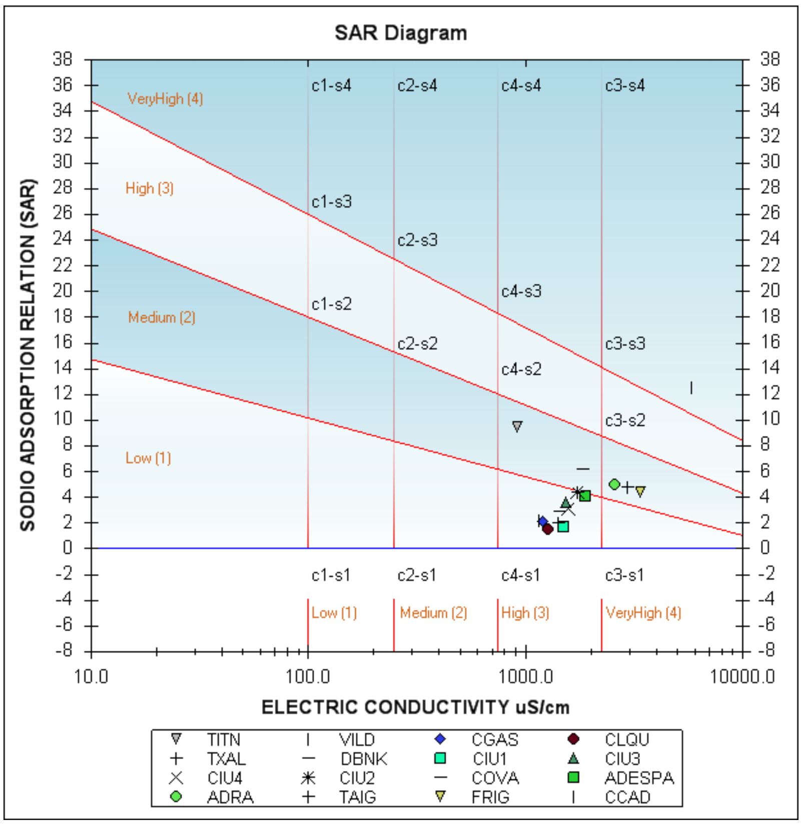


Figure 4-15 The Wilcox Diagram

<u>The Piper Diagram</u>

The Piper diagram *(Escuder et al, 2009)* illustrates graphically the nature of a given sample of water and reflects its connection to other samples. For example, the classification of water samples in a Piper diagram (Figure 4-16) can identify geological units that have similar hydrochemistry properties and can define the hydrochemical evolution along the groundwater flow line. The Piper diagram concentrations are expressed in milliequivalents per liter (meq / L) and represent the percentage of major anions in a triangle and the main cations into another triangle. Triangular axis values vary between 0 and 100 on each of the three sides. The triangle on the left axis values increase clockwise, and restart from zero at each corner of the triangle. The triangle on the right axis values increase in the opposite clockwise and restart to zero every corner of the triangle. The two sets of anions and cations represented into the two triangles are combined into a third rectangular diagram. The main purpose of the Piper diagram is to identify groups of water samples with identical or similar composition.

One of the advantages of using Piper Diagram is that a large number of water samples can be analyzed and illustrated on the same chart. The origin of different types of water can be identified.

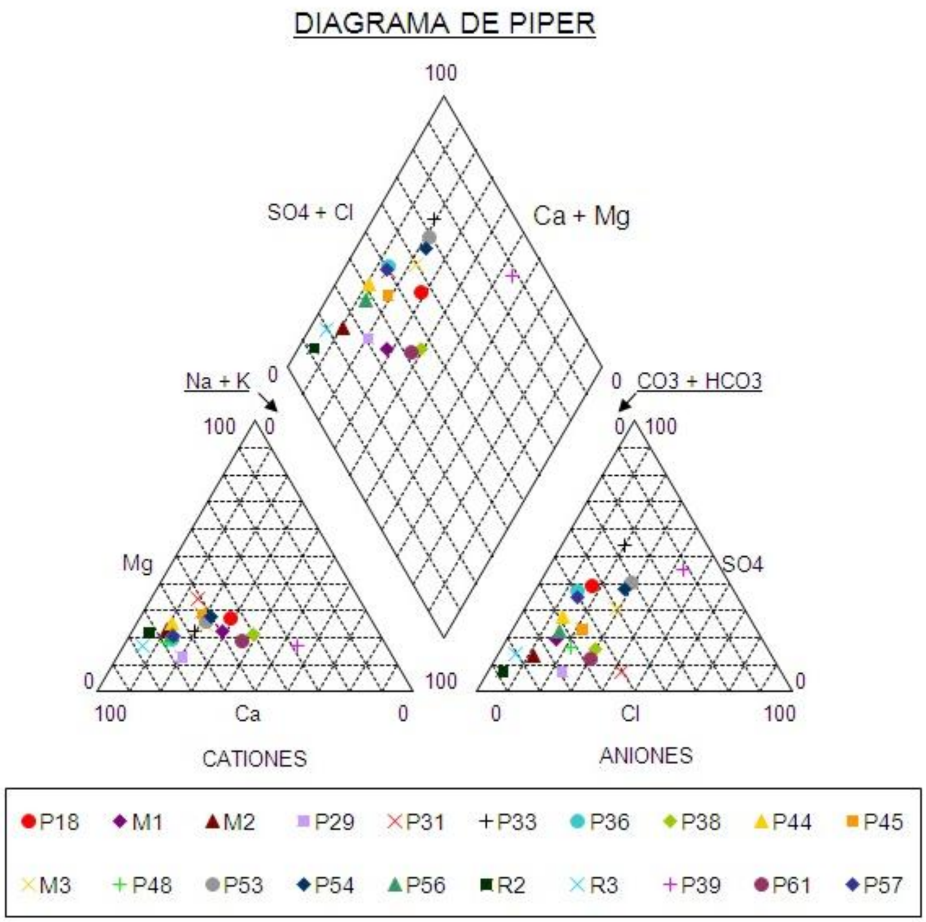


Figure 4-16 The Piper Diagram

Stiff Diagram

The Stiff diagram *(Escuder et al, 2009)* is a graphical representation of the values of cations and anions of a water sample. The Ions concentration in milliequivalents per liter is represented on the horizontal axis (meq / L). The anions are represented on the left side and the cations on the right side of the vertical axis. The values are represented on four rows and the resulting points are connected to form a polygon (Figure

4-17). Each water sample produces a different geometric shape and facilitates the visual identification as a support in water quality analysis.

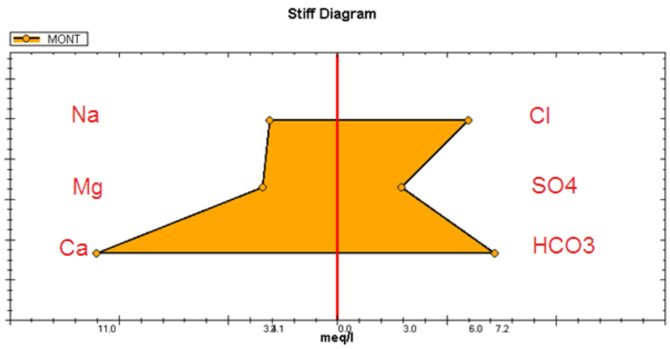


Figure 4-17 The Stiff diagram

The Stiff diagram tool can generate individually diagrams for a water sample (Figure 4-17) or Siff diagrams distributions on maps (Figure 4-18). The maps are generated automatically and illustrate distinct Stiff diagrams for the corresponding water samples corresponding to a certain measurement campaign. They can delineate zones in terms of major ions composition in an aquifer body. The application allows the scaling of diagrams to be visible on screen or on printed paper. Figure 4-18 show a map where the analyzed samples indicate the intrusion of salted water (the Stiff diagram polygons parallel to the shoreline).

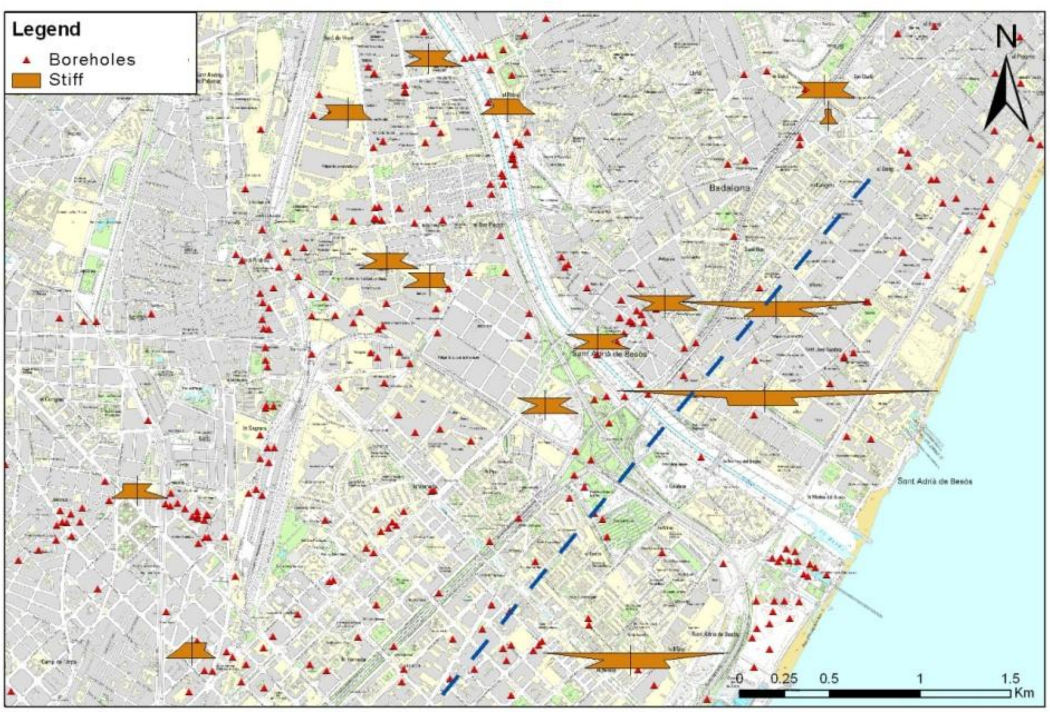
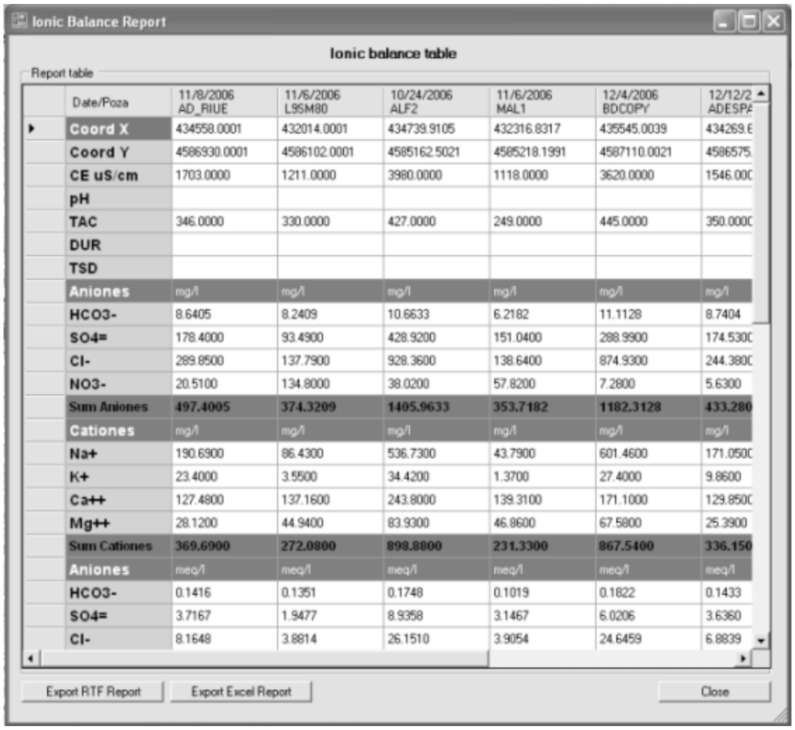


Figure 4-18 Stiff map

Ionic Balance

The Ionic balance (Figure 4-19) represents the systematization of the information for the water samples general chemistry. In the Ionic Balance tool are detailed relations and percentages of ions, pH, hardness and electric conductivity.


Ionic Balance Report

Ionic balance table

Report table

Date/Poza	11/8/2006 AD_RIUE	11/6/2006 L9SM80	10/24/2006 ALF2	11/6/2006 MAL1	12/4/2006 BDCOPY	12/12/2 ADESPA
Coord X	434558.0001	432014.0001	434739.9105	432316.8317	435545.0039	434269.6
Coord Y	4586930.0001	4586102.0001	4585162.5021	4585218.1991	4587110.0021	4586575.
CE uS/cm	1703.0000	1211.0000	3980.0000	1118.0000	3620.0000	1546.00
pH						
TAC	346.0000	330.0000	427.0000	249.0000	445.0000	350.000
DUR						
TSD						
Aniones	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
HCO3-	8.6405	8.2409	10.6633	6.2182	11.1128	8.7404
SO4=	178.4000	93.4900	428.9200	151.0400	288.9900	174.530
Cl-	289.8500	137.7900	928.3600	138.6400	874.9300	244.380
NO3-	20.5100	134.8000	38.0200	57.8200	7.2800	5.6300
Sum Aniones	497.4005	374.3209	1405.9633	353.7182	1182.3128	433.280
Cationes	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Na+	190.6900	86.4300	536.7300	43.7900	601.4600	171.050
K+	23.4000	3.5500	34.4200	1.3700	27.4000	9.8600
Ca++	127.4800	137.1600	243.8000	139.3100	171.1000	129.850
Mg++	28.1200	44.9400	83.9300	46.8600	67.5800	25.3900
Sum Cationes	369.6900	272.0800	898.8800	231.3300	867.5400	336.150
Aniones	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l
HCO3-	0.1416	0.1351	0.1748	0.1019	0.1822	0.1433
SO4=	3.7167	1.9477	8.9358	3.1467	6.0206	3.6360
Cl-	8.1648	3.8814	26.1510	3.9054	24.6459	6.8839

Export RTF Report

Export Excel Report

Close

Figure 4-19 Ionic Balance table as output of the application query

This application can query a large number of water samples as well as visualize and export results for reporting. The user can export the results into a spreadsheet as Excel type format (Microsoft) or to Word processor (Miscrosoft) for the automatic generation of reports.

In practice, checking the Ion balance is useful to eliminate large errors introduced due to the incorrect time of measurement for some parameters (pH, alkalinity, etc.), or due to the incorrect storage of the water samples (taking into account the pressure, the temperature, or the incorrect handling of the container).

Conclusions

This section describes an interactive toolkit to support GIS spatial analysis for hydrochemistry. The groundwater quality survey can be made by using monitoring and analysis tools that are able to manipulate large time-series datasets showing a spatial reference. Data correlation with the spatial distribution of the hydrogeological structures is compulsory. Within the urban environment the problem show a larger complexity due to the infrastructure interaction.

Within the collaboration framework between several Spanish and Romanian institutions a management, analysis, and modeling hydrogeological platform for urban areas was developed. The end-user is the Catalan Water Agency (ACA). This set of tools has been build on the basis of the data-sets characterizing the groundwater media of the Barcelona city and surroundings.

The developed set of instruments allow the chemical time-series analysis and visualization by using specific hydrochemical diagrams (Wilcox, Piper, etc) to which the spatial component is added. In this manner, maps showing the spatial distribution of various chemical parameters as well as maps illustrating specific hydrochemical parameters distribution (eg. Stiff diagram) can be generated.

It must be noted the use of spatial database as an environment for information storage and management for geological, hydrogeological and hydrochemistry (*Gogu et al. 2011*). Integration of hydrochemical information with detailed stratigraphic information, lithology, local and regional hydrogeological parameters, hydrogeological test results (pumping tests), hydrological characteristics, information on various observations and measurements give to the user a consistent image for the behavior of the studied aquifer.

4.2. Decision Support System for groundwater artificial recharge based on alternative sources of water

A Decision Support System (DSS) can be defined in many ways. One of the accepted definitions is "A spatially based computer application or data that assists a researcher or manager in a decision making process." This is quite a broad definition and it needs to be adapted, as the possibilities for types of DSS are limited only by the user group and the developer imagination. DSS are as diverse as the problems they help to solve. This diversity requires that DSS are built in a variety of ways using the most appropriate methods and tools for the individual application. The skills of potential DSS users show discrepancies as well, further requiring multiple approaches to DSS development. Highly trained user groups may want a powerful modelling tool with extensive functionality at the expense of ease of use. Other user groups less familiar with geographic information system (GIS) and spatial data may want an extremely easy to use application for a wide public or otherwise non-technical audience.The Geographical Information Systems (GIS) tools fall into one of two categories: general purpose or specific purpose. General-purpose GIS tools are programs that have extensive functionality and can be difficult for users unfamiliar with GIS and cartographic principles to learn. Specific-purpose GIS tools are programs that are written by a GIS programmer to provide a user group with specific functions in an easy-to-use package.

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. It has been developed in the frame of the GABARDINE project where the currently the Technical University of Civil Engineering University of Bucharest (UTCB) members completely supported the software development and have substantial contributions in the analysis (*Gogu et al., 2008, Gaitanaru and Gogu, 2008, Rahman et al., 2012*). 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-ofuse 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. 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, MAR location, and technology makes project planning multifaceted and complex.

GIS-based management and decision support system for site selection in artificial recharge

An intensive review of the respective literature has indicated that the modern and updated analysis techniques as GIS and Multi-Criteria Decision Analysis (MCDA) have not been well investigated and compiled in the field of MAR Managed Aquifer Recharge (MAR) site selection. In this respect, an unstructured, non-site specific and flexible decision analysis tool has been developed within the FP6 GABARDINE project (*www.gabardine-fp6.org/home.aspx/*). 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: (1) A comprehensive framework consisting of AHP, WLC, and OWA analysis techniques for spatial multi criteria analysis for MAR site selection; (2) A wide range of flexibility and preferences for criteria selection, standardization, and weighting; (3) An interactive user interface, which offers the standard techniques and leads the user systematically to complete the site selection process.

GIS Based Site Suitability Analysis Tool - 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

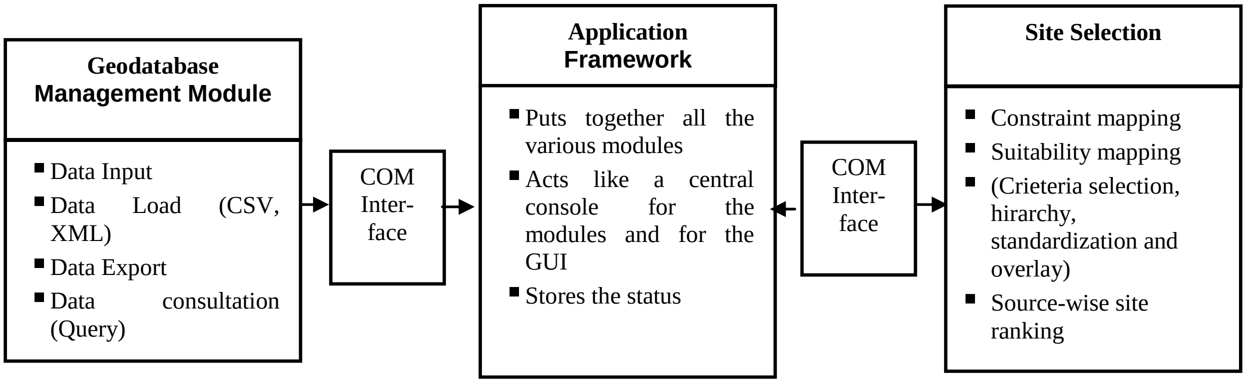


Figure 4-20 Structure of the site selection tool developed in the ArcGIS environment.

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 customisation, (2) codes are not accessible by the user, (3) all aspects of ArcGIS application can be used further, extended, and customized, (4) the customisation can be easily supplied to the client machines (*ESRI, 2004; Boroushaki and Malczewski, 2008*). Figure 4-20 shows the overall system development.

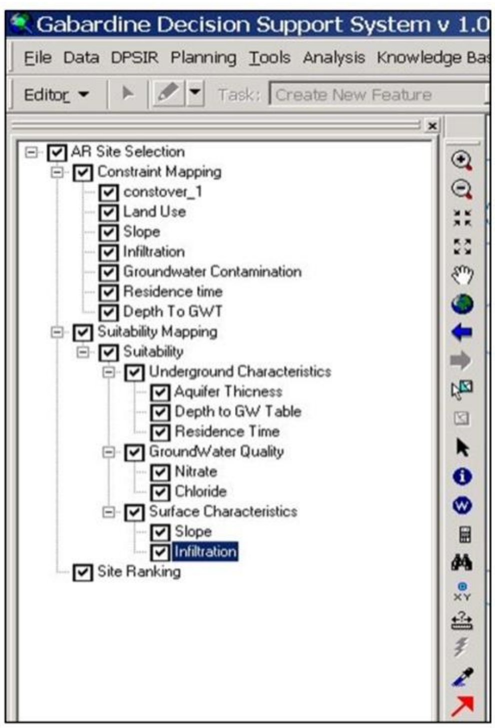


Figure 4-21 Site suitability analysis tool implemented as ArcGIS Display tab as part of the Gabardine DSS

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 (Figure 4-21) derive from this one.

The supporting database structure is an ArcGIS Personal Geodatabase (ESRI). The geodatabase can store, beside the geographical data, data behaviour rules such as domains, relationship classes, and custom behaviour. 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 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.

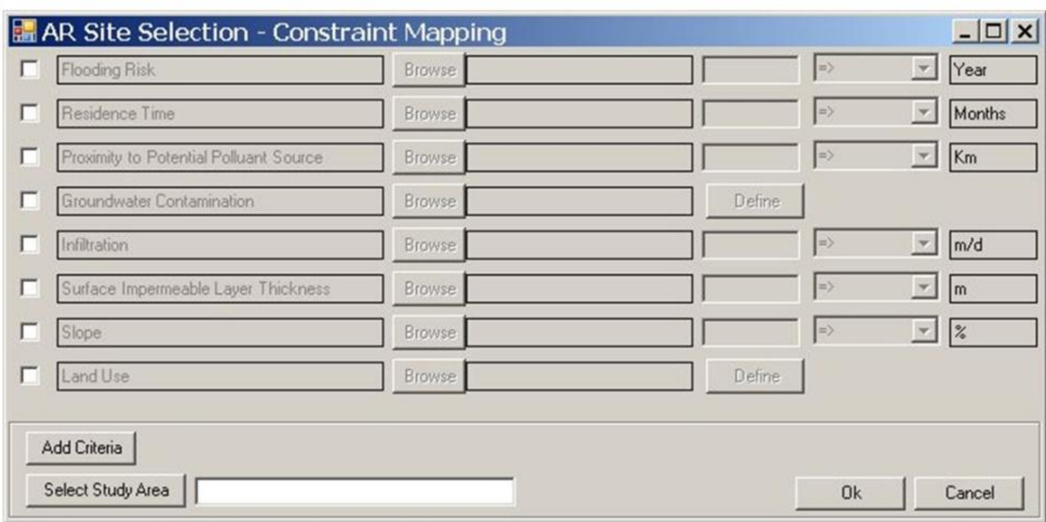


Figure 4-22 Interface to select constraint criteria and assign the threshold value

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.

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 **(**Figure 4-22**).** 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 (Figure 4-23). 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 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)*.

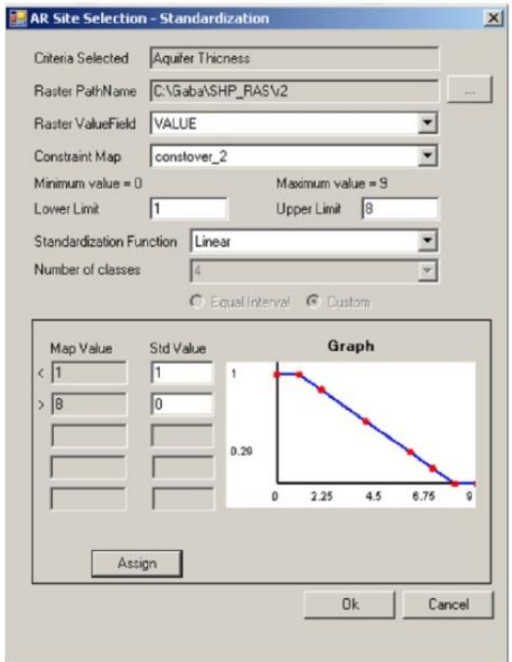


Figure 4-23 Standardization procedure

After finishing the weighting procedure, the user reaches the final steps of the site suitability mapping (Figure 4-24). 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 (Figure 4-24), taking into account the colour code for ecological status classification proposed by the Water Framework Directive (*Water Framework Directive, 2003*). The user has the opportunity to change the range of class manually.

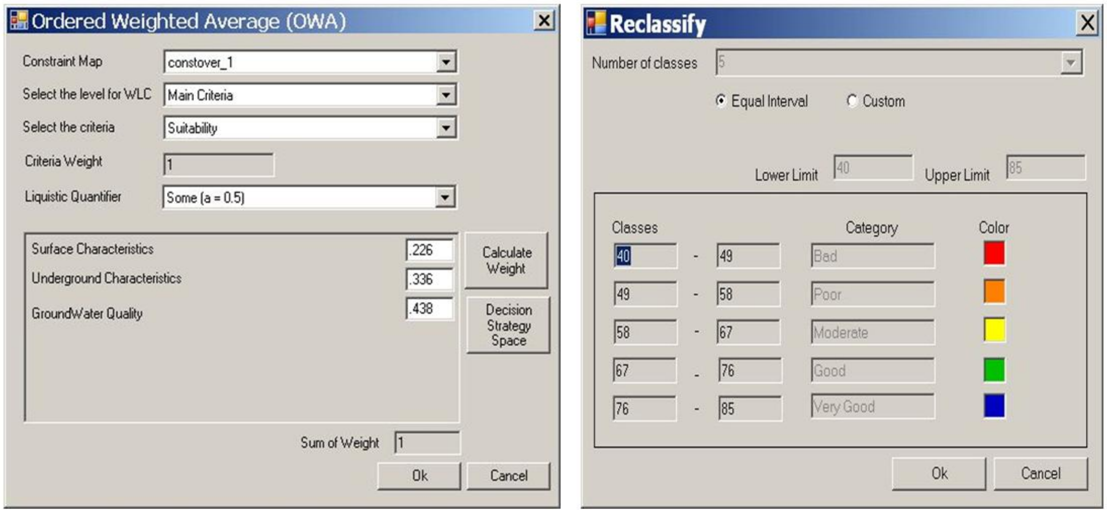


Figure 4-24 The Overlay procedure for the Suitability analysis (left) and the Reclassification step of the suitability map (right)

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 favourable 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.

<u>*A Case Study: The Querença-Silves Aquifer System of Algarve region in southern Portugal*</u>

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 all of the 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 (Figure 4-25).

The aquifer system of Querença - Silves is a major source of drinking water to the urban areas within the Algarve region. The Arade Dam is considered to be the most important drinking water source. The dam is located downstream of the Arade river. More than 50 hm^3 of river water per year are lost to the sea and in dry years there is a shortage of water resources (*Lobo-Ferreira and Oliveira, 2007*). MAR is considered as a potential strategy to store water during the wet season and use it during dry periods.

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.

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 $5 \cdot 10^{-3}$ to $3 \cdot 10^{-2}$. INAG *(2001)* presents the recharge value as being 220±54 mm/year. This represents a percentage of precipitation of around 40±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.

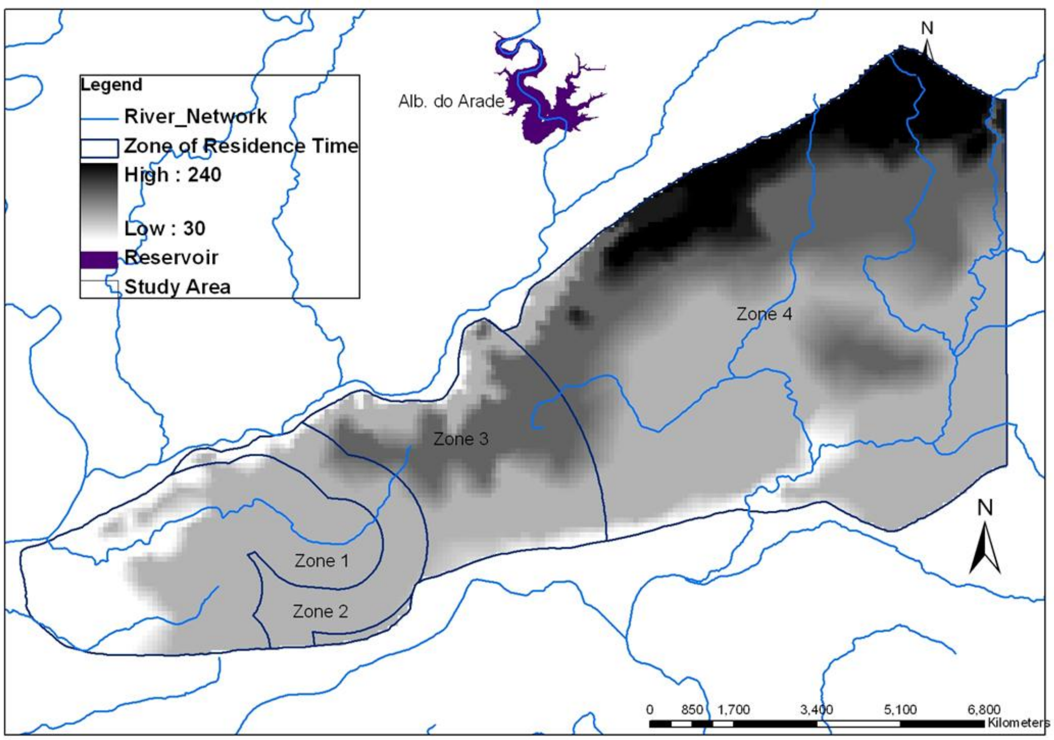


Figure 4-25 Study area (Querenca Silves Aquifer) map

Analysing 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, 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.

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 analysing their importance and relevance. Table 4-1 lists the selected criteria for constraint and suitability mapping, showing the relevance and the usefulness of each criterion for MAR site suitability mapping**.**

Table 4-1 List of criteria that were considered for this study

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 process, 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 depend 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.

<u>*Constraint Mapping*</u>

In order to screen out the non-feasible areas, constraint mapping was undertaken at an early stage. Table 4-2 shows the list of criteria and their threshold values for screening. For the land use map, land class feasibility was defined separately (Table 4-3). 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 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.

Table 4-2 List of Constraint Criteria together with Threshold Value

Criteria name	**Threshold values**	**Explanation**
Land use	-	See table 1.4-3
Infiltration rate (soil)	25 cm/day	The areas where infiltration rate is grater than 25 cm/day are considered as potential area.
Groundwater depth	5 m	The places where groundwater depth is grater 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 a least 6 month should be guaranteed.
Slope (topography)	5%	MAR is feasible for areas with less than 5% slope.

For the land use map each land class feasibility has been defined separately (Table 4-3).

Table 4-3 Categorization of the Lands use type at the study area

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 infiltatrate)	Feasible (value is 1)

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

Suitability Mapping

After analysing all available data and site characteristics, sub-criteria were selected according to their characteristics, and the main hierarchical structure was prepared. 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.

Figure 4-26 shows the suitable sites for MAR in the region using the WLC method.

Conclusions and Recommendations

This research section 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

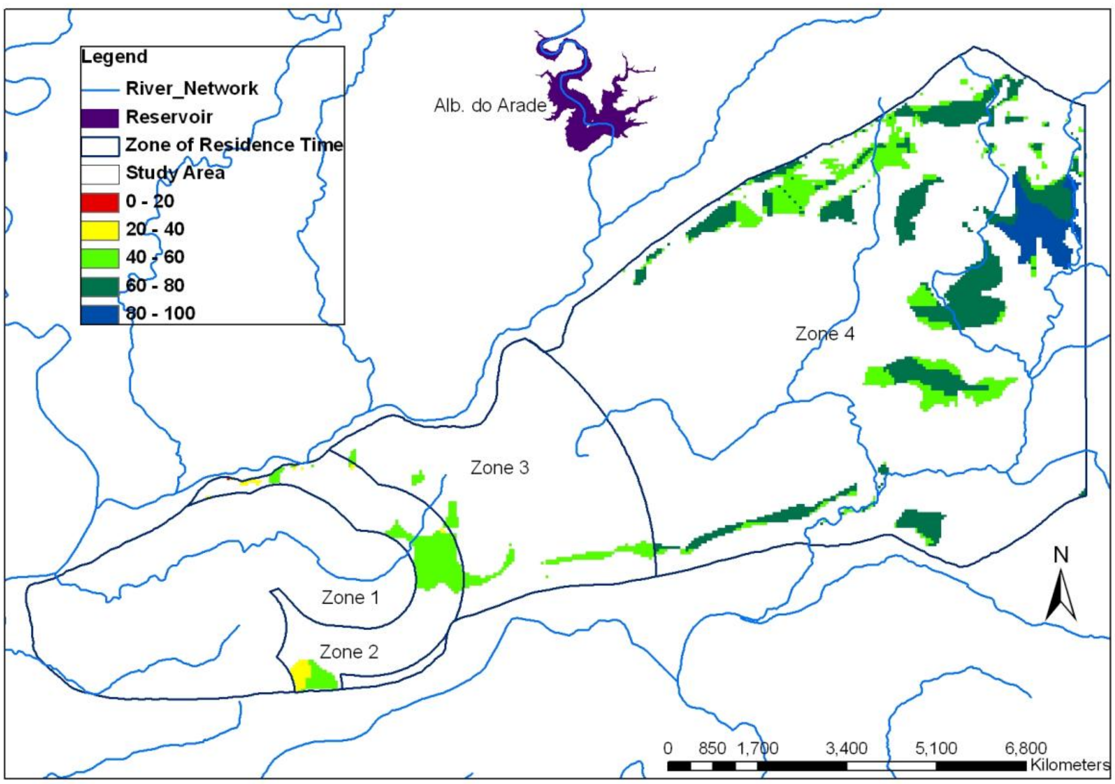


Figure 4-26 Site suitability for MAR based on WLC

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 et al., 1988*). In order to show the efficiency of the tool, a case study has been performed in Querenca 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. Socio-economic criteria, recharge and recovery water transportation cost, cost of excavation, etc. can be taken into consideration for further study.

SECTION II - ACADEMIC AND PROFESIONAL ACHIEVEMENTS

Academic achievements

During his professional activity until now, Dr. Constantin Radu Gogu completed several academic achievements briefly described in this section.

Between 2006 and 2012

- In 2011 initiated and organized the **Groundwater Engineering Research Centre** (*CCIAS*) in the Technical University of Civil Engineering, Bucharest.

  Currently he coordinates the **Groundwater Engineering Research Centre** (*CCIAS*) (*www.ccias.utcb.ro* - *Annex 2*). The centre research activity concentrates on the characterization of permeable media by means of hydraulic and hydrochemical data and on the human impact on groundwater. Applications include groundwater resources evaluation, urban groundwater, groundwater-infrastructure interaction, aquifer management, vulnerability assessment, ground pollution control, underground waste storage, and vadose zone study. Methods used are both regional and local in scale, of a quantitative nature, using flow and contaminant transport modeling. One part of the group develops geospatial data analysis and representation techniques and another one part works in data acquisition. CCIAS is currently coordinating or represents an active key partner in several national or European research projects as Sedimentary media modeling platform for groundwater management in urban areas (*www.utcb.simpa.ro*) or the FP7 project Tailored Improvement of Brownfield Regeneration in Europe (*www.timbre-project.eu*).

  CCIAS has an international young team (about 15 members): engineers, Master of Science students, PhD students, and Post-doctoral researchers. The young members are coordinated by several senior researchers that proved their scientific and technical expertise in Romania and abroad. Currently 4 PhD students focusing four distinct research topics are developing their thesis within the centre (3D sedimentary media hydrogeological modeling, Groundwater – infrastructure interaction, Urban impact on the aquifers, Modelling of soils behavior under static and dynamic loads). The youth are challenged and helped to publish scientific articles and to apply for national and international research and education grants/fellowships. Its members already obtained several international grants. The centre is equipped with updated hardware and software and benefit of its integration with other laboratories of the university: Water Quality Laboratory, Geotechnics Laboratory, and others.

- Set-up a hydrogeological experimental site (five wells, up to 25 m in depth, equipped with pumps and monitoring equipment) with the purpose to: (1) develop experimental research work and (2) for teaching purposes "in situ" hydrogeologic (pumping and tracer tests) and geophysical measurements (electrical sounding and profiling).
- Dr. Constantin Radu Gogu initiated in 2011 and currently is coordinating the Postdoctoral Research Program in Applied Hydraulics of the Technical University of Civil Engineering, Bucharest (*Annex 3*).
- Since 2011 is organizing a postgraduate course dedicated to the protection of groundwater resources at the Technical University for Civil Engineering, Bucharest. Its purpose is to offer to postgraduate students and to environmental engineers, a good understanding of theoretical and practical aspects related to groundwater flow and of physical, chemical, and biological processes that govern the contaminant transport (*Annex 4*).
- Introduced a new curriculum (since 2010) of “Environmental engineering spatial data models. Geospatial analysis fundaments” for the Master of Science level in Sustainable development (Technical University of Civil Engineering, Bucharest). The course has two main parts that cover one academic year. It focuses on understanding the spatial analysis fundamental techniques and environmental spatial data modeling.
- In 2011 was member of the PhD Committee (*Annex 5*) for the PhD in Environmental Sciences thesis submitted by Alberto Jimenez-Madrid entitled: “Establishing safeguard areas for the protection of groundwater intended for human consumption, in karst media, as required by Water Framework Directive”, Faculty of Science. University of Malaga (Spain).
- Starting with 2008 until now is one of the PhD thesis coordinators of Violeta Velasco at the Technical University of Catalonia, Barcelona (Spain), Department of Geotechnical Engineering and Geosciences. Subject: “Improving hydrogeological models of sedimentary media in an urban environment using GIS based 3D geological instruments”,
- Between 2006 and 2012 participated as Committee member to evaluate different Master of Sciences and Diploma paper works at the Technical University of Catalonia, Barcelona (Spain) and at the Technical University of Civil Engineering (Bucharest);
- Scientific reviewer (*Annex 6*) for different scientific papers submitted to Journal of Environmental Management (Elsevier), Advances in Water Resources (Elsevier), Water Resources Management (Elsevier), Hydrogeology Journal (Springer), Groundwater (Blackwell).

Between 2000 and 2005

- Special invited speaker at the “2nd Workshop World Organisation of Volcano Observatories”, 11 – 13 December 2002, USGS Menlo Park, California, USA (*Annex 7*)
- Designated (2003- 2004) by the Swiss Federal Institute of Technology - Institute of Cartography as delegate to the European Community to negotiate the partnerships in the frame of the Information Society Technology Program (FP6). This work was finalized with the participation of ETH Zurich in the ORCHESTRA (*http://www.eu-orchestra.org*) consortium (*Annex 8*).
- Participation to different scientific workshops in the frame of GEOWARN European Project in November 2000 and April 2001-Athens, Greece, in November 2001 Zürich, Switzerland (*Annex 8*).

Between 1998 and 2000

- Invited speaker in the frame of COST-A620 European project - “Vulnerability and risk mapping for the protection of carbonate (karst) aquifers", in April 1999-St.Veit/Glan, Austria, October 1998-Bled, Slovenia, May 1998-Neuchatel, Switzerland, and March 1998-Liege-Belgium (*Annex 9*).

Between 1994 and 1998

- Initiated, organized, and coordinated a two years Postgraduate school in Geographical Information Systems offering Diploma and Master of Sciences, developed in collaboration with Manchester Metropolitan University in the frame of UNIGIS (Manchester Metropolitan University, University of Salzburg, Free University of Amsterdam, University of Salford, University of Huddersfield) international universities network (*www.unigis.org*) (*Annex 10*);

Scientific workshops and conferences organizer

- 23 of December 2011; Seminar on Cartographic Web Services; Technical University of Civil Engineering, Bucharest, Romania
- 13 of September 2010; Workshop on Groundwater resources vulnerability assessment and mapping, University of Bucharest, Faculty of Geology and Geophysics, Romania;

- 5th of May 2010, The international workshop “Flood Risk Assessment and Alert Service for Romania”. Technical University of Civil Engineering, Romania;
- 8-11 October 2008, The international workshop: Current trends in hydrogeology modeling and investigation techniques as support for groundwater management and protection; Danube Delta, Tulcea, Romania;
- 2006 – 2007, International workshops (4 events) on “Sustaining Romanian research on groundwater protection”, University of Bucharest, Faculty of Geology and Geophysics, Romania
- 7- 8 June 2006 Workshop in Hydrogeology „Hydrogeology, the Universe, and everything” , Les Preses (La Garrotxa), Catalunia, Spain, Technical University of Catalunia, Spain;
- November 1998 “3rd Annual Big Meeting of UNIGIS Universities network”: Manchester Metropolitan University, University of Salzburg, Free University of Amsterdam, University of Salford, University of Huddersfield, Technical University of Civil Engineering Bucharest Sinaia, Romania;
- March 1996, the international seminar: “Geographical Information Systems on Urban Cadastre” Bucharest,

Research Grants

- 2005 – 2009 Senior Research Grant (Postdoctoral) awarded by Ministry of Research (Spain)-frame of “Ramon y Cajal” Scientific Research Program (*Annex 11*)
- June 1999 Research Grant awarded by Walloon Region (Belgium) for the project entitled "Aquifers vulnerability study based on GIS"
- 1998-1999 Research Fellowship awarded by Belgian Office for Scientific, Technical and Cultural Affairs (*Annex 12*) for the research project entitled "Application of Geographical Information Systems to optimize the preparation of spatial data for groundwater modelling applied in Global Change scenarios"
- 1997 – 1998 Grant awarded by Research Support Scheme of the Open Society Institute/Higher education Support Program - Prague, Czech Republic for the research project "Groundwater Vulnerability Assessment in Romania, Using Geographical Information Systems"(*Annex 13*)

Professional achievements

The following main achievements of Dr. Constantin Radu Gogu professional activity will be mentioned:

Research Projects

Project Director/ coordinator

- Sedimentary Media Modelling Platform For Groundwater Management In Urban Areas – SIMPA (*www.simpa.utcb.ro*), Project Director, 07.2010 – 06.2013
- Prototype aquifer vulnerability maps for Romania - ECAVAS, Project Director, 2007 – 2010
- 3D geological model of the sedimentary media in the Barcelona region to predict the behavior of the tunneling machine excavating the Subway L9 line. (Barcelona City - Airport)- GEO – 3D, Team leader, GIS solution development, 3D model designer, 10.2007 - 11.11.2009
- 3D hydrogeological modeling tools in sedimentary media - HEROES, Research project funded by the National Research Council of Spain (Consejo Superior de Investigation Scientifica) Project Director, 05.2007 – 11.11.2009
- Developing and application of a groundwater modeling platform for Barcelona city, Research project funded by the Ministry of Education and Research of Spain, Project coordinator, project developer, 02.2006 – 2009
- Geo-spatial system for natural hazard assessment studies in Switzerland - HazNETH, Team leader, project developer, Funded by Swiss National Funds and ETH Zürich (*www.hazneth.ethz.ch*),06. 2003 – 12.2005
- GIS Postgraduate School offering Diploma/Master of Sciences - UNIGIS (International Universities Network), Initiator and Project Manager in Romania (UTCB), 1994 – 1998

Team coordinator/member

- Tailored Improvement of Brownfield Regeneration in Europe- TIMBRE (*www.timbre-project.eu*), Team member, 01.2011- 2013
- Techniques, technology and ontology for geospatial data and services portals - TITOS, Spatial data developer, Geohidroconsult team coordinator, 08.2006 - 11.2008
- Integrated Information System for elaborating the Romanian Groundwater Atlas - SITAR, Team leader GIS solution implementation, Spatial database designer, 08.2006 – 11.2008

- Sustaining Romanian research applied to groundwater vulnerability and protection at the European level - AQUAPROTECT (*www.aquaprotect.ro*), Team leader, Project initiator, 08.2006 – 11.2007
- GEOMODELS regroups several universities and public research organizations having the purpose of applying and developing new geosciences technologies, Researcher, Spatial database designer, GIS analyst, 02. 2006 – 2009
- Groundwater Artificial recharge Based on Alternative sources of wateR: aDvanced INtegrated technologies and managEment – GABARDINE, Romanian team coordinator in charge with the GIS based Decision Support System (DSS), Funded by EU - FP6 (*www.gabardine-fp6.org/home.aspx*), 01. 2006 - 2008
- Spatial Data Infrastructures with Applications in Environment Protection - INSPAM, GIS analyst, 11.2005 – 2007
- Open Architecture and Spatial Data Infrastructure for Risk Management- ORCHESTRA, GIS analyst, Researcher, Funded by EU - FP6 (IST) (*http://www.eu-orchestra.org*), 05. 2003 – 12. 2004
- Geo-spatial warning systems, Nisyros volcano - GEOWARN, GIS analyst - Spatial database designer, Funded by EU – FP5 (IST) (*www.geowarn.com*), 08. 2000 – 06. 2003
- Prototype hydrogeological maps for the Walloon region, Belgium (Waremme–Momalle and Modave-Clavier, scale 1:25,000), GIS analyst - GIS team coordinator and trainer, 02.1999 – 08. 2000
- - Hydrogeological data base design – University of Liege/Department of Natural Resources and Environment - Ministry of the Walloon Region, Spatial database designer, GIS analyst, 10.1998 – 08. 2000
- -Application of Geographical Information Systems to optimize the preparation of spatial data for groundwater modeling applied in Global Change scenarios- *Belgian Office for Scientific, Technical and Cultural Affairs*, **PI, Researcher**, **GIS analyst,** 05.1998 – 05. 1999

Technical and research reports (see *Annex 14*) – about 40 technical and research reports

Protocols and framework agreements

- 2011 - Framework agreement between Technical University of Civile Engineering Bucharest and the National Institute of Research and Development for Land Reclamation ”ISPIF” Bucharest for scientific cooperation in the field of groundwater protection (*Annex 15*).
- 2011 - Framework agreement between Technical University of Civile Engineering Bucharest and the National Administration ”Romanian Water” - Arges-Vedea Basin Branch for scientific cooperation in the field of groundwater protection (*Annex 16*).
- 2010 - Framework agreement between Technical University of Civile Engineering Bucharest and Geological Survey of Spain for cooperation in the field of groundwater resources protection (*Annex 17*).

PART B

Planned scientific developments

The upcoming scientific research activity will focus mainly on urban groundwater modeling, hydrogeological data management and on groundwater resources protection by improving the vulnerability assessment methodologies and their implementation. An overview of these research directions is done in the subsequent paragraphs by outlining the following main actions:

- improving the geological models generation techniques by combining the stratigraphic analysis concepts with those of hydrogeological modeling;
- improve the hydraulic characterization methods of underground structures in relationship to groundwater;
- the development of a hydrogeological qualitative and quantitative information management framework in relationship to urban infrastructure (water supply, sewer system, subway lines, foundations, etc);
- the development of hydrogeological and geological data models needed for the spatial data infrastructure (INSPIRE);
- developing and applying groundwater protection strategies;
- consolidation of an already established team working in groundwater research topics that covers different knowledge areas (hydrogeology, geology, hydrology, structures and foundations, hydraulics, geographic informational system, informatics, mathematics, chemistry, biology).

Urban groundwater modeling and data management

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.

3D hydrogeological modeling tools for sedimentary media

Hydrogeological models are one of the basic tools to achieve an appropriate hydrologic management. On the other hand, it is also known that sedimentary media are usually very heterogeneous. The detailed modeling of these media is very complex for two reasons: (1) because of their heterogeneity, and (2) because of the fact that the tools needed for geological and hydrogeological data management and their implementation in hydrogeological models are not quite developed.

The objective is to gather the tools and methodologies that facilitate the integration of the 3D geological models of sedimentary media in the hydrogeological modeling of the processes of flow and transport of solutes. These tools should allow representing in the three dimensional space the heterogeneity of the sedimentary strata and their spatial distribution. Thus how connectivity implements into hydrogeologic models among the different sedimentary bodies will be better defined. In order to do so it is essential (1) to have enough data to allow acquiring detailed geological knowledge of the sedimentary media (2) to integrate the geological processes controlling the geologic formation, (3) to extrapolate, regarding the above-points and taking into account the possible application of different methodologies as deterministic and geostatistic models, as well as the petrophysic and hydraulic characteristics to the entire volume of the considered sediments, and (4) to implement all the information into flow and transport models to determine the location and the quality of the hydraulic resources by guaranteeing at the same time their reliable management.

This point includes subjects such as the characterization of groundwater, as well as the dynamics of water systems and their standard distribution in space. In this sense the main objective of this research direction is to define how the spatial distribution standards of the different hydraulic parameters, in a 3D sedimentary medium, integrate in the habitual hydrogeology modeling methodologies. Thus, the relationship between these obvious values and the effective-type values (which are the ones that actually define the dynamics of the aquifer and what is even more important for water resources, rule its behavior globally) could be explained. This knowledge is critical in order to correctly characterize an aquifer, as well as to deduce the modeling methodology that is more adequate to solve this problem.

Study of interaction between groundwater and sewer systems

Groundwater management in urban area has to take into account of possible and relevant phenomena arising from the complex interaction between subsurface water, surface water, and urban infrastructure. Conclusions mentioned in the literature and outlined also from two large scale research projects conducted in Romania for Bucharest city (SIMPA, *www.simpa.utcb.ro*) and in Spain for Barcelona city (HEROS- 3D hydrogeological modelling tools in sedimentary media, funded by the Ministry of Education and Research of Spain) show that the sewer network can act like a drainage system for the groundwater. It can also be easily proven that several sewer segments, located mainly in the unsaturated zone, contaminate the groundwater by leakage. The groundwater infiltration in the sewer conduits can cause the decrease of the groundwater level leading to structures instability problems as well as to the increase flow-rates of the sewer system. This affects seriously the wastewater treatment plants efficiency. The sewer network leakage cause groundwater pollution and locally could increase the groundwater level triggering buildings instability or other urban operational problems.

Solving the following main challenges, concerning the quantification of the groundwater interaction with the sewer system, will stand for this research direction elements of originality and innovation: (1) Modelling both exfiltrations of sewer conduits and infiltrations of groundwater in both laminar and turbulent flow regime; (2) Developing the possibility of using in models the real fluid properties and its variation, as wastewater have sensible distinct values of density and viscosity; (3) Introducing in the modelling process an improved quantification of the sewer network degradation due to ageing in terms of structural state and hydraulic parameters; (4) Improving the understanding of the sewers conduits clogging process by simulating the effect of leaking sewer in soils and in groundwater by using laboratory experiments.

Improving concepts of urban hydrogeological data management

Large quantities of geo-data are produced for the urban areas, due to the large amount of civil work projects and investigation studies. These are usually redundant and spread between different institutions or private companies. Time consuming operations like data processing and information harmonisation represents the main reason to systematically avoid the re-use of data. The urban groundwater data shows the same complex situation due to the fact that the urban elements like underground structures (subway lines, deep foundations, underground parkings, and others), urban infrastructure networks (sewer systems, water supply networks, heating conduits, etc), and drainage systems, surface water works and others shows a continuous modification.

In the past few years, transferring large amounts of information through internet has now become a feasible solution for sharing geoscience data and standard data transfer instruments have been developed. They allow easily updating and sharing through internet large geospatial databases between different institutions that do not necessarily use the same database structure. For Bucharest City (Romania) an integrated platform for groundwater geospatial data management is currently developed under the framework of a national research project (*www.simpa.utcb.ro*). This represents a solid data analysis base. It regroups data, information, models, and knowledge that will be exploited through services. The geological, hydrogeological, hydrogeochemical and geotechnical data are organized in a spatial-temporal database. The knowledge of various parameters at different detail scales (centimeter - kilometer) could bring to a reliable management of the groundwater resources and to provide information for various underground works and construction foundations in the studied area (Bucharest).

This platform represents an application of the EU Water Framework Directive (60/2000/EC) and of the EU Groundwater Directive (2006/118/EC) as a system of qualitative and qualitative information needed for groundwater management. The management platform meets the INSPIRE EU Directive concerning the spatial data structures, data transfer and availability in Europe. The development of web-based data access interfaces together with increased expectations on public and private institutions for delivery of re-usable geoscience data has led to interest in standardising data-exchange formats. The developed database structure could be used to design an extension for GeoSciML (GeoScience Mark-up Language) focusing on groundwater management and modelling.

On the basis of the developed platform, the proposed objectives for this research direction are:

- develop protocols for hydrogeological geospatial data query scenarios to optimize groundwater data management;
- improve the GroundWater Markup Language (GWML), a GML application to exchange groundwater related information, for groundwater sedimentary media in urban areas. GWML was developed by the Natural Resources Canada and it is an extension of another GML application - GeoSciML - designed to exchange geoscience (essentially geology) information (*Duffy and Sen 2005*). Therefore, GWML also borrows from Observation and Measurements (O&M: OGC 07-022r1) and Sampling Features (OGC 07-002r3) specifications.

Development of a process based groundwater vulnerability method

This research direction proposes to develop a method for the intrinsic vulnerability of groundwater resources assessment considering the properties controlling the contaminant transfer from the land surface to the groundwater surface.

A strong growing effort of European specialists focusing on groundwater vulnerability assessment has been shown during the last 15 years. It started at the end of the ‘90ies with the EU COST Action 620 “Vulnerability and Risk Mapping for the Protection of Carbonate (Karst) Aquifers” (*http://www1.unine.ch/chyn/php/publica_intro.php*) and continued with the need of implementing instruments for the European Water Framework Directive (2000/60/EC) and for the Groundwater Directive 2006/118/EC. One essential research direction they pointed out, trying also to provide reliable answers, was the removal of the empirical character of the vulnerability assessment methods. However important conclusions have been reached like the use of the source-pathway-target model and the application of the contaminant transfer time and contamination duration to define vulnerability, also no stable method has been resulted.

Vulnerability of aquifers is often considered as a relative, non-measurable, dimensionless property (*Gogu and Dassargues, 2000a*). This fact allows some flexibility in the assessment process. However, when testing different methods to the same area, the resulting maps may show dissimilarities or sometimes even strong discrepancies (*Gogu et al., 2003*). As consequence the results are difficult to be validated or even compared.

The lacks and drawbacks of the existing vulnerability methods are strongly related to the fuzzy and ambiguous definitions on which the vulnerability concept relies (*Brouyere et al 2001*). This has led to the use of aquifer vulnerability delineation procedures and classification criteria that differ from one EU member state to another. These procedures and criteria are even undefined for other states. The removal of the empirical character of the vulnerability assessment process should avoid the existing drawbacks and could provide reliable results. There is a clear need to develop a method for the intrinsic vulnerability of aquifers considering the properties controlling the contaminant transfer and the behavior of the contaminant at the entry point and its further evolution. The resulted method could be implemented in the common strategy of the EU member states to apply all the requests of the Water Framework Directive in a coordinated, coherent, and homogeneous manner.

At the end of the 90's the COST Action 620 generated an increase in the number of methods to assess the vulnerability of aquifers. However, the scientific challenges identified by Gogu and Dassargues (*2000a*) are still valid today. Currently there are two methods that attempt to remove the empiricism provided by most of the of vulnerability assessment methods. One is the VULK method (*Jeanin et al., 2001*) and a new method called APSU (protection of aquifers based on the sensitivity of the vulnerability, Popescu et al., 2010). Both methods are based on the same criteria for assessing vulnerability to contamination of aquifers. They use the transit time between the spillage of polluting the environment and its arrival at the objective of protection, its concentration and the duration of pollution at that point.

Analyzing the **APSU** method, one observes the following simplifications:

- The coefficient of runoff (representing the fraction of water that does not infiltrate the soil) was taken function of the land-use (forests, pastures, agriculture or bare soils), the slope and the soil texture (sands, silts, clays). The used values of this coefficient were adapted from Ebener *(2000)*.
- The effect of contaminant dilution due to the additional water recharge, coming from precipitation and feeding the cells laterally, has not been considered.

Concerning the first simplification, one can say that the water infiltration into soil has to take into account also the water content of the soil column through which the infiltration process takes place (described by the water content variation in depth). This is a major factor (time dependent) controlling the infiltration and consequently the runoff. More precise quantifications of the infiltration into soil can be obtained using Richards' equation *(Richards, 1931)* or using simplified methods such as *(Green & Ampt, 1911)*. Such models require a larger amount of data and extensive computations.

Concerning the second simplification, the consideration of the contaminant dilution due to the additional amount of rainfall water feeding through lateral inflow will increase the effect of attenuation, and so will reduce the lateral potential dangerosity (defined by the authors).

Aquifer vulnerability assessment using a process based methodology complying with the physics of groundwater flow and contaminant transport represent a research challenge. Removing the empirical character of the vulnerability assessment will eliminate the existing lacks and drawbacks of the currently used methods.

Teaching, theoretical and practical applications

The consolidation of the already established interdisciplinary research group functioning within the Groundwater Engineering Research Centre (CCIAS) will be one of the main research targets for the next years. Currently, its research applications include groundwater resources evaluation, urban groundwater, groundwater-infrastructure interaction, aquifer management, vulnerability assessment, ground pollution control, underground waste storage, and vadose zone study. An enlargement of its research activities, focusing on geophysical applications in hydrogeology, is foreseen. This will improve the data acquisition activity, having a strong impact on the data quality. The research activity will be funded through the national and European framework programs as well as by contracts with the national authorities, regulators, companies, and private sector.

Folowing the above mentioned planned research directions will be developed about 4 PhD thesis subjects within CCIAS in the near future. On this basis about two scientific articles of each PhD subject matter are forseen to be published in ISI indexed revues.

Increasing the visibility of CCIAS in relationship to the European research centres of similar interest will be another short term objective. This will be done to improve the quality of scientific research by participating to common research projects (national or European), exchange of students (PhD and MSc), exchange of researchers and by common publications. Collaboration protocols in this respect are already established (ex. Geological Survey of Spain) and their number is intended to be increased. A similar action will be performed at the national level. However here, the spectrum of potential partnership institutions will be substantially larger. It will include environmental authorities, water regulators, companies, local administrations and others.

Within CCIAS a 3 month postgraduate course dedicated to the protection of groundwater resources has been initiated and offers a good understanding of the theoretical and practical aspects related to groundwater flow and of physical, chemical, and biological processes that govern the contaminant transport. The course presents some of the severe problems close related to groundwater protection activities like: landfills, contaminated industrial sites, mines and oil exploitation closure. As these aspects could be solved only through a correct management of groundwater based on current knowledge and techniques the course has the following main objectives:

- Provide to students a solid theoretical basis in the fields of groundwater hydraulics, geology, biology, chemistry;

- provide practical skills in hydrogeological field tests (pumping tests, tracer tests, applied geophysics);
- Offer competences in analyzing qualitative and quantitative hydrogeological data;
- Train students in solving hydrogeological complex problems by using analytical and numerical methods;
- Present the newest techniques for groundwater quality remediation;
- Develop skills of current water resources management on the basis of the newest technologies.

A new curriculum for the Master of Science students of Sustainable development - Technical University of Civil Engineering, Bucharest has been developed. It is called: "Environmental engineering spatial data models. Geospatial analysis fundaments". The course has two main parts and covers one academic year. It focuses on understanding the spatial analysis fundamental techniques and environmental spatial data modeling. Basic concepts of spatial thinking are presented explaining: data and information description, current situation and trends, metadata notion, data models, and spatial operations for raster and vector models. Furthermore, the current approaches for managing hydrogeological data as well as spatial analysis data processing operations for groundwater numerical modelling are discussed. The course offers also an introduction in geostatistical analysis.

The course is completed with a consistent package of exercises. A first set of exercises are designed to develop the geo-spatial thinking and the general spatial data analysis. A second set will consist in small applications using data of distinct regions. Various aspects of developing the hydrogeological database for these regions are analyzed and discussed. These applications were carried out using various hydrogeological data processing tools developed in scope of various research projects like: Bucharest region aquifer system, Besós delta sedimentary media, Barcelona hydrogeological model, Llobregat delta hydrogeological model, and others.

An experimental site has been developed within Groundwater Engineering Research Centre (CCIAS). This has been set-up following three major directions: (1) develop experimental research work, (2) quantitative and qualitative monitoring of the "Pietrisurile de Colentina" aquifer structure, and (3) for teaching purposes "in situ" hydrogeologic (pumping and tracer tests) as well as for geophysical measurements (electrical sounding and profiling). The site made up five hydrogeological wells, up to 25 m in depth. They are equipped with submersible pumps with service discharges between 1 l/s and 5 l/s, and monitoring equipment for hydraulic head level measurement (electrical GWT sensors). The groundwater quality is monitored periodically analyzing physical and chemical parameters. Practical classes for students are organized in order to learn hydrogeological data acquisition techniques. This site will be used in various future research projects where in-situ experiments are needed.

Changing and opening the society perception, on the environmental protection and as consequence on quantitative and qualitative aspects of groundwater, has to be a permanent concern. This has to be done by information, education, sensibilization and constrain. The first three means of action are in the hands of educators and scientists and they have to act responsible by contributing to the society knowledge and behavior. A continous action will be performed in this sense by improving sistematically the university curriculum for students, through workshops and seminars to administration representatives, and by press articles to address our society.

PART C

References

Aller L, Bennet T, Lehr HJ, Petty JR, Hackett G (1987) - *DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeologic settings*. In: Ada OK, Robert S. Kerr Environmental Research Laboratory, US Environmental Protection Agency Report EPA-600/2–87–035, 622 pp.

Almeida, C.; Mendonça, J.L.; Jesus, M.R.; Gomes, A.J. (2000) - *Sistemas Aquíferos De Portugal Continental,* Relatório. INAG, Instituto da Água. Lisboa, Electr. Doc., CD-ROM

Al-Rashed, M. F., Sherif, M. M. (2001) - *Hydrogeological aspects of groundwater drainage of the urban areas in Kuwait City*, Hydrological Processes, Vol. 15, 2001, pp. 777-795.

Andreo, B., Ravbar, N., Vias, J.M. (2008) - *Source vulnerability mapping in carbonate (karst) aquifers by extension of the COP method: application to pilot sites.* Hydrogeology Journal, 17: 749-758

Avril P, Tavernier R, Hanotiaux G (1984) - *Maps of soils in Belgium, Beauraing* 184 E, scale 1: 20,000. Cartographic Centre of Southern Belgium, Gémbloux Faculty of Agronomic Sciences, Institute for encouraging the scientific research in industry and agriculture, Belgium [in French and Flemish].

Bishop, P.K., Misstear, B.D., White, M., Harding, N.J., (1998) - *Impacts of sewers on groundwater quality*, CIWEM 12, pp.216-23.

Blijenberg, H. (1998) - *Rolling stones? Triggering and frequency of hillslope debris flows in the Bachelard Valley, Southern French Alps. Utrecht*, Netherlands, Utrecht University.

Bonomi T (2009) - *Database development and 3D modeling of textural variations in heterogeneous, unconsolidated aquifer media: Application to the Milan plain*, Computers & Geosciences 35:134-145

Borgomano JRF, Fournier F, Viseur S, Rijkels L (2008) - *Stratigraphic well correlations for 3-D static modeling of carbonate reservoirs*, AAPG Bulletin 92: 789-824.

Bouwer, H., (2002) - *Artificial Recharge of Groundwater: Hydrogeology and Engineering*, Hydrogeology Journal, 10: 121-142

Bouezmanrni M, Dossin F, Habilis F, Rekk S, Ruthy I, Sorel A (2006) - *Hydrogeological mapping of the Wallon region* (Belgium), Proceedings of the 5th European Congress on Regional Geoscientific Cartography and Information Systems, Volume I, pg. 4-7

Boroushaki, S., Malczewski, J., (2008) - *Implementing an extension of the analytical hierarchy process using ordered weighted averaging operators with fuzzy quantifiers in ArcGIS*, Computers and Geosciences 34, 399e410.

Brouyere S, Jeannin PY, Dassargues A, Goldscheider N, Popescu I C, Sauter M, Vadillo I, Zwahlen F (2001) - *Evaluation and validation of vulnerability concepts using a physically based approach*, 7th Conference on limestone hydrology and fissured media. Becanson, 20-22 September 2001

Brombach, T., Hunziker, J.C., Chiodini, G., Cardellini, C., **(**2001) - *Soil diffuse degassing and thermal energy fluxes from the southern Lakki plain, Nisyros (Greece)*, Geophysical Research Letters 28, 69–72.

Cajot O, Monjoie A, LGIH (1995) - *CILE 953 Captage de Néblon II à Ama – Ocquier, Etude géophysique et hydrogéologique* [in French]. University of Liège, Belgium

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V., & Reichenbach, P. (1991) - *GIS techniques and statistical models in evaluating landslide hazard*, Earth Surface Processes and Landforms, 16, 427– 445.

Chang YS, Park .D (2004) - *Development of a web based Geographic Information System for the management of borehole and geological data*, Computers & Geosciences 30:887-897.

Chiodini, G., Cioni, R., Guidi, M., Raco, B., Marini, L., (1998) - *Soil CO2 flux measurements in volcanic* and geothermal areas, Applied Geochemistry 13, 543–552.

Civita M (1994) - *Le carte Della vulnerabilita degli acquiferi all'inquinamento*. Teoria& practica (Aquifer vulnerability maps to pollution). (in Italian), Pitagora Ed., Bologna.

Civita M, De Regibus C (1995) - *Sperimentazione di alcune metodologie per la valutazione della vulnerabilita degli aquiferi (in Italian)*, Quaderni di Geologia Applicata, Pitagora Ed. Bologna, 3, pp 63–71.

Custodio E and Llamas MR (1983) - *Hidrología Subterránea*. Ediciones Omega.España.

Daly D, Dassargues A, Drew D, Dunne S, Goldscheider N, Neale S, PopescuI C, Zwahlen F (2001) - *Main concepts of the 'European Approach for (karst) groundwater vulnerability assessment and mapping*. Hydrogeology Journal 10:340–345

Dai, F., Lee, C., Ngai, Y. (2002) - *Landslide risk assessment and management: An overview*. Engineering Geology, 64, 65– 87.

Dassargues A, Derouane J (1997) - *A modelling approach as an intermediate step for the study of protection zones in karstified limestones*, Karst Hydrology, Proc workshop W2, Rabat, Morocco, IAHS Publ. No 247, pp 71–79

Delacourt, C., Alleman, P., Casson, B., Vadon, H. (2004) - *Velocity field of the 'La Clapiere' landslide measured by the correlation of aerial and QuickBird satellite images*, Geophysical Research Letters, 31(15), 15619.

De Boyer C, Thys G, Fairon J, Michel J, Vrolix M (1996) - *Atlas du karst Wallon—Inventaire catographique et descriptif des sites karstiques et des rivieres soutteraines de la Walonie- Province de Liege*, La commission Wallonne d'etude et protection des sites souterrains, Belgium

DeMers M N (1997) - *Fundamentals of geographic information system*s, Wiley, New York

Di Clemente C., Laurent S (1986) - Contribution *à l'étude hydrogéologique de bassin Néblon*, Graduated diploma paper [in French], LGIH, University of Liège, Belgium

De Joode, A., van Steijn, (2003) - PROMOTOR-df: *A GIS-based simulation model for debris flow hazard prediction*. In Rickenmann, & Chen (Eds.), Debris flow hazards mitigation: Mechanics, prediction and assessment (pp. 1173– 1184). Rotterdam Millpress.

Doerfilger, N. (2005) - *Guide méthodologique, cartographie de la vulnérabilité en vue de la délimitation des périmètres de protection en milieu karstique*, Anexe du rapport BRGM/RP-53576-FR.

Doerfilger, N. Plagnes, V. (2009) - *Cartographie de la vulnérabilité des aquifères karstique, gude méthodologique de la méthode* PaPRIK, BRGM RP-57527-FR., France.

Doerfilger, N., Jauffret, D., Loubier, S. (2004) - *Cartographie de la vulnérabilité des aquifères karstiques en France Comte*, avec la collaboration de V. Petit, Rapport BRGM RP-53576-FR.

Doerfliger, N., (1996) - *Advances in karst groundwater protection strategy using artificial tracer tests analysis and multiattribute vulnerability mapping (EPIK method)*, PhD Thesis, University of Neuchatel, Switzerland, 308 pp.

Dohmann, M., Decker, J., Menzenbach, B., (1999) - *Water Contamination Due to Sewer Leackage*, Berlin, Springer.

Eiswirth, M., Hotzl, H., (1997) - *The impact of leaking sewers on urban groundwater*, Balkema, Rotterdam.

Ellis, J.B., Revitt, D.M., (2002) - *Sewer losses and interactions with groundwater quality*, Water Science and. Technology., p.195–202.

Escorcia J (2010) - *Modelación de los trabajos de tunelaje: una nueva herramienta para la toma de decisiones en tiempo real*, Master of Science Thesis. Universitat Politecnica de Catalunya, Barcelona (Spain)

Escuder R., Fraile J., Jordana, S., Ribeira F., Sánchez-Vila X., Vásquez-Suñé E. (2009) – *Hidrogeologia*, *Conceptos Basicos de hidrologia subterranea*, Fundacion Centro Internacional de Hidrologia Subterranea (FCHIS), Barcelona, Spain 768 p.

Fenz, R., (2005) - *Strategies of sewer maintenance (Strategien der Kanalinstandhaltung)*, Wiener Mitteilungen, 183, pp.91-118.

Foster SSD (1987) - *Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy*, In: van Duijvenbooden W, van Waegeningh HG (eds) TNO Committee on Hydrological Research, The Hague. Vulnerability of soil and groundwater to pollutants, Proc Inf 38, pp 69–86.

Freeze RA, Cherry JA (1979) - *Groundwater*, Prentice-Hall.

Gaitanaru S D, Gogu RC (2008)- *Decision Support System for groundwater artificial recharge based on alternative sources of water for semi-arid regions* - The 3rd conference dedicated to the national spatial data infrastructure - 11 - 12 December 2008, Bucharest – Romania

Ghayoumian, J., Ghermezcheshme, B., Feizinia, S., and Noroozi A.A., (2005) - *Integrating GIS and DSS for Identification of Suitable for Artificial Recharge, Case Study Meimeh Basin; Isfahan, Iran*, Environmental Geology; 47:493-500.

Gogu, R.,C, Dassargues A (2000a) - *Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods*, Environmental Geology 39(6):549–559.

Gogu RC, Dassargues A (2000b) - *Sensitivity analysis for the EPIK vulnerability assessment in a small karstic aquifer*, Hydrogeology Journal, 8:337–345

Gogu, R.C.(2001) - Advances in groundwater protection strategy using vulnerability mapping and hydrogeological GIS database, PhD Thesis, University of Liege - Faculty of Applied Sciences, Liege, Belgium

Gogu, R.,C, Carabin, G., Hallet, V., Peters,V., Dassargues, A., (2001) - *GIS based hydrogeological databases and groundwater modelling,* Hydrogeology Journal - Journal of the International Association of Hydrogeologists, Springer - Verlag, Germany , v.9, Issue 6, December 2001, pp.555-569.

Gogu, R.,C, Hallet, V., Dassargues, A., (2003) - *Comparison between vulnerability assessment techniques. Application to the Néblon river basin (Belgium*), Environmental Geology - International Journal of Geosciences, Springer - Verlag, Germany v.44 (8) November 2003, pp.881-892

Gogu R C, Hurni L, De Ketelaere D, Petch J; In: Zwahlen F (ed.), (2004) - Chapter 7.3 Data processing using GIS, *Vulnerability and risk mapping for the protection of carbonate (karst) aquifers*, European Commission - Directorate-general for Research, COST Action 620 - Final report, Brussels, Belgium, EUR 20912, 2003, pp.125-131.

Gogu R C., Freimark H, Stern B, Hurni L, (2005) - *Geo-portal system for natural hazard assessment studies for torrent streams and debris flow* - Geoinformation for Disaster Management, In: Peter van Oosterom, Siyka Zlatanova, Elfriede M. Fendel Eds., Springer, pp.1271-1281

Gogu R C., Dietrich V J., Jenny B, Schwandner F M., Hurni L (2006) - *A geo-spatial database concept for data-management of dormant volcanoes*; Computer & Geosciences, Elsevier, Canada, v. 32/1, pp. 29-41

Gogu R C, Vázquez – Suñe E, Font-Capo J, Monfort D, Velasco V, Carrera J, (2008) - *Integrated study for the simulation of the tunnelling process in sedimentary media*;. "Water and infrastructures of underground media" (November 24-26, 2008), Barcelona, Spain, 2008. AIH-GE, IGME, 2009.

Gogu, R.C., Velasco, V., Ionita, A., Vazquez-Sune, E., (2010) - *Sedimentary Media GIS Based Software Platform to Improve Groundwater Modeling* International Multidisciplinary Scientific GeoConference SGEM, Volume 1, pp. 281-289, Albena, Bulgaria (2010) ISBN-954918181-2.

Gogu RC, Velasco V, Vázquez-Suñè E, Gaitanaru D, Chitu Z, Bica I (2011) - *Sedimentary media analysis platform for groundwater modelling in urban areas*, Advances in the research of aquatic environment. Ed.Springer.

Goldscheider, N., Klute, M., Sturm, S., Holtz, H. (2000) -*The PI method – a GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers*, Zeitschrift fur angewandte geologie, 46(3):157-166.

Gontier P, Hallet V, Monjoie A, LGIH (1997) - *SWDE 971 Prise d'eau de Beauraing-Tamizon, Essais de traçage, Rapport intermediaire*. (Study for protection zones delineation of the Beauraing-Tamizon water supply system: Intermediary report made for Walloon Water Company), University of Liege, Belgium [in French], 28p.

Gustafsson, G. L. (2000) - *Alternative Drainage Schemes for Reduction of Inflow/Infiltration - Prediction and Follow-Up of Effects with the Aid of an Integrated Sewer/Aquifer Model*, Proceeding 1st International Conference on Urban Drainage via Internet, 2000, pp. 21-37.

Hallet V., Gogu R.G, Peters V, Ruthy I,(2000) - *Prototypes of the general hydrogeological maps for the Walloon Region (Waremme–Momalle and Modave-Clavier, scale 1: 25,000*, Ministry of the Walloon Region, Belgium [in French],Department of Natural Resources and Environment – January 2000

Hornef, H., (1983) - *Menaces to the quality of groundwater due to leaky public sewers and house drainage systems*, Korrespondenz Abwasser, pp.896-903.

Huggel, C., Kaab, A., Haeberli, W., Teysseire, Paul, F. (2002) - *Remote sensing based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps*. Canadian Geotechnical Journal, 39, 316– 330.

Innes, J. (1983) - *Debris flows*. Progress in Physical Geography, 7(4),469– 501.

Jeanin, P.Y., Cornaton, F., Zwahlen,F. and Perrochet, P., (2001) - *VULK: a tool for intrinsic vulnerability assessment and validation*. En 7th Conference on Limestone Hydrogeology and Fissured Media, pp. 185-190. Besancon, France.

Kilburn, C., Pasuto, A. (2003) - *Major risk from rapid, large-volume landslides in Europe* (EU Project RUNOUT), Geomorphology, 54,3–9.

Klinger, J., Wolf, L., Hotzl, H., (2005) - *Leaky sewers—measurements under operating conditions*, In: Fourth World Wide Workshop for Young Environmental Scientists (WWW-YES), Domaine de Cherioux, Vitry sur Seine, France..

Kniveton, D., de Graff, P., Granicas, K., Hardy, R. (2000) - *The development of a remote sensing based technique to predict debris flow triggering conditions in the French Alps*, International Journal of Remote Sensing, 21(3), 419– 434.

Lake R (2005) - The *application of geography markup language (GML) to the geological sciences*, Computers & Geosciences 31: 1081-1094.

Lin, P. -S., Lin, J. -Y., Hung, H. C., Yang, M. -D. (2002) – *Assessing debris flow hazard in a watershed in Taiwan*. Engineering Geology, 66, 295–313.

Liteanu, E., (1952) - *Geologia zonei orasului Bucuresti*, Studii Tehnice și Economice, Seria E, Hidrogeologie, Nr.1., p.3-80, Bucuresti.

Lobo Ferreira, J.P., Oliveira, L. (2007) - *Aquifer storage and recovery and applicability to Algarve (Portugal)*. In Proceedings XXXV IAH Congress, Groundwater and Ecosystems.

Lorente, A., Garcia-Ruiz, J., Begueria, S., Arnaez, J. (2002) - *Factors explaining the spatial distribution of hillslope debris flows*. Mountain Research and Development, 22, 32– 39.

Maidment D. R., (2002) - *Arc Hydro: GIS for Water Resources*, ESRI Press, Redlands, California.

Makris, J., Papoulia, J., Papanikolaou, D., Stavrakakis, G., (2001) - *Thinned continental crust below northern Evoikos Gulf, central Greece, detected from deep seismic soundings,* Tectonophysics 341, 225–236.

Mantovani, F., Soeters, R., van Westen, C. (1996) - *Remote sensing techniques for landslide studies and hazard zonation in Europe*, Geomorphology, 15, 213– 225

Martinez, S.E., Escolero, O. Wolf, L., (2010) - *Total Urban Water Cycle Models in Semiarid Environments-Quantitative Scenario Analysis at the Area of San Luis Potosi*, Mexico, Water resources Management, 25 No.1, pp.239-63. DOI 10.1007/s11269-010-9697-6.

McKean, J., Roering, J. (2004) - *Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry*, Geomorphology, 57, 331– 351.

Medina A., Carrera J. (2003) - *Geostatistic inversion of coupled problems: dealing with computational burden and different types of data*, Journal of Hydrology, 281, 251-264.

Metternicht G., Hurni L. ,Gogu R. (2005) - *Remote sensing of landslides: an analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments*, *Remote* Sensing of Environment, Elsevier, Canada, v. 98/2-3, pp. 284 – 303

Meus P (1993) - *Hydrogeologie d'un aquifere karstique du calcaire carbonifere en Belgique (Neblon et Anthisnes)*, Apport des tracages a la connaissance des milieux fissures et karstifies (in French). PhD Thesis, University of Liege, Belgium, 323 pp

Ming J, Pan M, Qu H, Ge Z (2010) - *GSIS: A 3D geological multy-body modeling system from netty cross-sections with topology*, Computers & Geosciencies 36: 756-767.

Monfort D , Font-Capo J, Vázquez – Suñe E, Gogu R C, Carrera J, (2009) - *Local behaviour of the groundwater media during the tunnelling process (Barcelona metro L9 study case)*, "Water and insfrastructures of underground media" (November 24-26, 2008), Barcelona, Spain, 2008; AIH-GE, IGME, 2009.

Monteiro, J.P. (2005) - *A Importacia Do Dimentionamento de Captacoes de Agus Subterraneas No Algarve – Passado*, Presente e Futuro, Manual Técnico de Engenharia, Águas Subterrâneas e Efluentes Tratados da GRUNDFOS, Lisboa, Expresso Gráfico.

Nakayama, T., Watanabe, M., Tanji, K., Morioka, T. (2007) - *Effect of underground urban structures on eutrophic coastal environment*, Science of The Total Environment, Vol. 373, No. 1, 2007, pp. 270-288.

Napolitano P., Fabbri A.G. (1996) - *Single parameter sensitivity analysis for aquifer vulnerability assessment using DRASTIC and SINTACS*. In : Kovar K and Nachtnebel HP (eds) Proc HydroGIS: Application of Geographic Information Systems in Hydrology and Water Resources Management, IAHS Publication No. 235, pp 559-566.

Ormeling, F (1995) - *Atlas information Systems*. Proceedings of the International Cartographic Conference ICA Barcelona, vol 2: 2127-2133

Petelet Giraud, E., Doerfilger, N., Crochet, P. (2000) - *RISKE: Méthode d'evaluation multicritère de la cartographie de la vulnerabilite des aquiferes karstiques.* Aplications aux systems des Fontanilles et Cent-Fonts (Herault, France). Hydrogeologie, 4:1461-1470.

Poeter, E. P., Hill, M. C. (1997) - *Inverse models: a Necessary next step in ground-water modeling*, Ground Water, Vol. 35, No. 2, 1997, pp. 250-260.

Popescu, C., Lazarescu, F., (1988) - *Concepția generală de amenajare complexă a râului Dâmbovita în municipiul București*, Hidrotehnica, 33, p.8.

Popescu, I.C., Brouyere, S., Derouane, J. Dassargues, A. (2010) - *Physically-based groundwater vulnerability assment for groundwater protection and land-use management.* Symposium de la Meuse 2010. Liege, Belgium.

Preene, M., Brassington, R. (2003) - *Potential Groundwater Impacts from Civil Engineering Works*, Water and Environment Journal, Vol. 17, No. 1, 2003, pp. 59-64.

Rahman M. Azizur, Bernd Rusteberg, R.C. Gogu, J.P. Lobo Ferreira, Martin Sauter (2012) - *A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge*, Journal of Environmental Management 99 (May 2012), doi:10.1016/j.jenvman.2012.01.003

Rapp, A., Nyberg, R. (1981) - *Alpine debris flows in northern Scandinavia*. Geografiska Annaler, 63A, 183–196.

Rauch, W., Stegner, T. (1994) - *The colmation of leaks in sewer systems during dry weather flow*, Water science technology., Vol. 30, No. 1, 1994, pp. 205-210.

Ravbar, N., Goldscheider, N. (2007) - *Proposed medthodology of vulnerability and contamination risk mapping for the protection of karst aquifers in Slovenia*. Acta Carstologica, 36(3): 461-475.

Ribeiro, L., Chambel, Lodwick WA, Monson W, Svoboda L (1990) - *Attribute error and sensitivity analysis of map operations in geographical information systems - suitability analysis*. International Journal Geographical Information Systems 4: 413-428.

Riera J (2011) - *L'estudi del comportament hidrogeològic de l'aquifer del Besòs en les rodalies del cmpus ciutadella de la Universitat Pompeu Fabra mitjançant un model numèric del flux*, Master of Science Thesis, Universitat Politecnica de Catalunya, Barcelona (Spain).

Ross M, Parent M, Lefebvre R (2005) - *3D geologic framework models for regional hydrogeology and land-use management: a case study from a Quaternary basin of southwestern Quebec*, Canada, Hydrogeology Journal, 13, 690-707.

Rueedi, J., Cronin, A.A., Morris, B.L., (2009) - *Estimation of sewer leakage to urban growndwater using depth specific hydrochemistry*,Water and Environment Journal, 23 No. 2, pp.134-44. DOI:10.1111/j.1747-6593.2008.00119.x.

Rusteberg, B.; Rahman, M.A.; Bear, J.; Bensabat, J.; Brouyère, S.Wojda, P.; Gogu, R.C., Power, H. (2008) - *The Gabardine Decision Support System for artificial recharge planning and management*. Conference on Water Reclamation and Aquifer Recharge, Maribor, Slovenia, Sept. 5-6, 2008.

Saaty, T.L., (1980) - *The Analytical Hierarchy Process*, Mcgraw-Hill, New-York.

Sebesan, I., Voinescu, I. (2010) - *Aspects related to hydrological phenomena incurred at metro tunnels construction and operation*, Ovidius University Annals Series: Civil Engineering, Vol. 1, No. 12, pp. 511-518.

Sen M, Duffy T (2005) - *GeoSciML: Development of a generic GeoScience Markup Language*, Computers & Geosciences 31: 1095-1103.

Strassberg G (2005) - *A geographic data model for groundwater systems*, Doctoral thesis, University of Texas, Austin, 229 pp.

Tripet J-P, Doerfliger N, Zwahlen F (1997) - *Vulnerability mapping in karst areas and its uses in Switzerland*. Hydrogeologie 3:51–57.

Van Elzakker, C P J M (1993) - *The use of electronic atlases*. In: Klinghammer I. et al. (Eds) Proceedings of the Seminar on Electronic Atlases

Van Stempvoort D, Evert L, Wassenaar L (1993) - Aquifer Vulnerability Index: a GIS compatible method for groundwater vulnerability mapping, Canadian Water Ressources Journal, 18: 25 – 37

Varnes, D. (1978) - *Slope movements, type and processes*. In R. Schuster, & R. Krizek (Eds.), Landslide analysis and control (pp. 11 –33). Washington, DC' Transportatoin Research Board

Vassilopoulou, S., Hurni, L., Dietrich, V., Baltsavias, E., Pateraki, M., Lagios, E., Parcharidis, I., (2002) - *Orthophoto generation using IKONOS imagery and high-resolution DEM: a case study on volcanic hazard monitoring of Nisyros Island (Greece)*, ISPRS Journal of Photogrammetry & Remote Sensing 57, 24–38.

Vázquez-Suñé E, Abarca E, Carrera J, Capino B, Pool M, Gámez D, Simó T, Batlle F, Niñerola J.M, Ibáñez X (2006) - *Groundwater modelling as a tool for the European Water Framework Directive (WFD) application: The Llobregat case,* Physics and Chemistry of the Earth 31, 1015–1029.

Vázquez-Suné, E., Sanchez-Vila, X. (1999) - *Groundwater modelling in urban areas as a tool for local authority management: Barcelona case study (Spain),* Impacts of Urban Growth on Surface Water and Groundwater Quality (Proceedings of IUGG 99Symposium HS5), Jul. 1999, IAHS Publications, Birmingham.

Velasco V, Cabello P, Vázquez-Suñè E, López-Blanco M, Ramos E, Tubau I (2011) - *A stratigraphic sequence based geological model for constraining hydrogeological modeling in the urbanized area of the Quaternary Besòs Delta (NW Mediterranean Coast, Spain)*, Geological Acta.

Velasco V, Gogu R, Garriga A, Monfort D, Vazquez-Suñé E, Ramos E, Carrera J (2010) -*Improving groundwater modeling of sedimentary media using GIS based 3D geological tools,* , 11-14 October 2010, Congress GeoDarmgstadt2010, Darmstadt, Germany

Vogt J (2002) - *Guidance Document on Implementing the GIS Elements of the Water Framework Directive*, http://www.ec-gis.org/docs/F2305/GIS-GD.PDF

Von Hoyer M and Sofner B (1998) - *Groundwater vulnerability mapping in carbonate (karst) areas of Germany*, Federal institute for geosciences and natural resources, Archiv no 117854, Hanover, Germany, 38 pp.

Vrba J, Zaporozec A (1994) - *Guidebook on mapping groundwater vulnerability*, Int Contrib Hydrol 16:131 pp.

Yager, R.R., (1988) - *On Ordered Weighting Averaging aggregation Operators in the Multicriteria Decision Making*, IEEE Transactions on Sys. Man and Cybernateics 18:183-190

Wolf, L., Eiswirth, M., Hotzi, H. (2006) - *Assessing sewer–groundwater interaction at the city scale based on individual sewerdefects and marker species distributions*, Environmental Geology, Vol. 49, No. 6, 2006, pp.849-857.

Wycisc P, Gossel W , Neumann Ch (2009) - *High-resolution 3D spatial modelling of complex geological structures for an environmental risk assessment of abundant mining and industrial megasites*, Computers & Geosciences 35: 165-182.

Zeiler, M., (1999) - *Modeling Our World—The ESRI Guide to Geodatabase Design*, Environmental Systems Research Institute, Redlands, CA 195pp.

Zwahlen, F. (2004) - *COST Action 620. Vulnerability and Risk Mapping for the Protection of carbonate (Karstic) Aquifers*. Final report. Brussel, Luxembourg.

Zhou, C., Lee, C., Li, J., Xu, Z. (2002) - *On the spatial relationship between landslides and causative factors on Lantau Island, Hong Kong*, Geomorphology, 43, 197– 207.

Reports

NRMMC, EPHC, NHMRC, (2009) - *Managed Aquifer Recharge Guidelines*. Australian Guidelines for Water Recycling, Natural Resources Management Ministerial Council, Environment Protection and Heritage Council, and National Health and Medical Research Council. http://www.ephc.gov.au/taxonomy/term/39.

CDPH (California Department of Public Health), (2008). - *Groundwater recharge reuse, draft regulation*.
Website:http://www.cdph.ca.gov/certlic/drinkingwater/Documents/Recharge/DraftRegulations.pdf

UN-Water (2008) - *Status Report on Integrated Water Resources Management and Water Efficiency Plans* for CSD16.

XMML, (2006) - XMML web site: *Solid Earth and Environment GRID, CSIRO*, July 2006, https://www.seegrid.csiro.au/twiki/bin/view/Xmml/WebHome

ESRI, (2004) - *ArcGIS Desktop Developer Guide: ArcGIS 9.1. ESRI*, Redlands, CA, 335pp. Gomes,

Water Framework Directive (WFD), (2003) - O*verall Approach to the Classification of Ecological Status and Ecological Potential*, WFD Common Implementation Strategy, Working Group 2A. Ecological Status (ECOSTAT), pp. 52.

GEOWARN consortium, (2003) - *GEOWARN, Geo-spatial Warning System—Synthesis Report*. Athens (Greece) and Zurich (Switzerland), 57pp. (http://www.geowarn.ethz.ch).

INAG (2001) - *Plano Nacional Da Água*. Lisboa, Instituto da Água – Direcção de Serviços de Recursos Hídricos, Ministério do Ambiente do Ordenamento do Território e do Desenvolvimento Regional,Webpage: http://www.inag.pt/inag2004/port/a_intervencao/planeamento/pna/pna.html

CILE, LGIH, INIEX (1989) - Etude de l'influence des sources de pollution sur l'exploitabilité du potentiel aquifère du synclinal de Comblain-au-Pont - Anthisnes. Study report for the Ministry of Walloon Region [in French]

CILE, LGIH, INIEX (1986) - Etude hydrogéologique du bassin versant du Néblon. Study report for the Ministry of Walloon Region [in French]