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Hydrogeological data modelling in groundwater studies

Thèse de doctorat
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Soutenue devant le jury composé de :

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ABSTRACT

Managing, handling, exchanging and accessing hydrogeological information depend mainly on the applied hydrogeological data models, which differ between institutions and across countries. Growing interest in hydrogeological information diffusion, combined with a need for information availability, require the convergence of hydrogeological data models. Model convergence makes hydrogeological information accessible to multiple institutions, universities, administration, water suppliers, and research organisations, at different levels: from the local level (on-site measurement teams), to national and international institutions dealing with water resources management. Furthermore, because hydrogeological studies are complex, they require a large variety of high-quality hydrogeological data with appropriate metadata in clearly designed and coherent structures.

To respond to the requirement of model convergence, easy information exchange and hydrogeological completeness, new data models have been developed, using two different methodologies. At local-regional level, the HydroCube model has been developed for the Walloon Region in Belgium. This logical data model uses entity-relationship diagrams and it has been implemented in the MS Access environment, further enriched with a fully functional user-interface. The HydroCube model presents an innovative holistic "project-based" approach, which covers a full set of hydrogeological concepts and features, allowing for effective hydrogeological project management. This approach enables to store data about the project localisation, hydrogeological equipment, related observations and measurements. Furthermore, topological relationships facilitate management of spatially associated data. Finally, the model focuses on specialized hydrogeological field experiments, such as pumping tests and tracer tests.

At the international level, a new hydrogeological data model has been developed which guarantees hydrogeological information availability in one standard format in the scope of the FP6 project GABARDINE ("*Groundwater Artificial recharge Based on Alternative sources of wateR: aDvanced INtegrated technologies and management*"). The model has been implemented in the ArcGIS environment, as a Geospatial Database for a decision support system. The GABARDINE Geospatial Database uses advantages of object-oriented modelling

(UML), it follows standards for geoscientific information exchange (ISO/TC211 and OGC), and it is compliant with the recommendations from the European Geospatial Information Working Group.

Finally, these two developed models have been tested with hydrogeological field data on different informatics platforms: from MS Access, through a proprietary ArcGIS environment, to the open source, free Web2GIS on-line application. They have also contributed to the development of the GroundWater Markup Language (GWML) Canadian exchange standard, compliant with Geographic Markup Language (GML). GWML has the potential of becoming an international HydroGeology Markup Language (HgML) standard with a strong and continuous support from the hydrogeological community.

Keywords: hydrogeological information, data modelling, model standardization, entity-relationship, unified modeling language

RESUME

La gestion, la manipulation, l'accès et les échanges de l'information hydrogéologique dépendent principalement des modèles de données hydrogéologiques, qui peuvent varier d'une institution à l'autre et d'un pays à l'autre. L'intérêt croissant porté à la diffusion de l'information hydrogéologique, combiné avec un réel besoin d'accessibilité, requièrent la convergence des modèles de données hydrogéologiques. La convergence de ces modèles rend l'information disponible pour l'ensemble des institutions, universités, administrations, compagnies d'eau et centres de recherche, sur plusieurs niveaux de gestion, allant du niveau local (équipes travaillant sur le terrain), au niveau national et international (institutions gérant les ressources en eau). De plus, la complexité des études hydrogéologiques nécessite une grande variété de données d'une qualité supérieure, organisées dans les structures de données cohérentes et archivées avec soin et donc décrites par leurs métadonnées.

Pour répondre au besoin de convergence des modèles de données, des échanges aisées et de la complétude hydrogéologique des structures, deux modèles de données hydrogéologiques ont été développés, utilisant deux méthodologies différentes. Au niveau local de gestion des données, le modèle HydroCube a été établi pour la Région Wallonne en Belgique. Ce modèle logique de données utilise l'approche entité-association et il a été implémenté dans MS Access. Il est enrichi avec des interfaces utilisateur. Le modèle HydrCube propose une approche innovante « basée-projet », qui couvre la plupart des concepts et entités hydrogéologiques nécessaires, ce qui améliore la gestion des projets hydrogéologiques. Cette approche facilite la gestion des données sur la location du projet, les équipements hydrogéologiques, mesures et observations disponibles ou acquises en cours du projet. Des relations topologiques facilitent la gestion de données spatialement associées. Le modèle couvre également les essais hydrogéologiques spécifiques, comme les tests de pompage et de traçage.

Au niveau international, un nouveau modèle de données hydrogéologiques a été développé. Ce modèle garantit la disponibilité des données hydrogéologique en un seul format dans le cadre du projet européen FP6 GABARDINE ("*Groundwater Artificial recharge Based on Alternative sources of wateR: aDvanced INtegrated technologies and management*"). Il a été implémenté dans l'environnement ArcGIS, sous forme d'une base de données spatiales au cœur d'un système d'aide à la décision. La base de données géospatiale GABARDINE utilise des avantages de la modélisation orienté-objet (UML), elle suit les standards relatifs aux échanges de données géospatiales (ISO/TC211 et OGC), et elle est compatible avec les recommandations du Groupe Européen sur Information Géospatiale.

Finalement, les deux modèles développés et présentés dans le cadre de cette thèse, ont été testés avec des données hydrogéologiques réelles. Ils ont été implémentés sous différents plateformes, allant de MS Access, jusqu'à l'application open-source et gratuite Web2GIS disponible en ligne, en passant par le système propriétaire ArcGIS. Les modèles ont également contribué au développement d'un standard canadien GroundWater Markup Language (GWML) conforme à la norme ISO 19136, Geography Markup Language (GML). GWML a le potentiel nécessaire pour devenir un futur standard international, Hydrogeology Markup Language (HgML), moyennant une contribution continue de la part de la communauté hydrogéologique.

Mots clés : information hydrogéologique, modélisation de données, standardisation de données, entité-association, unified modeling language

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List of publications

- « Geospatial information in hydrogeological studies » for Encyclopedia of Hydrological Sciences, manuscript in preparation
- « Hydrogeological data model: entity-relationship approach », for Ground Water, manuscript in preparation
- « Object-Oriented hydrogeological data model – implementation in the GABARDINE Geospatial Database » for Environmental Modelling & Software, manuscript in preparation

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- Wojda, P., Gogu R., Brouyère S., Rusteberg, B., « GIS-based Data Management and Decision Support System for artificial recharge planning in semi-arid regions », **May 2008**
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- ☐ Presentations
  - GWML and GABARDINE Geospatial Database workshop in the Geological Survey of Canada, **February 2008**
  - GABARDINE Geospatial Database presentation in the TNO, Utrecht, the Netherlands, **May 2007**
  - Base des données spatiales dans la Gestion Intégrée des Ressources en Eau, Ouagadougou, Burkina Faso, **December 2006**
  - New conceptual Entity-Relationship approach in hydrogeological data modelling, University of Bucharest, Romania, **April 2006**
  - HydroCube – base des données hydrogéologiques, series of lectures in the Walloon Region, **January-Februry 2005**
- ☐ Participation
  - Water reclamation and artificial recharge of aquifers workshop, Sabadell, Espagne, **March 2007**
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☐ Aquaterra

- Batlle-Aguilar, J., Wojda, P., Brouyère, S., **2005**. Compilation of data collected and fed into a hydrogeological database in the Walloon Meuse catchment region. Deliverable Basin R.311, Aquaterra -Integrated Project of the 6th EU RTD Framework Programme. Project no. 505428

☐ Walloon Region

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INTRODUCTION

General context

Hydrogeological data and information management is crucial for efficient integrated water resource administration, protection and exploitation. Hydrogeological data are complex because hydrogeological properties and parameters are spatially and temporally distributed. Furthermore, field work and data acquisition being very expensive and time-consuming, data retrieved from hydrogeological field tests and field campaigns should be available for any further research to reduce costs and efforts.

In order to guarantee adequate groundwater management, users and decision makers need a clear structuring of such available information. Hydrogeological data need to be accessed and transferred between different interested actors or organisations for their specific uses and applications. The transfer may be performed from a local level (on-site measurement teams), to national and international institutions dealing with water resource management issues (Figure 1). Local specialists require and create hydrogeological data from surveys. In such context, they need hydrogeological data coming from heterogeneous sources: neighbouring sites, monitoring networks, national databases. At the same time, local specialists are also potential producers of large amounts of data obtained in the scope of their field and laboratory observations and measurements. At a higher level, to manage groundwater resources for local communities in terms of quantity and quality, governmental administrations need hydrogeological information. Governmental administrations must also report on European Union Water Directives implementation to national and international institutions. Finally, the management of groundwater resources is international because groundwater bodies or aquifers usually do not fit with national borders and many transboundary watersheds should be managed by water authorities from different countries. As a consequence, seamless hydrogeological information exchange in a multi-language environment is needed for management and reporting.

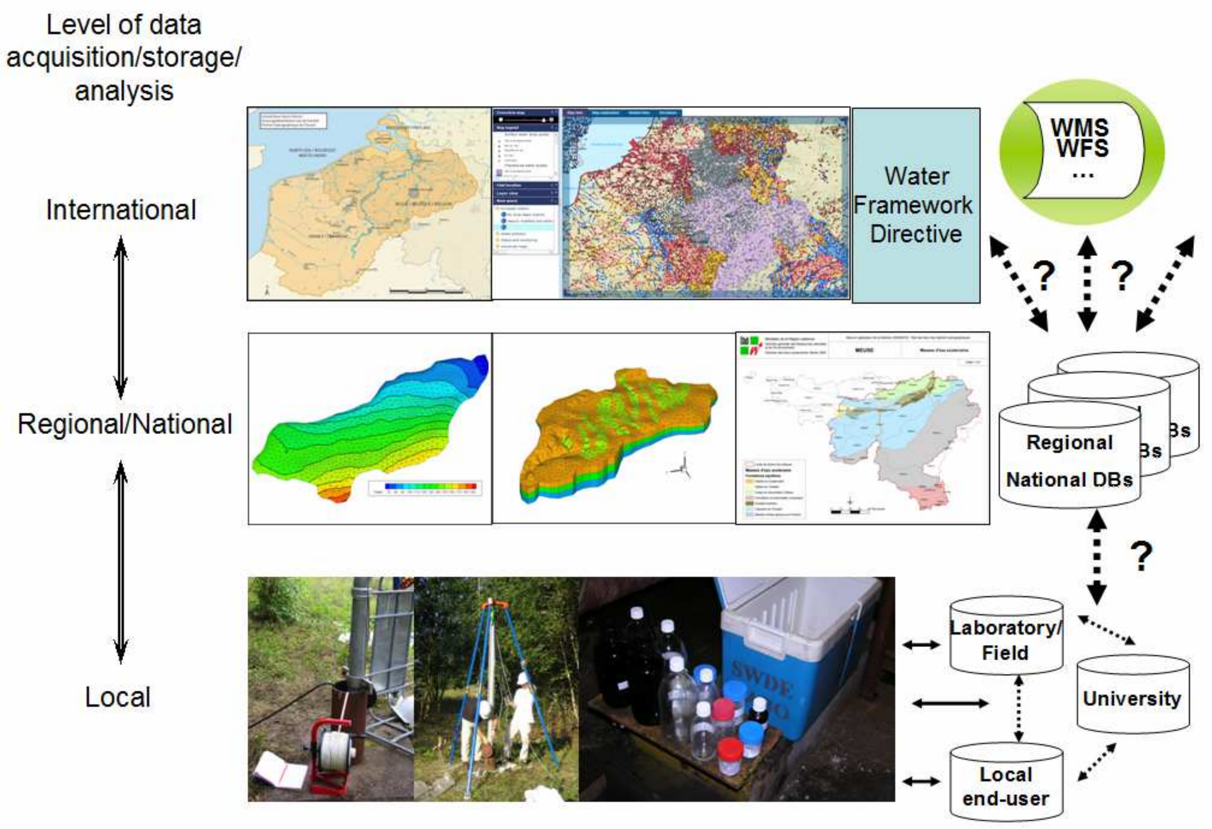


Figure 1. Hydrogeological information required and used at different levels of management, from local to international. As examples, WMS (Web Map Service) and WFS (Web Feature Service) are available services which can deliver geoinformation in a standardized format.

Nowadays, geological and hydrogeological information is increasingly recorded, stored and communicated in digital form. Paper, as a traditional carrier of data and information, in the form of classical hard copy media, reports, geological maps, cross sections or sketches, is less and less used for storage and transfer purposes. It is progressively becoming auxiliary to electronic carriers, the latter being coupled with computers and computer networks (Michalak, 2003a). This trend is accompanied by the growing use of computational methods to carry out geoscientific tasks (Brodaric et al., 2004). Using well-designed geospatial databases coupled with GIS allows for improving the speed and accuracy in data processing. New methods of data processing produce new forms of information, display them differently, changing our perception of the reality. Such a technological breakthrough in other related environmental domains significantly influences the hydrogeological domain.

To meet the requirements of data storage, sharing, and transfer, hydrogeological data modelling has to be performed, mainly at two levels, using specialized methodologies. First, clearly designed hydrogeological data models are needed at local and regional levels. Secondly, commonly accepted international data transfer standards should be developed and used. Data models should also respect wider data modelling principles and standards, from information, through geoinformation and geological information, to, finally, hydrogeological information, which specialises them. Such standards increase hydrogeological information availability and transparency, by ensuring an adequate data organisation and an accurate hydrogeological content documentation by metadata.

Research objectives

The main objective of this research was to develop an innovative hydrogeological data model, based on new appropriate data modelling techniques, and using available tools, in order to contribute to the standardisation of hydrogeological data models on two above-mentioned levels: local-regional and international.

The specific objectives are as follows:

- to characterize hydrogeological information,
- to identify and to implement an appropriate data modelling methodology,
- to identify and to adapt the hydrogeological data model to appropriate ISO/TC211 and OGC standards,
- to validate the developed model through first implementations.

A research in the framework of the Walloon Region HydroCube project

The first period of this research thesis, the standardization at local-national level, was funded by the Ministry of the Walloon Region of Belgium (Direction Générale des Ressources Naturelles et de l'Environnement). The project entitled "Development of the structure and user-interfaces of a hydrogeological database for the Walloon Region" was active from September 1st 2004 to October 30th 2005 with some further short contacts on development and maintenance.

Before the Walloon Region project implementation, first critical needs for hydrogeological data model convergence were identified. Hydrogeological information had to be accessible to multiple institutions, universities, administration, water suppliers, and research organisations. Furthermore, because hydrogeological studies are complex, they require a large variety of high-quality hydrogeological data with appropriate metadata in clearly designed and coherent structures. A need therefore existed to develop and implement hydrogeological data models that cover, as much as possible, the full hydrogeological domain.

To respond to the requirement of model convergence and easy information, a new data model, called HydroCube, presented in Chapter 2, has been developed. This logical data model uses entity-relationship diagrams and it has been implemented in the MS Access environment as the HydroCube database. It has been additionally enriched with a fully functional user-interface. The HydroCube database has now been used for 3 years by universities and administration in Belgium. The HydroCube model presents an innovative holistic "project-based" approach, which covers a full set of hydrogeological concepts and features, allowing for effective hydrogeological project management. This approach enables to store data about the project localisation, hydrogeological equipment, related observations and measurements. Furthermore, topological relationships facilitate management of spatially associated data. Finally, the model focuses on specialized hydrogeological field experiments, such as pumping and tracer tests.

A research in the framework of the GABARDINE project

The second period of this research thesis relates to the standardization at international level. It has been funded by the European Union FP6 STREP GABARDINE project ("*Groundwater Artificial recharge Based on Alternative sources of wateR: aDvanced INtegrated technologies and managEment*"). The project has been active since November 1st 2005 and it will finish on April 30th 2009. The project consortium is formed by 10 partner organisations in 6 EU countries, as well as Palestine and Israel.

The GABARDINE project focuses mainly on groundwater resources as the main source of freshwater in many arid and semi-arid regions, especially in the Mediterranean basin. In dry seasons, overexploitation problems appear, inducing, for instance, seawater intrusion or some biochemical reactions. Alternative sources of water have to be explored and followed up by economical and environmental feasibility studies of their use. The use of aquifers as the primal facility for large scale storage of water coming from these alternative sources should be then investigated along with techniques for artificial recharge and injection of that water, quality and quantity monitoring networks and natural purification and filtration processes.

In order to assure this complex, integrated scarce water resources management, one of the main objectives of the GABARDINE project is to develop a GIS-based Decision Support System. One of the integral parts of the GIS-based DSS is a Geospatial Database containing identified and required information (Figure 2). Furthermore, the DSS should integrate also embedded and external Tools (numerical models, simulation results, and scenarios) and Analysis Tools to provide decision makers with valuable tools in water resource management.

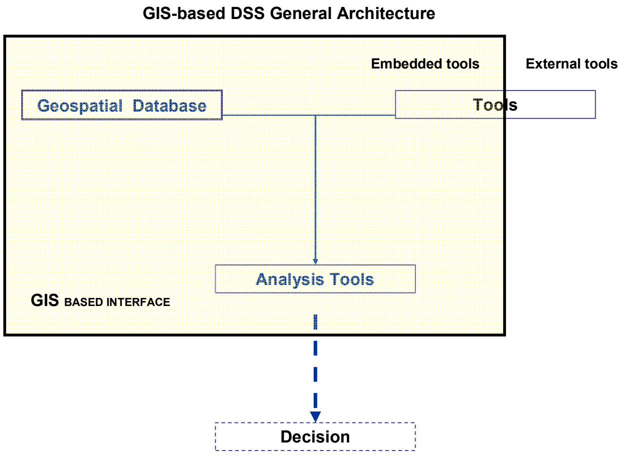


Figure 2. GIS-based Decision Support System general architecture (source: Gogu 2006, GeoHidroConsult).

The GABARDINE Geospatial Database has been conceived according to a "blue-print" in UML describing a hydrogeological data model, based on internationally accepted norms and specifications from ISO/TC211 and OGC, adapted due to the particularities of the ArcGIS desktop implementation platform. This GABARDINE Geospatial Database is described in Chapter 3.

Organization of the document

In the first chapter, a summary is given about the state of the art on hydrogeological data modelling and model implementations. Complexity and diversity of hydrogeological data, their structures and usages are underlined as a major issue. In order to enable easy information exchanges not only between specialists in hydrogeology but also in other domains, it is necessary to unify hydrogeological data models and to make them compatible with wider geospatial infrastructures.

The second chapter proposes a first solution for hydrogeological geospatial data structuring and harmonization: HydroCube, a unique hydrogeological data model developed and used in the Walloon Region of Belgium. The logical data model is described in details and the associated user interface is presented.

The third chapter presents a more advanced and innovative object-oriented hydrogeological data model, developed for the GABARDINE EC FP6 project. The object-oriented model is described by a series of UML diagrams and it follows ISO/TC 211 and OGC international norms and standards on geospatial information.

The fourth chapter describes the implementation and test of the hydrogeological data model with hydrogeological field data in the ArcGIS environment, and then in a free, open-source, web-based platform: Web2GIS. Furthermore, the HydroCube and the GABARDINE models contributions to the development of a Canadian groundwater transfer standard (GWLM: GroundWater Markup Language) are outlined.

Afterwards, general conclusions are presented and further works are proposed.

At the end, the terms and definitions section clarifies used vocabulary and expressions.

CHAPTER 1

GEOSPATIAL INFORMATION IN HYDROGEOLOGICAL STUDIES

1.1 INTRODUCTION

This chapter presents the most recent progresses in the domain of hydrogeological geoinformation storage and transfer. In the first section, the specificities of hydrogeological information are presented together with several definitions from geomatics for the sake of clarity of further explanations. In the second part, traditional and digital techniques of hydrogeological geospatial information storage and visualization are presented and their limitations are identified and described. Examples of several existing hydrogeological projects are summarized. In the third section, new solutions for seamless geospatial hydrogeological data management and transfer are proposed. In this regard, recent and ongoing projects dealing with geological and hydrogeological information modelling are presented. In the conclusions, new directions for hydrogeological system integration within wider environmental systems are outlined.

1.2 THE SPECIFICITY OF HYDROGEOLOGICAL INFORMATION

Hydrogeology, as one of the environmental sciences, is strongly related to other domains such as geography, geology and hydrology (Figure 3). These branches may be considered as mutually dependent, each of them having their own particularities. The interdependence between these domains has to be taken into consideration and clear relations between information from the different fields should be identified and established. In relation with the specific hydrogeological domain, the geographic domain should organise and deliver all the information and concepts on the localisation, spatial extent and topology of any information. The hydrologic domain should organise and deliver all information on the components of the water cycle interacting with groundwater. Finally, the geological domain should organise and deliver information on geological units and structures which contain groundwater. The information content and organisation of the specific hydrogeological domain should not overlap with any of the aforementioned domains. Furthermore, hydrogeological data and processes have their own particularities and they may require a detailed categorization and specialization, with a domain data model to be developed for hydrogeological data storage and transfer. As an example, drilling, wells and piezometers engineering aspects should be treated by one group of domain specialists, groundwater chemistry by another group, and groundwater flow modelling aspects separately by other experts.

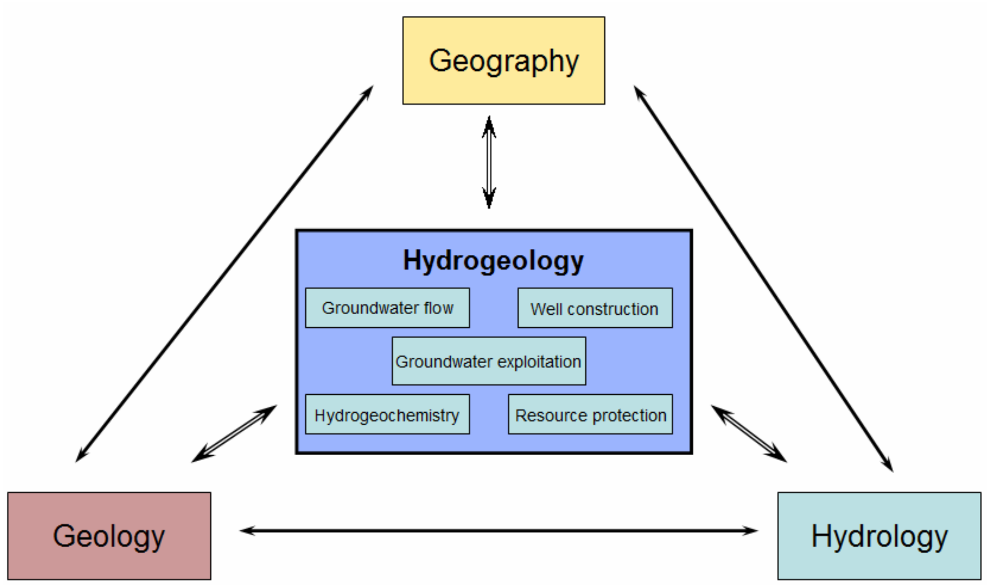


Figure 3. Interactions amongst hydrogeology-related domains: geography for space- and time-dependent problems, geology for porous/fractured media, hydrology for surface water resources. Within the single field of hydrogeology, several particular aspects should also be treated simultaneously and in conjunction with each other.

From a technical point of view, geospatial information can be subdivided into two main categories: generic and specific (Michalak, 2003a). Generic type of information is defined as common to many domains. For instance, geological and hydrogeological maps are elaborated on the same basis as other maps. Most of generic geospatial information coordinates are based on two-dimensional Cartesian (*x,y*) or any other reference systems. Rules concerning geometry and topology are the same, but the difference is in the semantic aspect and content of information. For generic information, the re-use of already established standards, communication protocols, and processing rules is very convenient and ensures a rapid development of new concepts and software applications. Hydrogeological information often requires a three-dimensional reference system (*x,y,z*) or a specific combination of dimensions in 2D, for instance to describe boreholes or well depths series or hydrogeological cross sections.

In addition, since many hydrogeological properties are time-dependent, time reference and time topology issues have to be considered explicitly (*x,y,z,t*). Classical time-dependent hydrogeological variables and properties are, for instance, piezometric levels, solute concentrations or pumping rates. The issue of time scale and time topology is standardized in

ISO 19109 – Geographic information – Temporal Schema (ISO, 2002) and discussed in details in Michalak (2005) for geological purposes.

As compared to other related domains, one of the main characteristics of hydrogeological data is their potential variability in time and space. There are also very specific types of hydrogeological information, such as (adapted and extended from Michalak, 2003b):

- the definition and the spatial extent of specific hydrogeological features such as aquifer/aquitard/aquiclude formations and groundwater bodies, specializing geological features;
- specific physico-chemical parameters describing the underground, such as hydraulic conductivity, effective porosity, geochemical composition of groundwater, all these parameters being spatially distributed and variable in time;
- hydrogeological cross-sections where geological units are described in terms of hydrogeological properties, together with interpreted groundwater levels;
- data describing the equipment of wells and piezometers, such as casings, screens, pumps, gravel packs, sealings;
- specific hydrogeological observations and measurements, namely piezometric and groundwater chemistry measurements, recharge/discharge rates, base flow;
- descriptions and interpretations of hydrogeological field experiments such as pumping tests and tracer tests.

1.3 FROM PAPER TO DIGITAL STORAGE

Paper-based storage is still widely used as hydrogeological information carriers, as non-graphical forms such as texts, tables and forms and graphical forms such as images, maps, and cross-sections. However, corrections or updates are very difficult to implement, and they generally require the creation of completely new documents. The visualization of hydrogeological observations and measurements is also limited. Finally, since hydrogeological data are usually numerous, processing of their paper form is very time-consuming and effort-demanding.

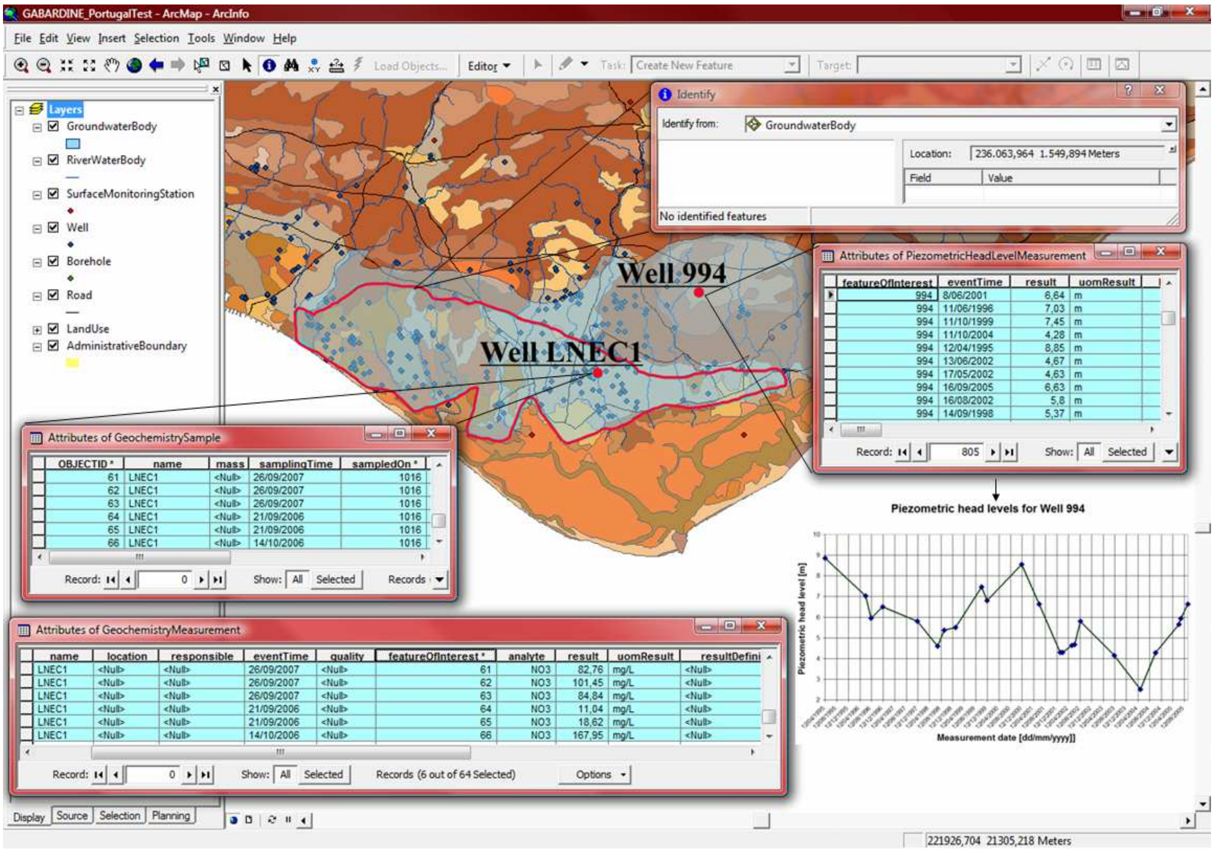
1.3.1 GEOGRAPHIC INFORMATION SYSTEMS IN HYDROGEOLOGY

Recent requirements for real-time data delivery and analysis combined with automatic data transfer between interested parties, monitoring networks and remote sensors have entailed the evolution from paper to electronic carriers. Furthermore, due to the importance of hydrogeological information in water resource management, its considerable amount and financial values, the hydrogeological community needs a flexible and structured way of digital data and information storage. Such tasks as data structuring and management are more and more embedded in Geographic Information Systems (GIS), which deliver information for decision makers and specialists in environmental domains dealing with spatial and temporal information.

GIS include different components, such as data, hardware, software, procedures, operators and analytical problem statements (Meeks and Dasgupta 2004). At first, GIS were used rather to create paper maps to analyse and display geospatial data. The map content, once introduced into a computer system, was designed to correspond with its paper image. Rapidly, a very useful discovery was made that the content remaining in the system is sometimes much more valuable then the paper representation itself. Digital records of information combined with GIS have offered the possibility to derive new information, more suitable and specific for a given problem further data processing, updates, or data transformations into other formats. GIS offer the user the opportunity to capture and to collect geospatial and non-geospatial data, where data sources can be numerous such as scanned paper maps, aerial photographs, remote sensors, field observations and measurements. Moreover, data stored in GIS do not require to be cut into separate sheets linked to scales, map projects and graphical representations, only the reference system is mandatory. Hydrogeological information can be grouped in layers, dynamically processed at a chosen scale, and displayed using a desired format by superposition with other thematic layers.

There are two classical ways of storing and representing geoinformation in a digital form: vector and raster formats. Hydrogeological information being difficult and expensive to obtain, the hydrogeological continuous environment can only be sampled on the point-type basis using available drillings, piezometers, wells or other monitoring stations, or on a line-type basis, using geophysical tests. The location of such point- (e.g. well or piezometer), line- (e.g. water gallery or excavation) and polygon- (e.g. aquifer or groundwater body extent) type features is stored in a vector format. On the contrary, results of observations and measurements may be represented in the form of a discrete coverage, for instance a raster, or they may be spatially interpreted (interpolated or extrapolated) in order to create a continuous coverage, where the property varies continuously across the domain.

These general observations are particularly valid in the field of hydrogeology, where natural hydrogeological units do not necessarily fit with administrative borders, or where natural water resources should be managed and protected using integrated, multidisciplinary approaches. GIS have significantly influenced hydrogeological field researches, laboratory activities, and observation methods. Using a structured geospatial database under GIS, any potential user is now able to easily access different hydrogeological data by selecting hydrogeological features by attributes or spatial queries. For instance, groundwater samples and groundwater quality measurements for selected wells can be accessed in order to establish a groundwater body quality status within the selected aquifer. Furthermore, piezometric measurements can be accessed and updated (Figure 4).



Identify

Identify from: GroundwaterBody

Location: 236.063,964 1.549,894 Meters

Field	Value

No identified features

Attributes of GeochemistrySample

OBJECTID *	name	mass	samplingTime	sampledOn *
61	LNEC1	<Null>	26/09/2007	1016
62	LNEC1	<Null>	26/09/2007	1016
63	LNEC1	<Null>	26/09/2007	1016
64	LNEC1	<Null>	21/09/2006	1016
65	LNEC1	<Null>	21/09/2006	1016
66	LNEC1	<Null>	14/10/2006	1016

Record: 0 Show: All Selected Records

Attributes of PiezometricHeadLevelMeasurement

featureOfInterest	eventTime	result	uomResult
994	8/06/2001	6,64	m
994	11/06/1996	7,03	m
994	11/10/1999	7,45	m
994	11/10/2004	4,28	m
994	12/04/1995	8,85	m
994	13/06/2002	4,67	m
994	17/05/2002	4,63	m
994	16/09/2005	6,63	m
994	16/08/2002	5,8	m
994	14/09/1998	5,37	m

Record: 805 Show: All Selected

Attributes of GeochemistryMeasurement

name	location	responsible	eventTime	quality	featureOfInterest *	analyte	result	uomResult	resultDefini
LNEC1	<Null>	<Null>	26/09/2007	<Null>	61	NO3	82,76	mg/L	<Null>
LNEC1	<Null>	<Null>	26/09/2007	<Null>	62	NO3	101,45	mg/L	<Null>
LNEC1	<Null>	<Null>	26/09/2007	<Null>	63	NO3	84,84	mg/L	<Null>
LNEC1	<Null>	<Null>	21/09/2006	<Null>	64	NO3	11,04	mg/L	<Null>
LNEC1	<Null>	<Null>	21/09/2006	<Null>	65	NO3	18,62	mg/L	<Null>
LNEC1	<Null>	<Null>	14/10/2006	<Null>	66	NO3	167,95	mg/L	<Null>

Record: 0 Show: All Selected Records (6 out of 64 Selected) Options

Figure 4. Example of the use of the GABARDINE Geospatial Database. On the left-hand side: for each groundwater sample ("Attributes of GeochemistrySamples" window) taken from the "LNEC1" well, nitrate analyses are reported ("Attribute of GeochemistryMeasurements" window). On the right-hand side: piezometric head level measurements are reported for the well "994". Observations and measurements can be exported to another software for further processing.

Hydrogeological studies require also numerous GIS tools when overlaying layers of information, from general geographical information, through hydrological and geological information to specific hydrogeological information. For instance, for groundwater vulnerability mapping or pollution risk mapping much information needs to be analysed. A geology map needs to be combined with topography information, soil-type and land-use maps. Moreover, a hydrological map and water table depths are overlaid and analyzed in the context of possible contaminant flow lines, advection and dispersion. In order to apply appropriate aquifer protection or decontamination measures, available water intakes localisation and exploitation schemes need to be known.

1.3.2 PROCESSING OF HYDROGEOLOGICAL INFORMATION

In order to conduct hydrogeological studies including water budgets, groundwater flow and contaminant transport modelling, or groundwater exploitation schemes, substantial amounts of data and information are required and, most often, automatically processed. Information processing is seen as an implementation of different algorithms in order to derive new information better suited for different uses (Michalak, 2003a). Processing of information stored in the paper form is never automatic, thus very time-consuming. For instance, a paper hydrogeological map, or a raster image as presented in Figure 4 is neither changeable nor interactive. Any further processing of presented piezometric values or hydrogechemistry measurements would be manual, which may add errors when copied elsewhere.

1.4 DIVERSITY OF HYDROGEOLOGICAL DATA MODELS

Almost every administration, municipality, water and environmental authority, and research organization have developed their own hydrogeological data models, implemented in different database management systems (Rodríguez *et al.*, 2007). The collection of hydrogeological data, their verification, data validating, and the construction of the databases and data services are regulated in almost every European country (Szalkai et al., 2007). Hydrogeological data are managed using both non-spatial and spatial systems, which are due to the wide thematic range and diverse types of requirements.

A detailed survey on groundwater databases and related information has recently been performed by the FP6 EC eWater project (www.ewater.eu). This survey proposes a classification of the following hydrogeological data types: well, water exploitation, monitoring - time series, maps, and related metadatabases. Hydrogeological data are collected at local, regional and national levels. Local municipalities, as well as local offices, are the most active data collectors in the following countries: Italy, France, Denmark, Holland and Hungary. Some of these data are directly loaded to the national databases in Denmark and France. Otherwise, local institutions have to supply these data to the regional/national data collection authorities. At the regional level, data collection is performed by provincial and regional authorities, regional water management organizations, water management agencies of river basin authorities and regional offices of research institutes. The concerned countries are: Italy, Hungary, Spain, and Holland – directly to the national database. On the contrary, in Slovenia, France, the Slovak Republic, the Czech Republic, Denmark and Sweden, data are not collected at the regional level. At the national level, each country performs such data collection, except from Austria. This is the responsibility of geological surveys in Lithuania, the Slovak Republic, the Czech Republic, Denmark, Sweden, France and Holland. In Slovenia and Hungary the situation is slightly different – two institutions manage the databases. At the national level, most of the organizations are responsible for making hydrogeological data available to the public. In several countries data are completely free, or the users can be charged for the service itself. Furthermore, there exists a big diversity of informatics systems, for GIS: from ArcGIS, through AutoDeskMap and MapInfo Professionnal, to GeoMedia Professional, and for DBMS: from MS Access, through SQL Server to Oracle. More detailed information and hydrogeological databases review for each concerned European country can be found in the on-line deliverables of the FP6 EC eWater project.

The diversity of standards and data schemas leads to difficulties in communication and data exchanges, which is particularly critical in the context of transboundary groundwater body management and information sharing. Different water agencies use different data formats. This situation makes it more complex to automatically exchange data coming from multiple sources or to communicate results of any hydrogeological study. Furthermore, hydrogeological data being widely used in other environmental domains and multidisciplinary studies, they are not easily available when they are dispersed in many formats and in many places. First, potential users are not even conscious about their existence due to the lack of any centralized hydrogeological data or metadata catalogue. Secondly, it is often difficult to access hydrogeological data because owners of hydrogeological information are hardly known. Data access privileges are not clearly exposed to users, or finally the proprietary data format is simply unknown or requires additional software licences. Last but not least, the lack of internationally accepted hydrogeological data storage and transfer standard makes it difficult to use open web standardized services, such as WMS, WFS, and WCS. As a consequence, many existing powerful tools for data management, visualisation or analysis, based on these services capabilities, can not be applied.

Several interesting projects, taken as typical examples of the existing hydrogeological data modelling are compiled in Table 1. Based on the analysis of the existing models, the following conclusions can be drawn. Despite the most common elements such as the technical description of the well and associated observation and measurements on piezometry and groundwater quantity and quality, it appears clearly from the review of existing data models that most of them were developed for relatively specific applications and according to different requirements. The identified models are described using different modelling designs and notations, and only a few of them use modern technologies or follow standards such as ISO 19136, described by GML for geographic data. At the ontological level, models propose different hydrogeological feature types and relationships. At the semantic level, the definitions and meanings of hydrogeological feature types are not common to all the models, leading to difficulties in further data understanding and interpretations. As a consequence, there is no existing most complete data model for the hydrogeological domain. Such a model should enable to deal with **a hydrogeological project** as a whole. First, data about the project localisation, performed hydrogeological studies, people in charge of different project aspects should be available. Second, information about groundwater natural and man-made features such as springs, sink-holes, trenches or wells, should be accessible. Furthermore, observations and measurements performed during hydrogeological field work and experiments such as pumping and tracer tests should be easily identifiable and obtainable.

Projet/Model Name	**References**	**Description**	**Original Input**
Underground injection well database	Hamerlinck, Wrazien, Needham, 1993	A GIS-based underground injection well database has been developed for the State of Wyoming. The main objective of the project was to determine geographic locations for 6700 injection wells to help in assessing their potential as point sources of groundwater contamination. The structure of this GIS database is based on Arc/INFO georelational vector data structure. For spatial data, represented by point, line and polygon geometries, an arc-node structure is prepared, while attribute data, describing spatial features are stored in a relational database. Project link: http://library.wrds.uwyo.edu/wrp/93-08/93-08.html	GIS-based database structure, suiting for vulnerability assessment
The Australian National Groundwater Data Transfer Standard	NGC Groundwater Data Standards Working Group in the National Groundwater Committee, 1999	This standardized hydrogeological data model was developed in Australia in order to unify different existing data models. The diversity in which groundwater data were stored and transferred was unnecessarily complicating natural groundwater resource management. The new hydrogeological model reduces the time required to reformat data, boosting significantly their productivity. It helps to overcome trans-boundary groundwater problems. Misinterpretations by users are reduced, together with confusion reading and displaying hydrogeological data. Project link: http://www.brs.gov.au/land&water/groundwater	Standard Groundwater Data Transfer Model at the level of the whole country
A geographic data model for groundwater systems	Maidment, 2002; Strassberg, 2005; Bernard, et al., 2005	The primary objective was to design a groundwater data model for describing, storing, visualizing, analyzing and communicating groundwater geospatial information at regional and local scales, combining surface and groundwater information. It takes advantage of the already developed ArcHydro surface water data model (Maidment, 2002). The model incorporates four major components, namely: "hydrogeological" features represented by points, lines polygons and multi-patches elements; "modelling" entity representing common modelling objects such as cells and elements; "surfaces" represented by rasters and TINs, used to define elevation or spatially distributed aquifer parameters; "times series" used to represent time dependent information. This data model has been extended by the Groundwater-AEM data model (Bernard et al., 2005) in order to allow using MLAEM (Multi-Layer Analytic Element Model) for groundwater flow numerical modelling. Project link: http://www.crwr.utexas.edu/gis/gishydro05/ArcHydroGroundwater/ArcHydroGroundwaterESRIUC2005.htm	Compatibility of the model with the widely applied ArcHydro model. Possibility of groundwater flow modelling using directly the implemented data model
A relational database for the monitoring and analyses of watershed hydrologic functions	Carleton et al., 2005	The Watershed Monitoring and Analysis Database is a relational application developed to manage hydrologic datasets. It stores and allows for manipulation of stream flow, water quality, and meteorological data. It has additional tools to assure quality of data and analyses, to correct conversion factors or finally to retrieve required data for analyses. The Database supports web integration and Local Area Network work, depending on the implementation platform. The on-line synchronisation can be performed. Project link: http://cat.inist.fr/?aModele=afficheN&cpsidt=16659730	Optimized storage requirements and retrieval rates, easy web integration, data replication within LAN

Projet/Model Name	**References**	**Description**	**Original Input**
A generic database for the application of hydrological and water resource models	Hughes, Forsyth, 2006	The SPATSIM (SPatial and Time Series Information Modeling) system has been developed using MapObjects. It incorporates a spatial data interface for access to the different types of information used in water resources analyses. All the information is stored within database tables with generic structures. The database where spatial elements (point, line and polygon types) are stored as shapefiles in the Paradox format has four dictionaries, which allows for easy data manipulation and errors limitation. It allows for storage and access of the information typically associated with water resource studies. The SPATSIM system contains several tools for the data exchange to facilitate movements of attribute data between different users. Project link: http://portal.acm.org/citation.cfm?id=1296607	Access to data for hydrological and water resource simulations models
HydroCube database	Wojda et al., 2007 manuscript in preparation	The HydroCube database has been developed and implemented in the Walloon region of Belgium (Wojda et al., 2007 C&G). It is partially based on HYGES database model developed previously by Gogu *et al.* (2001) in order to manage hydrogeological data, particularly in the scope of groundwater vulnerability assessment and modelling. The HydroCube database is based on a new formalized logical model of hydrogeological data, described by entity-relationship diagrams, and enriched with fully functional user interfaces. It enables to deal with a hydrogeological project as a whole, by managing the data about the project localisation, available hydrogeological studies, and contact people. Furthermore, necessary groundwater features, monitoring results, performed field tests descriptions and interpreted results can be stored. Project link: http://www.argenco.ulg.ac.be/GEO3_Hydrogeologie/banquedonnees_fr.html	Completeness of hydrogeological data model, including a model for specialised hydrogeological field experiments such as pumping tests and tracer tests
The basin of Mexico Hydrogeological Database	Carrera-Hernández and Gaskin, 2008	To manage efficiently regional water resources at the basin level, the use of both Relational Database Management System and a Geographic Information System is proposed. The Basin of Mexico Hydrogeological Database comprises data on climatological, borehole and run-off variables, providing information for the development of hydrogeological models. It allows also for geostatistical analyses using data directly from BMHDB. Hydrogeological data can be accessed and processed locally or remotely through open source software: postgreSQL, R and GIS GRASS packages. Project link: http://portal.acm.org/citation.cfm?id=1379720	Use of open source products, data gathering from different sources, Easiness of geostatistical analysis

Table 1. Examples of the data models that differ in their design and notation. They were developed to respond to particular needs, specific application and functionality

1.5 TOWARDS SEAMLESS HYDROGEOLOGICAL INFORMATION EXCHANGE

In nowadays information society, where multidisciplinary, multi-user and multi-language environments exist, hydrogeological information should be transferred seamlessly and rapidly, using machine-based protocols in order to avoid unnecessary efforts on data transformation, adjustment and interpretation. Due to the problems identified in the previous section, such as availability, accessibility, and exchange of hydrogeological information caused mostly by the hydrogeological data model diversity and interactions with other domains, the hydrogeological community needs to establish one public information exchange standard. Without any standardization of hydrogeological data and other types of data transfer, it is very expensive and difficult to exchange data between different producers and users in an efficient way. A first solution could be to store hydrogeological data, together with data coming from other domains in a central database (Figure 5). However, such central databases are never up-to-date, they are very expensive to maintain, and poorly enriched with additional tools, which limit their practical use by domain specialist.

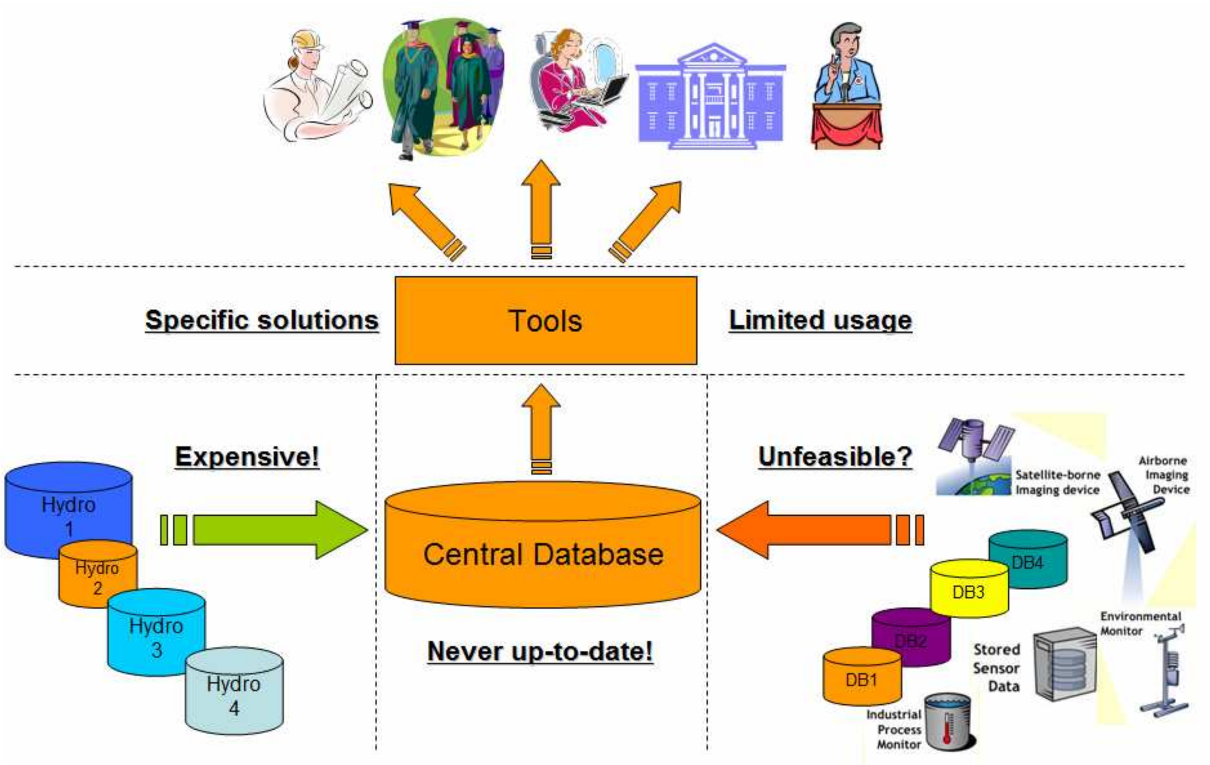


Figure 5. Without any standardization of hydrogeological data and other types of data, it is expensive and difficult to exchange data in an efficient way. A central database solution could be helpful; however it is never up-to-date, expensive to maintain, and poorly enriched with specific tools, which limit its usage for potential users (image source: WRON Australia, adapted).

The alternative to centralisation of information is to develop standards for data exchanges between systems. Standardisation can be considered mainly at two levels. At the local level, the same data model can be used. At the higher information exchange level, communication interfaces and exchange formats can be standardized. As it is difficult or even impossible to achieve an agreement of all the users on the local data storage model, a standard for hydrogeological information exchange should be established and the use of web services should be promoted (Figure 6). A Web Service is defined as a software system designed to support automatic and interoperable machine-to-machine interaction over a network, using XML. For the transfer of geoinformation, XML is specialized to GML-compatible application schemas.

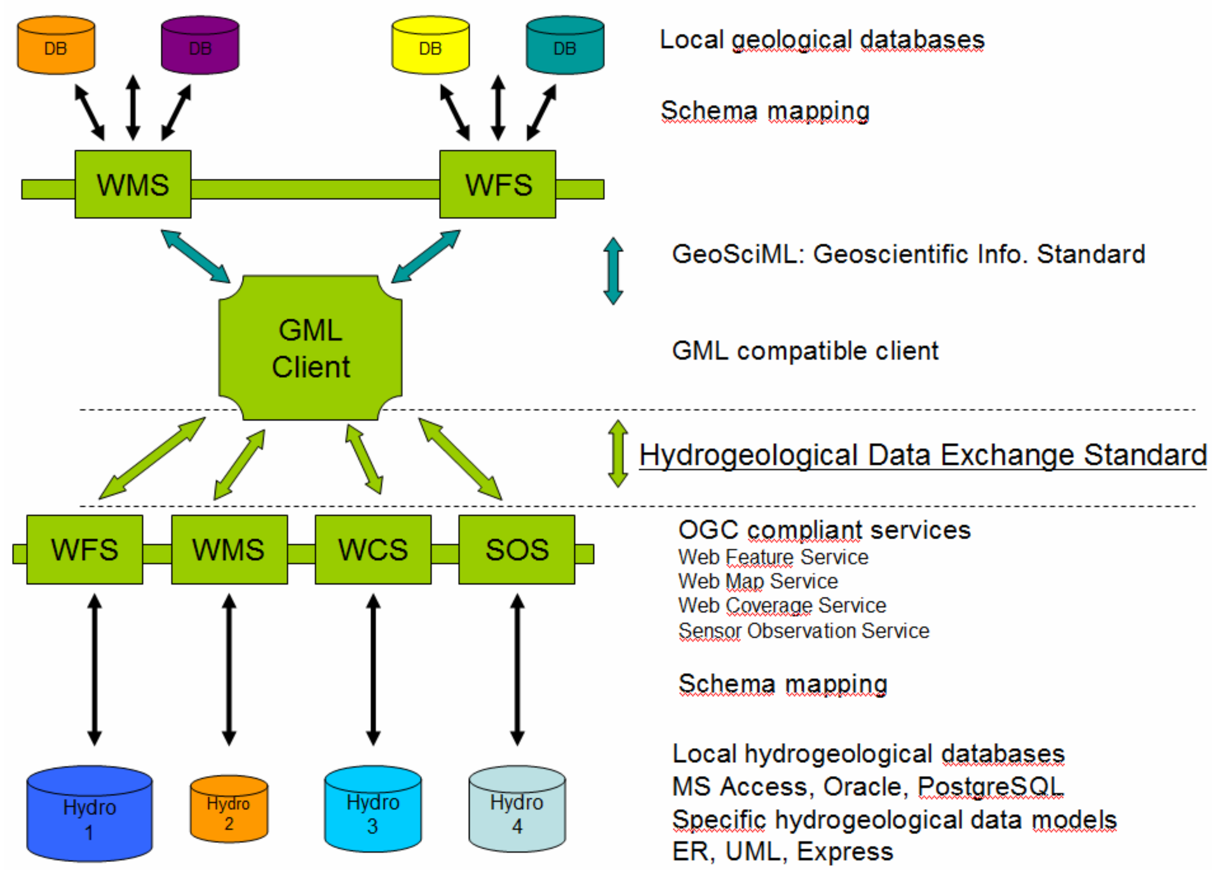


Figure 6. Hydrogeological databases with their specific data models may be mapped to standard web services, such as Web Map Service or Web Feature Service. Hydrogeological information will be then delivered to a GML-compatible client, using a standardized hydrogeological data format. The GML-compatible client is also able to read information from other sources, using other GML application schemas from various domains: geology, hydrology, geography, biology, economics…

Using the option of standardization of data exchange protocols, each user or group of users can establish or keep their own hydrogeological data model at the local level. The model may be implemented in any database management system, specific to the identified needs and applications. In order to exchange hydrogeological information, particular data models should be mapped to fit standardized web services and a future hydrogeological information exchange model. The schema mapping between local and standard data models can easily be developed by geoinformation specialists. Once this work is accomplished, data exchanges may be performed by standardized OGC web services in both ways: (1) local hydrogeological data can be made available for other users and domains with GML-compatible clients, respecting access restrictions, (2) local users can easily access other necessary hydrogeological and non-hydrogeological data and they add them to their databases, analyses and interpretations.

As a practical example, the following "case-study" can be given. A hydrogeologist needs to perform an advanced environmental analysis in order to establish a groundwater resources exploitation scheme. In the proposed solution, specialized GML-compatible tools can be used, and needed data are delivered by different web services, using the hydrogeological data exchange standard. A Web Feature Service delivers a detailed description of monitoring wells and piezometers, together with associated observations and measurements. A Web Map Service delivers geo-referenced neighbouring maps on which the above mentioned hydrogeological features can be drawn. Additionally, a Web Coverage Service delivers a coverage with spatially distributed transmissivity and hydraulic conductivity values for the studied aquifer. To adjust the analysis, a Sensor Observation Service might deliver the latest data on piezometric head levels retrieved by automatic sensors. In order to finalize the investigations, climatic, land-use and topography data can be provided by other services coupled with thematic distributed databases.

In order to achieve such an easy hydrogeological information exchange, several measures have to be taken:

- a data exchange standard covering the whole hydrogeological domain has to be developed by the hydrogeological community,
- existing geoinformation and technical standards should be used at different levels,
- concepts' overlapping with other related domains have to be avoided,
- the most recent techniques, methodologies and solutions from informatics should be applied at the development, implementation and maintenance levels.

A standard is a normative document, a technical or programmatic solution developed according to consensus procedures, which has been approved by normalization institutions or accepted informally due to a very wide use (Płoski, 1999; ISO: http://www.iso.org/iso/standards_development). As the hydrogeologic domain presents its own specificities, the domain specialists have to participate in the development process. Furthermore, to ensure a very extensive use of such an exchange standard, the latter have to cover the widest possible range of hydrogeological concepts, definitions, uses and implementations.

As far as geoinformation standards are concerned, hydrogeological data should be stored using standard protocols, data formats, and clearly organized data models. The data organization must be explicit, described using standard notations such as Entity-Relationship diagrams or Unified Modelling Language methodology, which allows for mapping between models and specialized web services.

As geomatics concepts and solutions evolve rapidly, only the newest methodologies should be used to create local, particular models, to establish hydrogeological data exchange standard and to map models. This implies the use of standardized notations and object-oriented principles at development, implementation and maintenance stages.

In the next section, several necessary geomatics concepts are briefly summarized to make further understanding easier. More details can be found in Terms and definitions Section at the end of this document. The most important data modelling principles are presented. Furthermore, advantages of object-oriented modelling in the hydrogeological domain are highlighted. Then, several hydrogeological projects allowing seamless information exchanges are described.

1.5.1 HYDROGEOLOGICAL DATA MODELLING

1.5.1.1 FROM MENTAL MODEL TO PHYSICAL DATA MODEL

Management, handling, and access to hydrogeological information depend mainly on four main categories of models, namely: mental, conceptual and more formalized logical models, leading finally to physical models of hydrogeological data (Figure 7). In the following section this formalism, used as a traditional and rigorous way of developing a model in geomatics, is described for the specific case of hydrogeological data modelling.

The mental model contains definitions, descriptions, and understanding of concepts and physical laws governing groundwater, flow and transport processes.

The conceptual model contains identified and defined existing hydrogeological entities and objects as well as relationships between them, for instance: a well occurrence is used to sample a groundwater body, which is hosted by an aquifer. The same well is also used to exploit the aquifer, exploitation of which requires additional quantity and quality observations and measurements. In consequence, in the conceptual model some entities have to be defined, for instance: Well, Groundwater Body, Aquifer, Geochemistry Measurement, Piezometric Head Level Measurements, Groundwater Extraction Volume, together with different relationships amongst these entities. As data are specific to the hydrogeological domain, this issue must be addressed directly by domain specialists, familiar with the geoinformation context. The conceptual model can be described using a semi-formal (free charts) or formalized (with defined semantics) notations, such as Entity-Relationship (ER), Unified Modeling Language (UML), or EXPRESS, but it does not depend on the technology nor change with different logical and physical implementations.

Based on the conceptual model, the logical model describes the structure of hydrogeological data. Using object-oriented modelling, such a model presents definitions of each hydrogeological entity with all its attributes, operations, methods and behaviours. All the identified relationships should be drawn. These are for instance the associations of aquifer sampling features with samples and observations made on these samples, or relationships between different steps of hydrogeological specialized field tests, such as pumping or tracer tests. Contrarily to the conceptual model, the logical model is technology dependent (e.g. ER or UML), but it does not depend on the implementation platform.

Finally, the physical model is no longer specific to hydrogeology, it is only dependent on the implementation platform.

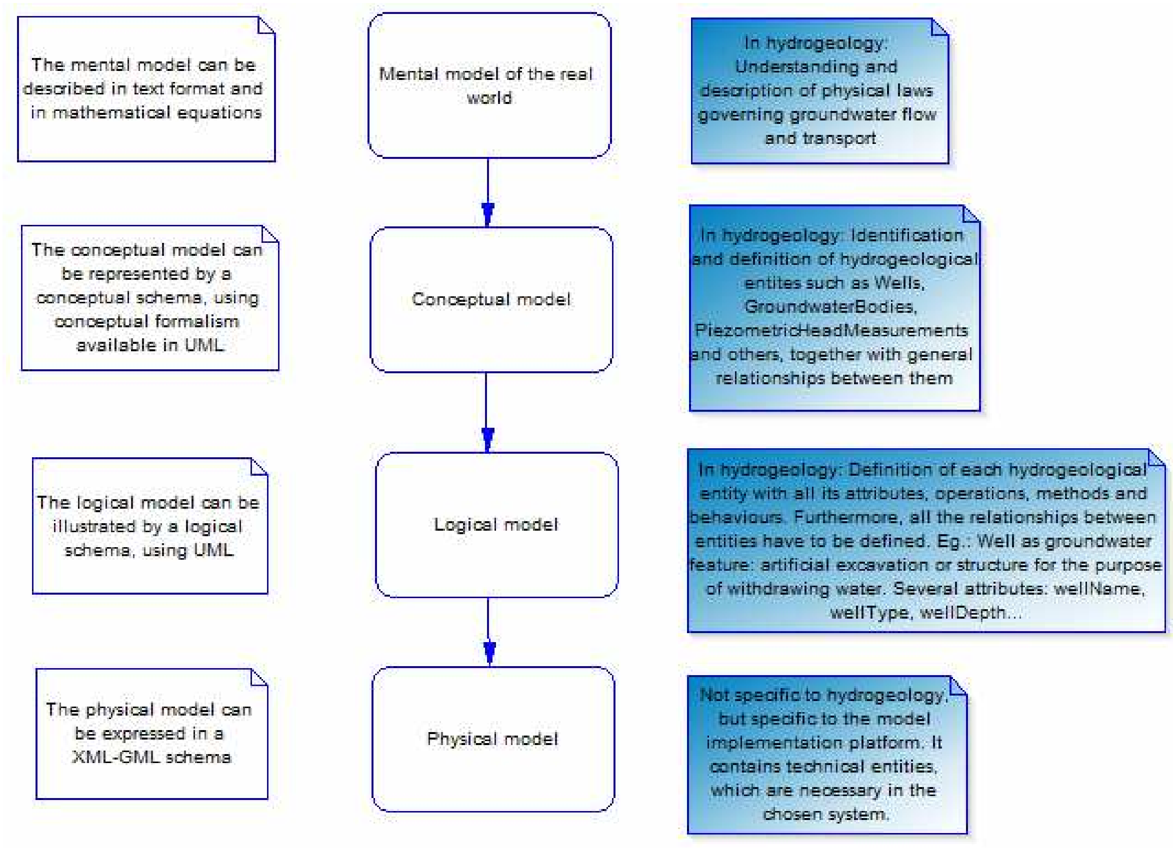


Figure 7. Different steps of data modelling with examples particular to the hydrogeological domain. A hydrogeologist has a mental model of the hydrogeological domain. In order to structure hydrogeological knowledge, a conceptual model has to be defined which consists in identifying hydrogeological entities and relationships amongst them. This can be formalized and detailed using logical models. Finally, the platform-dependent implementation process requires a physical model.

1.5.1.2 OBJECT-ORIENTED MODELLING AND UML

In the hydro-informatics domain, object-oriented methodology may be seen as a new solution for reducing the complexity of data models and software development (Subieta, 1998). To decrease complexity and convolution in any development process, one has to use decomposition and abstraction methods. Decomposition is used to divide any problem into more elementary sub-problems that can be treated individually. Abstraction enables to eliminate or to hide less important parts of the problem within a given context and at a given level of analysis. Furthermore, object-oriented models serve to match conceptual models and physical models with natural behaviour of human beings and their perception of reality.

Several fundamental object-oriented concepts are objects, classes, inheritance, abstraction and polymorphism. The geospatial object represents an instance of a class, which is based on the object-oriented paradigm, coming from UML (OMG, 2001, 01-09-67). The class is a descriptor of a set of objects that share the same attributes, operations, methods, relationships, and behaviour (ISO 19107). For instance, it can be a "Well" class, where one can find different attributes common to all the wells: name, geometry, localisation, owner and responsible party for exploitation, etc. The geospatial object is, for example one particular, identifiable well, located in the field, and called "well_1" as an instance of the "Well" class. Inheritance (generalization-specialization relationship), one of the most important object-oriented paradigms specifies that each super-class in the inheritance relationship delegates all its attributes, methods, and constraints to a child-class. Abstraction allows for simplifications by modelling and showing classes appropriate to the considered problem. The analyst can work at the most appropriate level of inheritance for a given aspect. Finally, polymorphism is a characteristic of being able to assign different meaning or usage to an object in different contexts, to have more than one form (ISO/TDS 19139). More exhaustive theoretical considerations, together with technical definitions of object-oriented concepts, with applications in the fields of geology and hydrogeology, can be found in Michalak and Leśniak (2003), Michalak (2003a and 2003b), Booch *et al.* (2002), Larman (2001), Carlson (2001), Graham (2001), Page-Jones (1999), Subieta (1999 and 1998).

A formalised language or notation must be used in order to develop object-oriented conceptual models of hydrogeological information and then to describe their structure from different points of view and at different stages of development, from requirements to implementation. Currently, the UML (Unified Modeling Language) notation is used in many different fields from the description of business processes to environmental issues such as hydrology or hydrogeology (Muller, 2000; Quatrani, 2002). As conceptual modelling in geomatics does not require all methodologies and possibilities of the UML notation, a narrower geomatics profile has been established, consisting in technical specifications accepted by ISO/TC211, and described in ISO 19103 (2001), with some additional information in ISO 19109, 19118, 19136 (XMML, 2006). Provided that these norms are followed, existing search, analysis and visualisation tools can be reused. Geographic objects encoded following ISO/TC211 and OGC are easily exchangeable for different users, no matter which proprietary or open source software is used.

UML developers wanted to address different scales of architectural complexity and different possible domains of application. Some of the fundamental advantages of using UML, as a standard conceptual schema language for hydrogeological data modelling, are that:

- both informaticians and hydrogeologists can understand the essence of the data model and its implementation (Vogt, 2002);
- it is possible to follow normative documents of the ISO 19100 series, together with standards issued by OGC, which require the use of the UML notation and provides methodologies for application schema development;
- the standards developed for other domains such as geography, hydrology, or geology can be extended or specialized to meet the needs of the hydrogeological domain, under the conditions that standards overlapping is avoided (Figure 3);
- previously developed and standardized tools for spatial data queries, data analysis, or data transfer can be reused, with no additional documentation;
- interoperable hydrogeological data exchanges between project actors will be possible using different web services for data search and delivery.

1.5.2 STANDARDS IN GEOSPATIAL INFORMATION

1.5.2.1 STANDARDIZATION INSTITUTIONS

In 1994, two independent and international standardization organisations were established, to bridge the gap in geoinformation standards: the Open GIS Consortium in USA (renamed to Open Geospatial Consortium in 2004), and the ISO Technical Committee 211 in Norway (Ostensen, 1995). The Open Geospatial Consortium, Inc (OGC) is an international industry consortium of 350 companies, government agencies and universities participating in a consensus process to develop publicly available interface specifications (OGC: http://www.opengeospatial.org/ogc). OpenGIS Specifications support interoperable solutions that "geo-enable" the Web, wireless and location-based services. The specifications empower technology developers to make spatial information and services accessible and useful to all kinds of applications. The ISO/TC211 Geographic information/Geomatics scope is focused on standardization in the field of digital geographic information (ISO/TC211: http://www.isotc211.org). It aims at establishing a structured set of standards for information on objects or phenomena directly or indirectly associated with a location relative to the Earth. According to the ISO/TC211 statement, geographic information standards may specify methods, tools, and services for data definition, description and management, data acquisition, processing, analysis, accessing, and visualisation. Furthermore, ISO/TC211 standards concern data and information transfer protocols in digital/electronic form between different users, systems and locations. They provide also a general framework for the development of domain- and sector-specific applications that use geospatial data. ISO/TC211 and OGC work very closely together with other actively engaged international professional bodies (FIG: International Federation of Surveyors, or ICA: International cartographic Association), UN agencies, and specific domain bodies (DGIWG for defence organization, ICAO for International Civil Aviation Organization).

1.5.2.2 GEOSPATIAL METADATA

A metadata record is a file of information in different forms, usually presented as an XML document, which provides basic characteristics of a data or information resource. It provides the: "who, what, when, where, why and how of the resource". Geospatial metadata can be used to document geoinformation resources in different formats, such as GIS files, or geospatial databases (FGDC, 2006, http://www.fgdc.gov/metadata). The ISO 19115 standard states that metadata give information about the identification, the extent, the quality, the spatial and temporal schema, spatial reference, and distribution of digital geographic data (ISO 19115, 2003). ISO standards apply rather to digital data, but their principles can be extended to many other forms of geographic data such as maps, charts, and textual documents, as well as non-geographic data. Metadata can also provide information about the up-to-datedness of data, the used standards, copyrights and ownership rights (Gaździcki, 2001). The availability of data can also be documented, together with the rules how they can be accessed and exchanged (Batcheller, 2007, in press). Finally, metadata can describe the content of a database: its schema, users, types of data, description of semantic of data, distribution and physical organization of data, their amount and statistics concerning data, and others (Subieta, 1999). Definition and presence of metadata, describing the existence, localisation, format, structure, and constraints of geoinformation allow for using data outside the system where the data were they have been created or stored. The data can be successfully shared, stored and used (Babaie and Babaei, 2005). Metadata help in the coordination of data acquisition; they inform about large datasets, reduce redundant storage, and clarify search results (Batcheller, 2007, in press).

Several related standards and technologies concerning metadata are continuously being developed. These are: ISO 19115 standard (2003), that specifies metadata; ISO 19139 (2004) provides an XML implementation of it, producing an XML-compatible description for geographic information; and finally, the Open Geospatial Consortium Catalogue Services-Web Profile (CSW) uses Web Services technologies to manage geographic metadata (Wei et al., 2007). The emergence of XML and Web Services technologies supports the distribution and transfer of geospatial information across Internet. Nowadays, there are many free and open source tools, as well as commercial software products implementing some of these standards. They support metadata search, viewing, editing, creation, and serving (catalogue services). These can be tkme, MetaScribe or MERMaid for freeware/shareware tools; ArcCatalog, ArcIMS Metadata server, GeoMedia Catalog, and SMMS for commercial tools.

1.5.2.3 HYDROGEOLOGICAL AND GEOLOGICAL DOMAINS STANDARDS

To create a standard for hydrogeological information transfer compliant with ISO/TC211 and OGC principles, existing geography and geology conceptual models should first be imported. Basic hydrogeological features can be described by generic information types, describing their position, geometry and some other more specific attributes. For this purpose, the following standards and markup languages should be reused for the development of the hydrogeological data exchange standard: Geography Markup Language (GML), eXploration and Mining Markup Language (XMML) and Geoscience Markup Language (GeoSciML). GML (Cox et al., 2002), is an XML grammar written in XML Schema which provides a large variety of objects for describing features, co-ordinate reference systems, geometry, topology, time, units of measure and generalized values. The ISO 19136 standard describes GML and it is intended to be used as a basis on the top of which more specific application schemas can be constructed, such as: XMML and GeoSciML. XMML (Cox, 2004) has been developed to support online data transfer for the exploration and mining industry by 3D Visualisation and Geological Modeling in CSIRO (Commonwealth Scientific and Industrial Research Organization) Australian organisation. GeoSciML (Sen and Duffy, 2005) has been built to exchange geoscientific information.

However, none of these standards conformant projects treats about hydrogeological information, which requires specific geoinformation types, presented in the previous section. As far as the hydrogeological domain is concerned, several identified projects focusing on hydrogeological information transfer standard are presented in Table 2. One of the most interesting and important for the hydrogeological domain would be GroundWater Markup

Language (GWML), a GML Application Schema. It is currently the only ongoing project concerning hydrogeological information transfer standard, completely compliant with ISO/TC211 and OGC norms. Figure 8 shows the position of GWML in the current landscape of GML and its application schemas developed specifically for different domains. GWML imports different concepts, definition and solutions from "upper" conceptual models, starting from geography, through exploration and mining industry standards to geoscientific information standards.

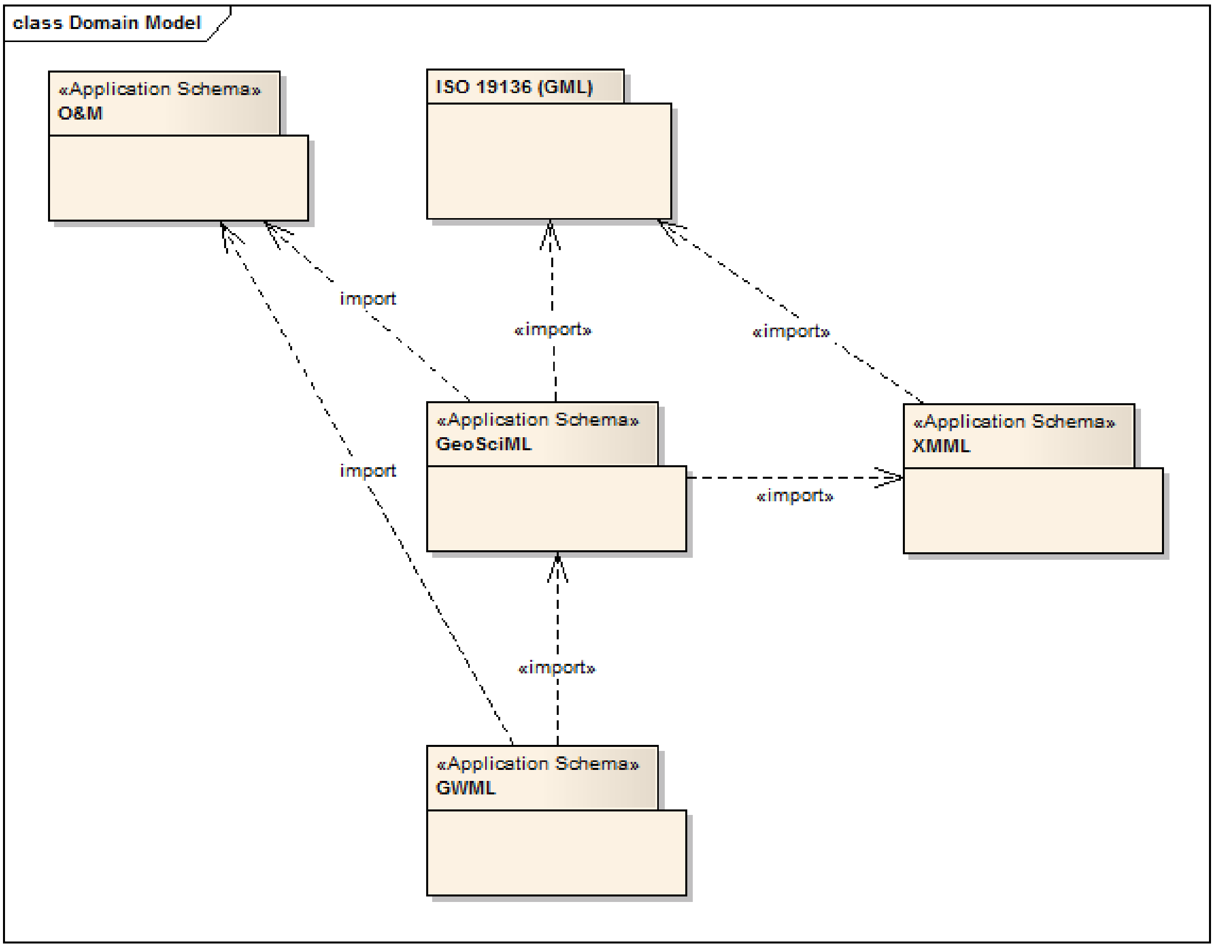


Figure 8. Simplified illustration of dependencies between the ISO 19136 standard and its derived application schemas specific to different domains.

Projet/Model Name	References	Description	Original Input
The Polish Hydrogeological Survey Database Integrator	Cabalska et al., 2005	The PHS Database Integrator, as a practical and applied tool, has answered to the needs for a sophisticated instrument for groundwater management (Cabalska et al., 2005). This project aimed at hydrogeological data integration, and at data gathering from multiple and heterogeneous available data sources. It integrates all hydrogeological databases existing in the Polish Geological Institute, such as Groundwater Monitoring database, HYDRO Bank and Hydrogeological Map of Poland in 1:50.000 scale, the latter being developed using an Intergraph technology (Fert et al., 2005). This solution allows for an effective hydrogeological data integration, retrieval, and analysis. It reduces also the time needed for data collection and data redundancy by its transparency. Project link: www.pgi.gov.pl/pdf/pg_2005_10_2_10.pdf	Specialized tool integrating hydrogeological information from multiple sources.
GABARDINE Geospatial hydrogeological database	Wojda et al., 2006	In order to use the advantages of object-oriented modelling, to follow the international standards for transfer of geospatial information (ISO/TC211 and OGC), and to be compliant with the recommendations from the European Geospatial Information Working Group (Vogt, 2002), a new hydrogeological data model called GABARDINE GDB has been developed. The model has been implemented in the ArcGIS environment, as a database for a Decision Support System for the EC FP6 GABARDINE project (**G**roundwater **A**rtificial recharge **B**ased on **A**lternative sources of wate**R**: a**D**vanced **IN**tegrated technologies and management) (Wojda et al., 2006). The proposed holistic Project-Oriented approach enables to deal with a hydrogeological project as a whole, by managing the data about the project localisation, available hydrogeological studies in the zone of interest, contact people and contributors. Furthermore, existing hydrogeological equipment, natural and man-made groundwater access features, monitoring results, field tests performed in the zone together with their results and possible interpretations can be gathered, visualized and analyzed. Project link: www.gabardine-fp6.org/	Hydrogeological data model described using the UML notation, following ISO/TC211 and OGC recommendations. Implemented in ArcGIS environment.
eWater project hydrogeolgical data model	Coordinated by Dr Alexei Tchistiakov	The main objective of the ongoing FP6 EC eWater project coordinated by the TNO Dutch Institute is to increase the cross-border availability, accessibility and re-usability of spatial data on quality, location and use of subsurface waters. In order to achieve this objective, a multilingual WEB GIS portal is under development. The portal will be accessible for the project partners, participating countries, national river basin authorities, and water suppliers. It will give an additional value to data service providers, insurance companies, planning and controlling organizations, as well as general public, making hydrogeological data and information available. The eWater architecture complies with the INSPIRE policy (INSPIRE: http://www.ec-gis.org/inspire), and the data will be usable not only by the suppliers, but they can also be included in Water Information System for Europe (WISE: http://water.europa.eu). Project link: http://ewater.geolba.ac.at/	First European project increasing availability and usability of hydrogeological data, using UML for data modelling and Web-based services for data exchange

Projet/Model Name	References	Description	Original Input
GroundWater Markup Language	Boisvert and Brodaric, 2007;	The GWML project is in its very early stage of development and discussions. Many applied concepts have been inspired from NADM-C1 (Boisvert et al., 2004), and imported or derived from XMML (Cox, 2004) and GeoSciML (Sen and Duffy, 2005), following a standardised GML extension pattern for Application Schemas. The interoperability framework of GWML is based on OGC standards. It incorporates GML-based standards such as Observation & Measurements (07-022r1, 2007), SensorML (07-000, 2007) and GeoSciML. Due to its compliant structure, it will be possible to use it in conjunction with OGC web service standards and protocols such as Web Mapping Services; Web Feature Service; Sensor Observation Service; Web Coverage Service. A specialized collaboration is performed on-line. GWML provides a very good starting point for groundwater data interchange format. Eventually, GWML might be used as the GML Application Schema (GeoSciML derived more precisely) for groundwater information exchange. Project link: http://ngwd-bdnes.cits.rncan.gc.ca/service/ngwd/exploration/ngwd/gwml.html?locale=en&SESSION=PUBLIC&.	GML-derived as its application schema and compliant with standards and norms issued by OGC and ISO/TC211

Table 2. Unifying hydrogeological data models and enabling information transfer.

1.6 CONCLUSIONS TO CHAPTER 1

Hydrogeological information management is very important for efficient integrated water resource administration, protection and exploitation. Since hydrogeological data are expensive, complex, spatially and temporally distributed, a clear structuring and transparent storage are necessary. Decision makers and interested users should easily access groundwater information coming from multiple sources.

Currently, traditional paper storage of hydrogeological data and information is replaced by an electronic carrier. This trend is accompanied by the growing use of computational methods to carry out geoscientific tasks. Real-time data delivery and analysis should be combined with automatic data transfer between groundwater actors, existing databases, monitoring networks and remote sensors. This information flux is needed at diverse levels: from the local level, through regional and national levels, to the international environment.

The main identified problem for easy, time- and effort-efficient transfer of information is diversity in hydrogeological data storage and formats. There are many database structures, suited for particular functions, needs and priorities, which make hydrogeological resources management complicated.

In order to overcome this problem, the hydrogeological community must undertake standardization efforts for hydrogeological information storage and transfer. Such a hydrogeological standard will improve data availability and exchange, as well as it will reduce misinterpretations by users who read and display hydrogeological data. Norms and standards coming from ISO/TC211 and OGC should be taken into account. A new hydrogeological standard should be then developed as a GML application schema, enabling data access through web-based services such as, for instance, WFS or WMS. It will be also possible to combine hydrogeological information with other related domains such as geology, geography, and hydrology. Presently, one of the most important examples being under development is GroundWater Markup Language as a specialization of GeoScientific Markup Language.

In Chapter 2, a first proposal of a local-regional standardization of hydrogeological data models, a HydroCube model, is presented. A detailed description of the modelling background and hydrogeological community needs are followed by a hydrogeologic data model itself, illustrated by Entity-Relationship diagrams. Several use-case examples are described.

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CHAPTER 2

HYDROGEOLOGICAL DATA IN AN ENTITY-RELATIONSHIP MODEL: HYDROCUBE

2.1 INTRODUCTION

As a consequence of the recent changes in information carriers described in the previous chapter, new needs for seamless data exchange, and the lack of convergence in data models, existing hydrogeological data models have to be adapted and sometimes completely re-designed. The elaboration process requires an accurate terminology at the following levels: general information concepts, geomatics, and specific hydrogeological issues (Michalak, 2003).

A new formalized logical model of hydrogeological data, HydroCube, is proposed here. The model is described by a series of normalized entity-relationship diagrams. The main objective of the HydroCube model is to respond to the requirements identified during discussions with actors, end-users, university teams and other institutions in the Walloon Region of Belgium. Growing interest for GIS technologies has forced the conception of a new and innovative hydrogeological data model, where entities are organized according to their geometry: point, arc and polygon. Spatial aspects are supported internally for point-type entities, while arc- and polygon-type entity geometries have to be handled externally. Complete sets of attributes and their data types for each entity are presented. The logical model defines also permissible value domains, such as code-list entities. Furthermore, the need for hydrogeological data availability and transfer between different universities and administration required a convergence in applied data models, HydroCube becoming a standard for data encoding and exchange by structured protocols.

In order to respond to the requirement of the most complete data model for the hydrogeological domain, the HydroCube model promotes an innovative “project-based” approach that deals with any hydrogeological project as a whole. First, one needs the data about the project localisation, previous hydrogeological studies, and contact people. Second, one requires available natural and man-made groundwater access features together with their associated quantity and quality observations and measurements. Technically, the data for each project can be stored in one database instance, or they can be differentiated by unique identifiers, where each identifier is composed of a defined prefix and an automatic number.

HydroCube presents also a pioneer logical model for hydrogeological field experiments such as pumping tests and tracer tests, including data about (1) experimental devices and conditions, (2) measurements taken during the tests, and (3) derived data such as interpretations.

The HydroCube logical model has been implemented through a physical model under the HydroCube database in MS Access ® and enriched with fully functional user interfaces that allow users and decision makers to focus only on the information content and management issues.

The first part of the paper presents the driving concepts of the development of the HydroCube logical model, based on a review of existing geological and hydrogeological data. Then, the main entities of the HydroCube model are presented, focusing on the most important aspects such as the geometry-based classification of hydrogeological entities, topological links, and the pioneer data model dealing with hydrogeological field experiments. The user interfaces functionalities are then presented. The conclusion proposes new directions for further developments of hydrogeological data models, respecting international standards and norms.

2.2 DRIVING CONCEPTS AND EXISTING DATA MODELS

Hydrogeological data, defined as individual fragments of information (Nowicki and Staniszkis, 2002), should be organised in order to provide the user with valuable hydrogeological information. Data are generally organised first using appropriate conceptual models at the highest level of abstraction, then using more tangible logical models, which describe the structure of data, using commonly accepted semi-formal and formal notations.

As mentioned in Chapter 1, three from the most interesting hydrogeological projects are technically described here after. “HYGES hydrogeological database” developed in the Walloon region, Belgium (Gogu, et al. 2001) relies on entity-relationship diagrams, is a GIS-based database offering facilities to model groundwater flow and contaminant transport, and to assess groundwater vulnerability. “The Australian National Groundwater Data Transfer Standard” made by The NGC Groundwater Data Standards Working Group in the National Groundwater Committee (1999), described by entity-relational diagrams using “crow’s-foot” notation, has been developed in order to unify different existing data models in Australia. It contains only basic hydrogeological features (such as wells or drains) and associated measurements. “A geographic data model for groundwater systems” based on the ArcHydro ESRI data model, developed at the University of Texas at Austin (Strassberg, 2005) attempts to extend the ArcHydro model (Maidment et al., 2004) to represent groundwater systems. It uses specific notations to describe the geodatabase structure and it focuses mainly on hydrogeological features used for groundwater flow modelling. It can be coupled with the Groundwater Modeling System (GMS®) software.

Nevertheless, the presented models do not deal with the hydrogeological domain in its entirety. They address very specific hydrogeological issues and functionalities. They do not cover all the necessary hydrogeological concepts in order to deal with an entire hydrogeological project, while the current trends focus more and more on integrated, project-based, management solutions. In particular, they do not allow storing hydrogeological data coming from field tests, such as pumping tests and tracer tests, or to manage topological relationships (for instance spatial relationships between an exploitation well and its protection zone). Fortunately, they can be consider as a first step for further developments, but they must be extended or adapted in order to respond to current needs.

For developing the HydroCube logical data model, the entity-relationship modelling has been adopted for two main reasons. First, normalized logical models expressed in entity-relationship diagrams are easy to implement in many popular and well known Relational Database Management Systems (RDBMS). This guarantees that the HydroCube logical model is easy to implement and ready to be used by most of the hydrogeological community. Secondly, whenever it turns out to be necessary to extend or enrich the model, one may pass to another notation, such as object-oriented modelling, using formalized mapping techniques. Nevertheless, it was assumed that comprehension and implementation of any object-oriented model require advanced knowledge and address to the specialists in geomatics. On the contrary, the HydroCube model rather addresses the users who are interested in a holistic project-based data management system focusing more on applied hydrogeology and field test data.

Before describing the HydroCube model, it is necessary, for the sake of clarity, to recall the definitions of different terms, such as entity, attribute, geospatial feature, and topological links.

An entity describes one and only one subject; it can be represented by a single table which contains information about this subject, for instance wells, sources, protection zones, or particular observations. Each entity contains attributes, which define different characteristics of occurrence, such as its name, type or owner (IBM, 2003).

A geospatial feature represents an abstraction of a phenomenon which belongs to the real world with geospatial attributes (geometric and topological) such as shape, extent, position, relation to other features. In geographic systems, features can be represented by vectors in simple geometrical forms: points, lines and polygons or their collections (Michalak and Leśniak, 2003).

All the geospatial data have geometrical and topological aspects. Information about the shape and the position of a feature is contained in the geospatial feature description. The shape and the position are expressed in coordinates in a Spatial Reference System (SRS). Topology, as a branch of geometry, describes the relationships amongst related or neighbouring features such as points, lines or polygons (ISO 19104 DIS). Topological relationships do not depend on the SRS and they describe the spatial relationships amongst geospatial features. The fact that one well is located near one river does not change, because this relation refers to their topological relationship. Mereology deals with association of one feature with another, as a part of it. When a spatial context is involved in associations it is dealt by mereotopology (Smith and Mark, 1998).

2.3 HYDROCUBE: THE WALLOON REGION HYDROGEOLOGICAL DATA MODEL

2.3.1 MAIN HYDROGEOLOGICAL ENTITIES

The HydrogeologicalFeature is the central entity of the data model (Figure 9). It has the abstract function of organizing all the elements and giving them common attributes such as a unique identifier, a name and a type. The identifier is public and unique across the model. Any external application can use this identifier to access any piece of information contained in the database.

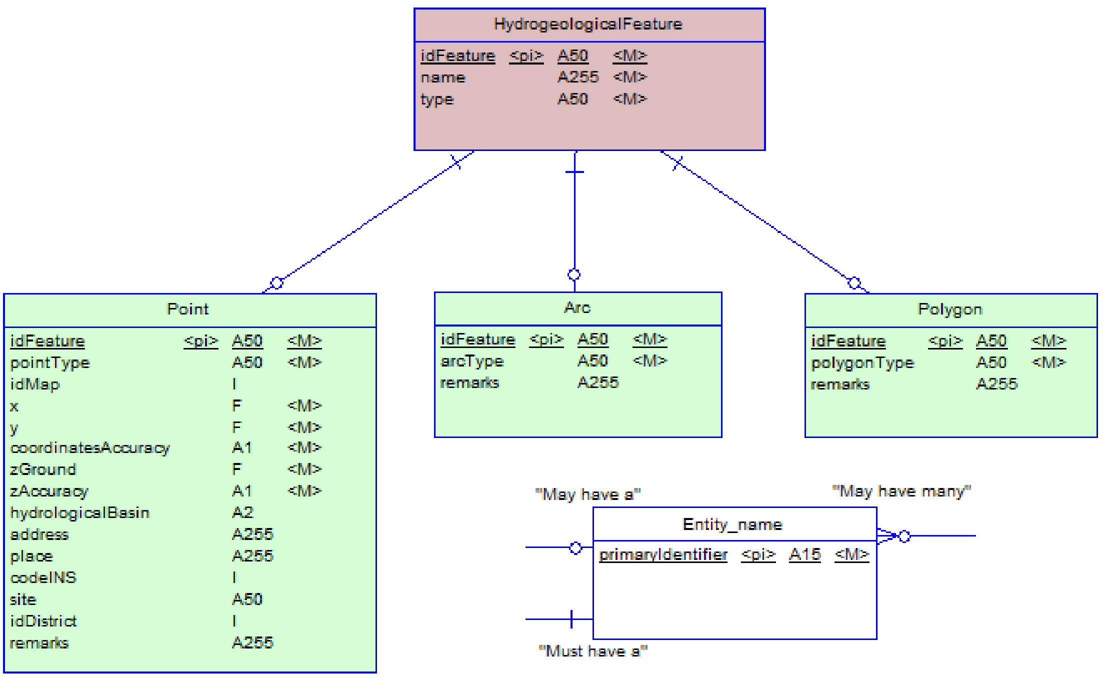


Figure 9. Basic entities of the HydroCube model. Data types and symbols notation for all the figures: A(x): characters(number); I: Integer (it can be also a primary identifier from a dictionary); F: float; SF: short float; DT: date and time; MBT: Multibyte; BL: Boolean; <pi>: primary identifier; <M>: mandatory value.

Following the convention on geometric classification of primitive features (GM_Primitive) and the conventional GIS geometry-first approach, used also in the Guidance Document on Implementing the GIS Elements of the Water Framework Directive (Vogt, 2002), the hydrogeological entities of HydroCube are classified according to their basic geometric characteristics (Figure 9). This solution presents a geometry-centric data model where all the elements are represented by points, lines, and polygons, all being 1D or 2D features. The proposed HydroCube model deals directly with the geometry of Point-type entities features, by explicit x, y, and z attributes. The geometry of Arc- and Polygon-type entities has to be handled externally, using a GIS-hybrid system. Time references for hydrogeological observations and measurements are managed by an additional “date” attribute in the concerned entities.

The different hydrogeological entities represent real world objects described by sets of attributes. Each attribute has a name, for instance “constructionDate” field in the “Well” entity, and a value, for instance “01/01/2000”. Such a value can be encoded manually, or taken from a proposed dictionary such as a code-list. In some cases, property values may refer to other features. For example, a “Spring” entity has a property “idRiver” which is the identifier of the River fed by the Spring.

The “Point” entity attributes describe the type and the location of each occurrence. The most important attributes are the type of the point (well, spring, surface water observation point…), the geographical coordinates with a description of their accuracy, and the address. The “Point” entity may have 11 specialized hydrogeological features, namely “SurfacePoint”, “Sinkhole”, “Spring”, “Borehole”, “Well”, “Excavation”, “InterpretationPoint”, “ObservationPoint”, “GeotechnicalPoint”, “GeophysicalPoint” and “ClimaticStation” (Figure 10). As an example, to encode information about a well, one needs to introduce the name and the type of this hydrogeological feature, together with its primary identifier (Figure 11). Geographical coordinates and address information is handled in the “Point” entity, together with other mandatory attributes.

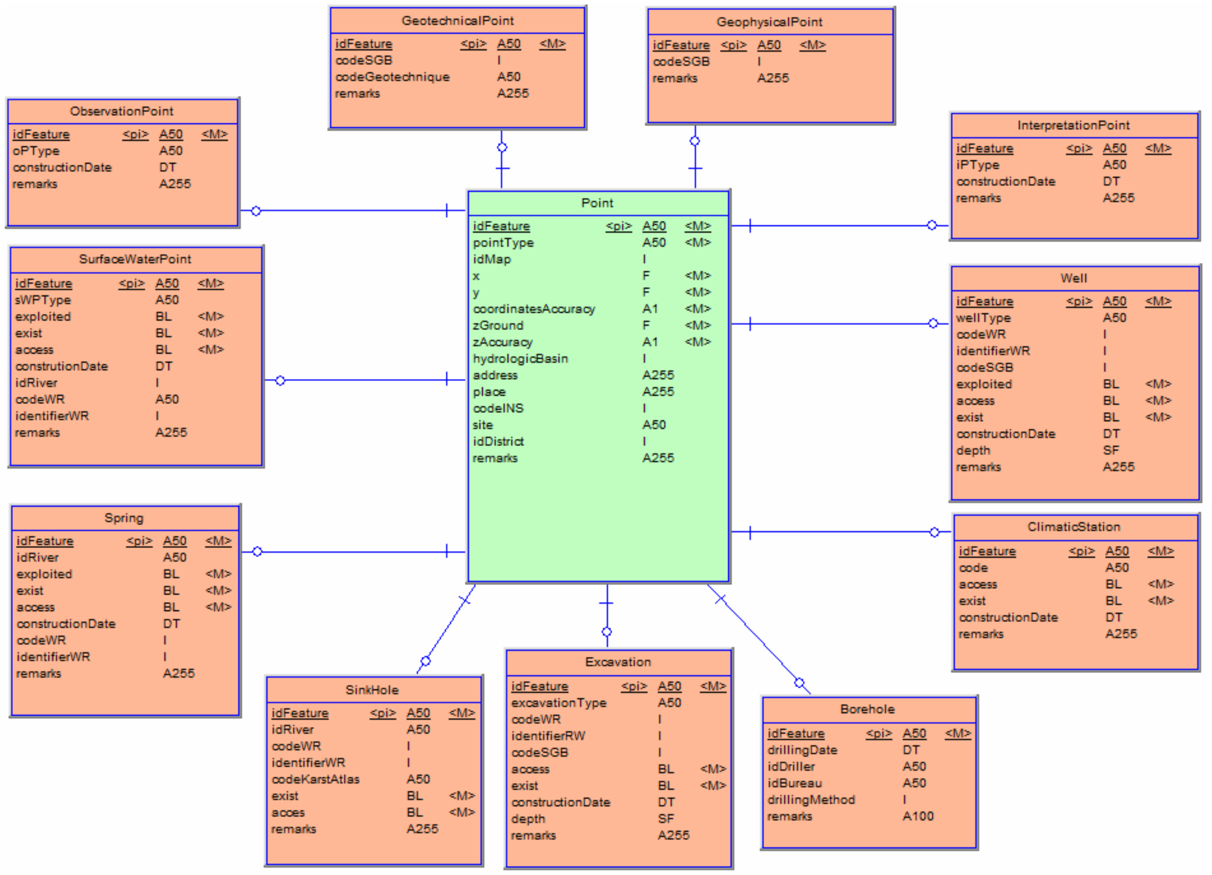


Figure 10. Entity-relationship diagram of point-type feature entities.

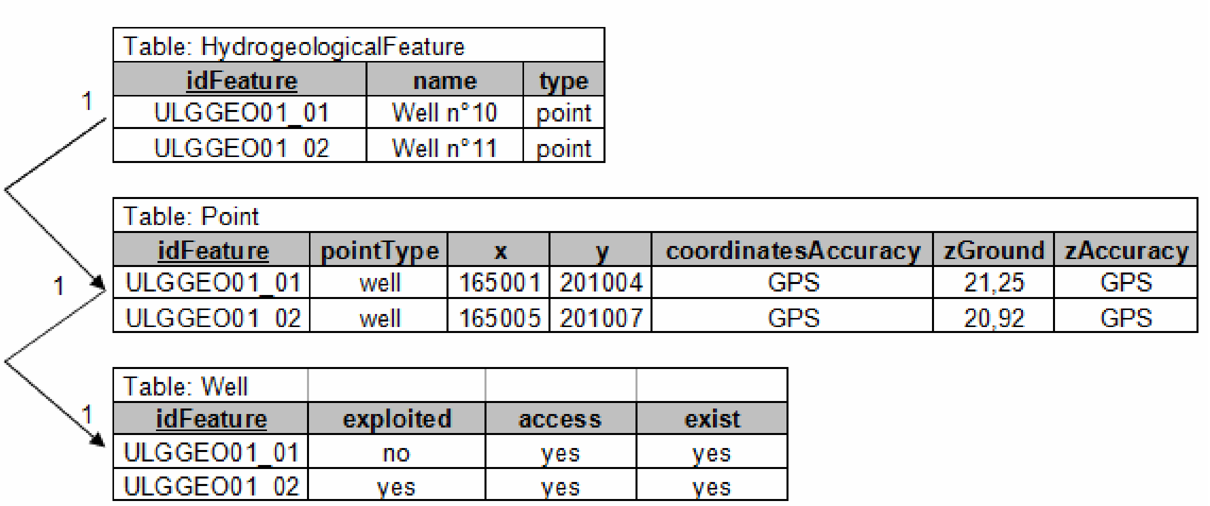


Table: HydrogeologicalFeature		
idFeature	**name**	**type**
ULGGEO01_01	Well n°10	point
ULGGEO01_02	Well n°11	point

Table: Point						
idFeature	**pointType**	**x**	**y**	**coordinatesAccuracy**	**zGround**	**zAccuracy**
ULGGEO01_01	well	165001	201004	GPS	21,25	GPS
ULGGEO01_02	well	165005	201007	GPS	20,92	GPS

Table: Well			
idFeature	**exploited**	**access**	**exist**
ULGGEO01_01	no	yes	yes
ULGGEO01_02	yes	yes	yes

Figure 11. Example of two well occurrences encoded in the HydrogeologicalFeature, Point and Well tables in the implemented database. Only the mandatory attributes are shown.

The "Arc" entity contains data about linear hydrogeological entities. There are three attributes: a mandatory "idFeature" as a primary identifier, a mandatory "arcType" and an optional remark. The "Arc" entity may have the following related entities: "WaterGallery", "River", "CrossSection", "GeophysicalArc" (Figure 12).

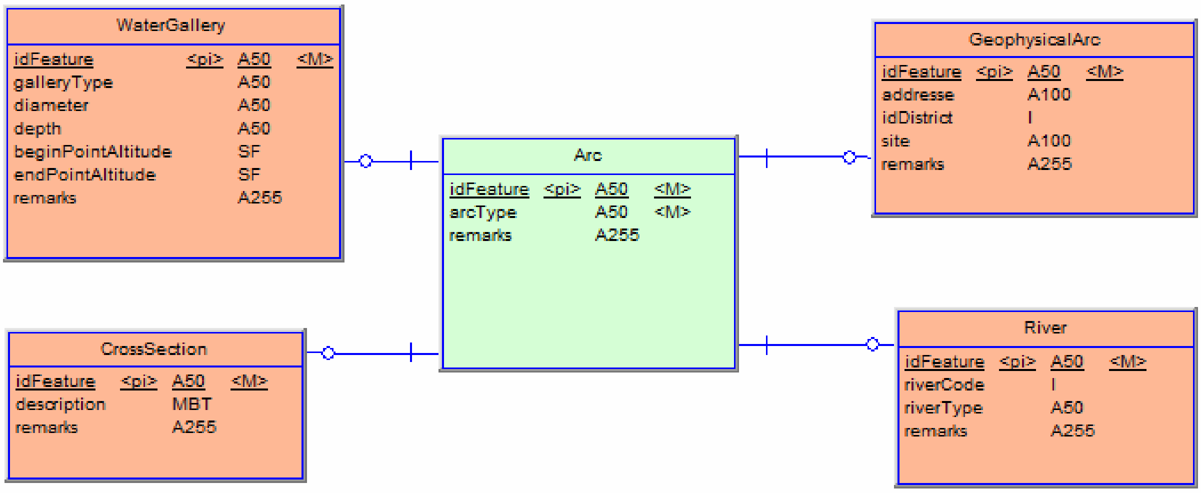


Figure 12. Entity-relationship diagram of linear feature entities.

The "Polygon" entity has three attributes. Two mandatory attributes are: (1) idPolygon as a primary identifier, (2) polygonType to describe its type, and (3) optional remarks. The "Polygon" entity may have 9 specialized hydrogeological entities, namely: "Mine", "HydrologicalBasin", "HydrogeologicalBasin", "ProtectionZone", "StudyZone", "GroundwaterBody", "SurfaceWaterBody", "MathematicalModel", "GeophysicalPolygon" (Figure 13).

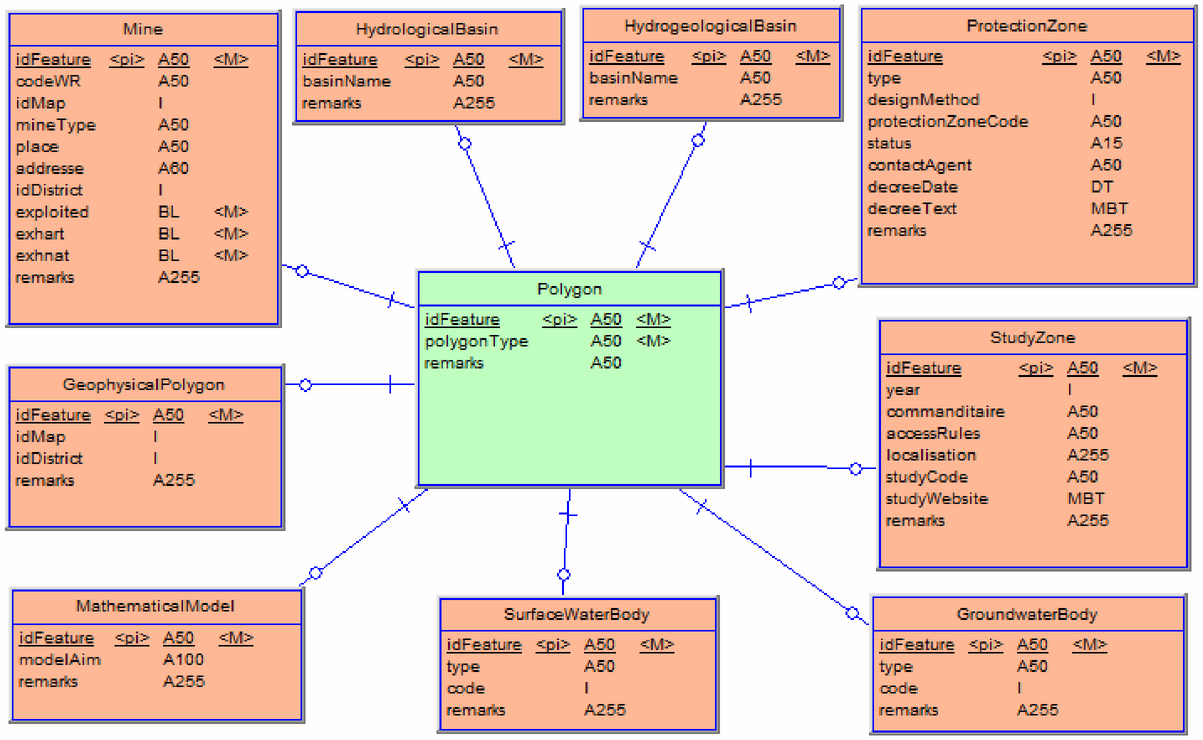


Figure 13. Entity-relationship diagram of polygon feature entities.

2.3.2 TOPOLOGICAL LINKS AMONGST HYDROGEOLOGICAL ENTITIES

In order to deal with a hydrogeological project as a whole, it is necessary to store information about spatial associations of the different elements, using topological relationships. This may consist in information about the study zone together with the natural hydrogeological features such as springs, lakes or man-made equipment to access groundwater. The HydroCube model uses link tables as a conceptual solution for defining and handling topological links among such hydrogeological features (Figure 14). Such link tables store many-to-many connectivity types (m:n), which identify the topologically related hydrogeological features and a link type which indicates the nature of the relationship. As an example, a link table can be used to associate a study zone and different wells and piezometers located within this zone and used in the scope of the hydrogeological project. Other useful topological relationships are links between, for instance, a water intake and its protection zones based on pollutants transfer time; observation wells and a pumping well used to perform a pumping test; sinkholes and a spring in a karstic system; or more generally, any hydrogeological feature such as wells, piezometers, rivers, springs constituting the monitoring network for a regional groundwater investigation.

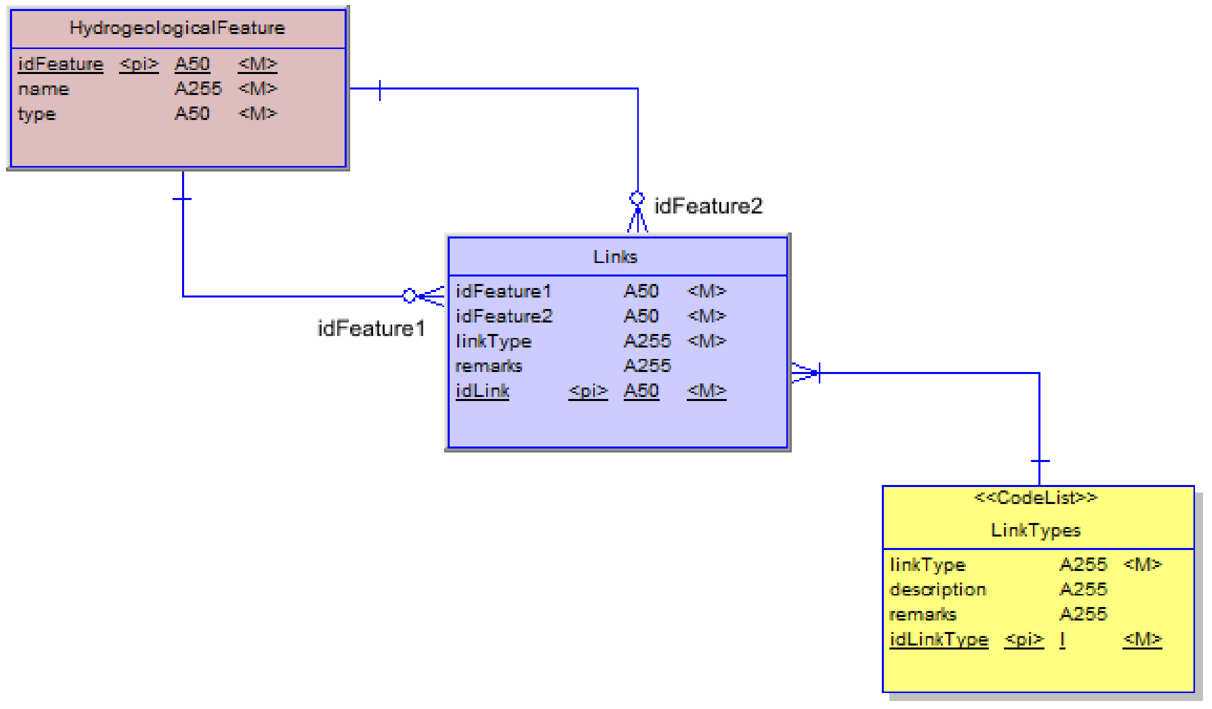


Figure 14. Links entity and related hydrogeological features.

2.3.3 CONTACT AND SUB-CONTACT ENTITIES

Different hydrogeological features can be related to a contact person, an organisation, or a laboratory. This information is stored in the HydroCube model in a **contact sub-model** (Figure 15). For example, a laboratory performing chemical analyses can be linked with the corresponding analyzed samples, or a study zone and its report can be associated to information on people that can be contacted for additional explanation or information on the results of the study. The contact table stores the data about the organisation or institution which employs people, the employees being stored in the “SubContact” entity. In order to define the role of any contact one can add a contact type, for instance: a water society, an individual person, a laboratory.

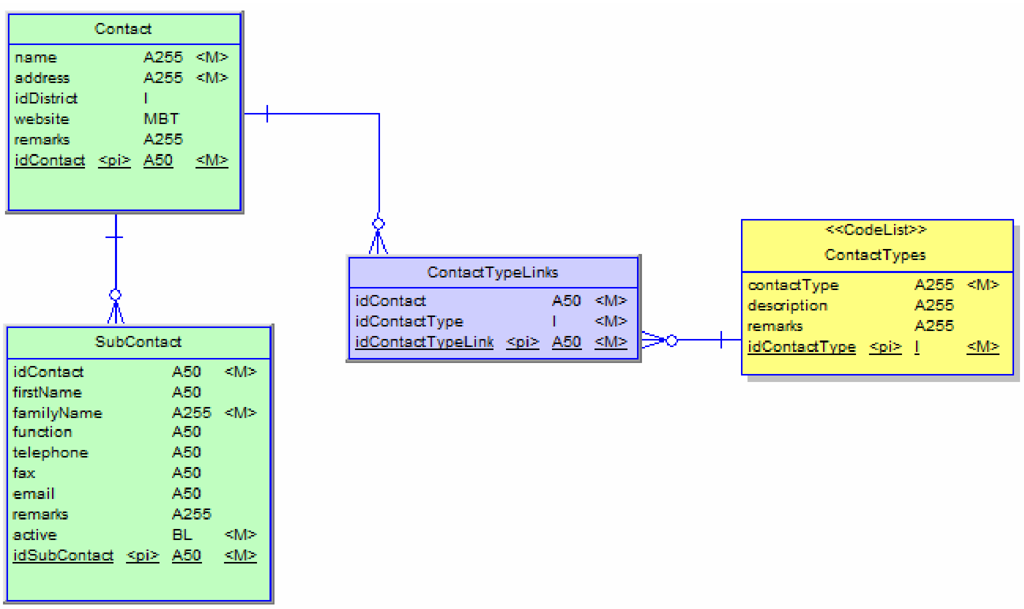


Figure 15. Contact sub-model and its entities.

2.3.4 OBSERVATIONS AND MEASUREMENTS

In the previous section, the main hydrogeological entities are described according to their primary geometry-type classification. However, an important amount of hydrogeological data focuses on additional information about hydrogeological equipment and measurements or on observations such as piezometric levels, lithological description, groundwater geochemistry samples or complex field tests. The description of this related information is presented in the next sections.

2.3.4.1 WELL EQUIPMENT DATA

The well "Equipment" entity stores and organises information on piezometers and wells, such as "Screen", "Casing", "Grouting", "GravelPack" and "ClayPlug" (Figure 16).

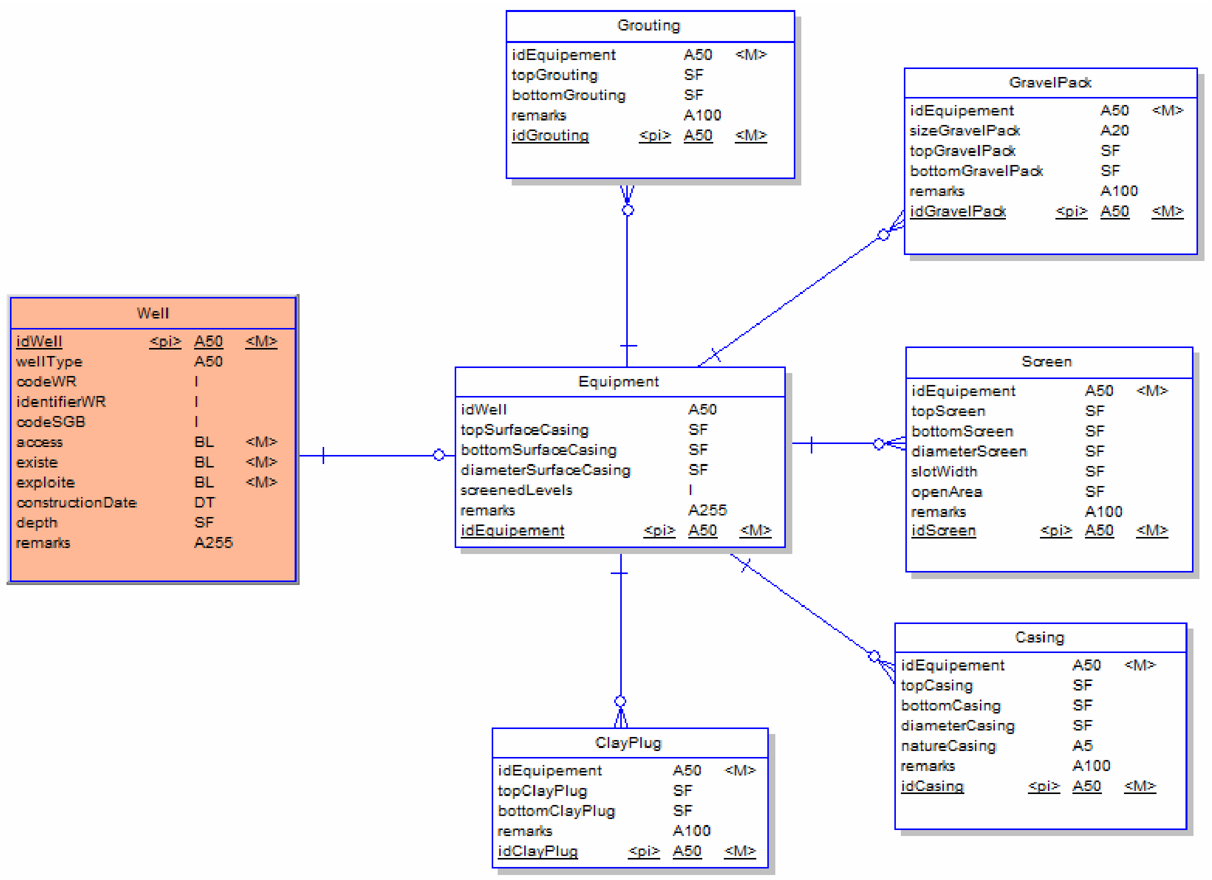
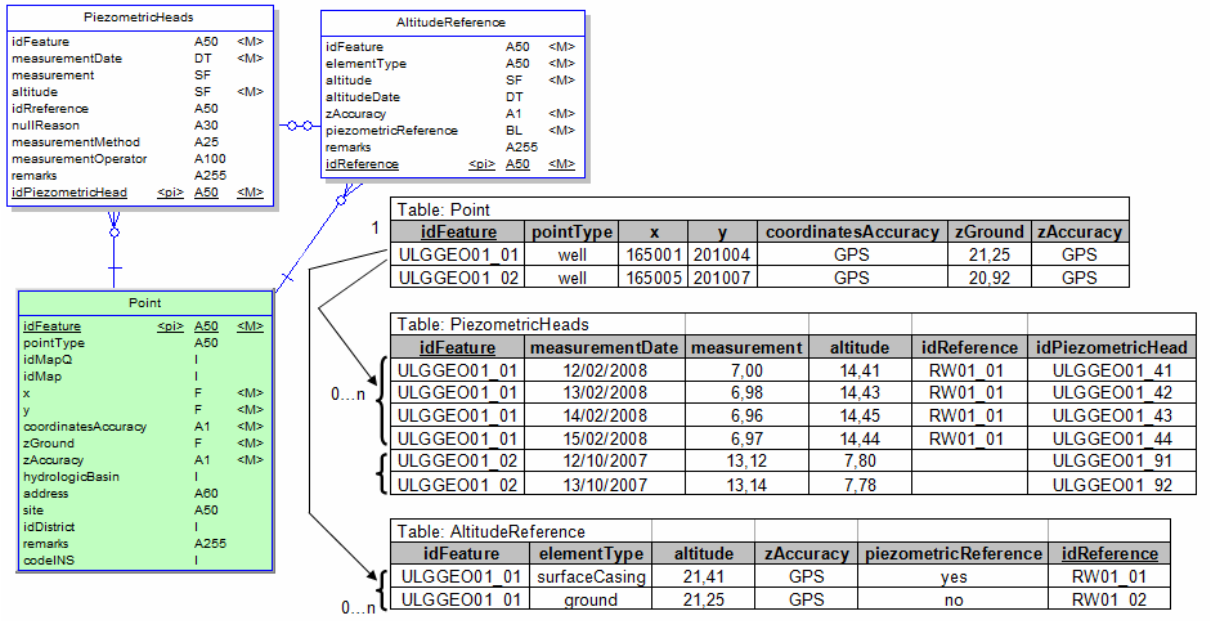


Figure 16. Relationships between well and its equipment entities.

2.3.4.2 *PIEZOMETRIC HEAD ENTITIES*

Piezometric head measurements can be seen as discrete episodes of data collection from one particular point-type hydrogeological feature (well, piezometer…). Any point-type hydrogeological feature may have many piezometric head level measurements (Figure 17). Each measurement has also a reference altitude (ground level, casing level…). For instance, “Well n°10” is associated with four piezometric head level measurements.



PiezometricHeads			
idFeature		A50	<M>
measurementDate		DT	<M>
measurement		SF	
altitude		SF	<M>
idRreference		A50	
nullReason		A30	
measurementMethod		A25	
measurementOperator		A100	
remarks		A255	
idPiezometricHead	<pi>	A50	<M>

AltitudeReference			
idFeature		A50	<M>
elementType		A50	<M>
altitude		SF	<M>
altitudeDate		DT	
zAccuracy		A1	<M>
piezometricReference		BL	<M>
remarks		A255	
idReference	<pi>	A50	<M>

Point			
idFeature	<pi>	A50	<M>
pointType		A50	
idMapQ		I	
idMap		I	
x		F	<M>
y		F	<M>
coordinatesAccuracy		A1	<M>
zGround		F	<M>
zAccuracy		A1	<M>
hydrologicBasin		I	
address		A60	
site		A50	
idDistrict		I	
remarks		A255	
codeINS		I	

Table: Point

idFeature	pointType	x	y	coordinatesAccuracy	zGround	zAccuracy
ULGGEO01_01	well	165001	201004	GPS	21,25	GPS
ULGGEO01_02	well	165005	201007	GPS	20,92	GPS

Table: PiezometricHeads

idFeature	measurementDate	measurement	altitude	idReference	idPiezometricHead
ULGGEO01_01	12/02/2008	7,00	14,41	RW01_01	ULGGEO01_41
ULGGEO01_01	13/02/2008	6,98	14,43	RW01_01	ULGGEO01_42
ULGGEO01_01	14/02/2008	6,96	14,45	RW01_01	ULGGEO01_43
ULGGEO01_01	15/02/2008	6,97	14,44	RW01_01	ULGGEO01_44
ULGGEO01_02	12/10/2007	13,12	7,80		ULGGEO01_91
ULGGEO01_02	13/10/2007	13,14	7,78		ULGGEO01_92

Table: AltitudeReference

idFeature	elementType	altitude	zAccuracy	piezometricReference	idReference
ULGGEO01_01	surfaceCasing	21,41	GPS	yes	RW01_01
ULGGEO01_01	ground	21,25	GPS	no	RW01_02

Figure 17. Point entity with its piezometric heads measurements and an example of implementation.

2.3.4.3 GROUNDWATER CHEMISTRY DATA

In many hydrogeological studies, there are numerous data describing groundwater chemistry. Groundwater samples taken from a sampling point are analyzed by a laboratory. The results are then reported and may be stored in the HydroCube database. Practically, the data model can store several samples/analyses for any hydrogeological feature (Figure 18). Each groundwater sample can be related with many geochemistry measurements of different parameters. The model also contains code-list entities, which preserve common naming conventions for standard parameters names and characteristics, types of samples or measurement networks. This solution follows geomatics specifications (e.g. ISO 19103 DTS), where class diagrams can contain code-list classes such as *collection types* and *enumerated types* (Whiteside 1999).

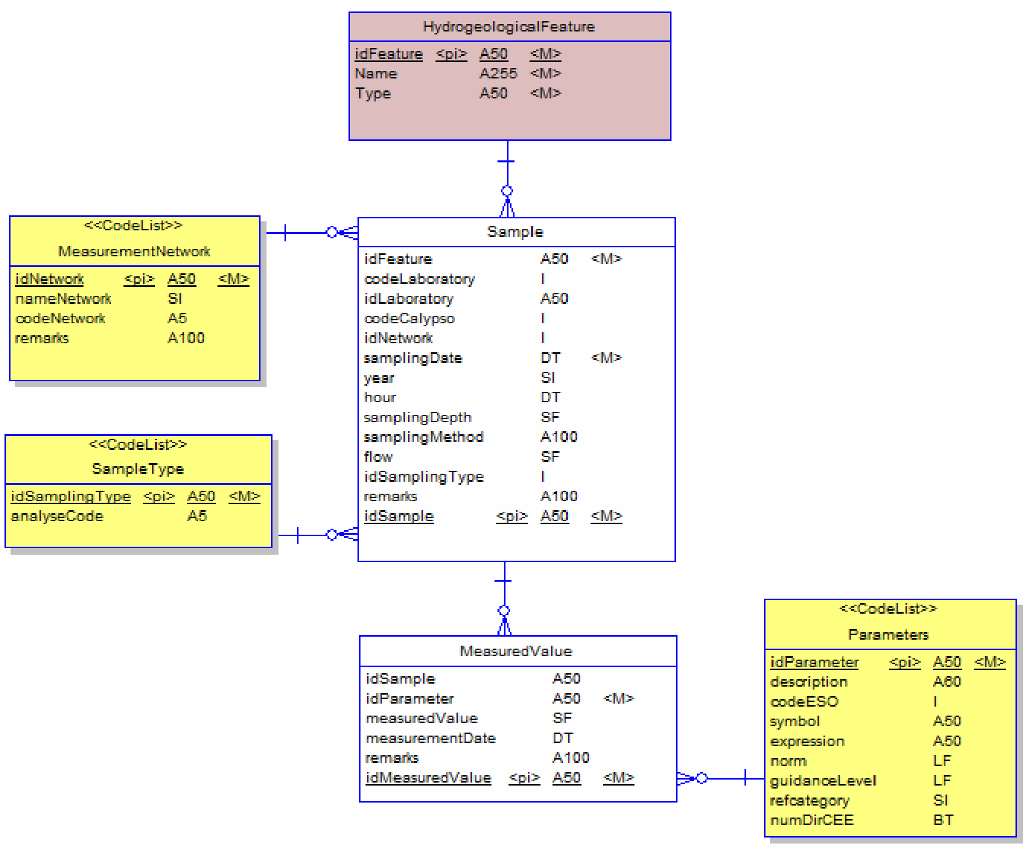


Figure 18. Entity-relationship diagram for chemical analysis sub-model.

2.3.4.4 *FIELD EXPERIMENTS: PUMPING TEST AND TRACER TEST ENTITIES*

Hydrogeological studies and decisions concerning groundwater resources management need to be based on reliable information about hydrogeologic conditions and parameters. Raw data can be retrieved through simple observations and measurements performed in order to have primary information. However, more complex hydrogeological parameters can only be obtained by performing more advanced field experiments, such as pumping tests and tracer tests.

Usually, these experiments produce large amounts of data, sometimes difficult to handle and to analyse. In order to facilitate field experiments management, data retrieval, and interpretations of results, an advanced data model for field experiments has been developed (Figure 19). The model proposes a three-phase generic framework which can be described as follows.

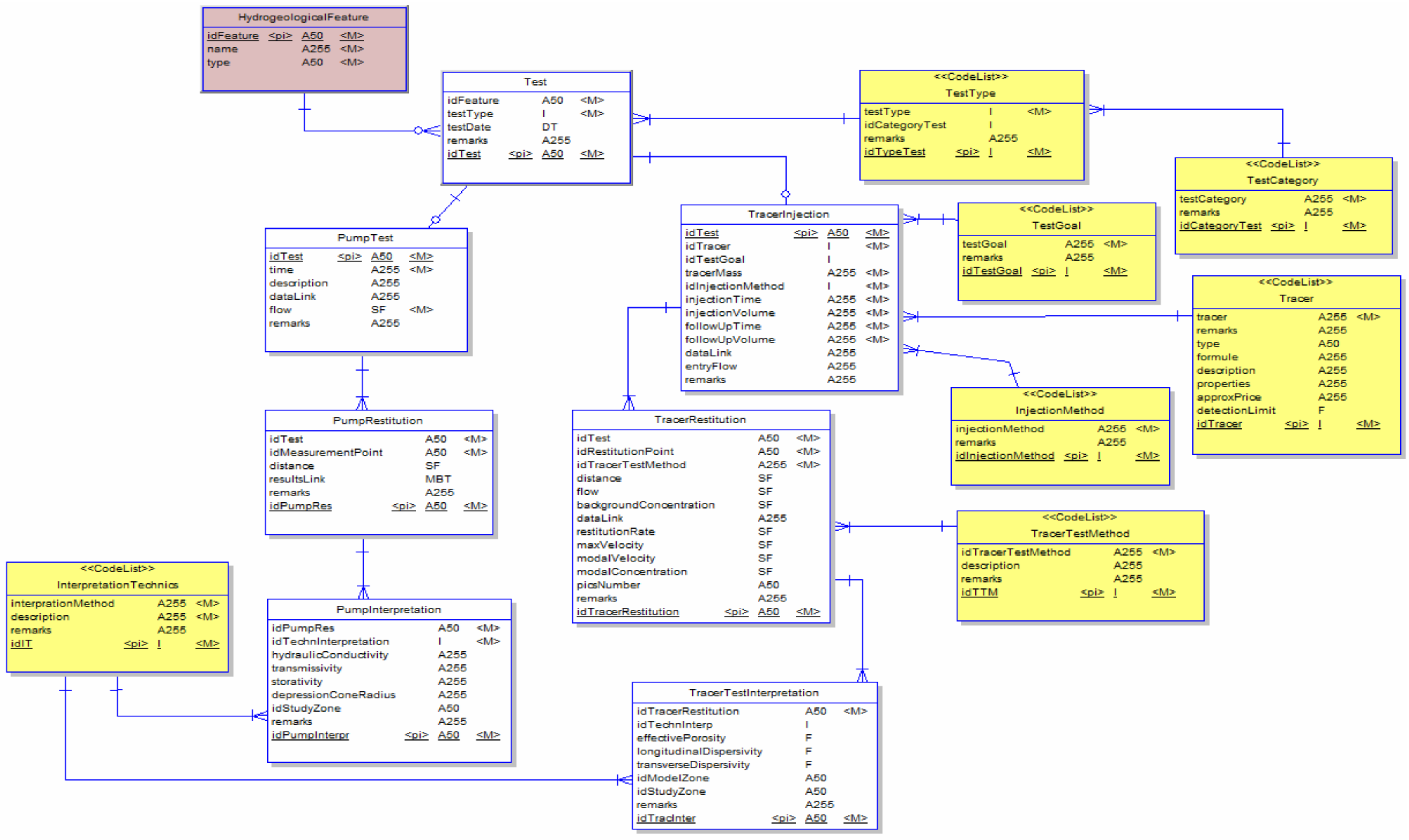


Figure 19. Entity-relationship diagram of test sub-model for pumping tests and tracer tests.

First, the experimental setup together with the experimental conditions of each field test are described in details. Information on the experimental setup consists in the exact location of the test, available hydrogeological features used to perform the test, such as wells, piezometers, or sensors. Information on the experimental conditions consists in the period within which the test was performed, the prevailing hydrogeological conditions and more specific data such as pumping rates. Second, measurements performed at different observation points can be stored in the form of time series, such as groundwater head drawdown curves or tracer breakthrough curves. Third, hydrodynamic and hydrodispersive parameter values obtained from the interpretation of the field tests can also be managed in the data model.

Pumping test entities enable to store information on the experimental setup which usually consists in a main pumping well and several surrounding observation wells and piezometers. The experimental conditions are the pumping rate profile associated with the pumping well. Time series of piezometric head level measurements retrieved during the pumping test are stored in association with the different observation points. Information on interpretation techniques, together with their results (such as hydraulic conductivity, transmissivity, storativity, specific yield, and depression cone radius) can be stored separately.

For tracer test entities, the experimental setup consists in the main injection point and several observation points, for instance, a pumping well, monitoring piezometers, or a spring. The experimental conditions include information on tracer injection, associated to the injection point and on tracer recoveries, associated to each observation point. Tracer injection conditions consist in the nature and quantity of the injected tracer and on a description of the injection profile, i.e., injection volume, duration and flush rate. Information on tracer recovery includes, among others, the tracer test method, tracer background concentration and the distance between the injection point and the recovery point. The tracer test entity can also store interpretations of results obtained using analytical or numerical simulation tools.

Practical examples of data encoded in the implemented HydroCube model are presented in Figure 20 for a pumping test. The “Test” entity occurrence is related to the ”HydrogeologicalFeature” (“Well n°10”) where the test was performed. It is also characterized by a test type and a date. Second, more detailed information is provided in the

“PumpTest” entity, such as the pumping rate profile. The results of the test are encoded in the “PumpRestitution” table, in the form of time series associated with each monitoring point. Different interpretations obtained using different analysis methods may finally be stored in the “PumpInterpretation” entity.

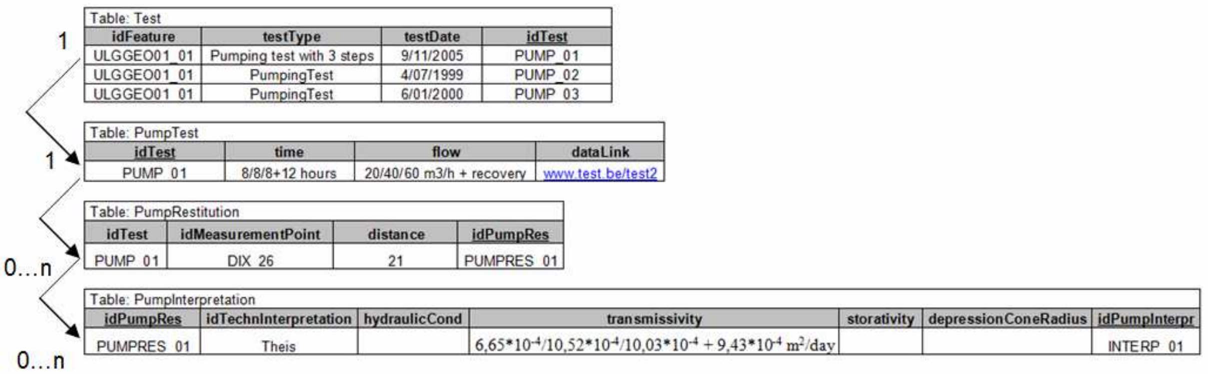


Table: Test

idFeature	testType	testDate	idTest
ULGGEO01_01	Pumping test with 3 steps	9/11/2005	PUMP_01
ULGGEO01_01	PumpingTest	4/07/1999	PUMP_02
ULGGEO01_01	PumpingTest	6/01/2000	PUMP_03

Table: PumpTest

idTest	time	flow	dataLink
PUMP_01	8/8/8+12 hours	20/40/60 m3/h + recovery	www.test.be/test2

Table: PumpRestitution

idTest	idMeasurementPoint	distance	idPumpRes
PUMP_01	DIX_26	21	PUMPRES_01

Table: PumpInterpretation

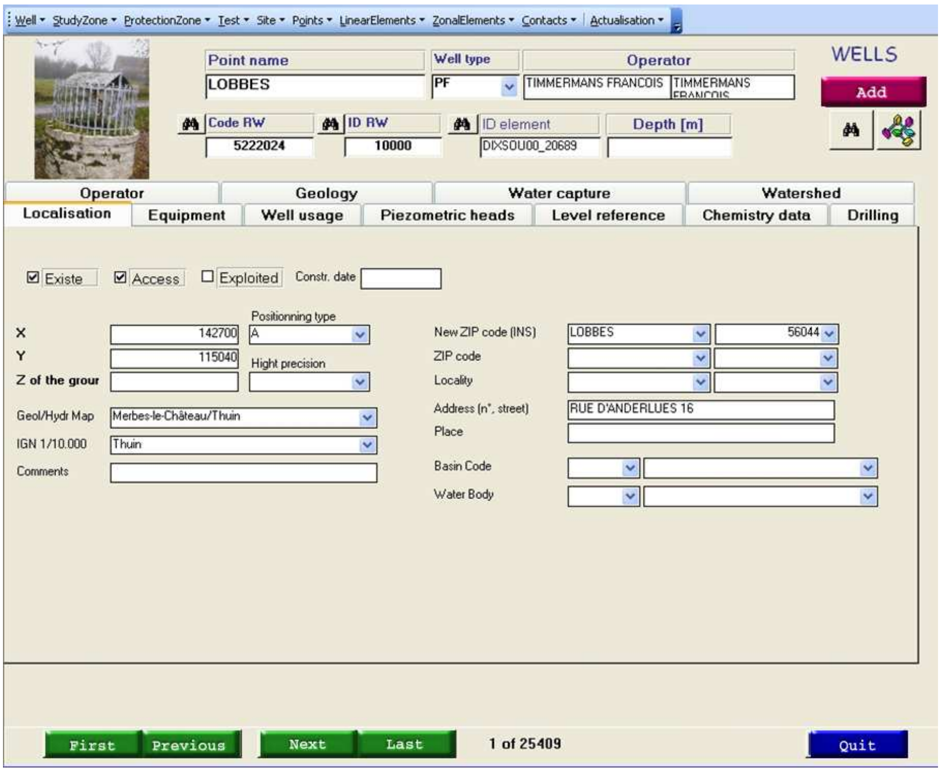
idPumpRes	idTechnInterpretation	hydraulicCond	transmissivity	storativity	depressionConeRadius	idPumpInterpr
PUMPRES_01	Theis		$6,65*10^{-4}/10,52*10^{-4}/10,03*10^{-4} + 9,43*10^{-4}$ m²/day			INTERP_01

Figure 20. Example of a pumping test encoded in the implemented model.

2.4 USER INTERFACE

Because HydroCube covers a full range of hydrogeological concepts, entities and relationships, its internal structure has become relatively complex. Once implemented in a Relational Database Management System, it definitely requires the development of a user-friendly interface. A series of graphical modules have been developed to support the user in handling, storing, and retrieving hydrogeological data.

Four main functionalities are provided in the HydroCube database user interface under MS Access: (1) encoding, (2) querying, (3) visualisation and (4) export. Different forms are available for “one-by-one” or “massive” data encoding. For instance, data on wells and piezometers are managed using the “Well” form (Figure 21), which allows encoding information such as the well name, its location etc. In this form, additional tabs of the well form allow for the introduction of related information: construction elements, identified aquifers, lithological description and others. Piezometric head level measurements or chemistry measurements performed on a water sample can be encoded through their respective Piezometric heads and Chemistry data tabs.



Point name: LOBBES
Well type: PF
Operator: TIMMERMANS FRANCOIS | TIMMERMANS FRANCOIS
Code RW: 5222024
ID RW: 10000
ID element: DIXSOU00_20689
Depth [m]:

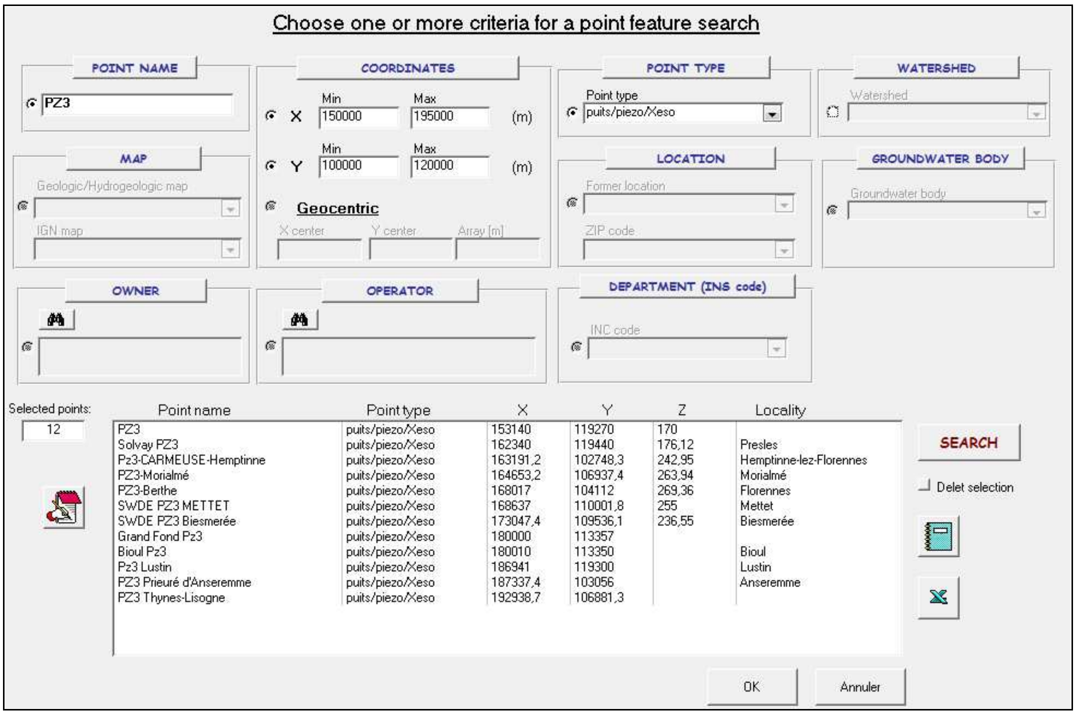
☑ Existe ☑ Access ☐ Exploited Constr. date

X: 142700
Y: 115040
Z of the grour:
Positionning type: A
Hight precision:
Geol/Hydr Map: Merbes-le-Château/Thuin
IGN 1/10.000: Thuin
Comments:
New ZIP code (INS): LOBBES | 56044
ZIP code:
Locality:
Address (n°, street): RUE D'ANDERLUES 16
Place:
Basin Code:
Water Body:

1 of 25409

Figure 21. Well form allows to introduce basic data describing a well. Specialized tabs permit to store additional information about construction elements, lithology and related observations and measurements.

The HydroCube interface provides specific query forms that allow using one or several search criteria and combining them for more advanced requests on the hydrogeological data stored in the database. The query forms allow one to choose point, arc and polygon-type features, based on the values of their attributes. More advanced non-spatial queries can also be defined using the standardized MS Access query builder. Since the MS Access implementation platform is not spatially enabled, point-type search only is available, be based on localisation attributes such as one particular region/map or based on a radial functions (Figure 22). More complex spatial queries can however be performed using external GIS software.



Choose one or more criteria for a point feature search

POINT NAME: ● PZ3

COORDINATES: ● X Min 150000 Max 195000 (m)
● Y Min 100000 Max 120000 (m)

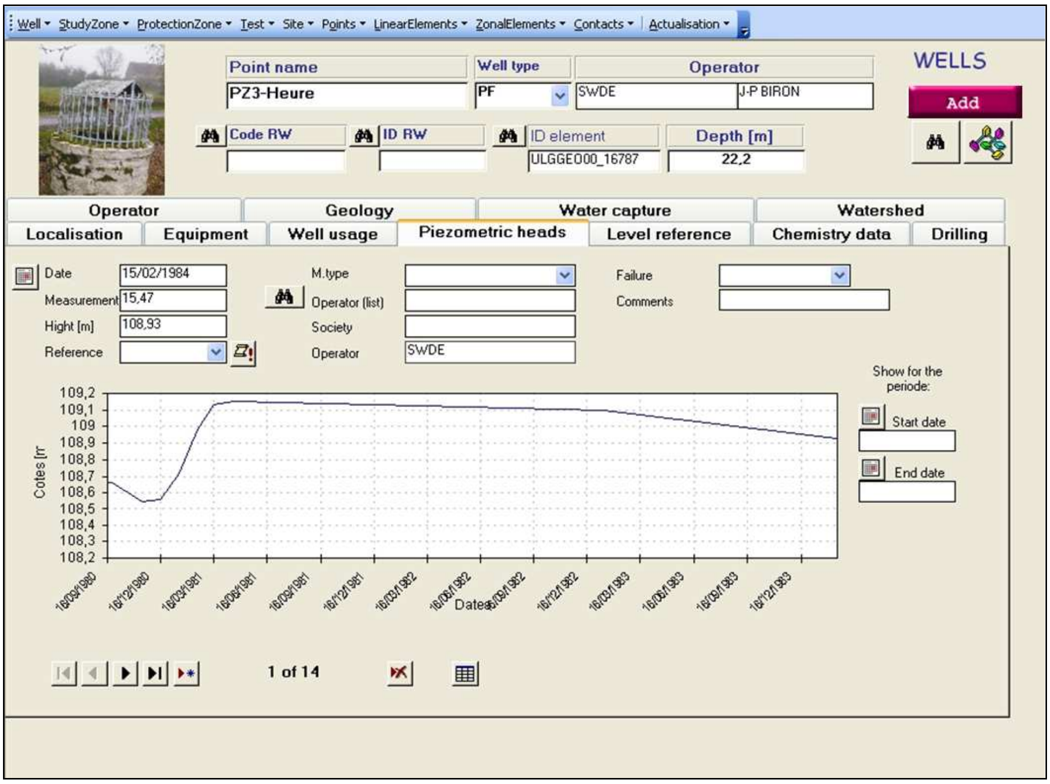
POINT TYPE: ● Point type puits/piezo/Xeso

Selected points: 12

Point name	Point type	X	Y	Z	Locality
PZ3	puits/piezo/Xeso	153140	119270	170	
Solvay PZ3	puits/piezo/Xeso	162340	119440	176,12	Presles
Pz3-CARMEUSE-Hemptinne	puits/piezo/Xeso	163191,2	102748,3	242,95	Hemptinne-lez-Florennes
PZ3-Morialmé	puits/piezo/Xeso	164653,2	106937,4	263,94	Morialmé
PZ3-Berthe	puits/piezo/Xeso	168017	104112	269,36	Florennes
SWDE PZ3 METTET	puits/piezo/Xeso	168637	110001,8	255	Mettet
SWDE PZ3 Biesmerée	puits/piezo/Xeso	173047,4	109536,1	236,55	Biesmerée
Grand Fond Pz3	puits/piezo/Xeso	180000	113357		
Bioul Pz3	puits/piezo/Xeso	180010	113350		Bioul
Pz3 Lustin	puits/piezo/Xeso	186941	119300		Lustin
PZ3 Prieuré d'Anseremme	puits/piezo/Xeso	187337,4	103056		Anseremme
PZ3 Thynes-Lisogne	puits/piezo/Xeso	192938,7	106881,3		

Figure 22. Query form for point-type hydrogeological features allows one to execute simple queries on attributes of features. Spatial queries, based on localisation or advanced queries can be performed when criteria are combined. The results of a data query is displayed in the list form and can be visualized at once, when all the features are chosen, can be exported into the MS Excel file, or can be transferred into the field form.

Data visualisation can be performed using several visualisation tools included in the HydroCube user interface. For example, piezometric head level measurements can be visualized, for a chosen period, for one particular well (Figure 23).



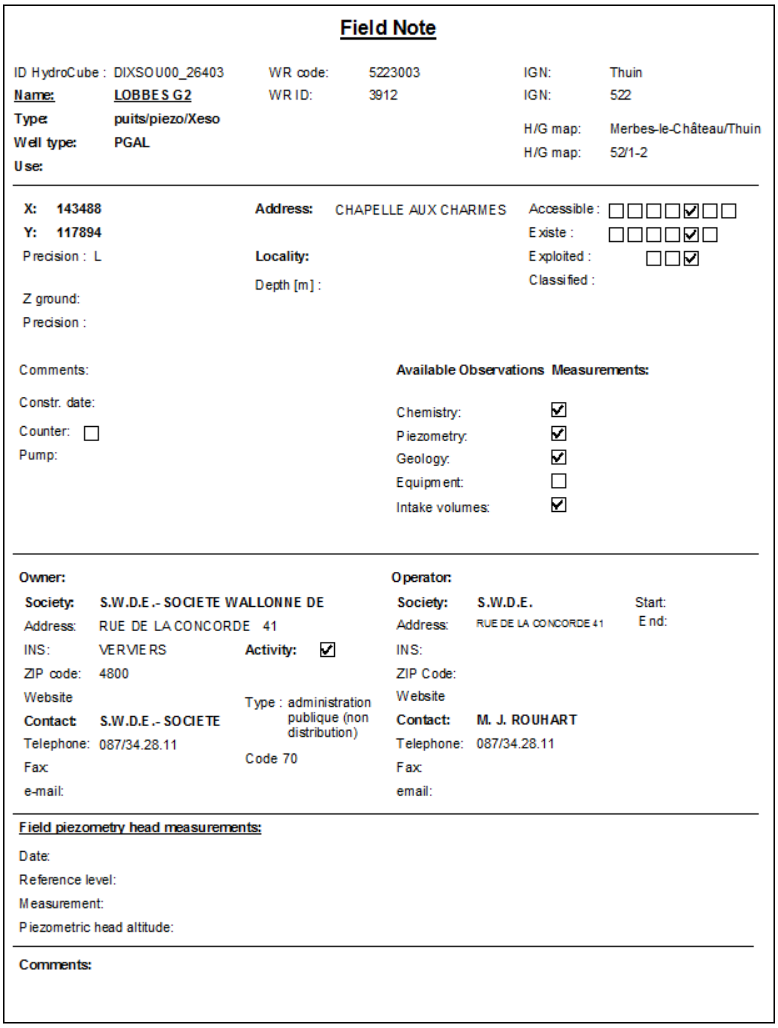
Point name: PZ3-Heure
Well type: PF
Operator: SWDE J-P BIRON
Code RW:
ID RW:
ID element: ULGGEO00_16787
Depth [m]: 22,2

Date: 15/02/1984
Measurement: 15,47
Hight [m]: 108,93
Reference:
M.type:
Operator (list):
Society:
Operator: SWDE
Failure:
Comments:

1 of 14

Figure 23. Piezometric head level measurements visualisation form allows one to view measurements for a chosen period of time.

Any data previously encoded in the HydroCube database can be exported to either MS Excel® or MS Word®, or to more specialized Field Forms that can be printed and further uses in the field during experiments and surveys (Figure 24). Such Field Forms allow compiling all the available information about existing wells and piezometers prior to additional measurements in the field.



Field Note

ID HydroCube : DIXSOU00_26403
Name: **LOBBES G2**
Type: **puits/piezo/Xeso**
Well type: **PGAL**
Use:

WR code: 5223003
WR ID: 3912

IGN: Thuin
IGN: 522
H/G map: Merbes-le-Château/Thuin
H/G map: 52/1-2

X: **143488**
Y: **117894**
Precision : L
Z ground:
Precision :

Address: CHAPELLE AUX CHARMES
Locality:
Depth [m] :

Accessible : ☐☐☐☐☑☐☐
Existe : ☐☐☐☐☑☐
Exploited : ☐☐☑
Classified :

Comments:
Constr. date:
Counter: ☐
Pump:

Available Observations Measurements:
Chemistry: ☑
Piezometry: ☑
Geology: ☑
Equipment: ☐
Intake volumes: ☑

Owner:
Society: **S.W.D.E.- SOCIETE WALLONNE DE**
Address: RUE DE LA CONCORDE 41
INS: VERVIERS
ZIP code: 4800
Website
Contact: **S.W.D.E.- SOCIETE**
Telephone: 087/34.28.11
Fax:
e-mail:

Activity: ☑
Type : administration publique (non distribution)
Code 70

Operator:
Society: **S.W.D.E.**
Address: RUE DE LA CONCORDE 41
INS:
ZIP Code:
Website
Contact: **M. J. ROUHART**
Telephone: 087/34.28.11
Fax:
email:

Start:
End:

Field piezometry head measurements:
Date:
Reference level:
Measurement:
Piezometric head altitude:

Comments:

Figure 24. Field form facilitates the preparation phase for the field work. Once the HydroCube database is queried through a search form, the user can export information into the Field form, where additional measurements or remarks can be noted.

2.5 CONCLUSIONS TO CHAPTER 2

HydroCube proposes a new logical model of hydrogeological data, described using entity-relationship diagrams. This model is based on a geometry-centric classification of hydrogeological features using point, arc, and polygon entities. It proposes an innovative and holistic "project-based" approach that covers a full set of hydrogeological concepts and features, allowing for efficient hydrogeological project management. In particular, the model enables the user to store data about the project location, existing hydrogeological equipment, related observations and measurements, and a very innovative and specialized model for hydrogeological field experiments such as pumping tests and tracer tests. The HydroCube model incorporates topological relationships that facilitate management of spatially associated data. It is implemented in an MS Access® database with a full set of user-interfaces to encode, query, visualize and export hydrogeological data for their subsequent use in groundwater management projects.

The HydroCube model has been used for 3 years now, for hydrogeological data management in many real studies, in different universities, as well as in administrations in the Walloon Region. It has been continuously fed by different local and regional projects such as the Hydrogeological Maps of the Walloon Region (Bouezmarni et al., 2006), large-scale groundwater modelling projects (Orban et al., 2004), the FP6 AquaTerra Project (Batlle Aguilar et al., 2007), groundwater vulnerability mapping (Popescu et al., 2004), among others. The HydroCube model and database being used in the Walloon region, rules have been defined for data encoding, and for semi-automatic periodic centralisation and update mechanisms.

The MS Access implementation platform ensures the HydroCube high performance on the team level, using a very cost-effective relational database management system with an easy but advanced programming interface. HydroCube can easily be coupled with any GIS software, which extends the database functionalities for arc- and polygon-type spatial entities. However, MS Access is not a multi-user environment and it presents some storage capacity limits. Because of these limits, first successful tests have already been performed in order to migrate to the ORACLE environment. The ORACLE project will be strictly based on the HydroCube logical model, and it will reuse its user interface.

Further work on the hydrogeological data model consists in the development of an Object-Oriented form, using UML notation and XML schema. This work (Wojda et al., 2006) is being done in the scope of the FP6 Project GABARDINE, focusing on groundwater artificial recharge based on alternative sources of water. The UML methodology will enrich the model with additional functionalities such as different entities behaviour, according to their specific types, additional topological relationships rules, as well as clearer constraints, which can be used during data encoding and transfer to avoid errors. This model can be made compliant with currently emerging norms and standards for geoinformation transfer such as ISO 19136 describing Geography Markup Language (GML) used for modelling, transport, and storage of geographic information (Cox et al., 2002; Lake, 2005). GML provides a large variety of objects for describing features, co-ordinate reference systems, geometry, topology, time, units of measure and generalised values. GML has already been extended to three domain specific application schemas: XMML (Cox, 2004), GeoSciML (Sen and Duffy, 2005; Simons *et al.*, 2006), and GWML (Boisvert, Brodeur, Brodaric, 2005).

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CHAPTER 3

OBJECT-ORIENTED HYDROGEOLOGICAL DATA MODEL: GABARDINE GEOSPATIAL DATABASE

3.1 INTRODUCTION

A new object-oriented physical hydrogeological data model is presented here which helps to maintain hydrogeological information availability in one standard format. It uses advantages of object-oriented modelling and it is compliant with the recommendations from the European Geospatial Information Working Group (Vogt, 2002). The hydrogeological data model is described using a series of the UML diagrams, following the object-oriented paradigms, as well as recommendations of the International Organization for Standardization with its Technical Committee 211 (ISO/TC211), and the Open Geospatial Consortium (OGC). This data model has been implemented in the ArcGIS environment, as a database for a decision support system developed in the scope of the FP6 project ("*Groundwater Artificial recharge Based on Alternative sources of wateR: aDvanced INtegrated technologies and managEment*"; http://www.gabardine-fp6.org/). Following the rules of the ArcGIS implementation platform, hydrogeological features are specialization of abstract classes and they are organized in packages of spatial feature datasets. The observations and measurements related to these features are organized in a non-spatial package, which follows the Observations and Measurements international standard (OGC 07-022r1, 2007).

Data modelling background on object-oriented modelling and UML is illustrated by a review of the existing geological and hydrogeological data models. Then, the new hydrogeological logical data model is presented. The structure and relationships of hydrogeological features are presented, followed by a description of associated observations and measurements. Based on the OGC Observations & Measurements international standard, a novel implementation of the data model for hydrogeological field tests such as pumping tests and tracer test is also described. The conclusions propose further developments as well as the possible contribution of the new hydrogeological data model to an international groundwater information exchange standard: Hydrogeology Markup Language.

3.2 DATA MODELLING BACKGROUND

The GABARDINE hydrogeological data model was inspired by several existing hydrogeological data models briefly described here after.

The HydroCube data model, described in Chapter 2, has been developed at the University of Liège for a holistic hydrogeological project management. It uses formalized entity-relationship diagrammatic notation to describe a logical model of hydrogeological data. It has been implemented in a standard MS Access database and enriched with fully functional user interfaces. However, the HydroCube model is described in a standard entity-relationship notation and its MS Access implementation lacks spatial components.

The Guidance document on the implementation of the GIS elements in the European Water Framework Directive (Vogt, 2002) presents several solutions for groundwater data modelling in the scope of resource management and reporting. The corresponding data model is described using simple UML-like notation and it proposes rather a general framework and guidelines, and not a final solution for hydrogeological data modelling.

The WaterStrategyMan project proposes a generic data model which enables describing a water system (surface and groundwater) in terms of water resources availability, demand, infrastructure, and administrative structures (ProGEA S.r.l, 2004). However, it does not meet the hydrogeological community objectives, as its aim was to deal with more general water resources management.

The GABARDINE hydrogeological data model takes also its inspiration from international standards or on-going standardization for storage and exchange of geospatial information:

- Geography Markup Language (GML) described by the ISO 19136 standard (Cox *et al.*, 2002; Lake, 2005), with its application schemas:
- eXploration and Mining Markup Language (XMML) (Cox, 2001),
- Geoscientific Markup Language (GeoSciML) (Sen and Duffy, 2005),
- GroundWater Markup Language (GWML) (Boisvert and Brodaric, 2007) in a first phase of development.
- Observations and Measurements (O&M) described by Observation schema (OGC 07-022r1, 2007) and Observation Features (OGC 07-002r3, 2007).

GML is an XML grammar written in XML Schema which provides a large variety of objects for describing features, co-ordinate reference systems, geometry, topology, time, units of measure and generalized values. The ISO 19136 standard describes GML. It is intended to be used as a basis for more domain specific application schemas, such as XMML, GeoSciML or GWML. XMML focuses on exploration and mining issues, with applications in the industrial sector. GeoSciML is as an on-going standardization for geoscientific information exchange format mainly for structural geology such as geological units, sampling features such as boreholes, geologic vocabulary, and earth materials. GWML is specifically being developed for the exchange of hydrogeological data, however its development is in the early stage and its proposals have not been tested yet. The OGC O&M international standard proposes a conceptual model and encoding for observations and measurements. Although the O&M with its application schemas are currently being standardized, they have been developed for generic geoinformation and they do not deal with specific hydrogeological data. The O&M standard is applicable to different domains and it needs to be implemented or extended to express hydrogeological observations and measurements, or specific hydrogeological field experiments.

3.2.1 OBJECT-ORIENTED MODELLING AND UML

The most important advantages of the object-oriented modelling can be enumerated as follows. First, the o-o modelling reduces complexity of the development process and software structure, it is essential for communication amongst partners and teams, and it guarantees an architectural soundness (OMG, 2001). Secondly, object-oriented modelling techniques have become the geoscientific standard and they enable to reach the model convergence across domains for interoperability. Using o-o modelling, it is possible to integrate a hydrogeological data model with other domain specific data models, under the condition that model overlapping is avoided. Furthermore, when data models are explored and applied by geospatial analysts, they assure an interoperable data exchange between different project actors by pre-defined data structures or by using open-web standards for geospatial information. Finally, object-oriented models expressed in UML (Unified Modeling Language) are easily adaptable and extensible with new components or available additional modules.

3.2.2 ARCGIS IMPLEMENTATION PLATFORM

The GABARDINE data model has been developed to be directly implemented in the ArcGIS software. As a consequence, the ArcGIS implementation platform has imposed several constraints, amongst which the specific framework for the model development and restricted name domains. The general framework for the UML model was developed by ESRI and it is based upon traditional GIS geometry-first approach. It means that every feature requires a unique geometry to be defined *a priori*. Therefore, it does not follow the General Feature Model formally defined by ISO TC/211 (ISO 19101 and ISO 19109), where every feature has a geometry property set to a point location, a line string in space or a bounded area (Sen and Duffy, 2005).

3.3 DESCRIPTION OF THE GABARDINE DATA MODEL

Any domain application schema should relate to one specific domain, importing other necessary components from externally governed application schemas (ISO/DIS 19110, 2001). As a consequence of that recommendation, specific hydrogeological feature classes have been developed in the GABARDINE model, with more general feature classes imported from other models, namely GML, XMML, and GeoSciML. All the elements have been adapted to fit ArcGIS implementation. The hydrogeological feature classes have been grouped in the following packages: AbstractFeatures, GroundwaterFeatures, Hydrogeology, and Observations&Measurements. All the diagrams presented in Chapter 3 use the following UML notation, Figure 25. The used terms are defined at the end of this thesis.

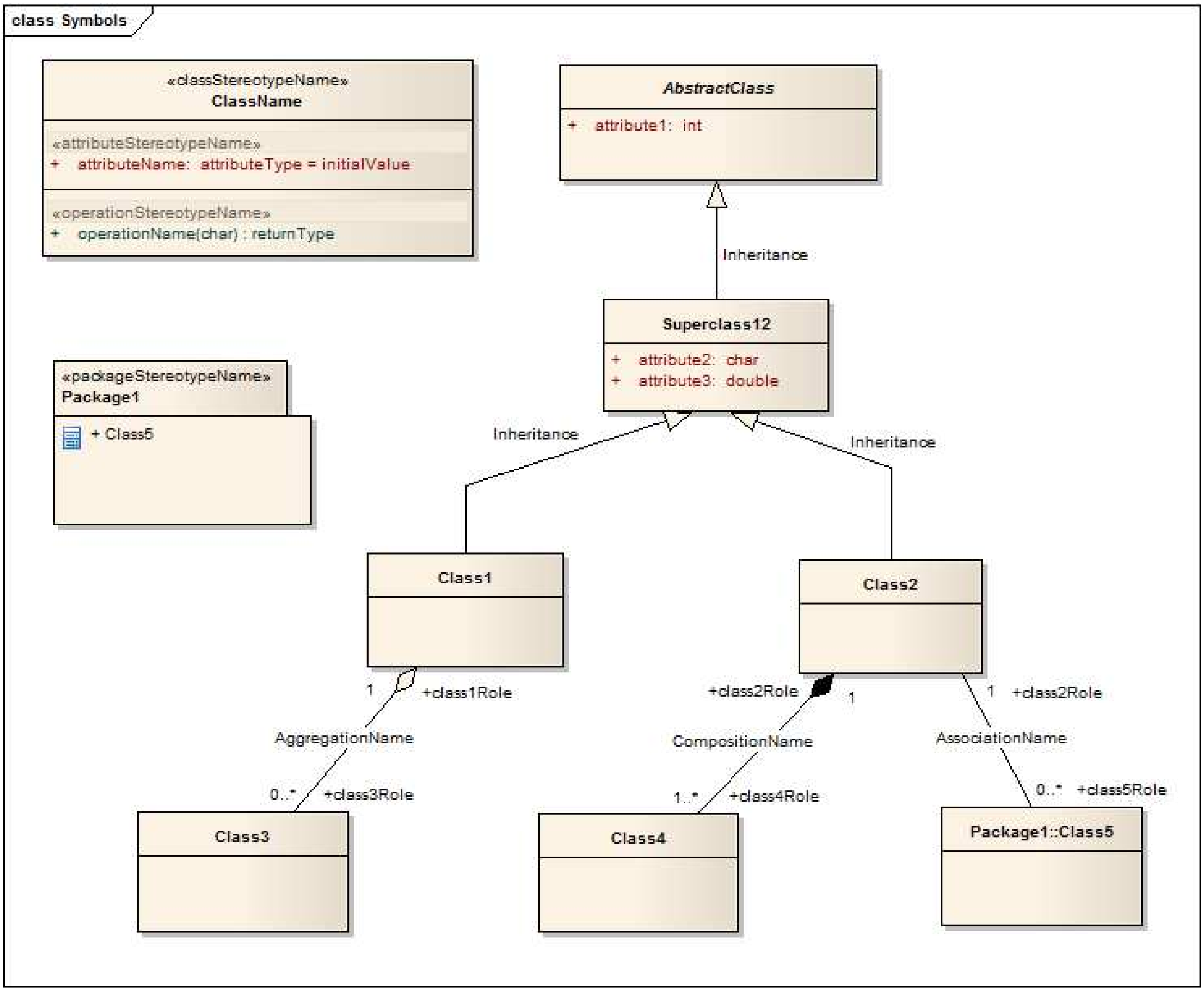


Figure 25. Symbols in the UML notation. All the terms are defined in the Terms and definitions section.

3.3.1 ABSTRACT FEATURES

The AbstractFeatures package contains only abstract classes which are common to different parts of the model (Figure 26). It contains the main super class “Feature”, which comes from ESRI pre-defined classes. The “Feature” class has one attribute defining the geometry of the geospatial feature, which is constant through the life-time of the feature class instance.

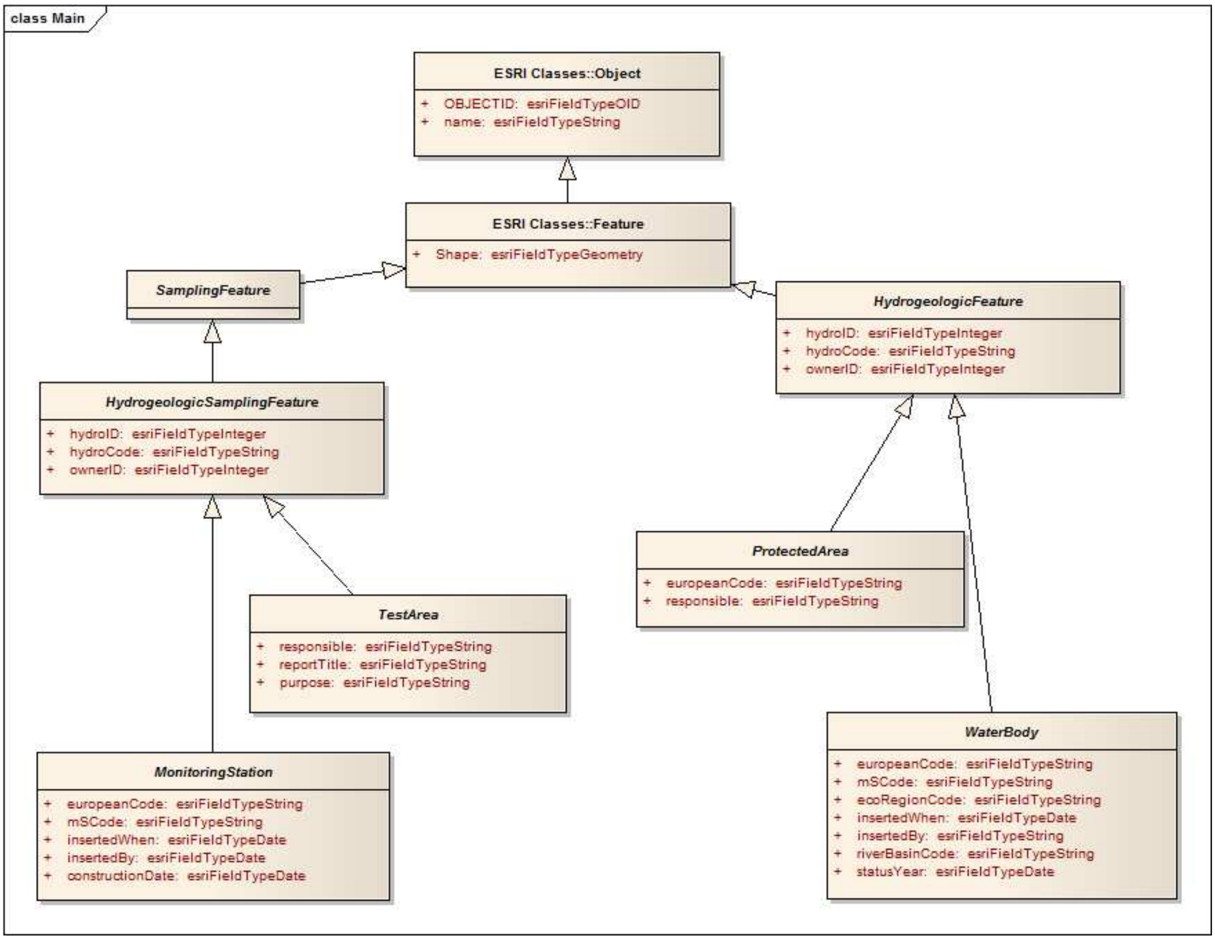


Figure 26. Abstract features of the GABARDINE data model.

The Feature class is extended by two abstract features, namely: SamplingFeature and HydrogeologicFeature. The SamplingFeature class is used primarily for making observations of any kind. It has a HydrogeologicSamplingFeature class specialization, defined as “a natural or constructed structure that allows access to groundwater or where the groundwater system is observed or measured” (National Groundwater Committee…., 1999). The hydrogeologic sampling feature can be used for two purposes: monitoring of hydrogeological conditions by observations and measurements, or groundwater exploitation by extraction or water injection.

The HydrogeologicSamplingFeature is extended by the MonitoringStation class and the TestArea class.

The HydrogeologicalFeature class represents any hydrogeologic geospatial feature which is **not** used for making observation. The HydrogeologicalFeature may be seen as a specialization of GeologicFeature from GeoSciML that represents “a conceptual feature that is hypothesized to exist coherently in the world, it corresponds with a "legend item" from a traditional geologic/hydrogeologic map” (GeoSciML). The HydrogeologicFeature class is extended by the following abstract classes: WaterBody, ProtectedArea.

HydrogeologicSamplingFeature and HydrogeologicFeature constitute two main elements in the developed data model. They provide a unique identifier for geospatial features, available for any internal or external components or software and they have three attributes: hydroID, hydroCode and ownerID.

3.3.2 GROUNDWATER SAMPLING FEATURES

The GroundwaterSamplingFeatures package is stereotyped as a <<Feature Dataset>>. It contains a number of sampling features derived directly from the HydrogeologicalSamplingFeature class, namely: Well, MultipleWell, Spring, Sinkhole, Excavation, Trench, Drain, and Gallery (Figure 27). These specific concrete feature classes instantiate geospatial sampling features with different attribute values. For instance, the Well class creates a feature called “Well n°1”, with the following attributes: a code, an owner, a pre-defined type, a depth and an elevation.

To monitor the groundwater and surface water status and to appropriately manage this information, the WFD makes an explicit distinction between Surface Water Monitoring and Groundwater Monitoring (Vogt, 2002). In the GABARDINE data model, respective classes were created. The abstract super class “MonitoringStation” is described with the following attributes, Table 3.

MonitoringStation	
Attribute	**Definition**
name	indicates the name of the station
europeanCode	indicates a unique code incorporating the ISO Country Code plus the MSCode
mSCode	indicates a unique code for the monitoring station

Table 3. MonitoringStation class attributes.

The child GroundwaterMonitoringStation class has the following attributes: **type** which defines if the station is operational, or of any other type; **depth** which indicates the station depth in meters.

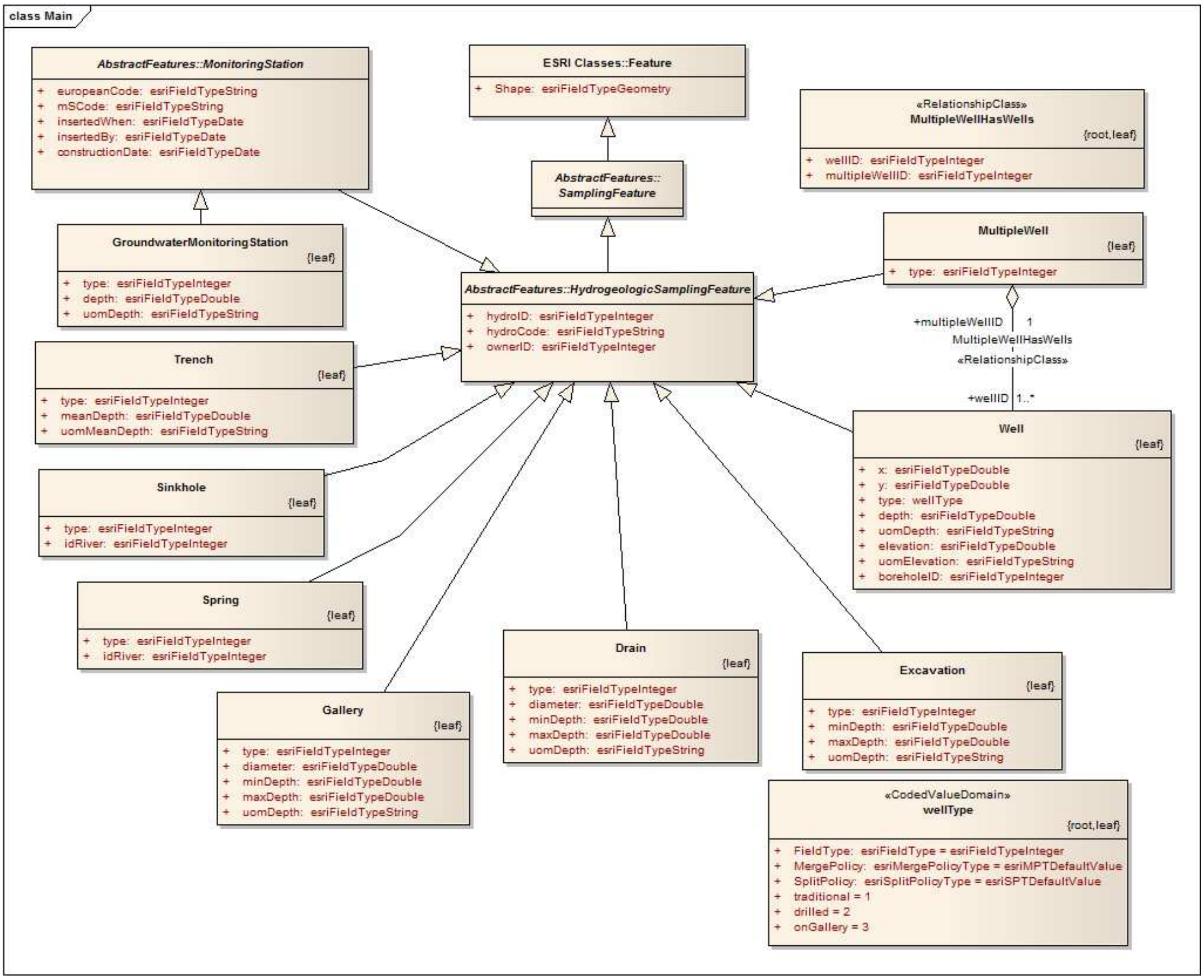


Figure 27. Sampling feature classes derived from the HydrogeologicSamplingFeature abstract super class.

3.3.2.1 CONSTRUCTION ELEMENTS SUB-PACKAGE

Groundwater sampling features such as springs or wells may have multiple construction elements (Figure 28). For instance, a production well can be equipped with a full suite of casing, screens, seals, gravel packs, pumps to increase its productivity, or to automate the groundwater exploitation.

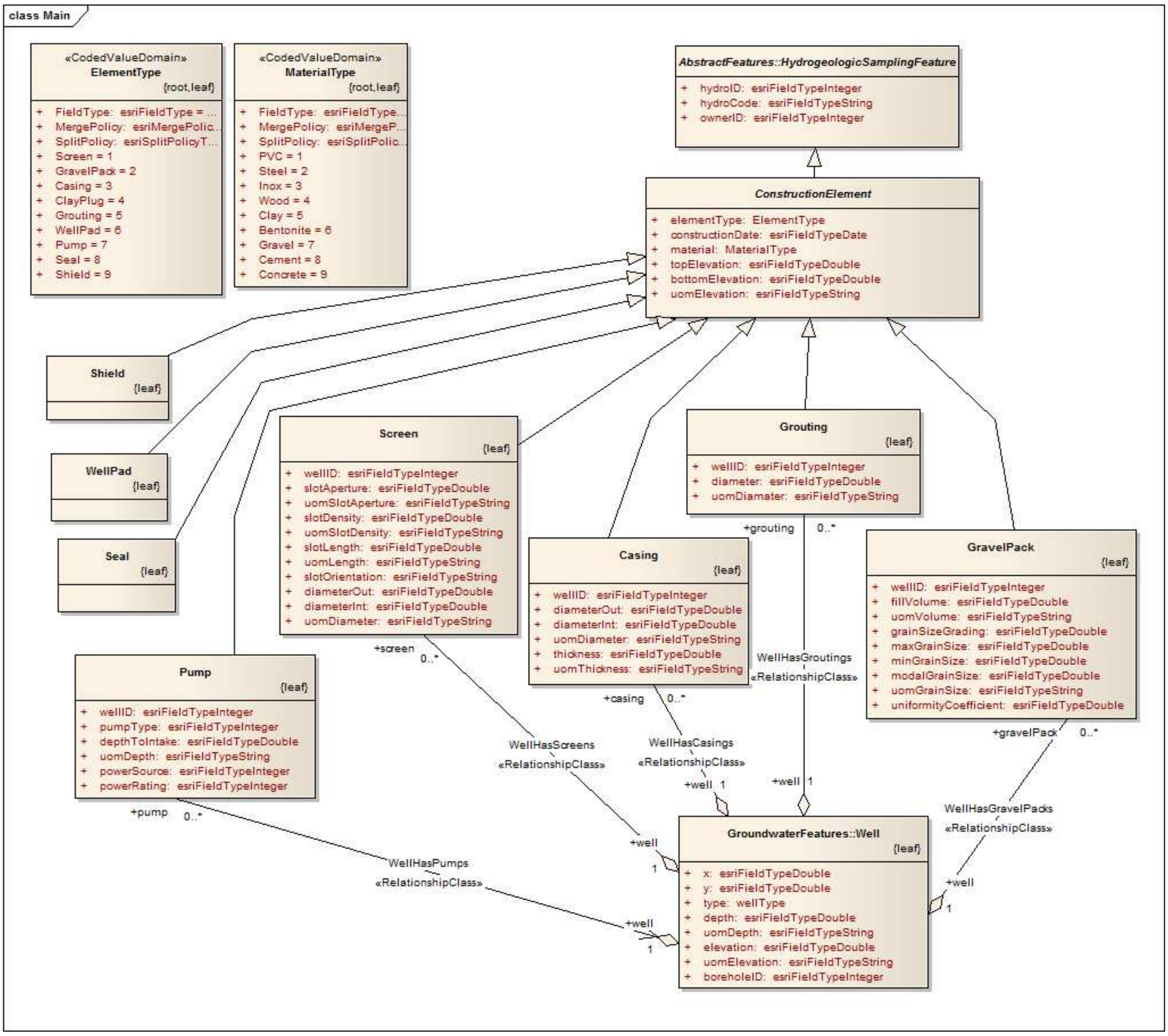


Figure 28. Construction elements sub-package describes all the necessary construction element classes. A construction element is defined as a man-made module of a groundwater feature that improves access to groundwater.

The Casing class has the following attributes describing the cross section dimensions, Table 4.

Casing	
Attribute	**Definition**
diameterInt	indicates the inner diameter of the casing
diameterOut	indicates the outer diameter of the casing
uomDiameter	indicates the unit of measure for the diameters
thickness	indicates the thickness of the casing element
uomThickness	indicates the unit of measure for the thickness

Table 4. Casing class attributes.

The Screen class has the following attributes, Table 5.

Slot	
Attribute	**Definition**
slotAperture	indicates the slot aperture in the screen
uomSlotAperture	indicates the unit of measure for the slot aperture
slotDensity	indicates the slot density of the screen
uomSlotDensity	indicates the unit of measure for the slot density
slotLength	indicates the slot length in the screen
uomSlotLength	indicates the unit of measure for the slot length
slotOrientation	indicates the slot orientation in the screen
uomSlotOrientation	indicates the units of measure of slot orientation

Table 5. Slot class attributes.

All the construction element classes are associated with groundwater sampling features. As an example, the Screen class is associated with the Well class (Figure 29. Aggregation WellHasScreens between the Well and the Screen feature classes.). The "Screen level 3" feature instantiated from the Screen feature class, is described by its properties. It is associated with the "Well n°1" feature, instantiated from the Well feature class.

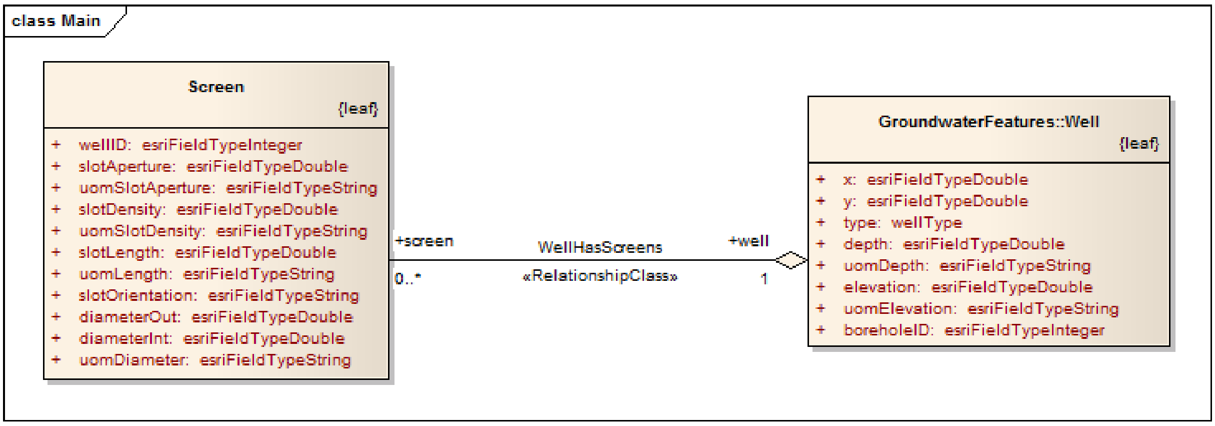


Figure 29. Aggregation WellHasScreens between the Well and the Screen feature classes.

3.3.2.2 BOREHOLE SUB-PACKAGE

This part of the model has been developed according to the XMML specifications regarding the Borehole profile (XMML, 2006), which have been incorporated within GeoSciML 2.0 (Figure 30). However, for implementing the Borehole sub-package, several concepts have been adapted according to the ArcGIS implementation platform requirements (Figure 31). Furthermore, the GABARDINE data model assumes that the Well class is not a specialization of the Borehole class, which is another sampling feature, giving just a location for a well feature. The association between a well and its borehole is made by the boreholeID attribute in the Well class.

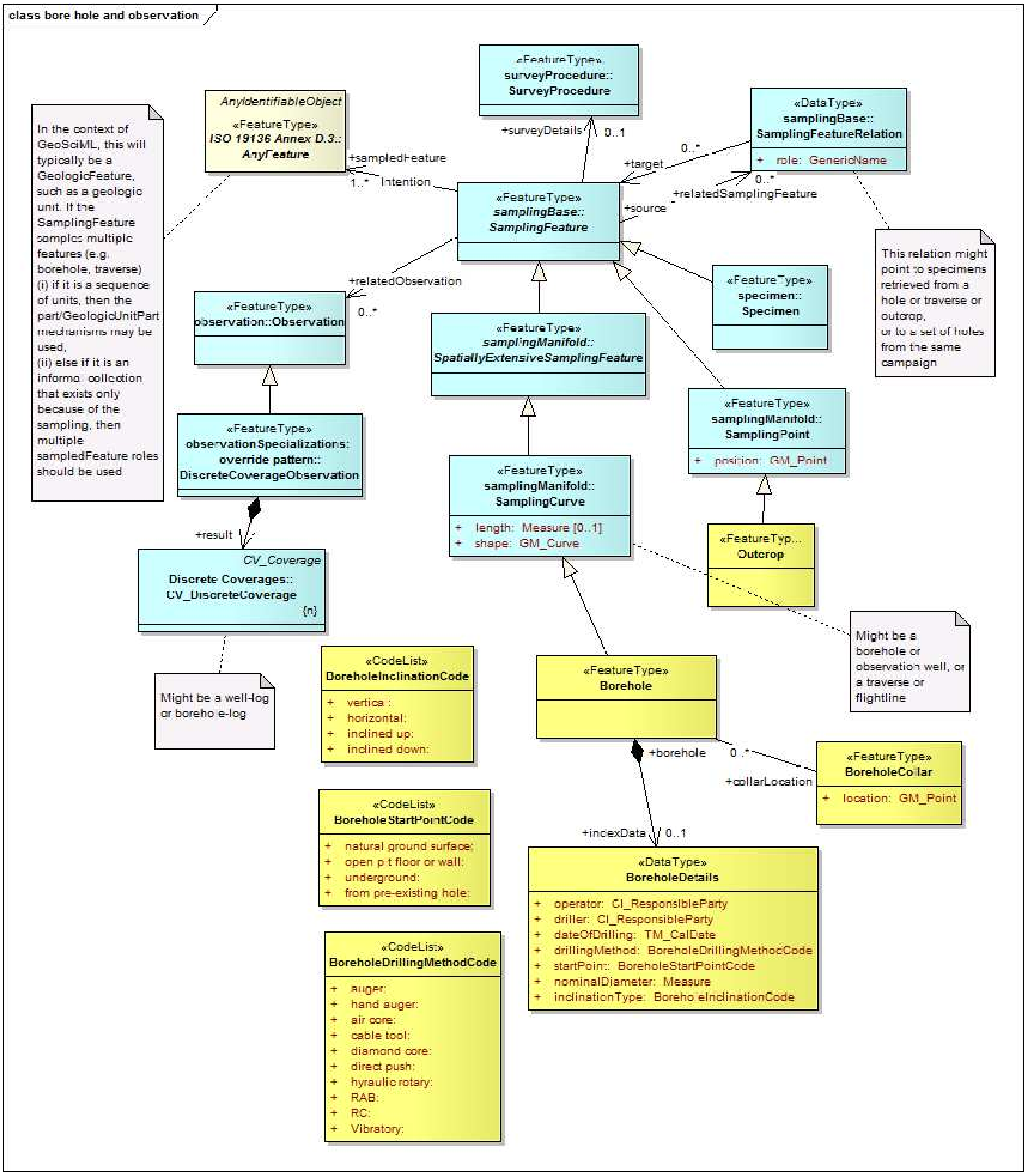


Figure 30. Borehole package from GeoSciML 2.0. The Borehole class is a specialisation of the SamplingCurve class and it has an association with the BoreholeCollar class. Borehole details are aggregated by the appropriate BoreholeDetails class, (source: GeoSciML 2.0).

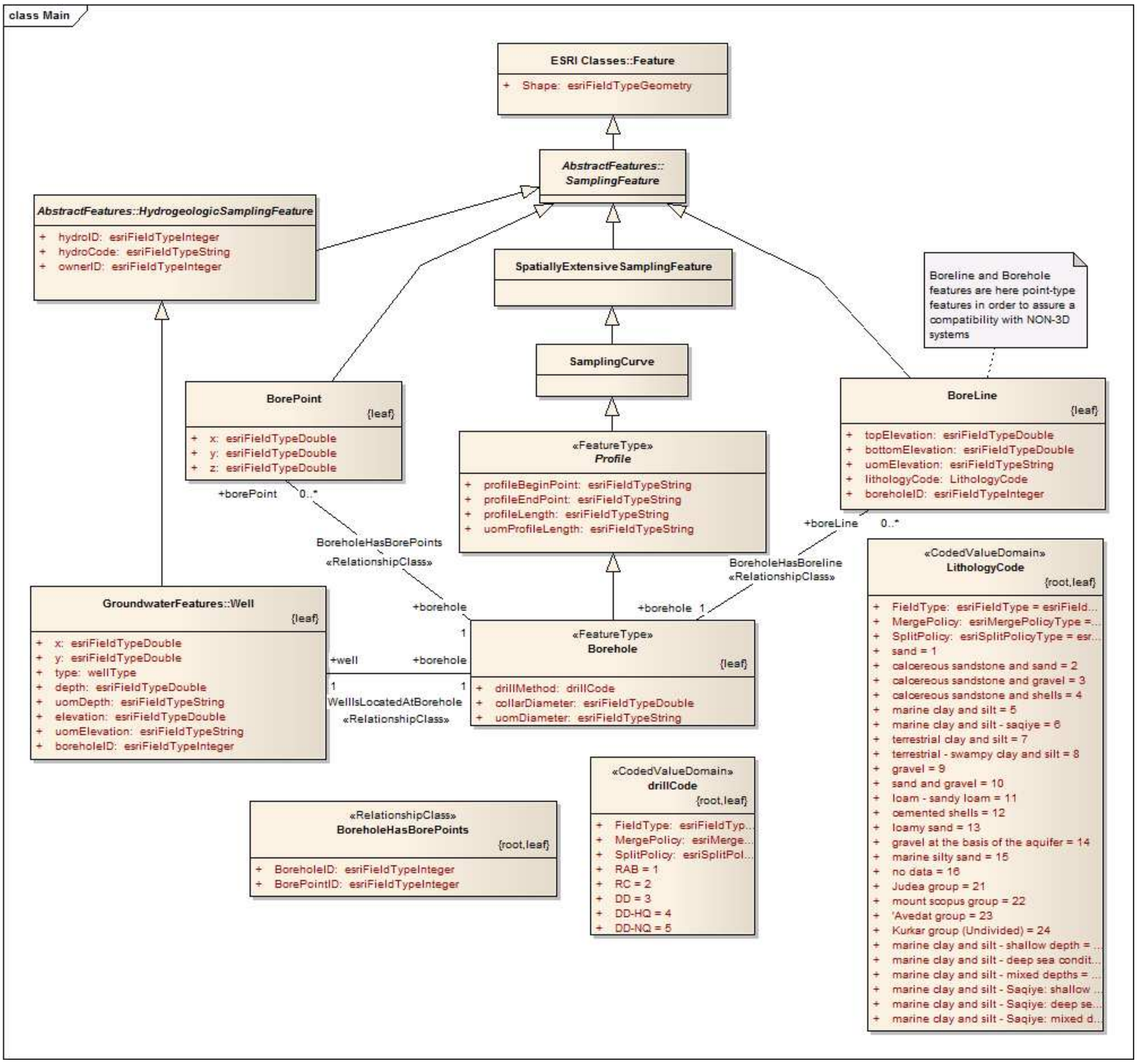


Figure 31. The Borehole sub-package implemented in the GABARDINE data model, based on the XMML/GeoSciML borehole profile proposal. The Borehole class enables to store Lithology codes. It is associated with the Well class.

3.3.3 OBSERVATIONS AND MEASUREMENTS

Geospatial data illustrated in the previous part of this document are not sufficient to describe the aspects concerning integrated groundwater resources management. Hydrogeologists and decision makers need raw and interpreted observations and measurements, associated with geospatial features in order to make decisions. In order to respond to this need, the GABARDINE model contains an important package, called "Observations&Measurements". This data model, presented here after, is based on the HydroCube logical data model (Wojda *et al.*, 2008), and it has been adapted according to the OGC recommendation documents. The solution is based on the Open Geospatial Consortium recommendation and discussion documents (OGC 03-022r3 and 05-087r3), recently as International Standard, 07-022r1 (2007).

3.3.3.1 Single observation or measurement

The Observations&Measurements package allows organizing information on different kinds of single measurements such as surface water level measurements, piezometric head level measurements, water volume measurements and water geochemistry measurements (Figure 32).

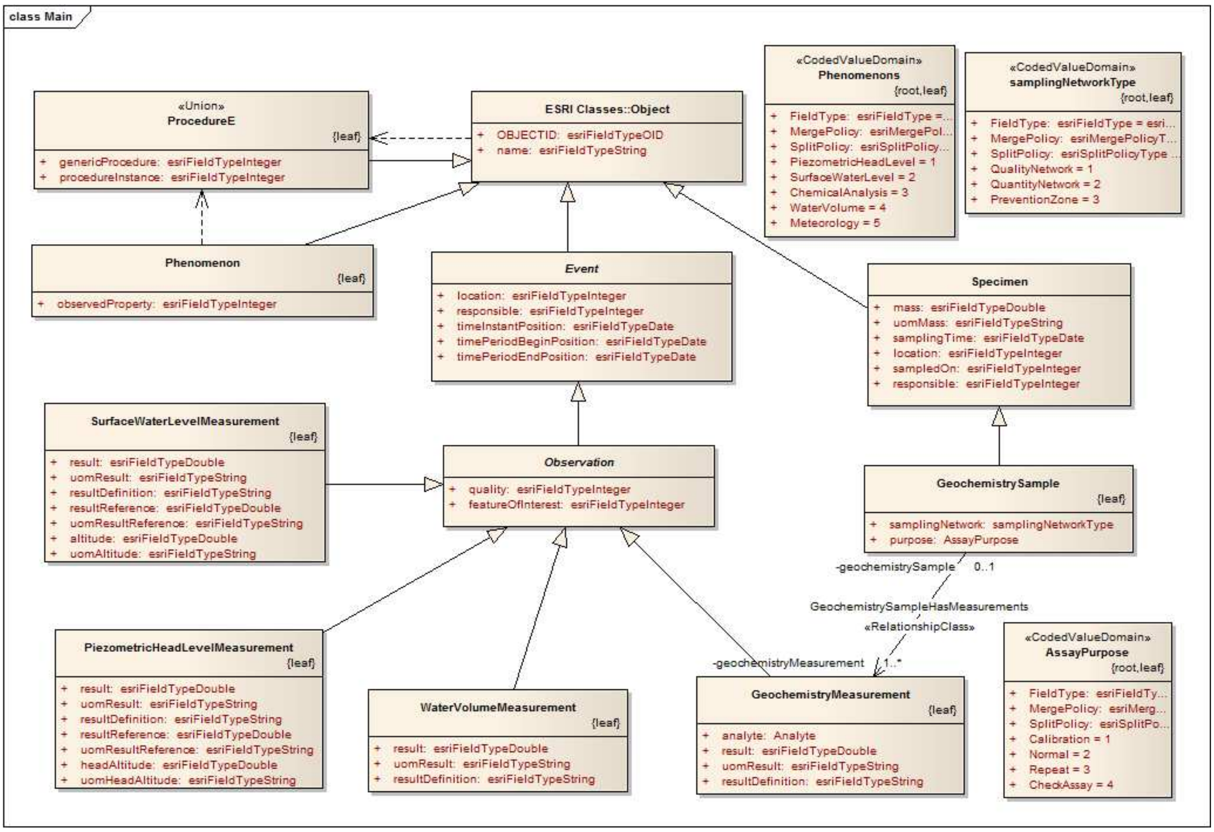


Figure 32. Observations and measurements classes derived from the Observation class.

According to the OGC documents (OGC 03-022r3 and 05-087r4), an Observation is a specialization of an event with a result which has a value describing some phenomenon. An observation binds a result to a feature of interest, upon which the observation was made (Figure 33). A coverage may appear as a consequence of observations, either as the result of a single observation or by compiling results from a suite of observations with a consistent observed property (OGC 07-022r1, 2007).

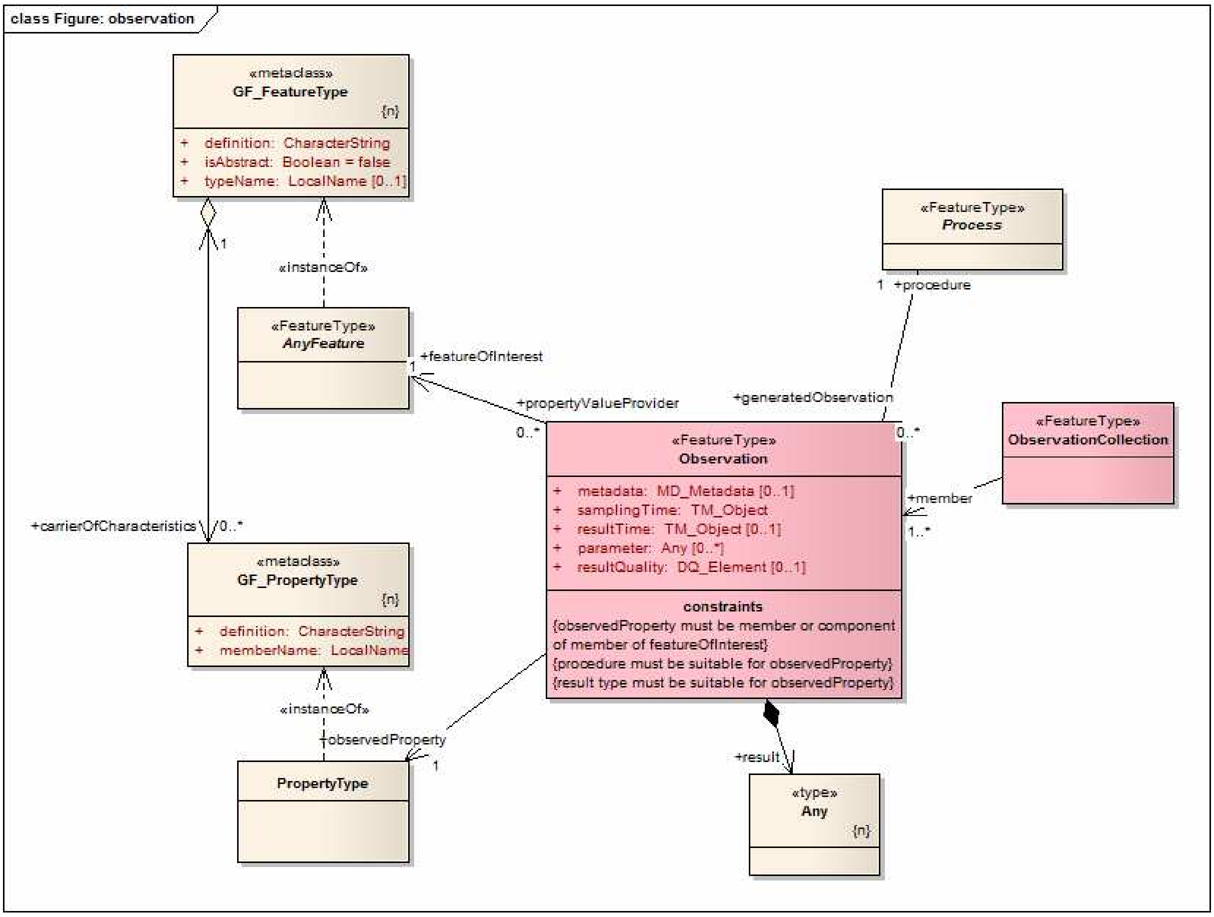


Figure 33. Observation as a value provider for AnyFeature class, Observation & Measurements IS version 1.0 (source: OGC 07-022r1, 2007).

In the proposed hydrogeological model, the Event class inherits from non-spatial Object ESRI class. The Event class is primarily characterized by a time whose value is a temporal object (ESRI date-type). It has the following attributes, Table 6.

Event	
Attribute	**Definition**
location	indicates the location of data acquisition system or sensor, where the observation is made
responsible	records the person or the organisation in charge of the observation
timeInstantPosition	records the observation time instance
timePeriodBeginPosition	records the observation begin time period
timePeriodEndPosition	records the observation end time period

Table 6. Event class attributes.

The AbstractObservation class inherits from the Event class, and it adds the following properties: **quality** gives a description of the quality of the observation; **featureOfInterest** indicates any feature regarding which the observations are being made. According to OGC, the latter could be also called the **target** of the observation, such as a sample, a lake, a well, or river segment, etc.

The AbstractObservation specialisations add the following properties: **result** records the result of the observation or measurement; **uomResult** indicates the unit of measure for the particular measurement; **resultDefinition** gives the definition of the structure of the obtained result. The OGC document 05-087r4 (2006) states that in some data transfer formats it is necessary that any record contains a description of its structure (ISO 19103, 2001), as given in the resultDefinition.

In order to store and transfer geochemistry measurements, the GeochemistrySample class was created. The GeochemistrySample permits to store information on a groundwater sample, on which water chemistry measurements are performed. The GeochemistrySample class inherits from the Specimen class and adds the following attributes, Table 7.

GeochemistrySample	
Attribute	**Definition**
mass	indicates the mass of the specimen
uomMass	indicates the unit of measure of the mass of the specimen
sampleTime	indicates the time when the specimen was sampled
location	describes the original location of the specimen, from where the specimen was taken
sampledOn	indicates any Feature, to which the specimen is related

Table 7. GeochemistrySample class with its attributes.

The GeochemistrySample class is associated with the GeochemistryMeasurement class by a [0…1] to [0…n] relationship. The latter inherits from the AbstractObservation class and it adds, as other specialisation classes, the following properties, Table 8.

GeochemistryMeasurement	
Attribute	**Definition**
result	records the result of the observation or measurement
uomResult	indicates a unit of measure for a particular measurement
resultDefinition	gives the definition of the obtained result

Table 8. GeochemistryMeasurement class with its attributes.

3.3.3.2 *OBSERVATION COLLECTION*

Single observations may be aggregated into an Observation Collection, the latter being treated itself as an observation (Figure 34).

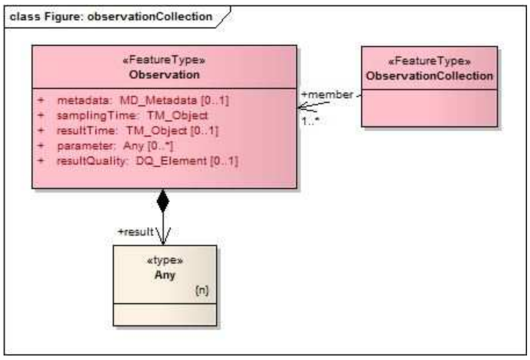


Figure 34. Observation collection that binds arbitrary observations, OGC 07-022r1, 2007.

For instance, during a field trip, a geologist performs different observations such as piezometric level measurements in a series of wells, surface water level in a nearby river, and groundwater sampling for geochemistry analyses (Figure 35). The ObservationCollection is a very convenient bag for a set of observations whose descriptions are largely independent of each other. Furthermore, if the *observationTarget* of these observations and measurements is common for all different phenomena, this attribute can be promoted as a property of the Observation Collection.

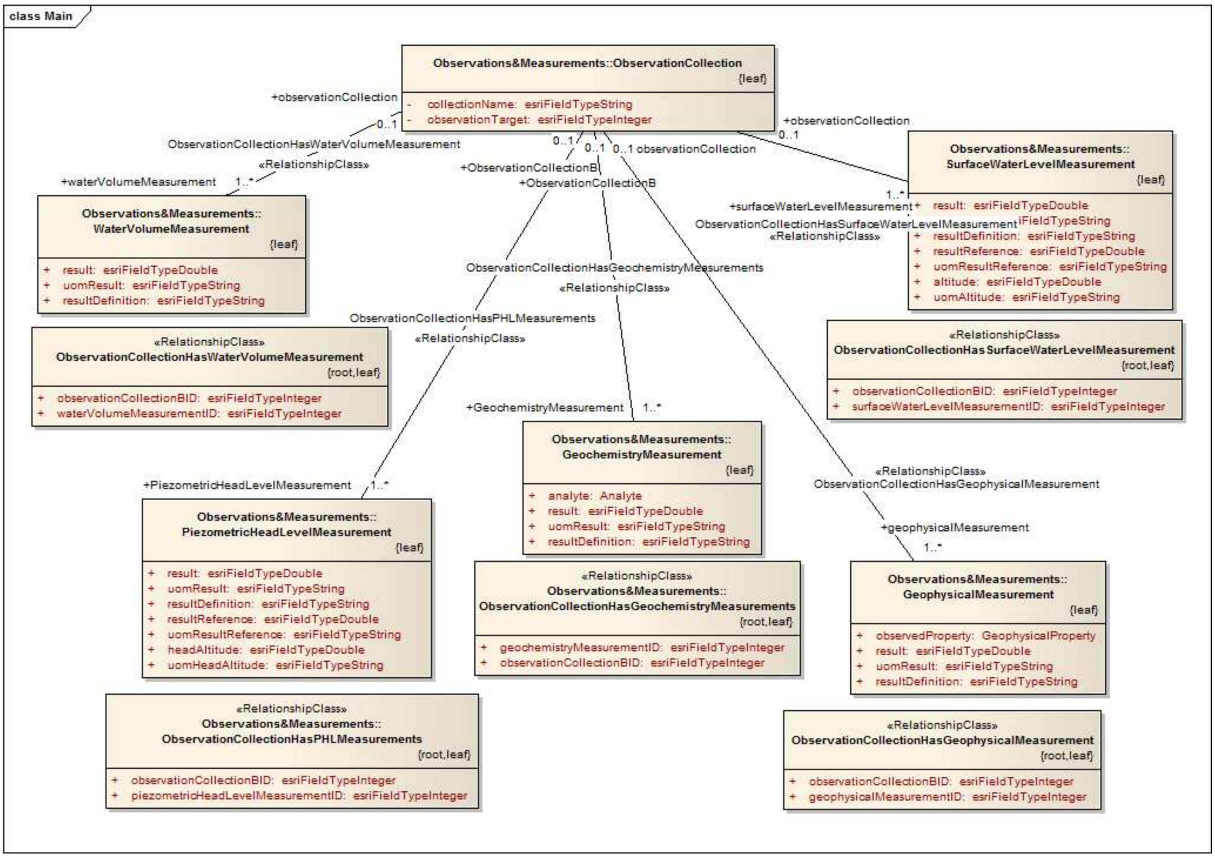


Figure 35. Different observations and measurements specialized classes association with the Observation Collection class.

3.3.3.3 OBSERVATION ARRAY

Contrarily to the observation collection which can contain heterogeneous types of information, the ObservationArray class associates a sequence of homogenously typed observations concerning one phenomenon, such as piezometric levels, tracer concentrations or geophysical property measurements (Figure 36). This sequence can be treated as a Time series or a Depth/Distance series. As an example, piezometric head level measurements can be performed in different observation wells during a Pumping test. These measurements should be encoded within one observation array and treated as a time series in a further analysis.

Homogeneity of observations is defined such that the value of the *observablePhenomenon* property of the members is unique (OGC 03-022r3 and 05-087r4). Therefore, the Observation Array can contain the *observablePhenomenon* attribute, which will be inherited by all its members. Furthermore, if the Observation Array concerns one target or if it is performed using the same common procedure, the *observationTarget* or *using* properties can also be promoted to the ObservationArray class. The ObservationArray class is a specialisation of the ObservationCollection class to which it adds the following attributes, Table 9.

ObservationArray	
Attribute	**Definition**
arrayName	defines the name of the Observation Array
observablePhenomenon	identifies the promoted observed phenomenon
arrayType	defines the type of the array taken from the ArrayType coded value domain
testID	is a unique identifier, which links the Observation Array to one particular test

Table 9. ObservationArray class and its attributes.

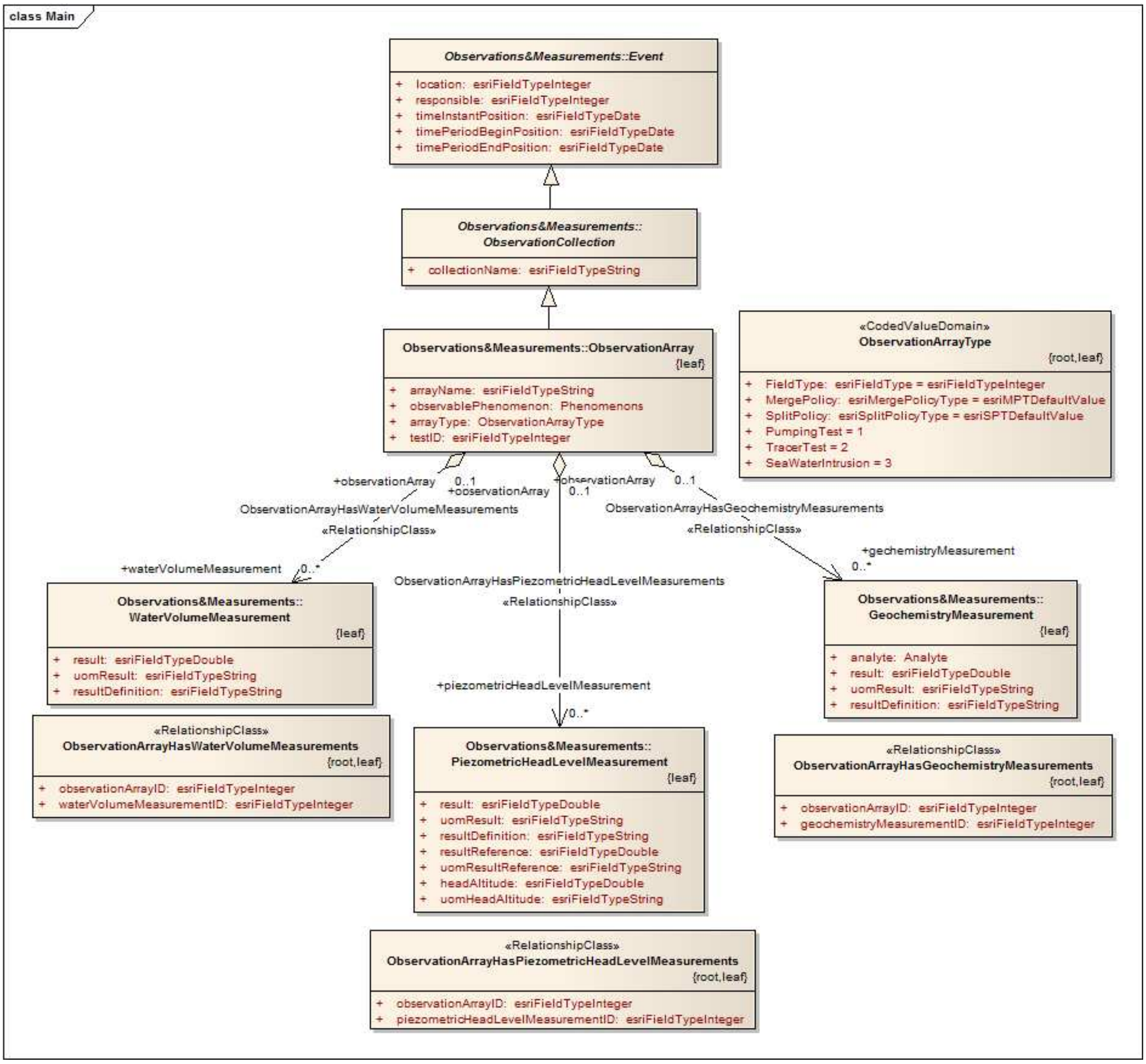


Figure 36. Observation Array for a collection of observations, where the observable property on the members is constant.

3.3.3.4 HYDROGEOLOGICAL FIELD TESTS

Hydrogeological studies, analyses, as well as decisions concerning integrated water resources management need to be based on viable information about hydrogeologic and hydrologic conditions and parameters. Raw data can be retrieved through simple observations and measurements performed in order to have primary information. However, more complex hydrogeological tests are often performed, such as pumping tests or tracer tests and their results and subsequent interpretations are available and have to be stored.

The general framework for most of the hydrogeological tests such as pumping and tracer tests is composed of three main parts (Table 10).

<table>
<tr><th></th><th>Pumping Test</th><th>Tracer Test</th></tr>
<tr><td rowspan="5">Experimental setup & test conditions</td><td></td><td>Injection point</td></tr>
<tr><td colspan="2">Pumping well</td></tr>
<tr><td colspan="2">Observation points</td></tr>
<tr><td></td><td>Injection profile</td></tr>
<tr><td colspan="2">Outflow profile</td></tr>
<tr><td>Observations and measurements</td><td>Drawdown curves</td><td>Concentration evolution</td></tr>
<tr><td>Interpretations</td><td>transmissivity
hydraulic conductivity
storativity
…</td><td>effective porosity
longitudinal dispersivity
transverse dispersivity
…</td></tr>
</table>

Table 10. Main groups of data of hydrogeological field experiments.

Firstly, the experimental setup has to be described. This consists in the location of the test, its equipment such as instruments, sensors, observation points, materials (i.e. tracer type and quantity…). Then, experimental conditions such as test duration, groundwater flow, and pumping/injection rates) have to be stored.

Secondly, the spatial and temporal variations of parameters such as water level measurements or tracer concentrations are monitored in different observation points. At the end, different interpretation methods can be performed using the monitored datasets. The results of such interpretations can be stored for further use.

All the information related to such experiments should be organised and stored in an efficient and straightforward way, described in the following sections.

3.3.3.4.1 Pumping tests

The experimental setup is composed of a pumping well and observation wells, and it associated with observations and measurements, such as a pumping profile in for the pumping well together with initial piezometric heads (Figure 37). Measurements retrieved during the pumping test can be grouped within one observation array, as they concern one homogenous type of data (piezometric head level measurements). After pumping test, results analysis, different interpretations can be stored in the PumpingTestInterpretaion class. This class contains estimates of aquifer properties and parameters (such as transmissivity values) as derived from the interpretation of any drawdown curve monitored in any observation well. The technique of interpretation used to obtain the estimates of aquifer properties have to be stored together with the results.

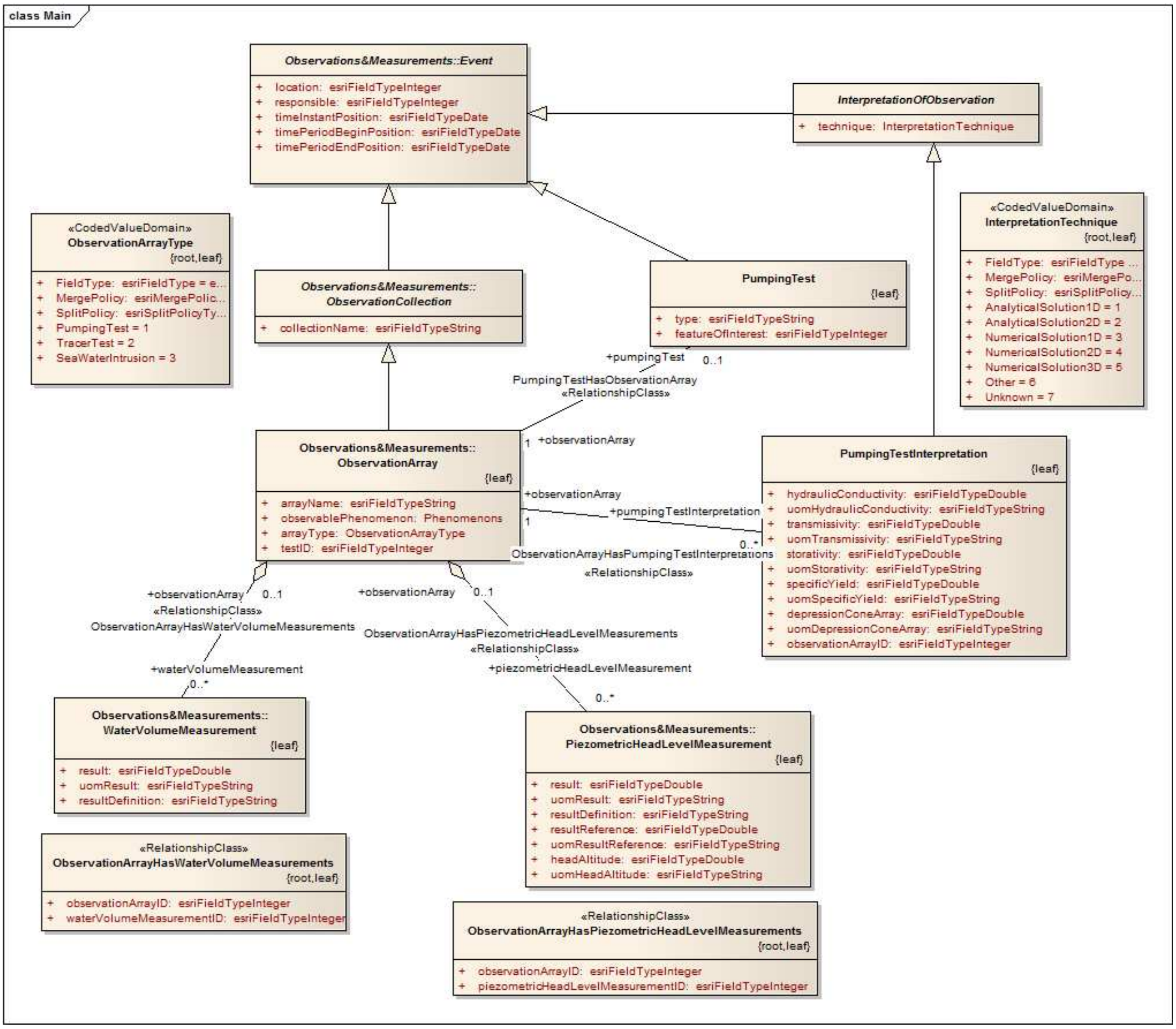


Figure 37. The hydrogeologic pumping test class together with its related classes. The pumping test class is defined as a specialization of the Event class and extends it with several additional attributes.

The PumpingTest class is related to the ObservationArray collection by the [0..1] to [1…1] PumpingTestHasObservationArray association. Therefore, one pumping test is linked to its observation array, containing the set of observations taken in different observation points, such as pumping well, piezometers, wells, trenches and others. An observation array is associated with different measurements such as WaterVolumeMeasurements for pumping rates established at the pumping well (Figure 38) and PiezometricHeadLevelMeasurements at observation points.

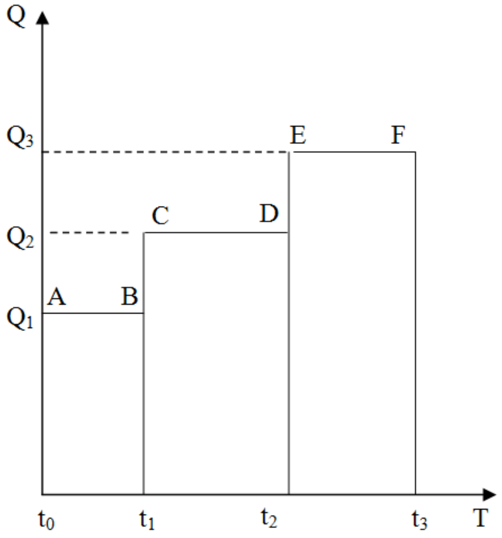


Figure 38. Pumping profile information which can be stored and transferred by the data model. Three different pumping rates are associated with their respective time steps.

The Event class is a parent class for most of the concerned by a pumping test classes. It has three child classes: PumpingTest, ObservationCollection, and InterpretationOfObservation. The ObservationCollection class is extended by the ObservationArray class. The attribute ObservationArrayType is set to the value: PumpingTest. The PumpingTest class extends Event with the following attributes, Table 11.

PumpingTest	
Attribute	**Definition**
type	indicates the type of the pumping test taken from the PumpingTestType coded value domain
featureOfInterest	indicates the feature of interest, the well or multiple well from which water is pumped

Table 11. Attributes of the PumpingTest class.

The InterpretationOfObservation class extends the Event class with the **technique** attribute, which describes the technique of the interpretation taken from the InterpretationTechnique coded value domain.

The ObservationArray class is related to the PumpingTestInterpretation class by the [1…1] to [0…n] ObservationArrayHasPumpingTestIntepretations relationship. The latter is a child class of the abstract InterpretationOfObservation class. It extends it with the following attributes: **hydraulicConductivity**; **transmissivity**, **storativity**; **specificYield**; **depressionConeRadius** indicates the depression cone maximal radius interpreted from the pumping test results; **observationArrayID** indicates the observation array to which the interpretation is associated.

3.3.3.4.2 Tracer tests

The experimental setup of a tracer test includes at least an injection well and several observation points, where the observation point might also be the same as the injection point (Figure 39).

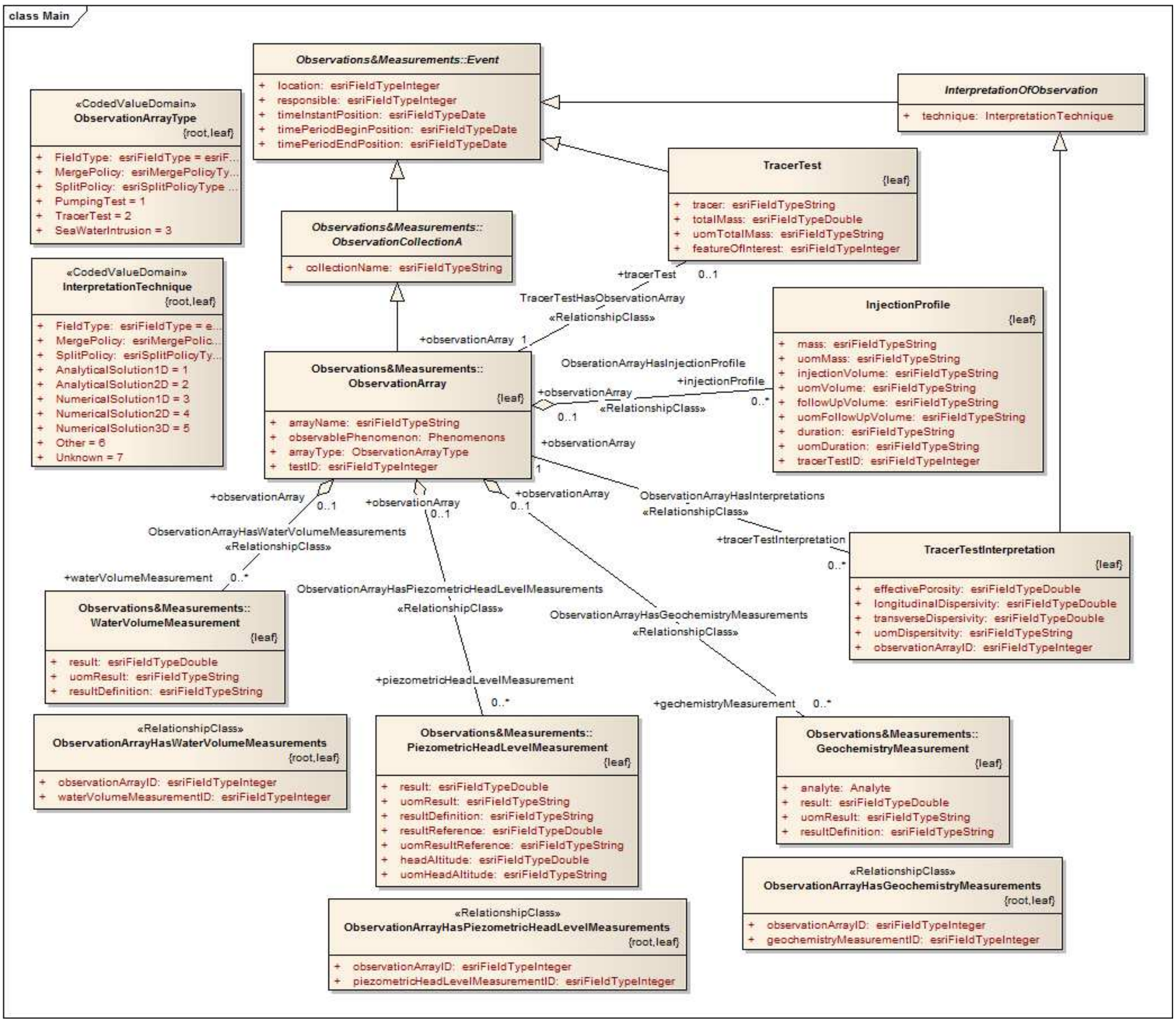


Figure 39. Conceptual model illustrating hydrogeologic tracer test class together with other related classes. The tracer test class is defined as a specialization of the Event class and extends it with several additional attributes.

The injection profile is described by the nature of the injected tracer, the tracer mass or concentration versus time. For instance, a LiCl solution at x_1 concentration was injected, during t_0-t_1 period. During t_1-t_2 period a LiCl solution at x_2 concentration was introduce to the groundwater system, etc. All the information can be stored as an injection profile A-I (Figure 40).

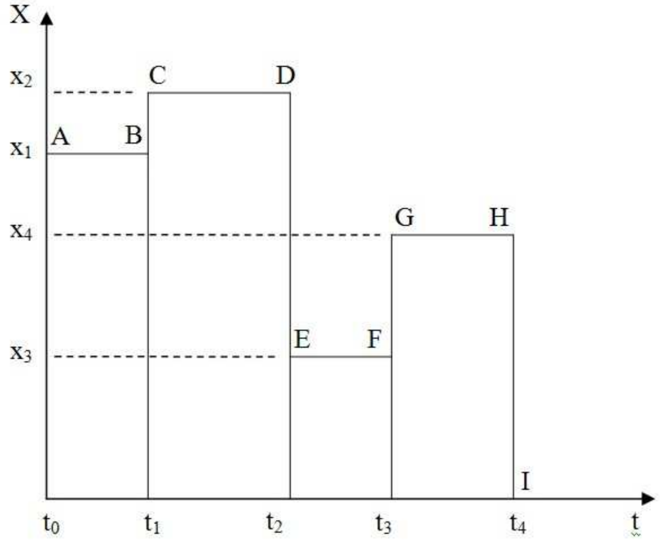


Figure 40. Injection profile describes how the tracer is being injected. Different time-dependent injection variables can be stored, such as the concentration, the injection rate and the volume of the injected solution.

After injection, tracer concentrations are measured in different observation points, by sampling, or they can be monitored directly in situ, with appropriate instruments or sensors. Measurements may be grouped in an observation array, because they concern a tracer concentration evolution in different locations.

At the end of the tracer test different interpretations of obtained results, using different simulation tools (analytical, numerical or both) can be encoded with the reference to each interpretation technique. The aquifer parameters resulting from different interpretation framework, such as effective porosity, or longitudinal and transverse dispersivity values can also be stored.

Technically in the data model, the Event class has four subclasses: ObservationCollection, TracerTest, InjectionProfile, and InterpretationOfObservation (Figure 39). The ObservationCollection abstract class is extended by the ObservationArray class, whose the arrayType attribute is set to the TracerTest value. The TracerTest class extends the Event abstract class with the following properties, Table 12. The InjectionProfile class also extends the Event class and adds the following properties, Table 13.

TracerTest	
Attribute	**Definition**
tracer	indicates the tracer which was injected in the feature of interest. Tracer code can be taken from the Tracer coded value domain
totalMass	indicates the mass of the injected tracer
uomTotalMass	indicates a unit of measure for the mass of the injected tracer
featureOfInterest	indicates the feature of interest, the well or multiple well where the tracer was injected

Table 12. TracerTest class attributes.

InjectionProfile	
Attribute	**Definition**
mass	indicates the mass of the injected tracer
uomMass	indicates a unit of measure for the mass of the injected tracer
injectionVolume	indicates the injection volume
uomVolume	indicates a unit of measure for the injected volume
duration	indicates the injection duration
uomDuration	indicates a unit of measure for the injection duration
followUpVolume	indicates the follow-up volume
uomFollowUpVolume	indicates the unit of measure of the follow-up volume
tracerTestID	indicates to which tracer test, the injection profile is related

Table 13. InjectionProfile class attributes

Similarly to the pumping test classes, the TracerTest class is associated with the ObservationArray by the [0..1] to [1…1] TracerTestHasObservationArray association. An observation array contains a list of features of interest (i.e. different wells or piezometers) where different measurements of tracer concentration were collected.

An ObservationArray instance can be associated with different tracer test interpretations, encoded in the TracerTestInterpretation class. The latter contains hydrogeological parameters interpreted using different methods, and it extends the InterpretationOfObservation abstract class with the following attributes: **effectivePorosity**; **longitudinalDispersivity**; **transverseDispersivity**; **observationArrayID** indicates the unique identifier of the Observation array, from which all interpretations have been made.

3.4 EXAMPLE OF IMPLEMENTATION

In order to exchange hydrogeologic information, one has to use a commonly understandable language, based on a shared data transfer model. The use of XML for data transfer has become accepted for the following reasons: XML is partially self-documenting, there are common methods for parsing XML files, for reading their structure and for transforming them to other formats.

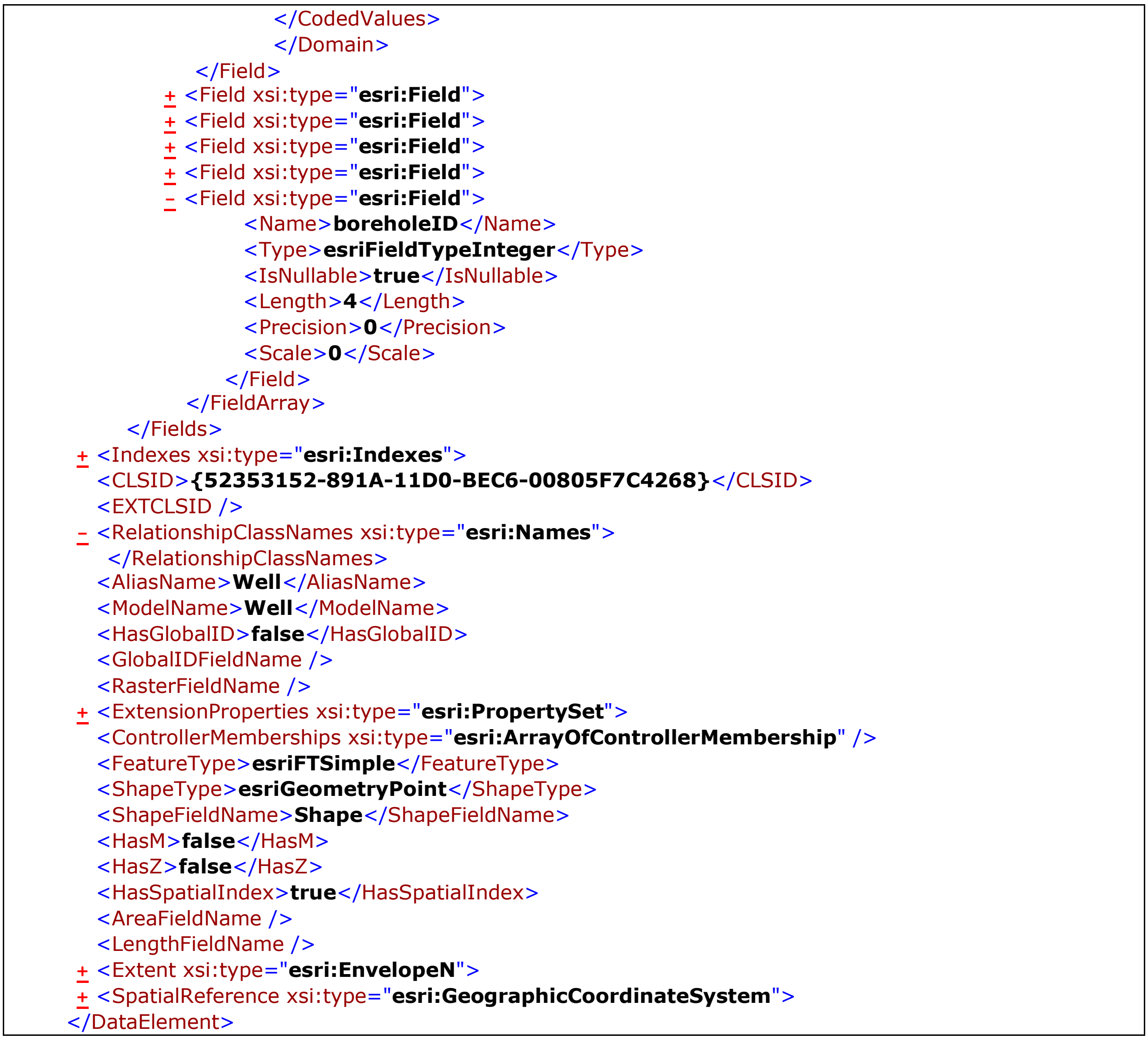
After the model implementation in the ArcGIS platform, a Geodatabase is created and it can be fed with data coming from different sources. However, the use of ArcGIS as an implementation platform adds additional constraints. For instance, abstract classes can generate instances, or associations should be established at the lowest inheritance level.

For data exchange, an XML file, based on the Geodatabase schema (XSD file) can be automatically generated. Nevertheless, two main requirements need to be considered. First, the architecture of the databases needs to be compatible with each other. Second, all the related data need to be transferred, due to the specific management of primary and secondary keys.

The examples presented here-after present several generated XML files. Each generated file is divided into two parts. The first part describes the data structure, strictly based on the implemented data model and the second part uses this schema to store hydrogeological data.

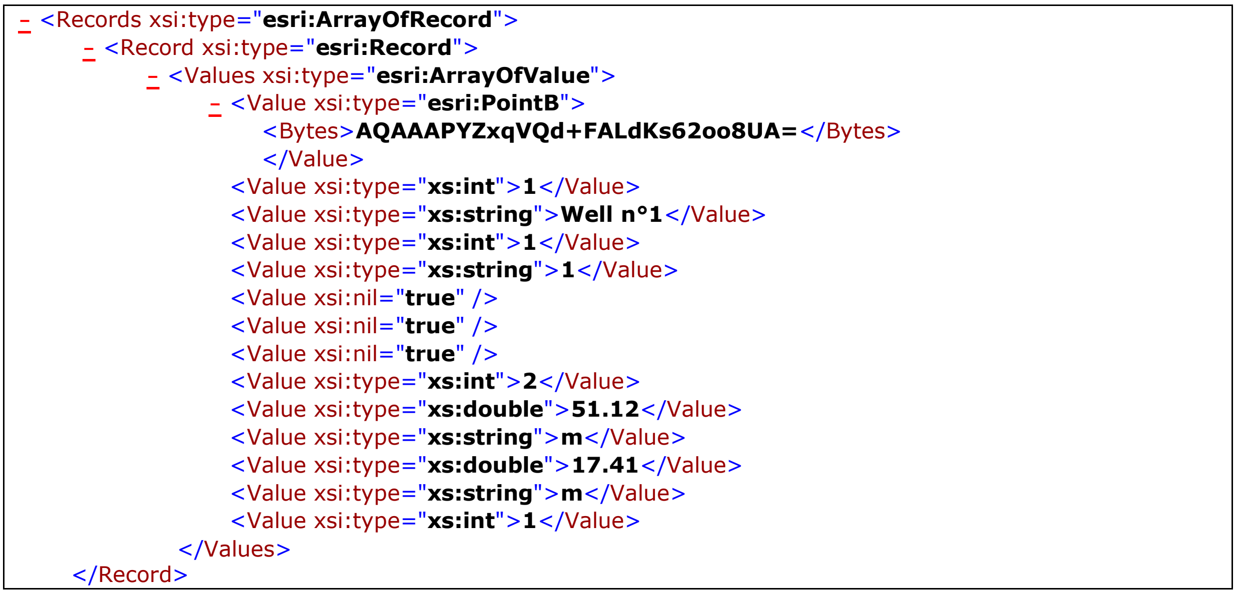
The first example illustrates the Well class definition, with its attributes and relationships (Figure 41). Then, two instances of the Well class are presented (Figure 42).

```
- <DataElement xsi:type="esri:DEFeatureClass">
       <CatalogPath>/FD=GroundwaterFeatures/FC=Well</CatalogPath>
       <Name>Well</Name>
       <MetadataRetrieved>true</MetadataRetrieved>
     + <Metadata xsi:type="esri:XmlPropertySet">
       <DatasetType>esriDTFeatureClass</DatasetType>
       <DSID>37</DSID>
       <Versioned>false</Versioned>
       <CanVersion>false</CanVersion>
       <HasOID>true</HasOID>
       <OIDFieldName>OBJECTID</OIDFieldName>
     - <Fields xsi:type="esri:Fields">
         - <FieldArray xsi:type="esri:ArrayOfField">
           - <Field xsi:type="esri:Field">
             <Name>Shape</Name>
             <Type>esriFieldTypeGeometry</Type>
             <IsNullable>true</IsNullable>
             <Length>0</Length>
             <Precision>0</Precision>
             <Scale>0</Scale>
             <Required>true</Required>
           + <GeometryDef xsi:type="esri:GeometryDef">
             <AliasName>Shape</AliasName>
             <ModelName>Shape</ModelName>
              </Field>
           + <Field xsi:type="esri:Field">
           + <Field xsi:type="esri:Field">
           + <Field xsi:type="esri:Field">
           + <Field xsi:type="esri:Field">
           + <Field xsi:type="esri:Field">
           + <Field xsi:type="esri:Field">
           + <Field xsi:type="esri:Field">
           - <Field xsi:type="esri:Field">
                 <Name>type</Name>
                 <Type>esriFieldTypeInteger</Type>
                 <IsNullable>true</IsNullable>
                 <Length>4</Length>
                 <Precision>0</Precision>
                 <Scale>0</Scale>
                 <AliasName>type</AliasName>
                 <ModelName>type</ModelName>
               - <Domain xsi:type="esri:CodedValueDomain">
                 <DomainName>wellType</DomainName>
                 <FieldType>esriFieldTypeInteger</FieldType>
                 <MergePolicy>esriMPTDefaultValue</MergePolicy>
                 <SplitPolicy>esriSPTDefaultValue</SplitPolicy>
                 <Description />
                 <Owner />
               - <CodedValues xsi:type="esri:ArrayOfCodedValue">
               - <CodedValue xsi:type="esri:CodedValue">
                 <Name>traditional</Name>
                 <Code xsi:type="xs:int">1</Code>
                   </CodedValue>
               - <CodedValue xsi:type="esri:CodedValue">
                 <Name>drilled</Name>
                 <Code xsi:type="xs:int">2</Code>
                   </CodedValue>
               - <CodedValue xsi:type="esri:CodedValue">
                 <Name>onGallery</Name>
                 <Code xsi:type="xs:int">3</Code>
                   </CodedValue>
```



```
                        </CodedValues>
                        </Domain>
                   </Field>
                 + <Field xsi:type="esri:Field">
                 + <Field xsi:type="esri:Field">
                 + <Field xsi:type="esri:Field">
                 + <Field xsi:type="esri:Field">
                 - <Field xsi:type="esri:Field">
                       <Name>boreholeID</Name>
                       <Type>esriFieldTypeInteger</Type>
                       <IsNullable>true</IsNullable>
                       <Length>4</Length>
                       <Precision>0</Precision>
                       <Scale>0</Scale>
                     </Field>
                 </FieldArray>
             </Fields>
         + <Indexes xsi:type="esri:Indexes">
           <CLSID>{52353152-891A-11D0-BEC6-00805F7C4268}</CLSID>
           <EXTCLSID />
         - <RelationshipClassNames xsi:type="esri:Names">
             </RelationshipClassNames>
           <AliasName>Well</AliasName>
           <ModelName>Well</ModelName>
           <HasGlobalID>false</HasGlobalID>
           <GlobalIDFieldName />
           <RasterFieldName />
         + <ExtensionProperties xsi:type="esri:PropertySet">
           <ControllerMemberships xsi:type="esri:ArrayOfControllerMembership" />
           <FeatureType>esriFTSimple</FeatureType>
           <ShapeType>esriGeometryPoint</ShapeType>
           <ShapeFieldName>Shape</ShapeFieldName>
           <HasM>false</HasM>
           <HasZ>false</HasZ>
           <HasSpatialIndex>true</HasSpatialIndex>
           <AreaFieldName />
           <LengthFieldName />
         + <Extent xsi:type="esri:EnvelopeN">
         + <SpatialReference xsi:type="esri:GeographicCoordinateSystem">
       </DataElement>
```

Figure 41. The example of the definition of the Well feature class with its attributes and relationships. Once the schema is defined, it is easy to attribute the values to the listed properties.



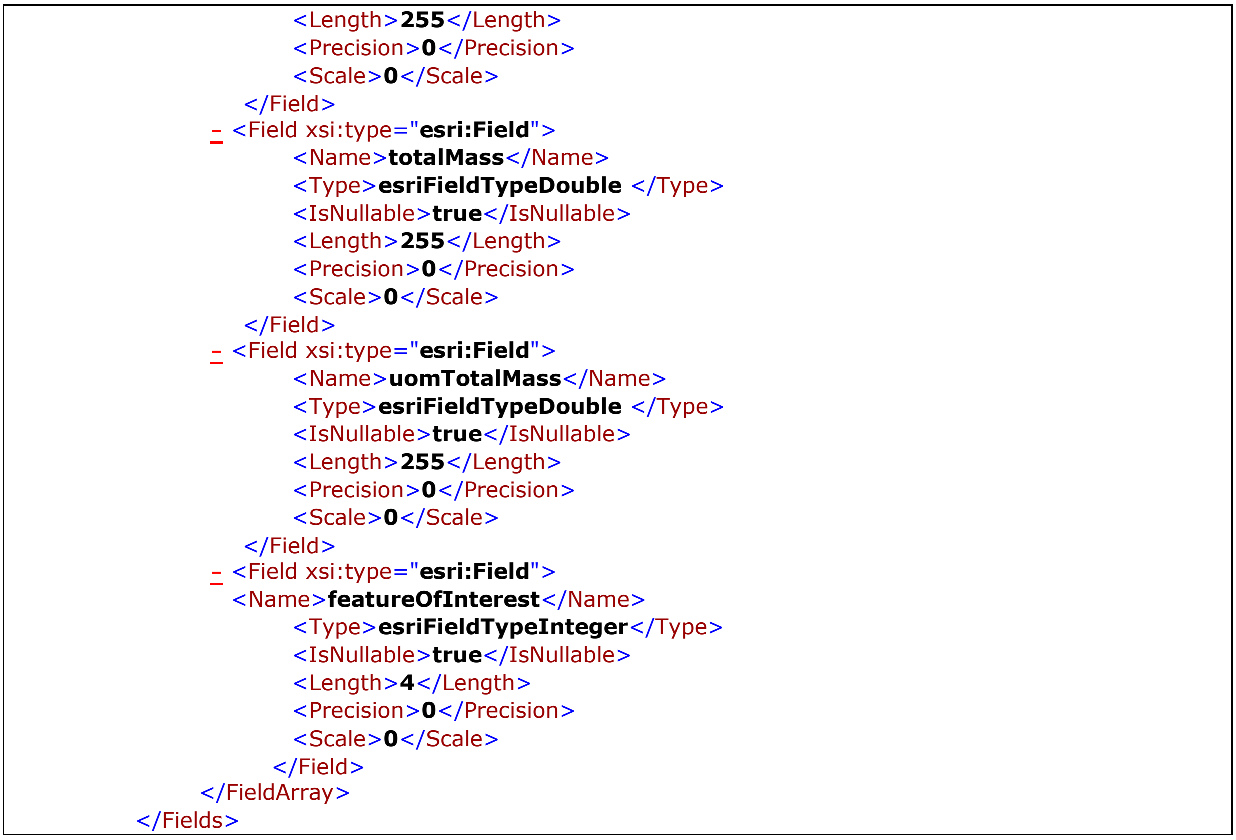
```
- <Records xsi:type="esri:ArrayOfRecord">
    - <Record xsi:type="esri:Record">
        - <Values xsi:type="esri:ArrayOfValue">
            - <Value xsi:type="esri:PointB">
                <Bytes>AQAAAPYZxqVQd+FALdKs62oo8UA=</Bytes>
                </Value>
              <Value xsi:type="xs:int">1</Value>
              <Value xsi:type="xs:string">Well n°1</Value>
              <Value xsi:type="xs:int">1</Value>
              <Value xsi:type="xs:string">1</Value>
              <Value xsi:nil="true" />
              <Value xsi:nil="true" />
              <Value xsi:nil="true" />
              <Value xsi:type="xs:int">2</Value>
              <Value xsi:type="xs:double">51.12</Value>
              <Value xsi:type="xs:string">m</Value>
              <Value xsi:type="xs:double">17.41</Value>
              <Value xsi:type="xs:string">m</Value>
              <Value xsi:type="xs:int">1</Value>
          </Values>
    </Record>
```

```
     - <Record xsi:type="esri:Record">
         - <Values xsi:type="esri:ArrayOfValue">
             - <Value xsi:type="esri:PointB">
                 <Bytes>AQAAAKw5rrUi8OVA3Bnyyj/p9EA=</Bytes>
                   </Value>
                 <Value xsi:type="xs:int">2</Value>
                 <Value xsi:type="xs:string">Well n°2</Value>
                 <Value xsi:type="xs:int">2</Value>
                 <Value xsi:type="xs:string">2</Value>
                 <Value xsi:nil="true" />
                 <Value xsi:nil="true" />
                 <Value xsi:nil="true" />
                 <Value xsi:type="xs:int">2</Value>
                 <Value xsi:type="xs:double">60.01</Value>
                 <Value xsi:type="xs:string">m</Value>
                 <Value xsi:type="xs:double">13.41</Value>
                 <Value xsi:type="xs:string">m</Value>
                 <Value xsi:type="xs:int">3</Value>
               </Values>
           </Record>
       </Records>
```

Figure 42. Two instances of the Well feature class: Well n°1 and Well n°2 with the values of their properties described in the schema document in Figure 41.

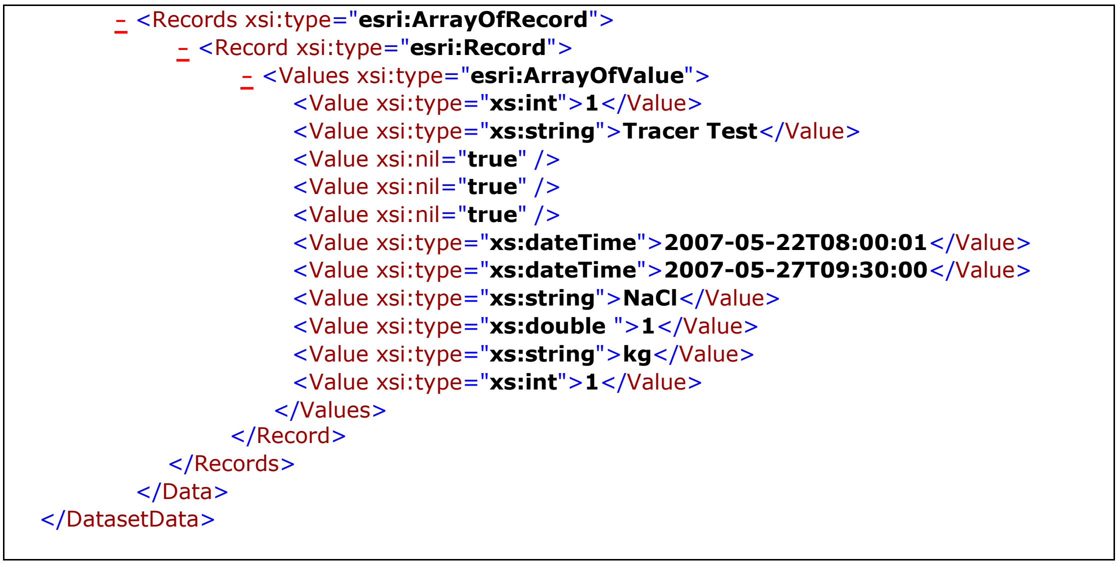
The second example illustrates a hydrogeological tracer test encoded and transferred using an XML file (Figure 43 and Figure 44). Figure 43 illustrates the description of the tracer test structure (<Fields>). Figure 44 illustrates attribute values for a tracer test (<Records>).

```
- <DatasetData xsi:type="esri:TableData">
      <DatasetName>TracerTest</DatasetName>
      <DatasetType>esriDTTable</DatasetType>
  - <Data xsi:type="esri:RecordSet">
  - <Fields xsi:type="esri:Fields">
      - <FieldArray xsi:type="esri:ArrayOfField">
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          - <Field xsi:type="esri:Field">
                <Name>timePeriodBeginPosition</Name>
                <Type>esriFieldTypeDate</Type>
                <IsNullable>true</IsNullable>
                <Length>8</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
             </Field>
          - <Field xsi:type="esri:Field">
                <Name>timePeriodEndPosition</Name>
                <Type>esriFieldTypeDate</Type>
                <IsNullable>true</IsNullable>
                <Length>8</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          - <Field xsi:type="esri:Field">
                <Name>tracer</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>true</IsNullable>
```



```
            <Length>255</Length>
            <Precision>0</Precision>
            <Scale>0</Scale>
        </Field>
      - <Field xsi:type="esri:Field">
            <Name>totalMass</Name>
            <Type>esriFieldTypeDouble </Type>
            <IsNullable>true</IsNullable>
            <Length>255</Length>
            <Precision>0</Precision>
            <Scale>0</Scale>
        </Field>
      - <Field xsi:type="esri:Field">
            <Name>uomTotalMass</Name>
            <Type>esriFieldTypeDouble </Type>
            <IsNullable>true</IsNullable>
            <Length>255</Length>
            <Precision>0</Precision>
            <Scale>0</Scale>
        </Field>
      - <Field xsi:type="esri:Field">
        <Name>featureOfInterest</Name>
            <Type>esriFieldTypeInteger</Type>
            <IsNullable>true</IsNullable>
            <Length>4</Length>
            <Precision>0</Precision>
            <Scale>0</Scale>
          </Field>
     </FieldArray>
</Fields>
```

Figure 43. Tracer test description encoded in the XML format, according to the Geodatabase XML Schema. The tracer test is characterized by its duration, a tracer type, its mass, diluted quantity, a follow-up volume and others.

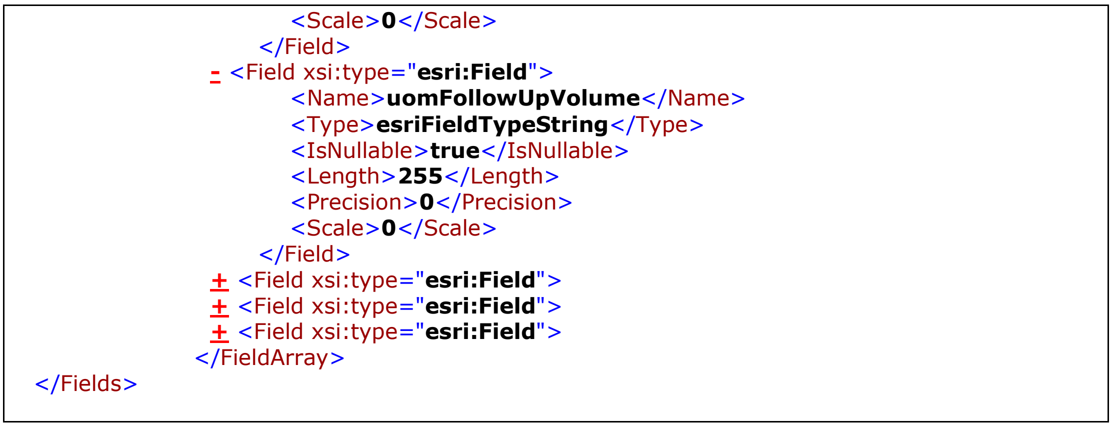


```
     - <Records xsi:type="esri:ArrayOfRecord">
          - <Record xsi:type="esri:Record">
               - <Values xsi:type="esri:ArrayOfValue">
                   <Value xsi:type="xs:int">1</Value>
                   <Value xsi:type="xs:string">Tracer Test</Value>
                   <Value xsi:nil="true" />
                   <Value xsi:nil="true" />
                   <Value xsi:nil="true" />
                   <Value xsi:type="xs:dateTime">2007-05-22T08:00:01</Value>
                   <Value xsi:type="xs:dateTime">2007-05-27T09:30:00</Value>
                   <Value xsi:type="xs:string">NaCl</Value>
                   <Value xsi:type="xs:double ">1</Value>
                   <Value xsi:type="xs:string">kg</Value>
                   <Value xsi:type="xs:int">1</Value>
                  </Values>
              </Record>
          </Records>
       </Data>
</DatasetData>
```

Figure 44. Tracer test description encoded in the XML format, according to the Geodatabase XML Schema. The tracer test is characterized by its duration, a tracer type, its mass, diluted quantity, and others.

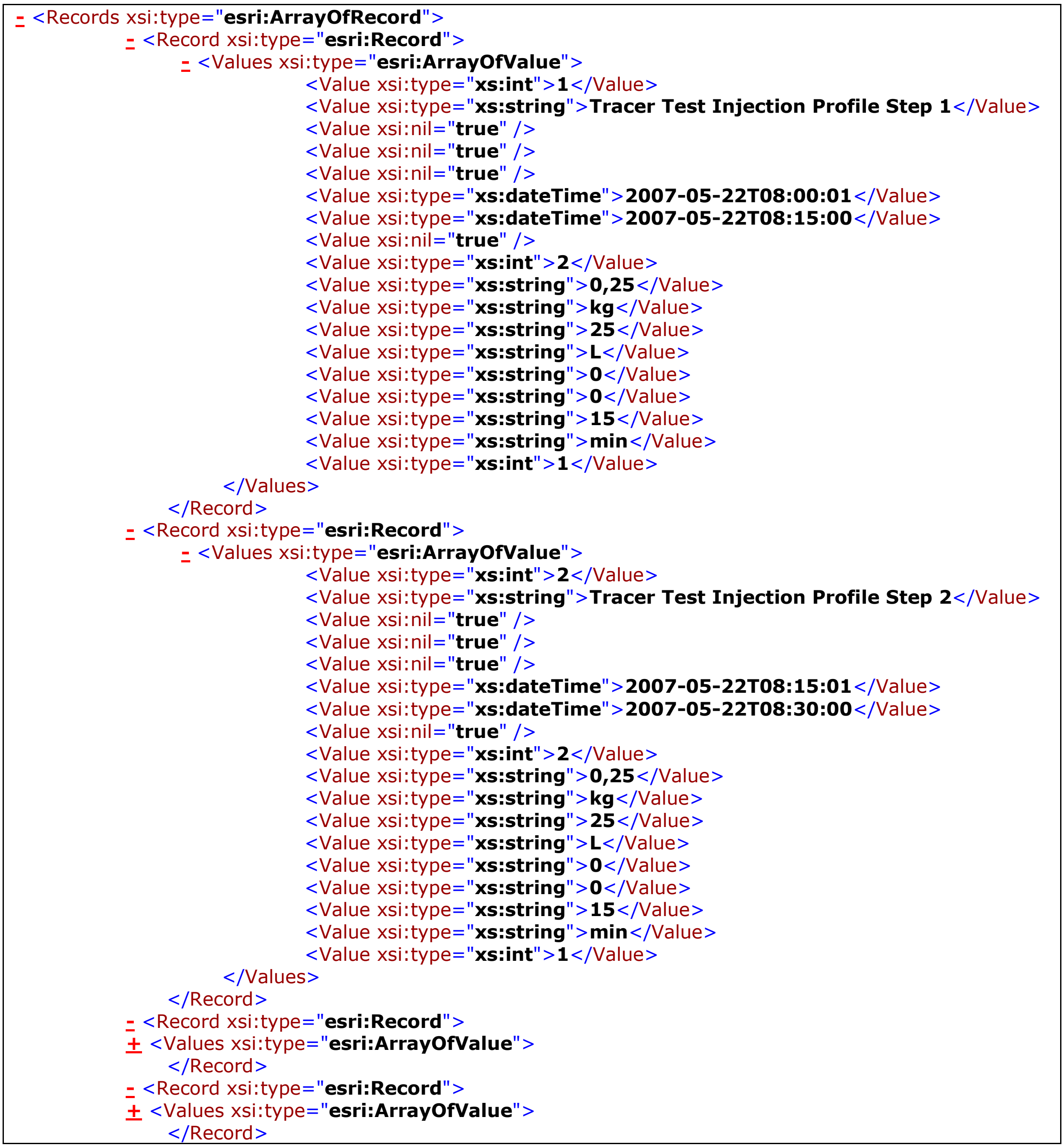
The next example presents the injection profile of the tracer test (Figure 45 and Figure 46).

```
  - <Data xsi:type="esri:RecordSet">
  - <Fields xsi:type="esri:Fields">
      - <FieldArray xsi:type="esri:ArrayOfField">
          + <Field xsi:type="esri:Field">
          - <Field xsi:type="esri:Field">
                <Name>name</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>false</IsNullable>
                <Length>100</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          - <Field xsi:type="esri:Field">
                <Name>timePeriodBeginPosition</Name>
                <Type>esriFieldTypeDate</Type>
                <IsNullable>true</IsNullable>
                <Length>8</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          - <Field xsi:type="esri:Field">
                <Name>timePeriodEndPosition</Name>
                <Type>esriFieldTypeDate</Type>
                <IsNullable>true</IsNullable>
                <Length>8</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          - <Field xsi:type="esri:Field">
                <Name>mass</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          - <Field xsi:type="esri:Field">
                <Name>uomMass</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          - <Field xsi:type="esri:Field">
                <Name>injectionVolume</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          - <Field xsi:type="esri:Field">
                <Name>uomVolume</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          - <Field xsi:type="esri:Field">
                <Name>followUpVolume</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
```



```
                <Scale>0</Scale>
              </Field>
           - <Field xsi:type="esri:Field">
                <Name>uomFollowUpVolume</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
              </Field>
           + <Field xsi:type="esri:Field">
           + <Field xsi:type="esri:Field">
           + <Field xsi:type="esri:Field">
          </FieldArray>
</Fields>
```

Figure 45. Tracer test injection profile definition, according to the Geodatabase XML Schema.



```
- <Records xsi:type="esri:ArrayOfRecord">
        - <Record xsi:type="esri:Record">
            - <Values xsi:type="esri:ArrayOfValue">
                     <Value xsi:type="xs:int">1</Value>
                     <Value xsi:type="xs:string">Tracer Test Injection Profile Step 1</Value>
                     <Value xsi:nil="true" />
                     <Value xsi:nil="true" />
                     <Value xsi:nil="true" />
                     <Value xsi:type="xs:dateTime">2007-05-22T08:00:01</Value>
                     <Value xsi:type="xs:dateTime">2007-05-22T08:15:00</Value>
                     <Value xsi:nil="true" />
                     <Value xsi:type="xs:int">2</Value>
                     <Value xsi:type="xs:string">0,25</Value>
                     <Value xsi:type="xs:string">kg</Value>
                     <Value xsi:type="xs:string">25</Value>
                     <Value xsi:type="xs:string">L</Value>
                     <Value xsi:type="xs:string">0</Value>
                     <Value xsi:type="xs:string">0</Value>
                     <Value xsi:type="xs:string">15</Value>
                     <Value xsi:type="xs:string">min</Value>
                     <Value xsi:type="xs:int">1</Value>
               </Values>
           </Record>
        - <Record xsi:type="esri:Record">
            - <Values xsi:type="esri:ArrayOfValue">
                     <Value xsi:type="xs:int">2</Value>
                     <Value xsi:type="xs:string">Tracer Test Injection Profile Step 2</Value>
                     <Value xsi:nil="true" />
                     <Value xsi:nil="true" />
                     <Value xsi:nil="true" />
                     <Value xsi:type="xs:dateTime">2007-05-22T08:15:01</Value>
                     <Value xsi:type="xs:dateTime">2007-05-22T08:30:00</Value>
                     <Value xsi:nil="true" />
                     <Value xsi:type="xs:int">2</Value>
                     <Value xsi:type="xs:string">0,25</Value>
                     <Value xsi:type="xs:string">kg</Value>
                     <Value xsi:type="xs:string">25</Value>
                     <Value xsi:type="xs:string">L</Value>
                     <Value xsi:type="xs:string">0</Value>
                     <Value xsi:type="xs:string">0</Value>
                     <Value xsi:type="xs:string">15</Value>
                     <Value xsi:type="xs:string">min</Value>
                     <Value xsi:type="xs:int">1</Value>
               </Values>
           </Record>
        - <Record xsi:type="esri:Record">
        + <Values xsi:type="esri:ArrayOfValue">
           </Record>
        - <Record xsi:type="esri:Record">
        + <Values xsi:type="esri:ArrayOfValue">
           </Record>
```

```
        - <Record xsi:type="esri:Record">
            - <Values xsi:type="esri:ArrayOfValue">
                      <Value xsi:type="xs:int">5</Value>
                      <Value xsi:type="xs:string">Tracer Test Injection Profile Step 5</Value>
                      <Value xsi:nil="true" />
                      <Value xsi:nil="true" />
                      <Value xsi:nil="true" />
                      <Value xsi:type="xs:dateTime">2007-05-22T09:00:01</Value>
                      <Value xsi:type="xs:dateTime">2007-05-22T09:30:00</Value>
                      <Value xsi:nil="true" />
                      <Value xsi:type="xs:int">2</Value>
                      <Value xsi:type="xs:string">0</Value>
                      <Value xsi:type="xs:string">kg</Value>
                      <Value xsi:type="xs:string">0</Value>
                      <Value xsi:type="xs:string">L</Value>
                      <Value xsi:type="xs:string">100</Value>
                      <Value xsi:type="xs:string">L</Value>
                      <Value xsi:type="xs:string">30</Value>
                      <Value xsi:type="xs:string">min</Value>
                      <Value xsi:type="xs:int">1</Value>
                </Values>
            </Record>
        </Records>
  </Data>
```

Figure 46. Values of the attributes defined in the tracer test injection profile: 4 injection steps (only two are explicitly visible) followed by injection of water to push to push the tracer.

The fourth example illustrates the interpretation of the tracer test results (Figure 47 and Figure 48).

```
- <DatasetData xsi:type="esri:TableData">
      <DatasetName>TracerTestInterpretation</DatasetName>
      <DatasetType>esriDTTable</DatasetType>
    - <Data xsi:type="esri:RecordSet">
    - <Fields xsi:type="esri:Fields">
      - <FieldArray xsi:type="esri:ArrayOfField">
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          - <Field xsi:type="esri:Field">
                <Name>timeInstantPosition</Name>
                <Type>esriFieldTypeDate</Type>
                <IsNullable>true</IsNullable>
                <Length>8</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
            </Field>
          + <Field xsi:type="esri:Field">
          + <Field xsi:type="esri:Field">
          - <Field xsi:type="esri:Field">
                <Name>technique</Name>
                <Type>esriFieldTypeInteger</Type>
                <IsNullable>true</IsNullable>
                <Length>4</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
                <AliasName>technique</AliasName>
                <ModelName>technique</ModelName>
              - <Domain xsi:type="esri:CodedValueDomain">
                    <DomainName>InterpretationTechnique</DomainName>
```

```
                  <FieldType>esriFieldTypeInteger</FieldType>
                  <MergePolicy>esriMPTDefaultValue</MergePolicy>
                  <SplitPolicy>esriSPTDefaultValue</SplitPolicy>
                  <Description />
                  <Owner />
                + <CodedValues xsi:type="esri:ArrayOfCodedValue">
                </Domain>
            </Field>
        - <Field xsi:type="esri:Field">
                <Name>effectivePorosity</Name>
                <Type>esriFieldTypeDouble</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
          </Field>
        - <Field xsi:type="esri:Field">
          <Name>longitudinalDispersivity</Name>
                <Type>esriFieldTypeDouble</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
          </Field>
        - <Field xsi:type="esri:Field">
                <Name>transverseDispersivity</Name>
                <Type>esriFieldTypeDouble</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
          </Field>
        + <Field xsi:type="esri:Field">
        - <Field xsi:type="esri:Field">
                <Name>uomDispersivity</Name>
                <Type>esriFieldTypeString</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
        </Field>
        - <Field xsi:type="esri:Field">
                <Name>observationArray</Name>
                <Type>esriFieldTypeInteger</Type>
                <IsNullable>true</IsNullable>
                <Length>255</Length>
                <Precision>0</Precision>
                <Scale>0</Scale>
        </Field>
      </FieldArray>
</Fields>
```

Figure 47. Tracer test interpretation in the Geodatabase XSD compliant form. The results for interpreted effective porosity and longitudinal and transversal dispersivities are indicated.

```
- <Records xsi:type="esri:ArrayOfRecord">
  - <Record xsi:type="esri:Record">
      - <Values xsi:type="esri:ArrayOfValue">
            <Value xsi:type="xs:int">1</Value>
            <Value xsi:type="xs:string">Tracer Test Interpretation
               n°1</Value>
            <Value xsi:nil="true" />
            <Value xsi:nil="true" />
            <Value xsi:type="xs:dateTime">2007-05-27T15:27:10</Value>
```

```
                    <Value xsi:nil="true" />
                    <Value xsi:nil="true" />
                    <Value xsi:type="xs:double">4</Value>
                    <Value xsi:type="xs:double">0,13</Value>
                    <Value xsi:type="xs:double">5,2</Value>
                    <Value xsi:nil="true" />
                    <Value xsi:type="xs:int">1</Value>
                    <Value xsi:type="xs:string">m</Value>
                   <Value xsi:type="xs:string">199</Value>
                  </Values>
              </Record>
            </Records>
        </Data>
   </DatasetData>
```

Figure 48. Tracer test interpretation in the Geodatabase XSD compliant form. The results for interpreted effective porosity and longitudinal and transversal dispersivities are indicated.

3.5 CONCLUSIONS TO CHAPTER 3

Standard structures and protocols for groundwater data have a lot of benefits. First of all, if one protocol for data transfer exists, environmental resource management is not unnecessarily complicated (The Australian National Groundwater Data Transfer Standard, 1999). A generic standard bridges the gap between different information providers and information users. It reduces transformation costs and time. Furthermore, the possibility of misunderstanding of data is significantly reduced, when data are uniformly structured, well defined and documented. Finally, some financial saving can be realised, when different organisations and users share the development costs of supporting infrastructure and software.

Due to its first ArcGIS implementation platform, the current physical model is not fully compliant with the GML standard. To make it compliant, an XSLT transformation may be performed to convert this format to GML or GeoSciML formats. However, the GML format does not respond to the needs of the hydrogeological community, which requires its own particular standard, such as HgML (HydroGeology Markup Language). This standardization process requires adaptations, tests and discussions amongst members of the hydrogeologic community. A future HgML language, used as an international standard for transfer of hydrogeological data, will clearly enhance data exchanges between different local, regional, national and international organisations, as well as other interested parties. Data access, availability, hydrogeological studies, and finally, hydrogeological or environmental reporting will be easier, more viable, and complete.

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CHAPTER 4

APPLICATION: DATA MODEL IMPLEMENTATION FOR INTEGRATED WATER RESOURCES MANAGEMENT

4.1 GABARDINE IMPLEMENTATION

The purpose of this chapter is to present a first case-study of the hydrogeological data model implemented under the GABARDINE Geospatial Database, in the proprietary ArcGIS environment.

Tests of the Geospatial Database were performed in Portugal, in 2006, with available data coming from the Algarve region, where nitrates problems have been identified within the context of multilayer aquifers. The tests consisted in non-spatial and spatial data identification and collection, data introduction into the system, and first data processing and analyses using ArcGIS standard tools. According to the Project-Oriented approach, the Portuguese case-study environment has been characterized by:

- its localisation: regional and geographical data where different scales can be taken into consideration;
- the equipment that is available or constructed for exploring the problem: information about groundwater devices such as wells, springs, galleries and many others with their characteristics and specific equipment such as casings, screens, pumps…;
- groundwater monitoring results such as observation and measurements retrieved in the field using sensors;
- field tests results, interpretations and derived data coming from the tests performed to know better the geological and hydrogeological environment and its parameters.

The Project-Oriented approach proposed for the GABARDINE Geospatial Database allowed for a precise outlook on data and more efficient data management. This approach is transparent for the user, who does not need to know the internal structure of data. It allowed an easy and comprehensible data integration, sharing and transfer between different users and project partners.

4.1.1 DESCRIPTION OF PROJECT COMPONENTS

The Project-Oriented Geospatial database for GABARDINE was implemented in the GIS environment. A first validation cycle was carried out, consisting in data transfer into the database using various available sources of data from the GABARDINE project partners, such as existing databases, Internet resources, spreadsheets, hand-written field data, data coming from GPS and others. The validation phase enabled several adjustments and improvements of the internal technical structure and it produced some first results on data visualisation, manipulation, management and interpretation.

All the examples illustrated below were created during this testing and validating period performed in Portugal, at the LNEC National Institute of Engineering Sciences, between October 30 and November 10, 2006. The data used during this work come from the LNEC and other Portuguese sources.

4.1.1.1 LOCALISATION DATA

In Portugal, the first step of an overall environmental analysis consists in a global view of the problem, its localisation, spatial extent and possible impacts. The following data were collected and introduced to the Geospatial Database:

- administrative boundaries of the country or region, management units which can be even trans-boarder;
- topological maps providing the terrain morphology, existing infrastructure, roads;
- land cover and land use maps;
- soil types, geological and lithological types;
- hydrologic maps with rivers, lakes, river basin districts;
- hydrogeological water districts with their groundwater and surface water bodies…

The first example (Figure 49) presents a general view on Portugal, with its digitized administrative boundary, and the Algarve region highlighted in the South. The second example (Figure 50) illustrates the Algarve region, with different land-use types, with the contours of three aquifers in the region of the GABARDINE test sites. The third example (Figure 51) presents the local area in more detail, with different identified soil types. The user can also have a view on selected aquifers.

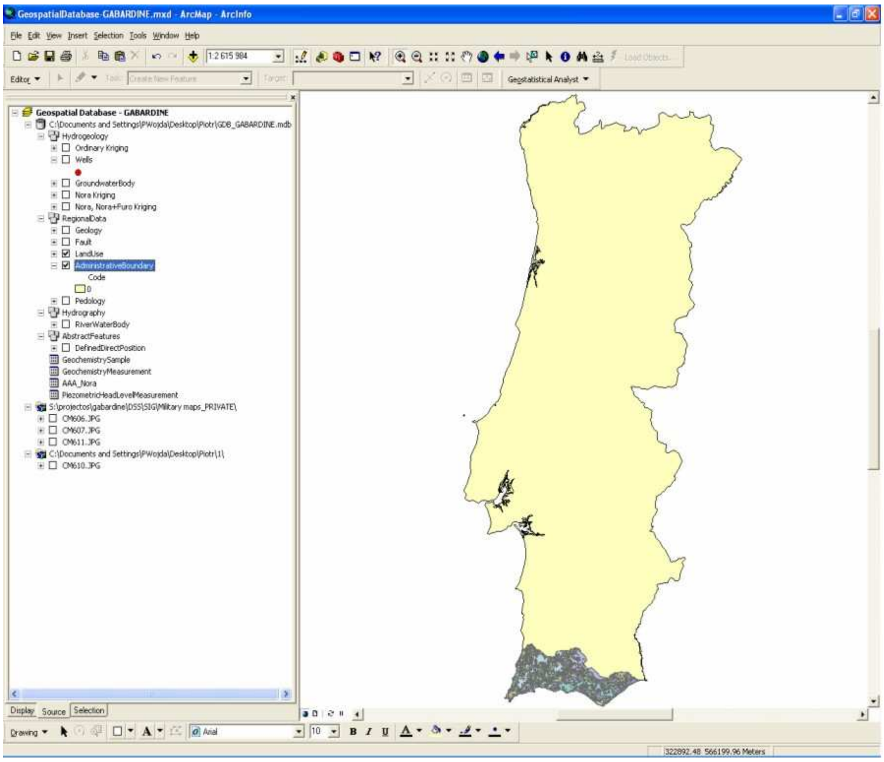


Figure 49. GABARDINE Geospatial database content: administrative boundary of Portugal with the Algarve region in the South of Portugal (data source: LNEC).

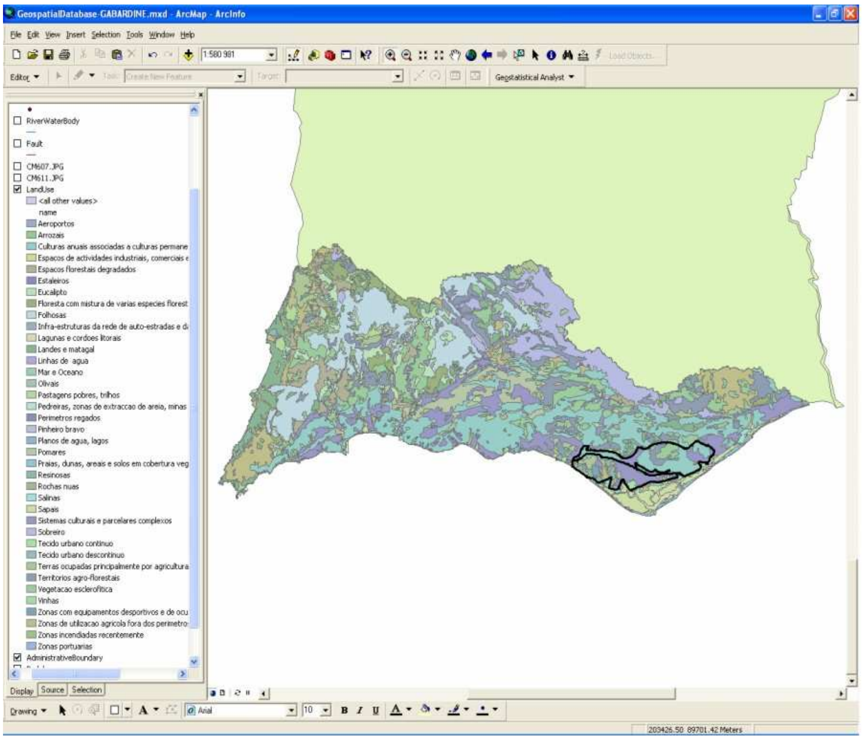


Figure 50. GABARDINE Geospatial database content: Algarve region classified according to the Corine land cover types. Three aquifers of interest are indicated (data source: LNEC).

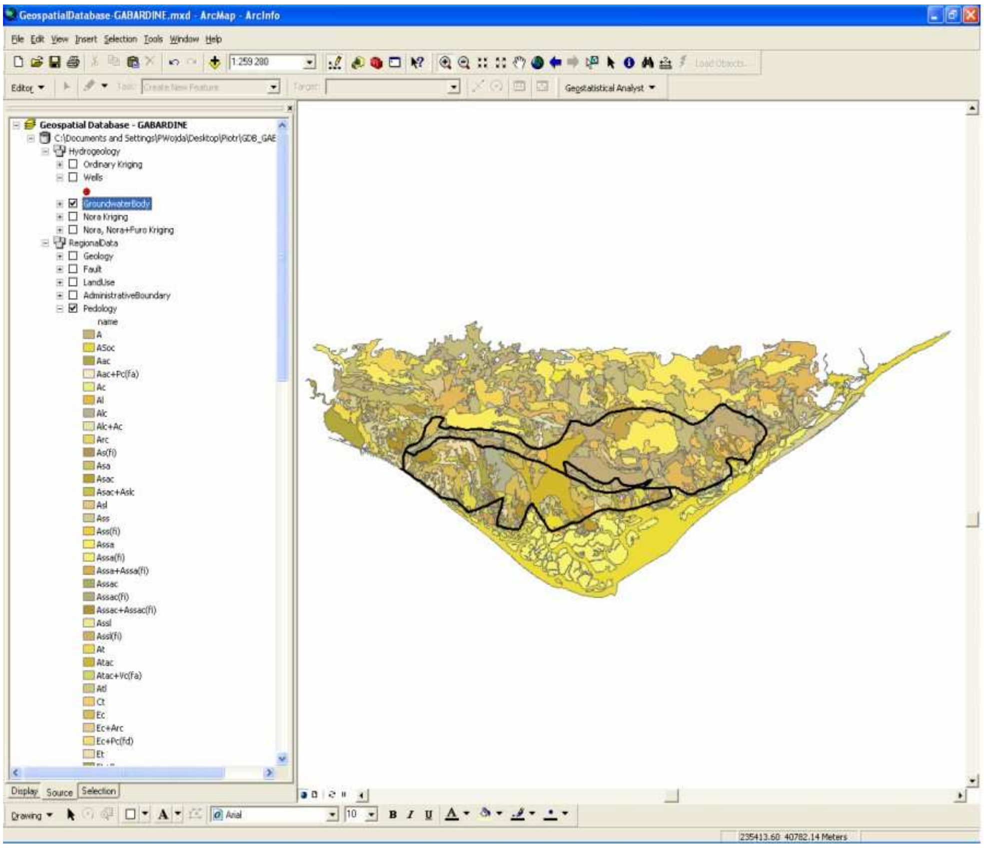


Figure 51. GABARDINE Geospatial database content: localisation of three studied aquifers and the corresponding soil types of the region (data source: LNEC).

Localisation data presented above were completed with data on available groundwater features and their hydrogeological equipment. The details are given in the next section.

4.1.1.2 SITE EQUIPMENT

The natural and man-made site elements identified during the Portuguese tets are the following:

- wells, piezometers;
- galleries, excavations;
- springs, sinkholes;
- trenches, drains;
- monitoring stations (gauging stations, climatic stations, groundwater quality and quantity stations) within a monitoring network…

Additional information on specific equipment characteristics such as: casings, seals, screens, gravel packs…, has also been introduced to the Geospatial Database. Figure 52 shows different wells and piezometers available in the Algarve region, as stored in the Geospatial Database. Figure 53 shows two different types of monitoring stations with a river network existing in the Algarve region: gauging stations and climatic stations, which are grouped within a national monitoring network.

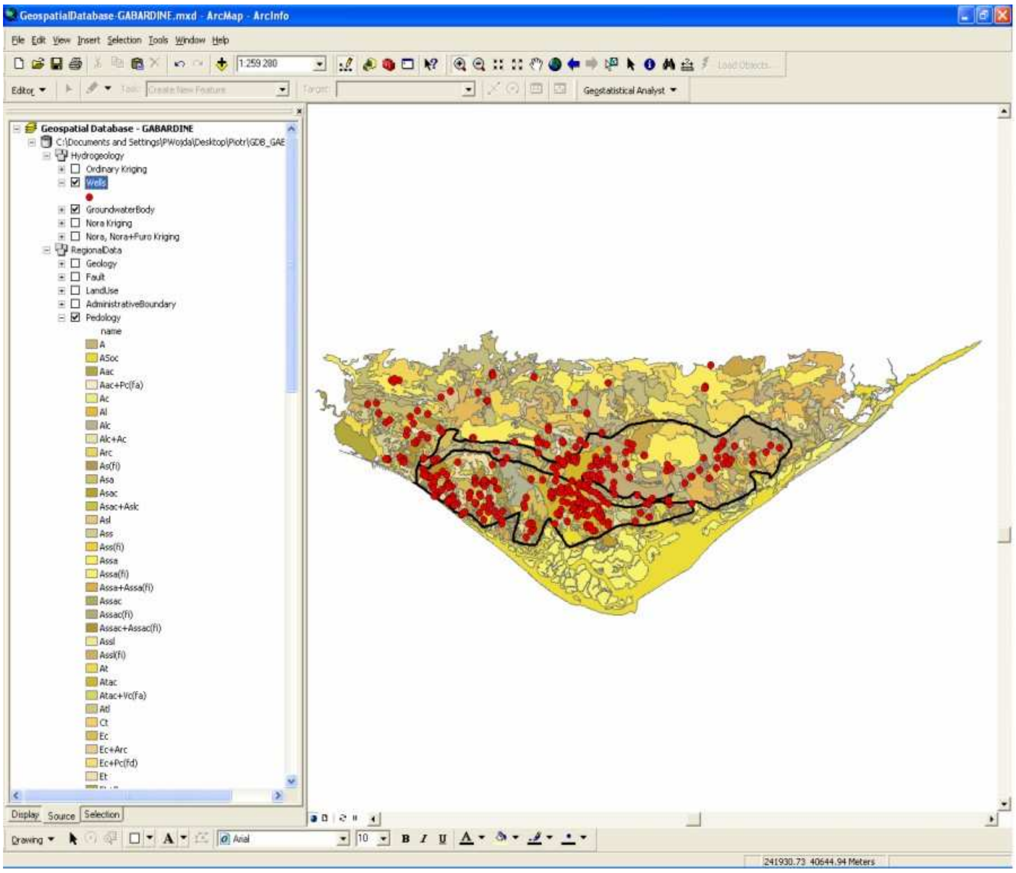


Figure 52. GABARDINE Geospatial database content: localisation of available wells in the test site region (data source: LNEC).

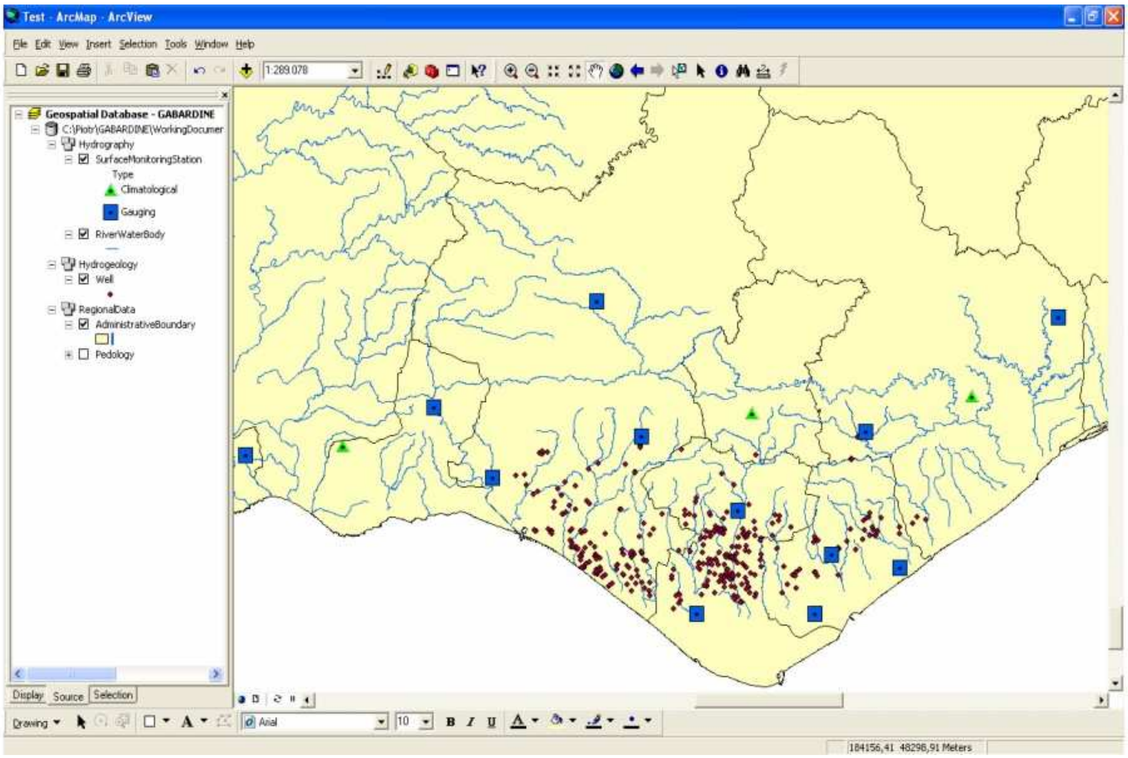


Figure 53. GABARDINE Geospatial database content: localisation of monitoring stations differentiated according to their types - gauging and climatic stations. Information is shown with wells available in the region (data source: LNEC).

4.1.1.3 OBSERVATIONS AND MEASUREMENTS

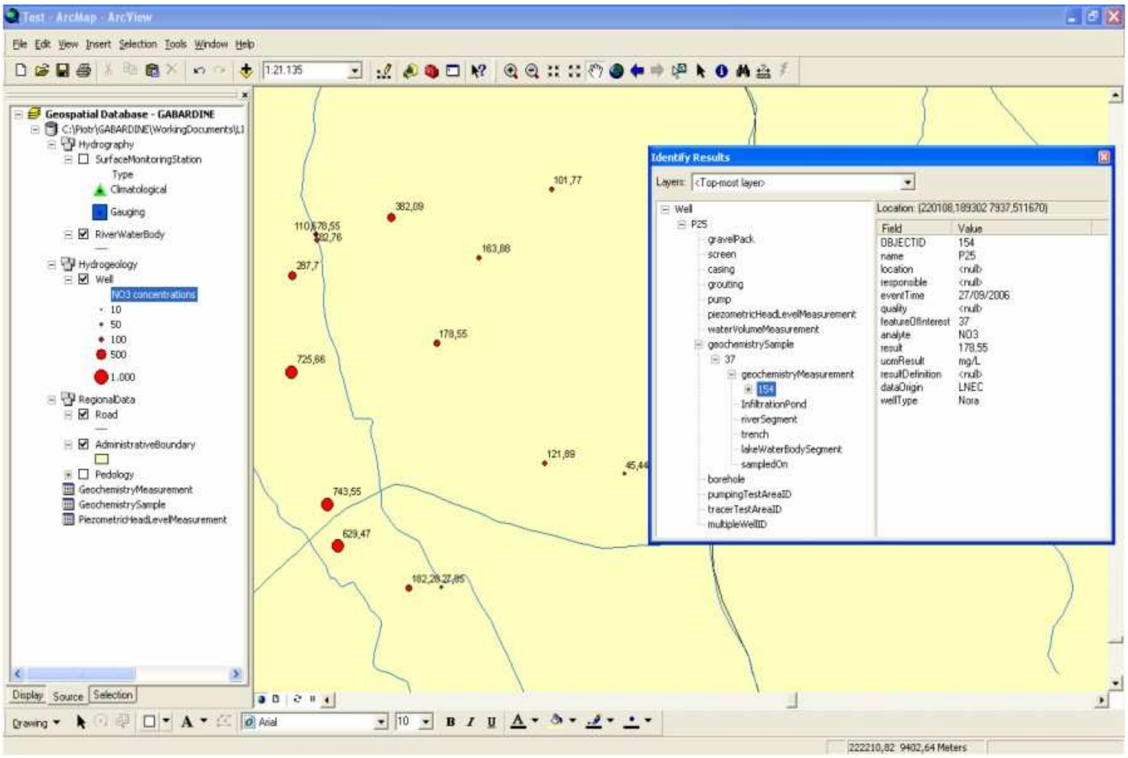
4.1.1.3.1 Primary data

Any environmental analysis is based on sound information available from observations and measurements retrieved from hydrological and hydrogeological observation points. The main data collected monitored at monitored groundwater points and in monitoring stations are the following:

- piezometric head level measurements;
- surface water level measurements;
- water volumes (“+” when recharged or injected in; “-“ when extracted);
- water geochemistry measurements performed in-situ or on extracted water samples;
- climatic data such as precipitation, temperature, pressure, cloud-cover.

All the observations and measurements data are stored with the measurement point references, units of measures, analyte codes (where the analytes are species subject to observation) and the procedures used for data collection. This allows for further data treatment, analyses or validation.

A first example shows a nitrate concentration measurement made on a water sample retrieved from a given well, during a monitoring campaign (Figure 54). This comes together with additional information such as the date of sampling, the measurement result, and its unit of measure. More details can be added, if needed for post-treatment or validation purposes.

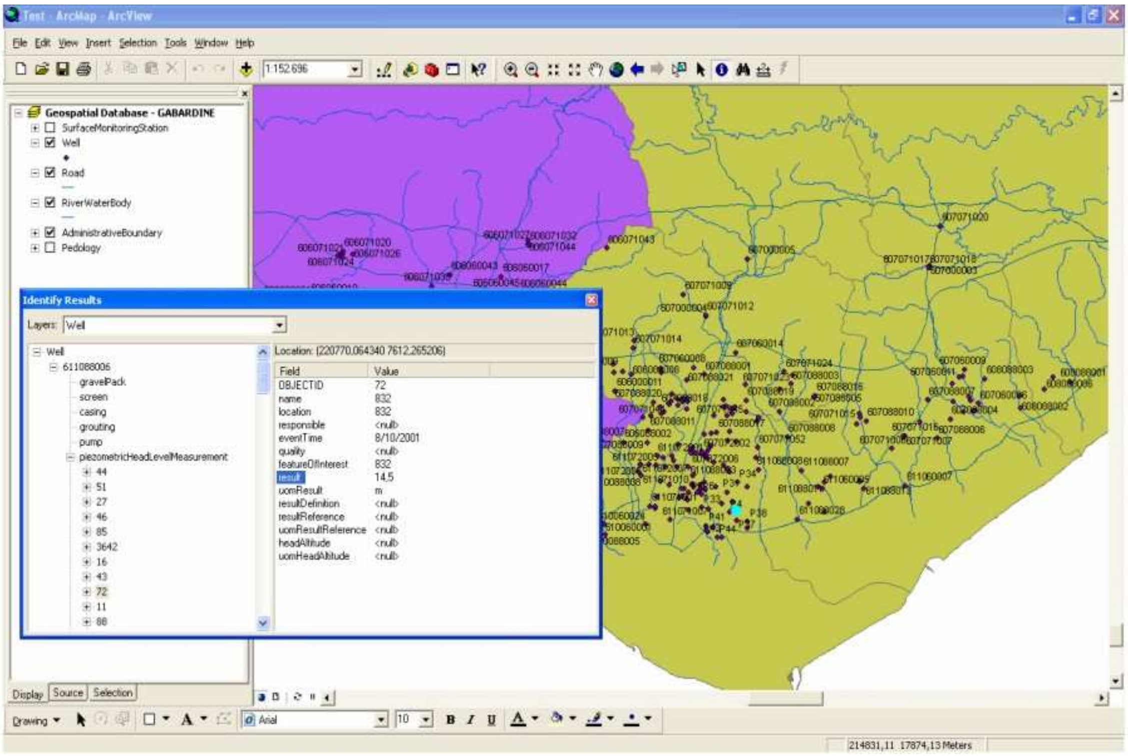


Location: (220108,189302 7937,511670)

Field	Value
OBJECTID	154
name	P25
location	<null>
responsible	<null>
eventTime	27/09/2006
quality	<null>
featureOfInterest	37
analyte	NO3
result	178,55
uomResult	mg/L
resultDefinition	<null>
dataOrigin	LNEC
wellType	Nora

Figure 54. GABARDINE Geospatial database content: nitrate concentration measurement done on a water sample retrieved in the piezometer P25. Measurement can be stored together with information about procedure, specialised sensor or method of measurement, units of measure and responsible person (data source: LNEC).

A second example illustrates a piezometric head level measurement performed in a selected well (Figure 55). The measurement has the following components: a depth to water table, a reference level allowing obtaining the absolute value, a unit of measure. Furthermore, other times, depth or distance series of data and measurements can also be stored in the database.



Location: (220770,064340 7612,265206)

Field	Value
OBJECTID	72
name	832
location	832
responsible	<null>
eventTime	8/10/2001
quality	<null>
featureOfInterest	832
result	14,5
uomResult	m
resultDefinition	<null>
resultReference	<null>
uomResultReference	<null>
headAltitude	<null>
uomHeadAltitude	<null>

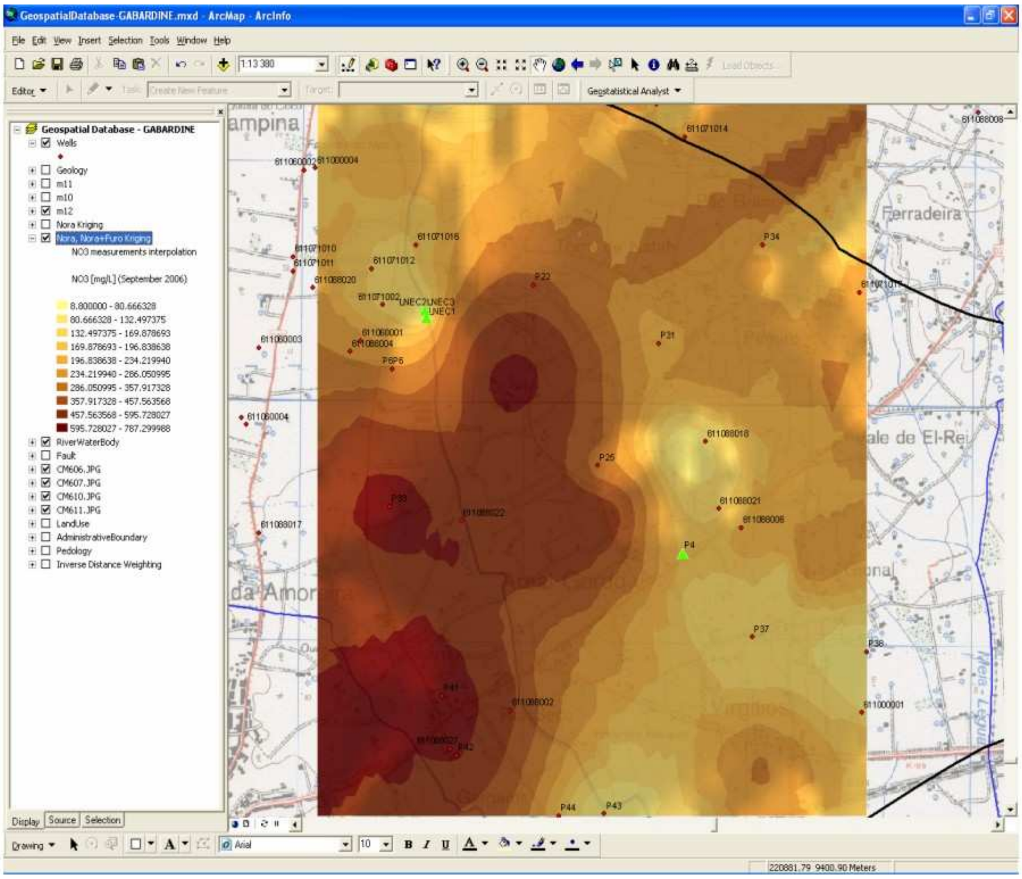
Figure 55. GABARDINE Geospatial database content: piezometric head level measurement with its associated reference (data source: LNEC).

4.1.1.4 *INTERPRETATIONS*

Raw data, combined with observations retrieved during hydrogeological and geophysical tests can be used to improve the analysis. The results of a pumping test can be used to calculate different hydrogeological parameters such as hydraulic conductivity or transmissivity. The results of a tracer test can be used to identify hydrodispersive and hydrochemical processes and to estimate the associated parameters.

Various analyses and interpretation tools can be built-in the Geographical Information Systems, and they can also be available through external programmes, where the exchange of data is based on standardized protocols. Interpretations can be visualised at discrete points or the interpreted results can be spatially distributed using interpolation or extrapolation and taking into consideration some of the geological particularities and constraints.

As an example for the Algarve region, a spatially interpolated map of nitrate concentration is presented in Figure 56.



Geospatial Database - GABARDINE
- ☑ Wells
- ☐ Geology
- ☐ m11
- ☐ m10
- ☑ m12
- ☐ Nora Kriging
- ☑ Nora, Nora+Furo Kriging
  - NO3 measurements interpolation
  - NO3 [mg/L] (September 2006)
  - 8.800000 - 80.666328
  - 80.666328 - 132.497375
  - 132.497375 - 169.878693
  - 169.878693 - 196.838638
  - 196.838638 - 234.219940
  - 234.219940 - 286.050995
  - 286.050995 - 357.917328
  - 357.917328 - 457.563568
  - 457.563568 - 595.728027
  - 595.728027 - 787.299988
- ☑ RiverWaterBody
- ☐ Fault
- ☑ CM606.JPG
- ☑ CM607.JPG
- ☑ CM610.JPG
- ☑ CM611.JPG
- ☐ LandUse
- ☐ AdministrativeBoundary
- ☐ Pedology
- ☐ Inverse Distance Weighting

Figure 56. GABARDINE Geospatial database: an example of interpolation of nitrate concentrations (Inverse Distance Weighted) retrieved during one field campaign in September, 2006, (data source: LNEC).

Another example for the Algarve region is a map of interpolated piezometric head level measurements on the basis of a series of measurements in wells. The appropriate wells were selected based on the following criteria: depth, well type, number of reached aquifers (Figure 57).

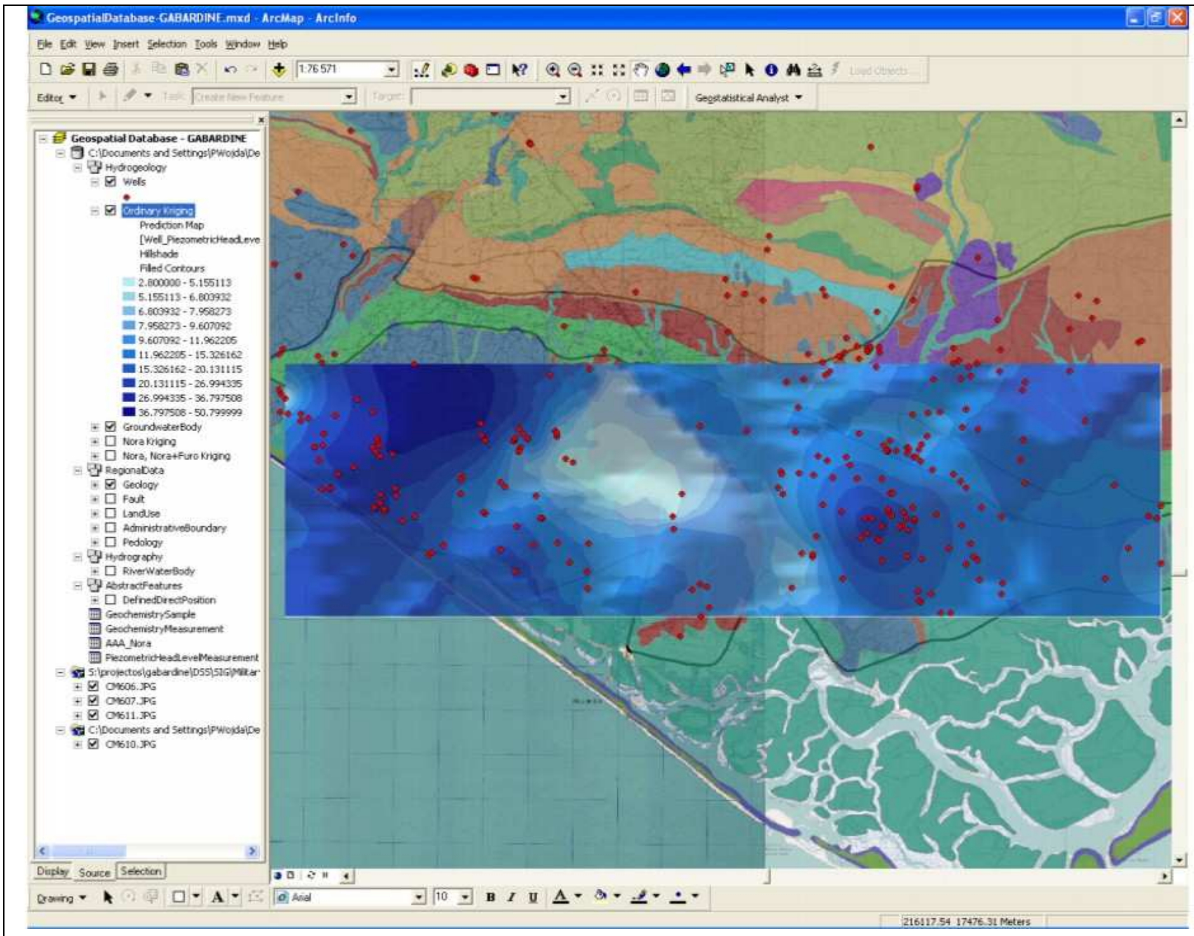


Figure 57. GABARDINE Geospatial database: an example of interpolation of piezometric head level measurements (Inverse Distance Weighted) based on the results retrieved from deep drilled wells reaching one aquifer (data source: LNEC).

4.1.2 CONCLUSIONS TO THE GABARDINE IMPLEMENTATION

This first implementation and tests in a proprietary ArcGIS system proved that the object-oriented hydrogeological data model is valid and it enables an efficient management and analysis of hydrogeological data. The tests with Portuguese data were successful and they have been extended and performed with Israeli, Greek and Spanish data. Furthermore, the Geospatial Database being an integral part of the GABARDINE Decision Support System contributes to its development allowing for the integration.

The main advantage of this new database is the fact that it is structured according to a clear description of the project components: location, hydrological and hydrogeological equipment, primary data, and interpretation. There are many additional, technological advantages of using

]

the Geospatial database. First of all, a precise and technically documented structure enables interoperable data exchanges between different actors. Secondly, it allows additional analyses using external or embedded tools, once the automatic transfer protocols have been defined. Then, one can use the Geospatial database structure for other projects. This promotes the project worldwide dissemination. Last but not least, it is possible to integrate the GABARDINE tools in other international initiatives such as the Infrastructure for Spatial Information in Europe (INSPIRE), eContent and eContentplus which aims to support the development of multi-lingual content for innovative on-line services across the European Union, Water Information System for Europe (WISE) or Water Framework Directive (WFD).

Nonetheless, the use of ArcGIS software is not free and it requires a licence, which can be a drawback for many users. To overcome this problem, and to test the object-oriented model in an open source and free environment, further tests have been performed using Web2GIS, developed in the Geomatics Unit at University of Liège (Laplanche, 2006).

4.2 WEB2GIS IMPLEMENTATION

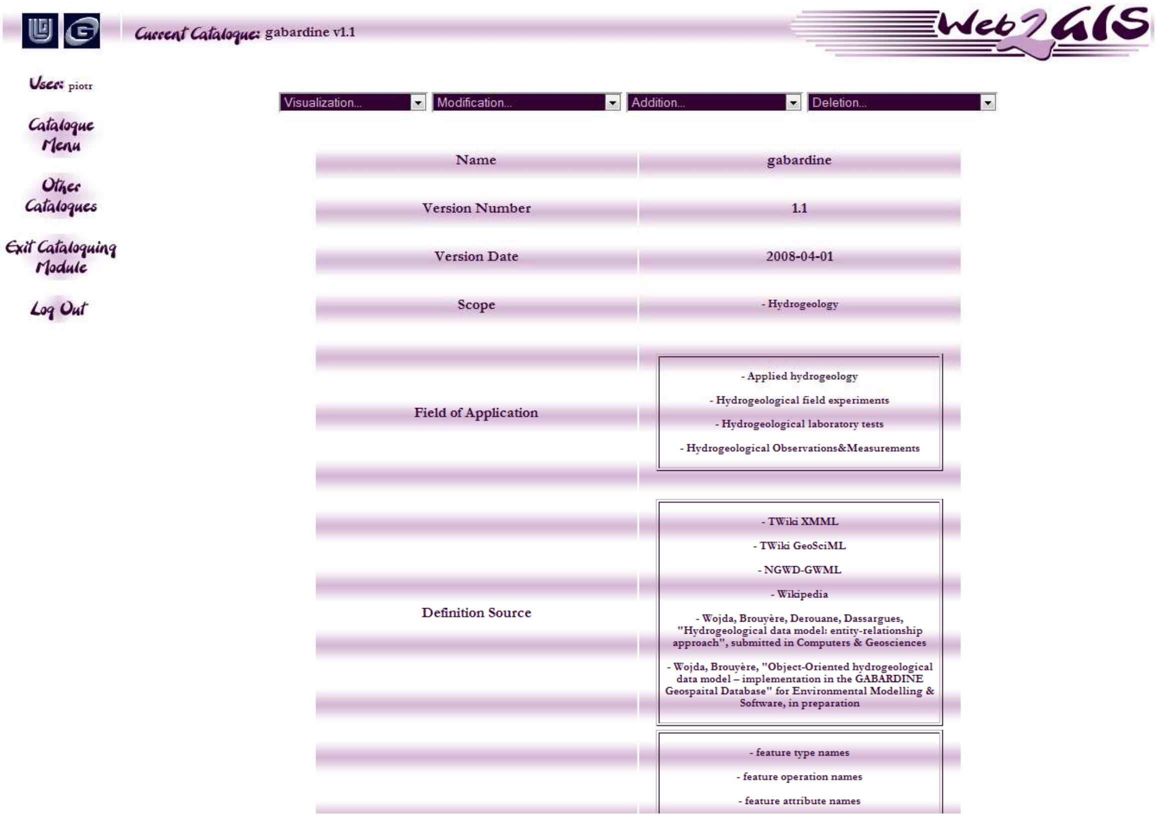
In order to test the versatility and flexibility of the object-oriented hydrogeological data model presented in Chapter 3, the model has also been implemented in the Web2GIS Open Source free system developed in the Geomatics Unit of the University of Liege. Web2GIS is a web-based spatial database conception environment, which is supported and maintained on a server using exclusively Open Source software such as Apache, PHP, PostgresSQL/PostGIS and PhpMapScript/MapServer (Laplanche, 2008). This modular solution promotes the use of international standards coming from ISO/TC211 and OGC. Every module of Web2GIS is designed to facilitate the work of different classes of users, from spatial data producers, through spatial database designers, finally, data users. The modules are as follows:

- the Cataloguing Module enabling a description of spatial data specifications;
- the Conceptual Modelling Module for spatial database designers;
- the Implementation Module to generate an instance of a spatial database and then to populate it with data;
- the Cartographic Module allowing for spatial data visualisation and querying;
- the Privilege Management Module used for user rights management.

During the experiment of the implementation, each of the 5 Web2GIS modules has been used, enabling different phases such as data specification, design of a spatial database and its implementation, and finally management, visualisation and querying of hydrogeological data. The next section describes the methodology used for the data model implementation and use.

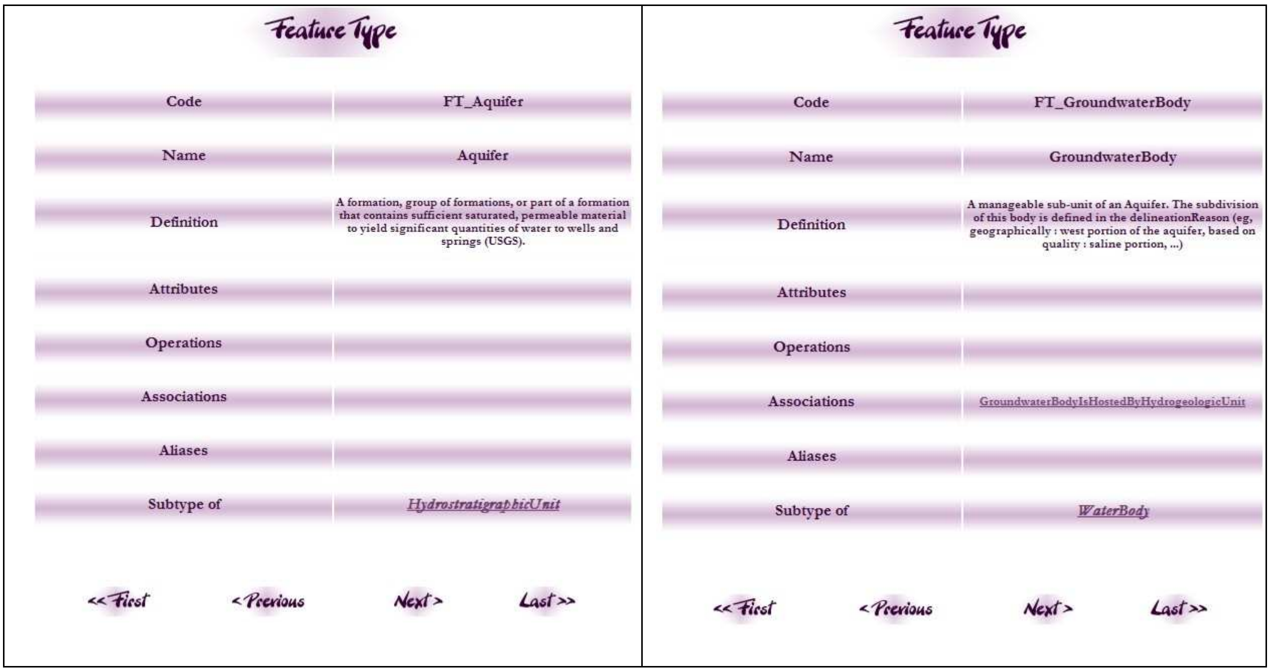
4.2.1 DATA SPECIFICATION

In order to follow the ISO/TC211 standard on feature cataloguing (ISO 19110, 2005), a specialised “gabardine” feature catalogue has been created in the Web2GIS environment using the Cataloguing Module (Figure 58). The definition of the feature types and their attributes has been based on the analysis performed for the object-oriented database described in the previous chapter. Associations between the feature types have also been defined (Figure 59).



Name	gabardine
Version Number	1.1
Version Date	2008-04-01
Scope	- Hydrogeology
Field of Application	- Applied hydrogeology - Hydrogeological field experiments - Hydrogeological laboratory tests - Hydrogeological Observations&Measurements
Definition Source	- TWiki XMML - TWiki GeoSciML - NGWD-GWML - Wikipedia - Wojda, Brouyère, Derouane, Dassargues, "Hydrogeological data model: entity-relationship approach", submitted in Computers & Geosciences - Wojda, Brouyère, "Object-Oriented hydrogeological data model – implementation in the GABARDINE Geospaital Database" for Environmental Modelling & Software, in preparation
	- feature type names - feature operation names - feature attribute names

Figure 58. The Web2GIS Cataloguing Module enables to describe and structure any spatial and non-spatial data according to the ISO 19110 standard on Feature Cataloguing. Using this module, hydrogeological data have been organized and appropriate terms have been defined in the Feature Catalogue.



Code	FT_Aquifer
Name	Aquifer
Definition	A formation, group of formations, or part of a formation that contains sufficient saturated, permeable material to yield significant quantities of water to wells and springs (USGS).
Attributes	
Operations	
Associations	
Aliases	
Subtype of	*HydrostratigraphicUnit*

Code	FT_GroundwaterBody
Name	GroundwaterBody
Definition	A manageable sub-unit of an Aquifer. The subdivision of this body is defined in the delineationReason (eg, geographically : west portion of the aquifer, based on quality : saline portion, ...)
Attributes	
Operations	
Associations	GroundwaterBodyIsHostedByHydrogeologicUnit
Aliases	
Subtype of	*WaterBody*

Figure 59. Aquifer and GroundwaterBody feature types defined within the “gabardine” feature catalogue. A data producer or a database designer can see types definitions, possible associations, and hertitage relationships (subtype of).

This phase of the experiment showed that all the necessary hydrogeological Feature Types defined in the object-oriented model can be designed in an Open Source software and in a ISO 19110 compliant form. The Web2GIS PHP-based user interface enables the user to create a feature catalogue, to define the necessary feature types, and finally to query and visualise all available feature types. The Cataloguing Module guarantees ISO 19110 compatibility, data availability and data structuring for data producers. It provides also a basis for conceptual database modelling, which is described in the next section.

4.2.2 DATABASE DESIGN

Once all the features types have been defined and major associations between them established, a database designer can model a specific database, using one or many available Feature Catalogues. The Conceptual Modelling Module uses the UML notation for standard application design, following the ISO 19109 (2005) describing the rules for applications schema. It enables to fully document a database application before its real implementation.

The hydrogeological data model is organized into 5 packages, namely: Borehole, ConstructionElement, HydrogeologicSamplingFeature, Hydrogeology, and

ObservationsMeasurements. Each package is identified by different colour and it contains several feature types with their associations, imported from the Cataloguing Module. The model presented in Figure 60, corresponds to the object-oriented model presented in Chapter 3, with minor modifications. These modifications are due to the fact that Web2GIS imposes less technological and technical constraints than a proprietary ArcGIS environment. As a consequence, Web2GIS enables easier and more natural data modelling. For instance, Web2GIS can be used to establish a Feature Catalogue according to ISO/TC211 standards, Web2GIS allows for the associations inheritance down to specialized classes, or finally Web2GIS makes it easy to load and manage spatial data, directly in PostgreSQL/PostGIS spatial database.

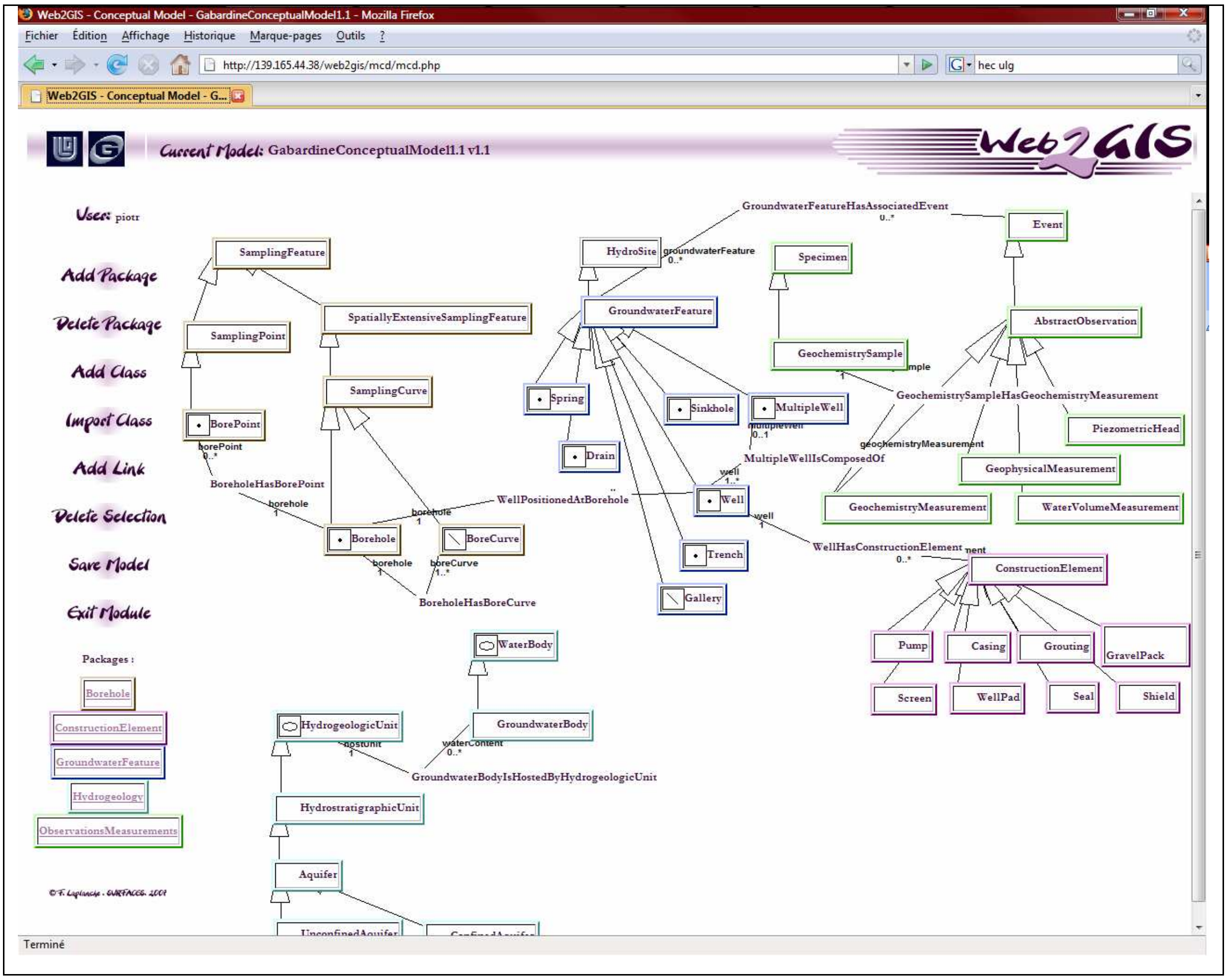
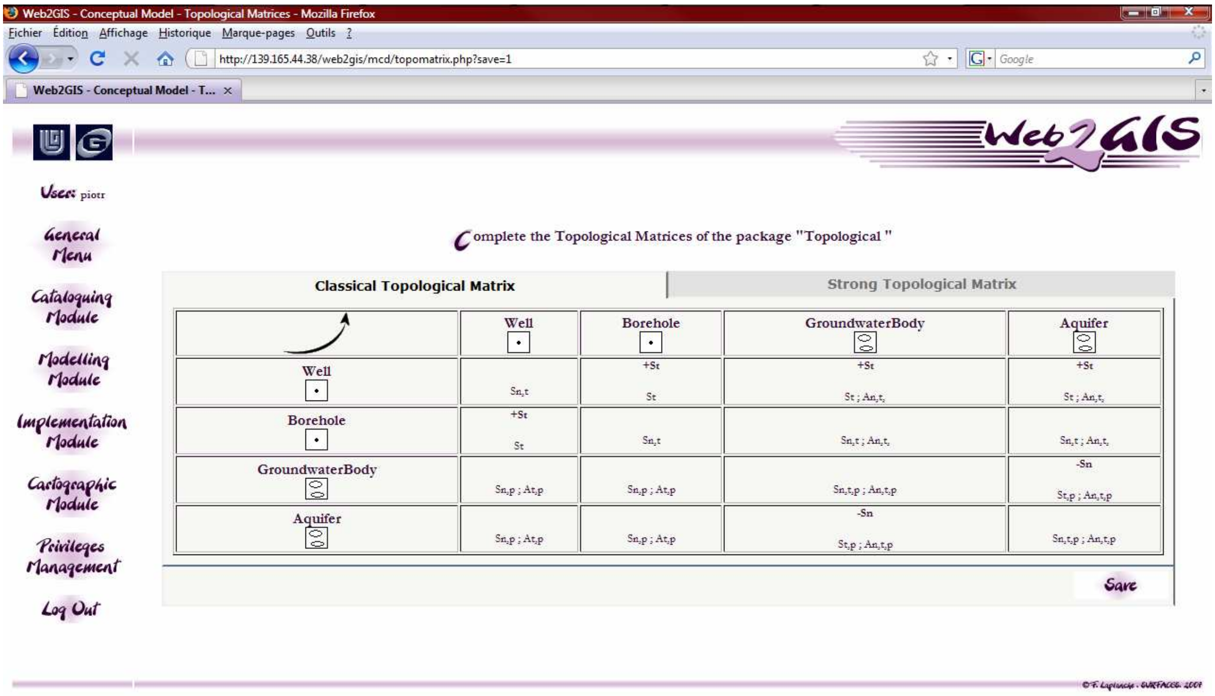


Figure 60. Conceptual Modelling Module: Hydrogeological data model presented in the Web2GIS implementation. Packages are identified by their colour codes, each package contains imported feature types and their associations.

As far as topological constraints are considered, the Conceptual Modelling Module allows for their definition, using the CONGOO formalism (Pantazis and Donnay, 1996), where every 2D topological state between two spatial objects can be characterized by combining two basic topological relationships (superimposition and adjacency) and three different levels of application (null-partial-total). More details about the implementation of the topological notions can be found in Laplanche (2006).

As example, several topological relationships have been established between spatial features of the implemented model (Figure 61). Using these topological constraints, possible relationships between each object of two classes can be defined as mandatory or forbidden.



Complete the Topological Matrices of the package "Topological "

	Well	Borehole	GroundwaterBody	Aquifer
Well	Sn,t	+St St	+St St ; An,t,	+St St ; An,t,
Borehole	+St St	Sn,t	Sn,t ; An,t,	Sn,t ; An,t,
GroundwaterBody	Sn,p ; At,p	Sn,p ; At,p	Sn,t,p ; An,t,p	-Sn St,p ; An,t,p
Aquifer	Sn,p ; At,p	Sn,p ; At,p	-Sn St,p ; An,t,p	Sn,t,p ; An,t,p

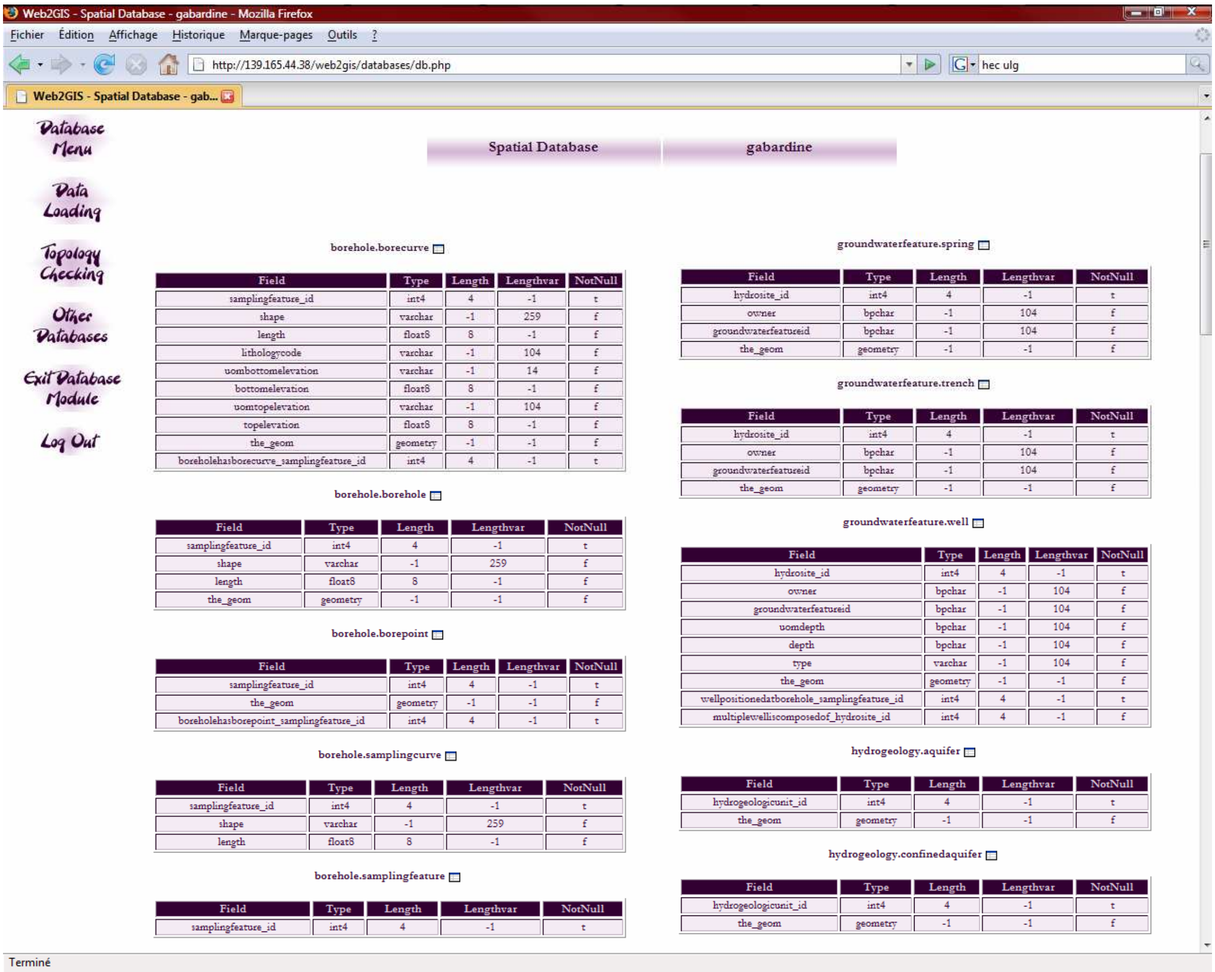
Figure 61. Classical topological matrix established for 4 spatial features. For instance, mandatory topological constraints are as follows: a Well feature has to be totally superimposed with a Bohehole feature, or a GroundwaterBody feature has to be hosted by an Aquifer feature (non-superimposition is forbidden, while partial or total superimpositions are allowed).

4.2.3 SPATIAL DATABASE IMPLEMENTATION AND MANAGEMENT

The data model described in the previous section and presented in the UML notation has been used to generate a schema of a spatial database. The Web2GIS application allows for **spatial** data modelling, using an object geometry extension, as a particular type of attribute, based on ISO 19107 standard (2003) concerning spatial schema.

The hydrogeological data model has been implemented directly in the PostgreSQL/PostGIS environment (Figure 62). Tables were created according to the following rules (Laplanche, 2008):

- spatial classes of the data model give birth to spatial tables;
- depending on cardinalities of associations, one association can give birth to an additional table or just a foreign key attribute in the appropriate table;
- a composition relationship leads to a referential integrity constraint between the "whole" and its "parts";
- generalization/specialization is translated by inheritance between tables.



borehole.borecurve

Field	Type	Length	Lengthvar	NotNull
samplingfeature_id	int4	4	-1	t
shape	varchar	-1	259	f
length	float8	8	-1	f
lithologycode	varchar	-1	104	f
uombottomelevation	varchar	-1	14	f
bottomelevation	float8	8	-1	f
uomtopelevation	varchar	-1	104	f
topelevation	float8	8	-1	f
the_geom	geometry	-1	-1	f
boreholehasborecurve_samplingfeature_id	int4	4	-1	t

borehole.borehole

Field	Type	Length	Lengthvar	NotNull
samplingfeature_id	int4	4	-1	t
shape	varchar	-1	259	f
length	float8	8	-1	f
the_geom	geometry	-1	-1	f

borehole.borepoint

Field	Type	Length	Lengthvar	NotNull
samplingfeature_id	int4	4	-1	t
the_geom	geometry	-1	-1	f
boreholehasborepoint_samplingfeature_id	int4	4	-1	t

borehole.samplingcurve

Field	Type	Length	Lengthvar	NotNull
samplingfeature_id	int4	4	-1	t
shape	varchar	-1	259	f
length	float8	8	-1	f

borehole.samplingfeature

Field	Type	Length	Lengthvar	NotNull
samplingfeature_id	int4	4	-1	t

groundwaterfeature.spring

Field	Type	Length	Lengthvar	NotNull
hydrosite_id	int4	4	-1	t
owner	bpchar	-1	104	f
groundwaterfeatureid	bpchar	-1	104	f
the_geom	geometry	-1	-1	f

groundwaterfeature.trench

Field	Type	Length	Lengthvar	NotNull
hydrosite_id	int4	4	-1	t
owner	bpchar	-1	104	f
groundwaterfeatureid	bpchar	-1	104	f
the_geom	geometry	-1	-1	f

groundwaterfeature.well

Field	Type	Length	Lengthvar	NotNull
hydrosite_id	int4	4	-1	t
owner	bpchar	-1	104	f
groundwaterfeatureid	bpchar	-1	104	f
uomdepth	bpchar	-1	104	f
depth	bpchar	-1	104	f
type	varchar	-1	104	f
the_geom	geometry	-1	-1	f
wellpositionedatborehole_samplingfeature_id	int4	4	-1	t
multiplewelliscomposedof_hydrosite_id	int4	4	-1	f

hydrogeology.aquifer

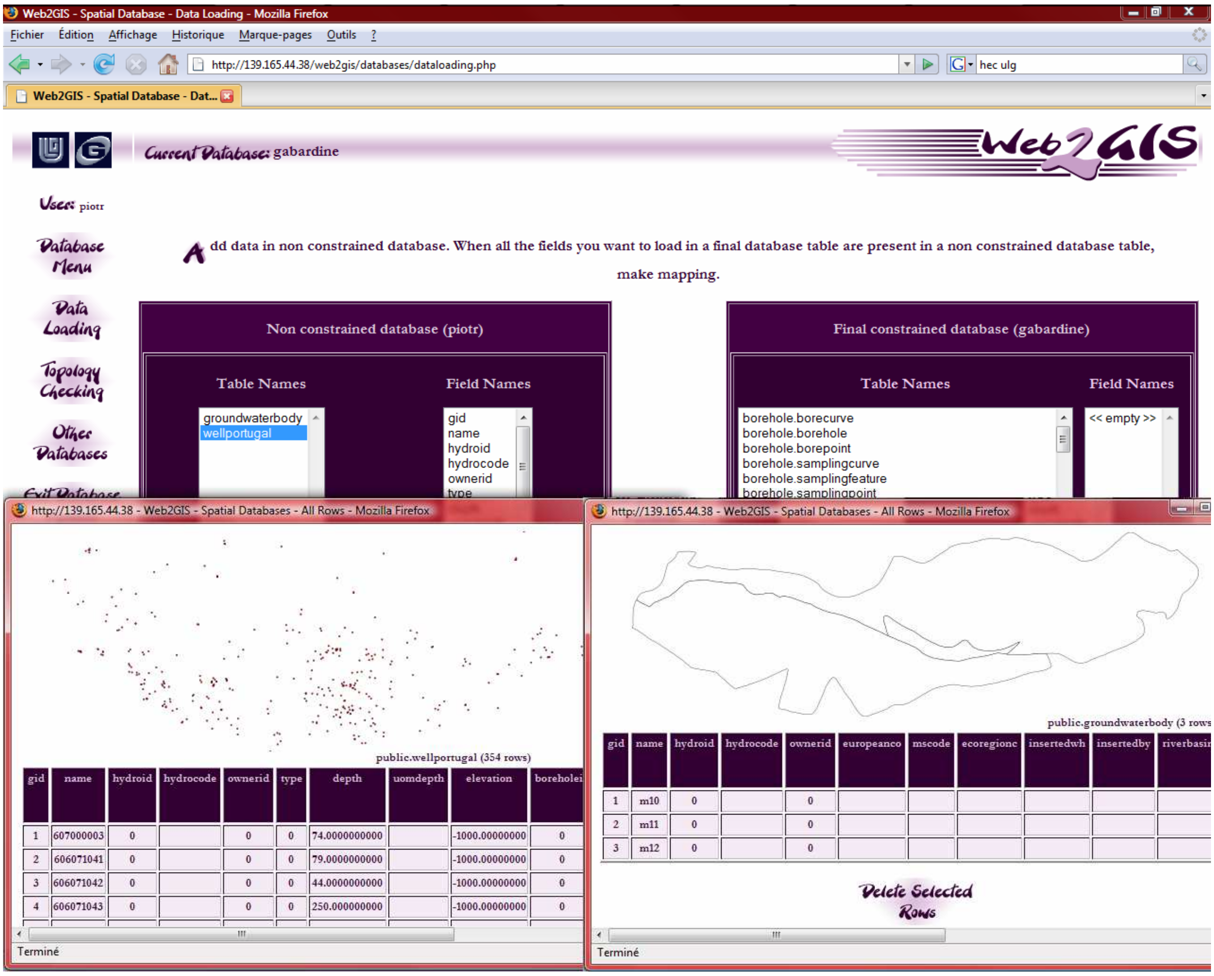
Field	Type	Length	Lengthvar	NotNull
hydrogeologicunit_id	int4	4	-1	t
the_geom	geometry	-1	-1	f

hydrogeology.confinedaquifer

Field	Type	Length	Lengthvar	NotNull
hydrogeologicunit_id	int4	4	-1	t
the_geom	geometry	-1	-1	f

Figure 62. Implemented spatial data model as a PostgresSQL/PostGIS database instance. Spatial tables have a special geometry attribute.

After creating a database instance, the Web2GIS application allows for data loading under two formats: text files for spatial or non-spatial data, and Shapefiles for spatial data. The loading process is performed in two steps. First, data are loaded in a non-constrained database, which does not take into consideration topological constraints (Figure 63).



Current Database: gabardine

User: piotr

Add data in non constrained database. When all the fields you want to load in a final database table are present in a non constrained database table, make mapping.

public.wellportugal (354 rows)

gid	name	hydroid	hydrocode	ownerid	type	depth	uomdepth	elevation	boreholei
1	607000003	0		0	0	74.0000000000		-1000.00000000	0
2	606071041	0		0	0	79.0000000000		-1000.00000000	0
3	606071042	0		0	0	44.0000000000		-1000.00000000	0
4	606071043	0		0	0	250.000000000		-1000.00000000	0

public.groundwaterbody (3 rows

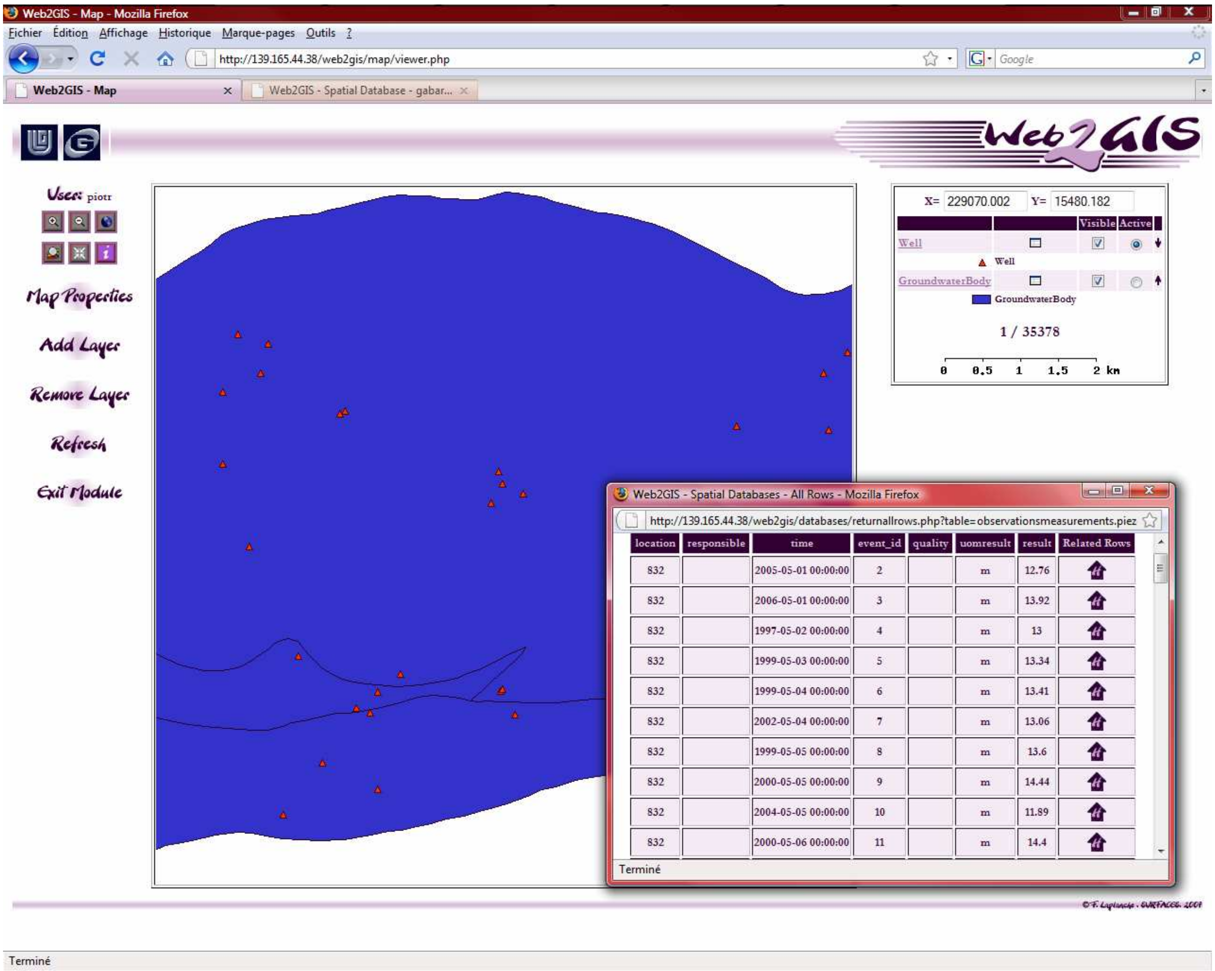
gid	name	hydroid	hydrocode	ownerid	europeanco	mscode	ecoregionc	insertedwh	insertedby	riverbasir
1	m10	0		0						
2	m11	0		0						
3	m12	0		0						

Figure 63. Loading spatial and non-spatial data into a non-constrained database. On the left-hand side, a window presenting available wells on the Portuguese test site. On the right-hand side, a window presenting groundwater bodies in the Algarve region (data source: LNEC).

Then, the user can verify that his data comply with all the topological constraints. The data and the database can be checked, and necessary modification can be performed, using the Web2GIS interface. The spatial database is then available for further exploitation by SQL clients or GIS particular software.

4.2.4 HYDROGEOLOGICAL DATA VISUALISATION AND QUERYING

The Cartographic Module enables spatial data visualisation and simple querying, this module being based on the Open Source MapServer software and its PHP library PhpMapScript (Laplanche, 2008). The user can freely display and query PostGIS non-spatial data (Figure 64) or spatial tables (Figure 65), and use the following OGC standard services: Web Feature Services (WFS) and Web Map Services (WMS). Available functionalities are: zooming, panning, classification according to the field values, association visualisation and others.

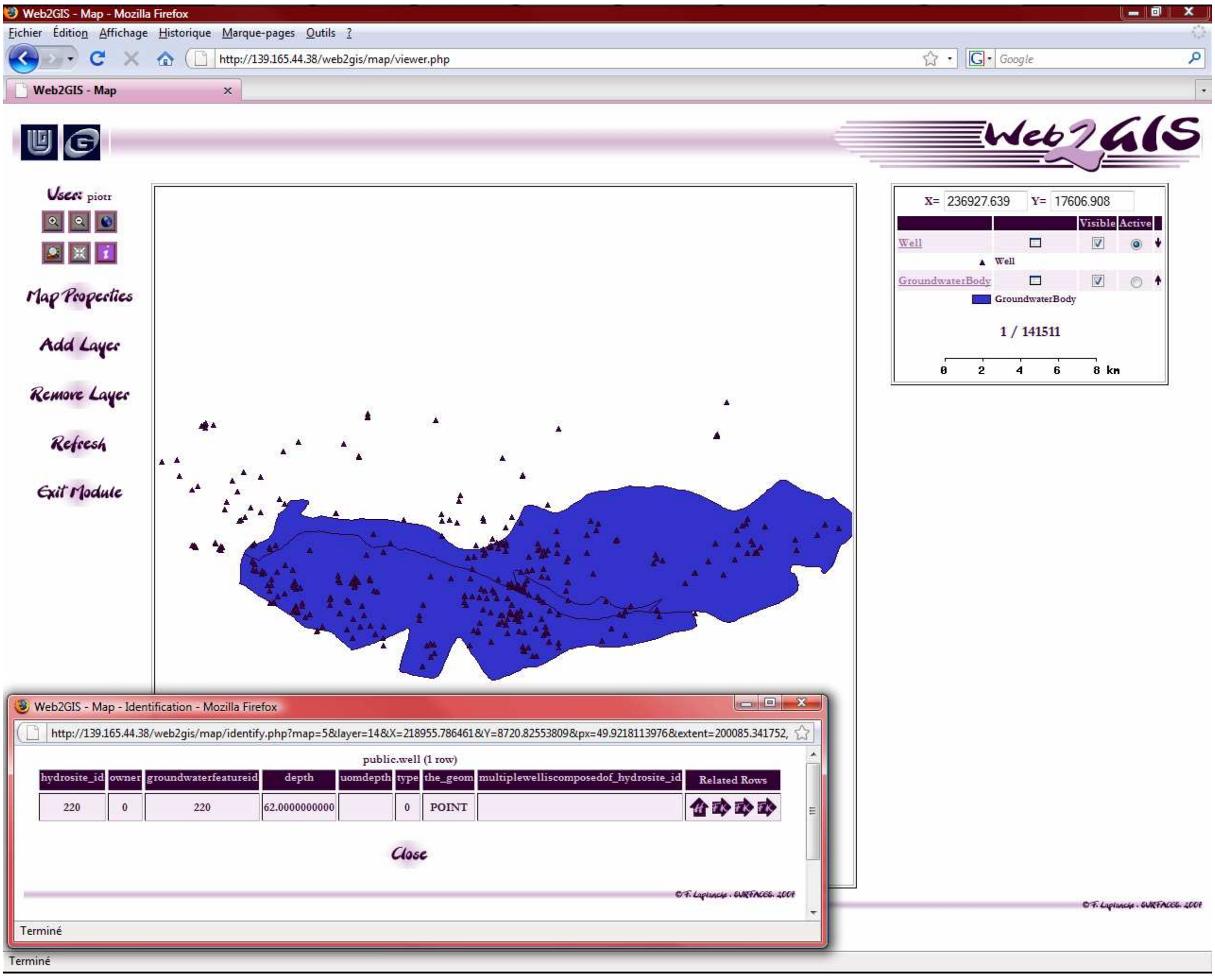


X= 229070.002 Y= 15480.182

http://139.165.44.38/web2gis/databases/returnallrows.php?table=observationsmeasurements.piez

location	responsible	time	event_id	quality	uomresult	result	Related Rows
832		2005-05-01 00:00:00	2		m	12.76	⌂
832		2006-05-01 00:00:00	3		m	13.92	⌂
832		1997-05-02 00:00:00	4		m	13	⌂
832		1999-05-03 00:00:00	5		m	13.34	⌂
832		1999-05-04 00:00:00	6		m	13.41	⌂
832		2002-05-04 00:00:00	7		m	13.06	⌂
832		1999-05-05 00:00:00	8		m	13.6	⌂
832		2000-05-05 00:00:00	9		m	14.44	⌂
832		2004-05-05 00:00:00	10		m	11.89	⌂
832		2000-05-06 00:00:00	11		m	14.4	⌂

Figure 64. Additional window showing piezometric head level measurements taken in the selected well: “832”. All measurements must have a date, a value and a unit of measures, and may have other additional information (data source: LNEC).



public.well (1 row)

hydrosite_id	owner	groundwaterfeatureid	depth	uomdepth	type	the_geom	multiplewelliscomposedof_hydrosite_id	Related Rows
220	0	220	62.0000000000		0	POINT		

Figure 65. Visualisation and querying of spatial data, using the Cartographic Module. Several Groundwater Bodies have been displayed in the background, together with the Well active layer, presenting available wells. An additional window shows some first details of a chosen well, together with its associated information (data source: LNEC).

4.2.5 CONCLUSIONS TO WEB2GIS IMPLEMENTATION

The Web2GIS running in the Web environment and controlled by the Privilege Management Module, allows for the implementation of a spatial data model as described in Chapter 3. The implementation follows ISO/TC211 and OGC standards for spatial information. The generated spatial database has been fed with hydrogeological field data. The model implementation and the spatial database generation have been successful. Field hydrogeological data have been loaded into the database and visualised, explored and queried using specialized GIS free software delivered within the Cartographic Module. Hydrogeological data such as aquifers, wells, well equipment and different observations and measurements have efficiently been introduced into the database and analysed, using available tools. This test proves that the hydrogeological data model is compatible and flexible enough to be used with free and Open Source software on a Web-based platform, without any expensive and proprietary systems.

4.3 GABARDINE DATA MODEL CONTRIBUTION TO GWML

GroundWater Markup Language (GWML) is a Canadian standard data format for hydrogeological data exchange. GWML is derived from the Geography Markup Language (GML) standard used for geographical data exchange and it extends two other standards: GeoScience Markup Language (GeoSciML) used for geoscientific data exchange, and Observations & Measurements used for exchange of observations and measurements made by humans or machines (Boisvert et al., 2005). GWML can be considered as a natural extension of GeoSciML, importing concepts such as Geologic Units, Rocks, and Minerals, and adding entities such as hydrogeologic units, hydrogeologic properties, water wells and water budget entities (Boisvert and Brodaric, 2007). GWML uses also SensorML, which enables to exchange data about sensors in an OGC GML compliant data format.

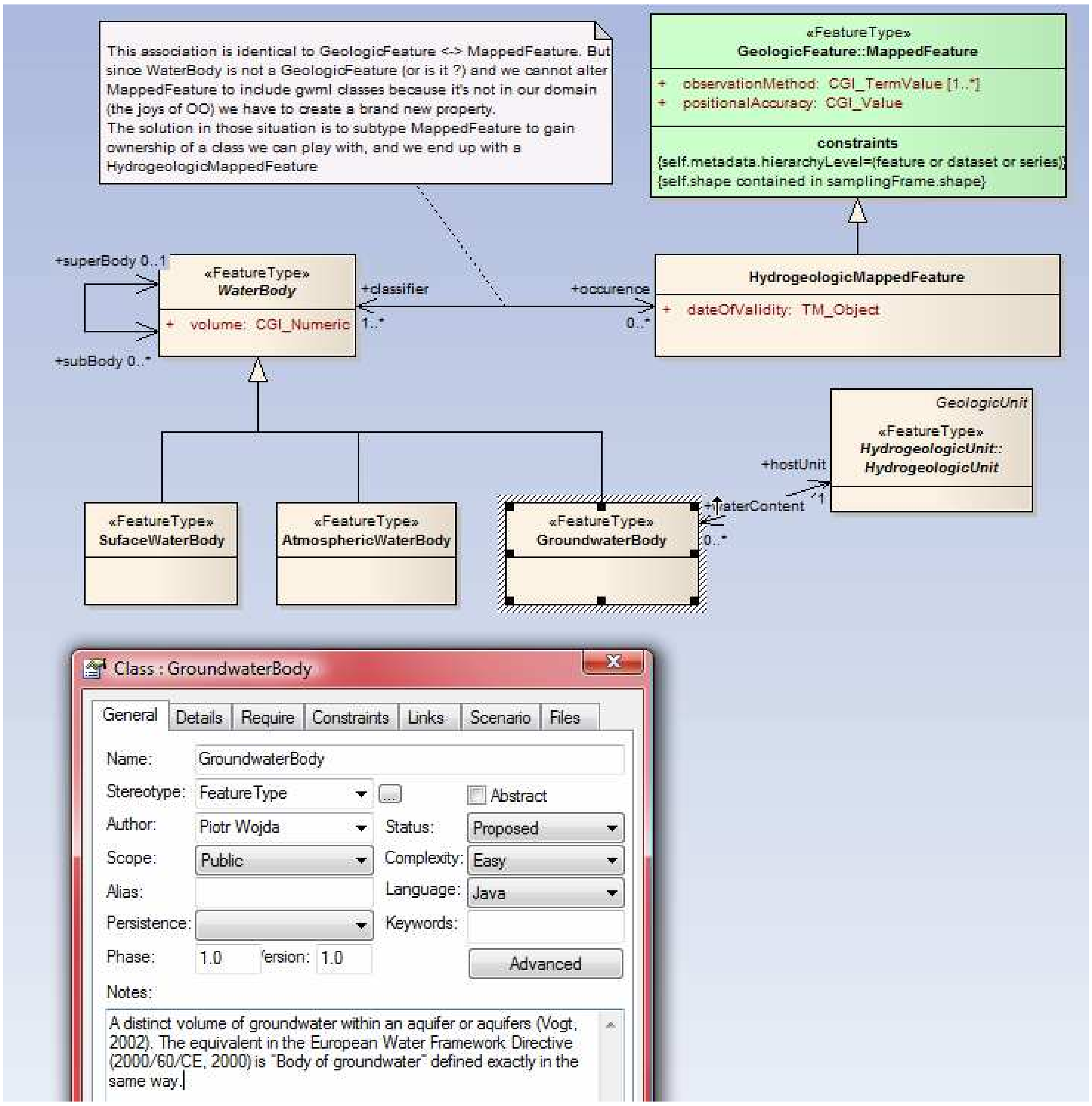
GWML is being integrated in the OGC web services infrastructure and it can be used in conjunction with the following services: Web Mapping Service, Web Feature Service, Sensor Observation Service, and Web Coverage Service. GWML can be a part of a request to these services or as a part of the resulting response (http://ngwd-bdnes.cits.rncan.gc.ca/service/ngwd/exploration/ngwd/gwml.html, 2008).

The purpose of the GWML development and data exchange model is to deliver groundwater data using a standard format and to open geospatial web service protocols. The model should enable data interoperability across different groups of interested parties: from data providers, through scientists, ending up with decision makers.

The current work on GWML is being done mainly by two means: internet/e-mail discussions and workshops. The present work has contributed to different practical and theoretical discussions, team work, as well as to one Canadian workshop, held between 4 and 8 February, 2008.

The main contribution topics are the following: (1) definitions of groundwater body and aquifer feature classes, (2) borehole functions versus water well functions, (3) specific hydrogeological observations and measurements such as pumping tests, tracer tests and others, (4) hydrogeologic properties class, and finally (5) the concept of Water as a concrete class. The most important decisions, concerning these subjects, taken during the meeting are reported in the next section of this thesis.

The Groundwater Body concept has been adapted from the European Water Framework Directive (2000/60/EC, 2000) and is defined in GWML as a distinct volume of groundwater within an aquifer or aquifers (Vogt, 2002). It inherits from the WaterBody class, which is a mass or a volume of water, constrained geographically and/or structurally (Figure 66). This class is considered as a distinction between water as a material and water as a feature.



This association is identical to GeologicFeature <-> MappedFeature. But since WaterBody is not a GeologicFeature (or is it ?) and we cannot alter MappedFeature to include gwml classes because it's not in our domain (the joys of OO) we have to create a brand new property.
The solution in those situation is to subtype MappedFeature to gain ownership of a class we can play with, and we end up with a HydrogeologicMappedFeature

Name: GroundwaterBody
Stereotype: FeatureType
☐ Abstract
Author: Piotr Wojda
Status: Proposed
Scope: Public
Complexity: Easy
Alias:
Language: Java
Persistence:
Keywords:
Phase: 1.0 'ersion: 1.0
Notes:
A distinct volume of groundwater within an aquifer or aquifers (Vogt, 2002). The equivalent in the European Water Framework Directive (2000/60/CE, 2000) is "Body of groundwater" defined exactly in the same way.

Figure 66. WaterBody class and its specialised classes: SurfaceWaterBody, AtmosphericWaterBody and GroundwaterBody (source: GWML, 2008).

It was also concluded that both Borehole and WaterWell are sampling features according to the GML-GeoSciML specifications, where a "SamplingFeature" is a feature used primarily for taking observations (GeoSciML, 2008). In this context, a distinction has to be made between a WaterWell which samples a groundwater body and a Borehole which samples an aquifer (the geological underground) and reports this sampling by, in the form of, for instance, a lithological log. Figure 67 presents the WaterWell class and its associations.

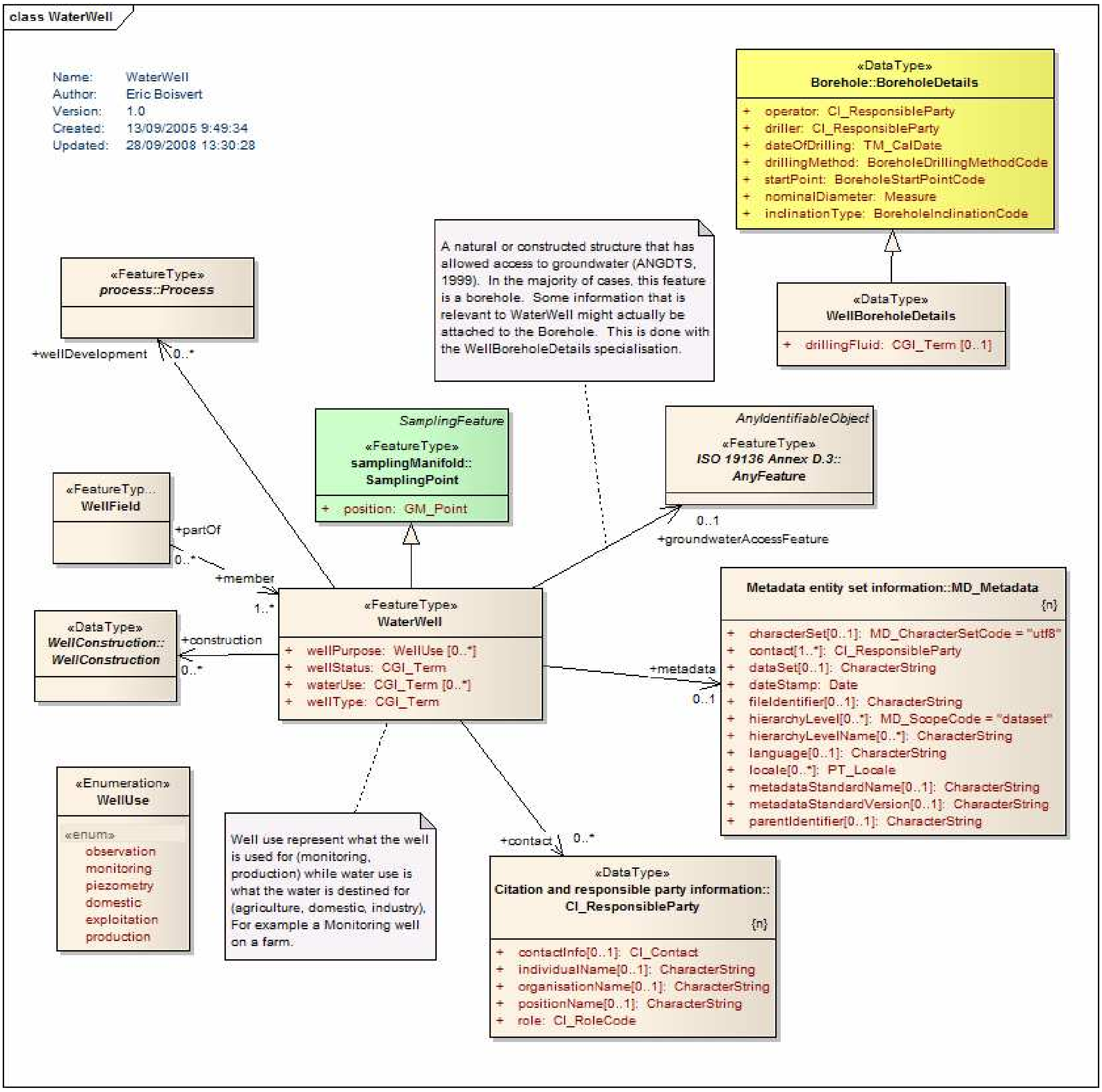


Figure 67. Waterwell as a SamplingFeature with its associated classes (source: GWML, 2008).

Specific classes were created in order to deal with particular hydrogeological tests, such as pumping tests and tracer tests, as detailed in Section 3.3.3.4 (Figure 68). The Process class together with its associated classes stores observations and measurements recorded during a pumping test, while the DependentObservationCalculation class enables to store interpretations of the results. An XML file which illustrates a pumping test in details is enclosed in Annex 1.

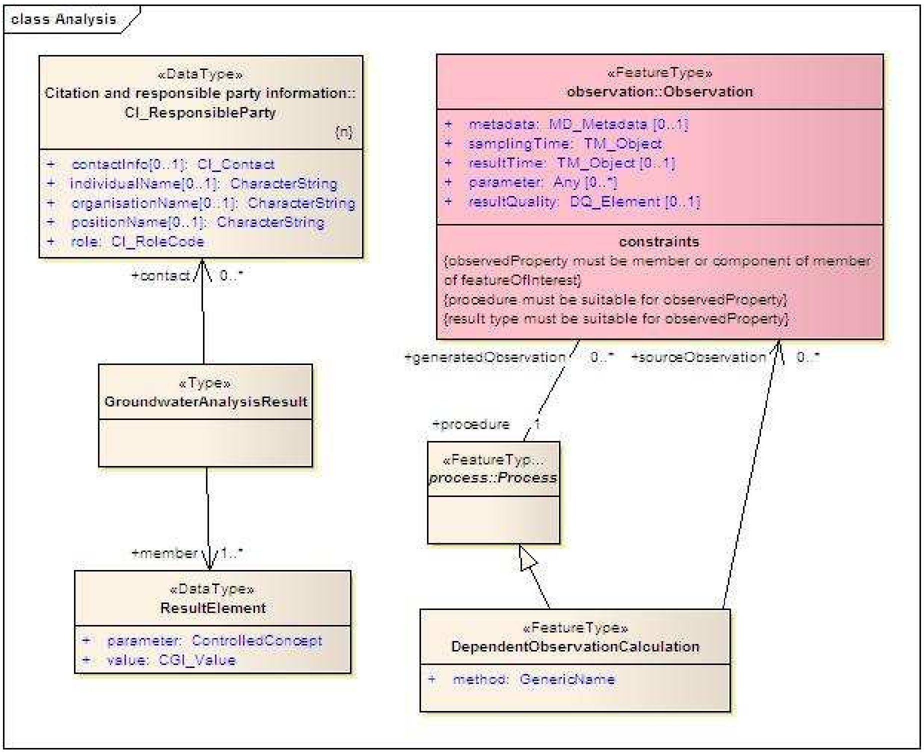
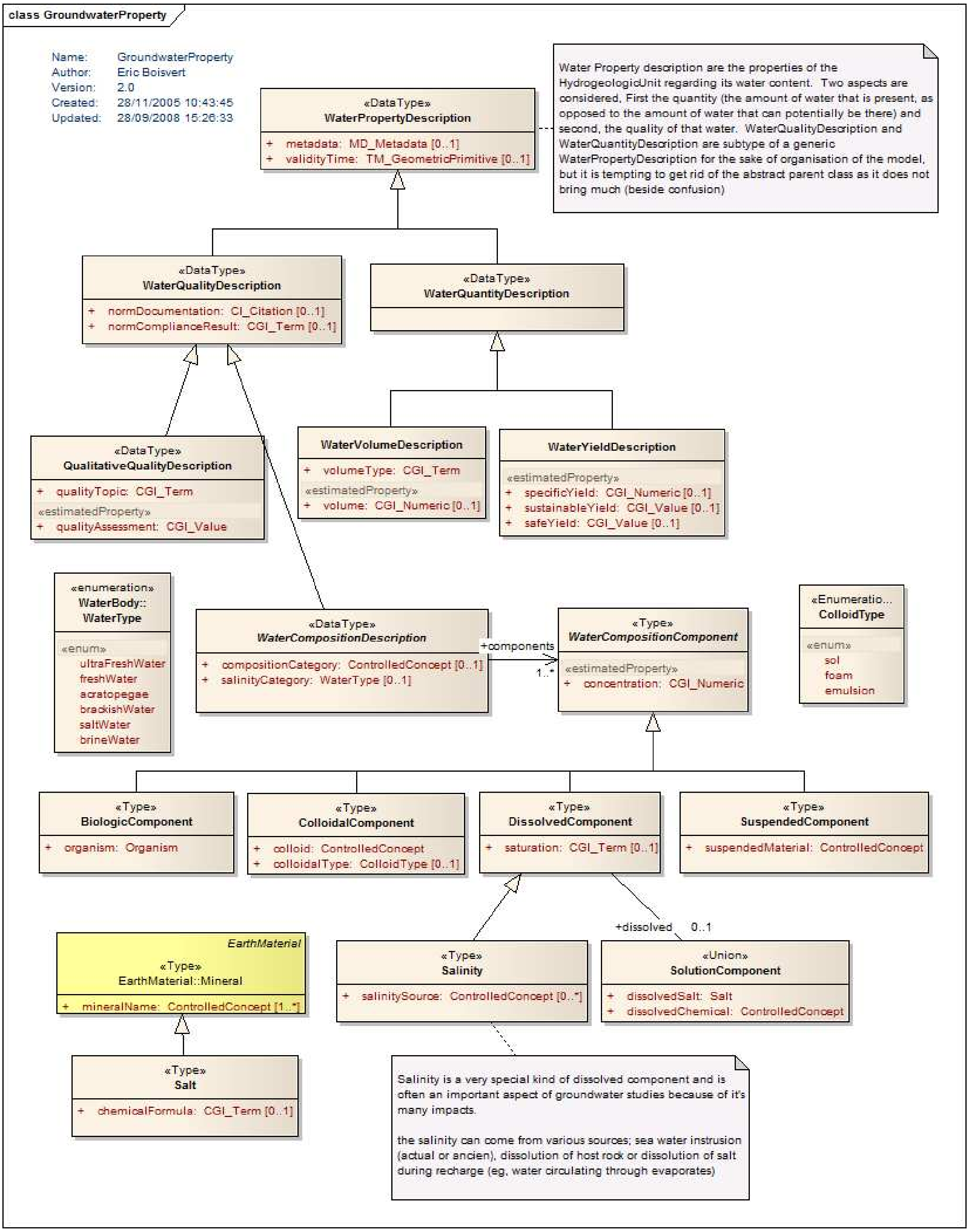


Figure 68. Conceptual model dealing with Hydrogeological pumping tests. Process class allows storing observations and measurements retrieved during a pumping test, while DependentObservationCalculation enables to store interpretations of the results (source: GWML, 2008).

The GWML sub-model used to store observations and measurements was tested during the Canadian workshop with data coming from the HydroCube database. The first example of piezometric head level measurements is shown in Annex 2. Three groundwater level measurements (WL1, WL2, and WL3) taken at different times are reported, together with the coordinates of the well and the reference elevation used for measurements. The second example, made of two parts, illustrates geochemistry measurements performed on a groundwater sample taken from a groundwater body (Annex 3). The first section, “walloon_gechem.xml” provides the necessary information on water geochemistry components which are measured: bromide, silicium, conductivity, pH, nitrates. The second section, “waterWell3.xml”, describes samples of water pumped from the well at different dates, together with the results of measurements performed on the samples.

Different hydrogeologic properties have been discussed. WaterPropertyDescriptions are the properties of the HydrogeologicUnit regarding its water quantity and second, the water quality (Boisvert, 2008). Hydrogeologic properties are categorized in the following three classes. (1) WaterQualityDescription allows for storing a list of common properties related to water quality assessment, and it is a head of a substitution list which includes Qualitative and Quantitative water quality properties, (2) WaterQuantityDescription further divided into 2 separate classes. As a result of these discussions and tests, the WaterQuantityDescription class has been split into 2 different concepts, one for global quantity of water in the aquifer, and the other expressed as a flux of water that can be retrieved: WaterVolumeDescription and WaterYieldDescription (Figure 69).



Water Property description are the properties of the HydrogeologicUnit regarding its water content. Two aspects are considered, First the quantity (the amount of water that is present, as opposed to the amount of water that can potentially be there) and second, the quality of that water. WaterQualityDescription and WaterQuantityDescription are subtype of a generic WaterPropertyDescription for the sake of organisation of the model, but it is tempting to get rid of the abstract parent class as it does not bring much (beside confusion)

Salinity is a very special kind of dissolved component and is often an important aspect of groundwater studies because of it's many impacts.

the salinity can come from various sources; sea water instrusion (actual or ancien), dissolution of host rock or dissolution of salt during recharge (eg, water circulating through evaporates)

Figure 69. Hydrogeologic properties categorised in two main classes: WaterQualityDescription, WaterQuantityDescription (source: GWML, 2008, modified).

As far as the concept of Water as a class is considered, the conclusions of the workshop, as well as the analysis of existing hydrogeological data models indicated that this concept is not necessary and brings some confusion. As a consequence, this concept has been removed from the GWML model.

In conclusion, first tests with field hydrogeological data, performed during the workshop in Québec and reported in this work proved that the GWML model is ready to be used. However, the work on that model has not been finalised yet and further tests and development performed by the hydrogeological community are strongly required.

4.4 REFERENCES TO CHAPTER 4

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CONCLUSIONS & PERSPECTIVES

CONCLUSIONS AND RESEARCH OUTCOMES

5.1 MAIN RESEARCH OUTCOME

To contribute to the standardization of hydrogeological data models, the main objective of this research was to develop an innovative hydrogeological data model, used mainly at two levels: at the local-regional level and then at the international level. To reach this objective, particularities of hydrogeological information have been identified and characterized in a wider context of geospatial information structuring and transfer.

The analysis of existing data models has shown that the hydrogeological community needs more complete and universal data models, with convergence and standardization of their structures which can provide seamless data exchange mechanisms. To respond to these needs, two hydrogeological data models have been proposed: HydroCube and GABARDINE.

The HydroCube model uses the Entity-Relationship modelling technique considered as the most appropriate for a simple and efficient implementation in Relational Database Management Systems. The HydroCube model proposes a "project-oriented" approach that enables to deal with a hydrogeological project as a whole, taking all its important aspects into account. The model implemented in the MS Access® database has been used for 4 years now in many regional, national and international projects, at the regional and national levels.

The GABARDINE model uses the object-oriented Unified Modeling Language, which is the most adequate development methodology in the context of geospatial information exchange, ISO/TC211 standards, and OGC norms. The first model implementation and tests with hydrogeological field data were performed in the ArcGIS environment.

These two models have enabled an efficient contribution to the development of a Canadian standard for hydrogeological data transfer: GroundWater Markup Language. Through many on-line discussion cycles, e-mail exchanges between the project participants, as well as a workshop held in Québec, GWML has been adjusted, adapted and finally tested with first hydrogeological field data.

Finally, the two hydrogeological data models have been validated through their implementations in relational non-spatial and spatial databases or applications such as MS

Access®, ArcGIS, and Web2GIS. Extensive tests with field hydrogeological data have confirmed their soundness.

5.2 PERSPECTIVES

The experimental and practical use of the models presented in this thesis by the hydrogeological community will allow their improvement and applicability in hydrogeological studies. The HydroCube model, already tested and currently used in many projects is promoted as an easy, ready-to-use, and efficient solution for small to medium hydrogeological teams. The GABARDINE model, enriched with fully-functional user interface, has already been used to store data coming both from field and bibliographical investigations. Both models have partially contributed to the development of GroundWater Markup Language (Figure 70).

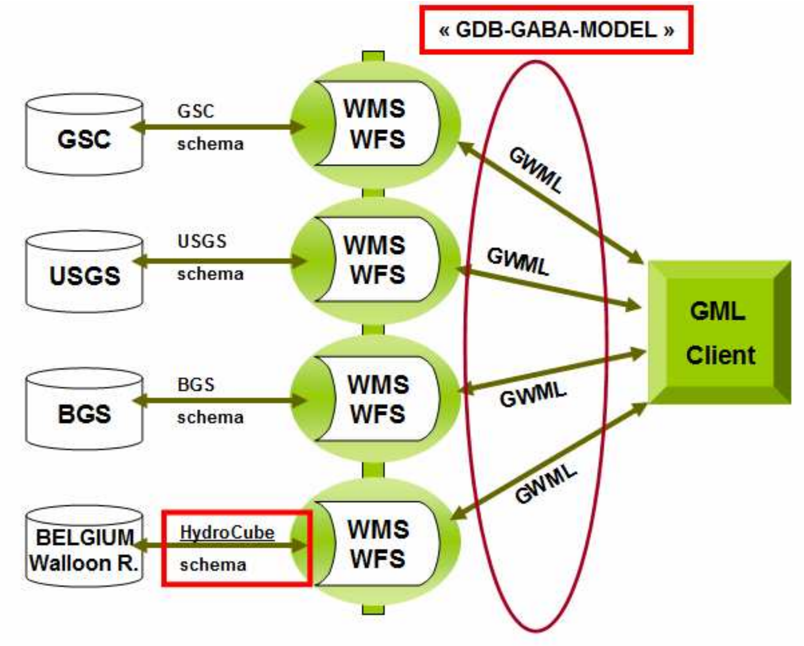

Figure 70. Contribution of the HydroCube schema and the GABARDINE model to the geoinformation infrastructure. The Canadian GWML or HgML will be the common markup language for exchange of hydrogeological information across different GML compatible clients, (image source: XMML, IAMG06, adapted).

This contribution should be continued at the international level. GroundWater Markup Language, strictly based on current ISO/TC211 and OGC norms and standard, has the potential to become the hydrogeological information transfer standards. It is compliant with Open Web Services promoted by the Geoscientific community: WFS, WCS, WMS, and SOS as ones of the most important. In multidisciplinary, multi-user and multi-language environments, hydrogeological information must be transferred seamlessly and rapidly. To avoid unnecessary efforts to be spent on data transformation, adjustment and interpretation, transfers have to be performed by these above mentioned machine-based services. The use of GWML will enable an efficient information exchange between hydrogeologists themselves, as well as within a wider community, by GML compatible clients. It will certainly improve availability, accessibility, and exchange of hydrogeological information.

TERMS AND DEFINITIONS

Abstraction – a process that enables to eliminate or to hide less important parts of the problem within a given context and at a given level of analysis (Booch, Jacobson, Rumbaugh, 2000).

Aggregation – a special form of association that specifies a whole-part relationship between the aggregate (whole) and a component part (ISO 19116:2004).

Array - in computer science an array is a data structure consisting of a group of elements that are accessed by indexing. In most programming languages each element has the same data type and the array occupies a contiguous area of storage (Black, 2008).

Association – a semantic relationship between two or more classifiers that specifies connections among their instances (ISO 19103:2005).

Bag – a finite, unordered collection of related items (objects or values) that may be repeated (ISO 19107:2003).

Class - a descriptor of a set of objects that share the same attributes, operations, methods, relationships, and behaviours (ISO 19107).

Composition – a form of aggregation which requires that a part instance be included in at most one composite at a time, and that the composite object is responsible for the creation and destruction of the parts (ISO 19103:2005)

Coverage - a feature that acts as a function to return values from its range for any direct position within its spatial, temporal or spatiotemporal domain (ISO 19123:2005).

Data - (singular datum) data are individual fragments of information. While organised data are proper elements of information, disorganised data can not be seen as information and are often useless. The organisation of data can be explicit, in markup languages for instance, or implicit, the location of an address on the envelope decides whether that is the addressee address or sender’s one. Secondly, data can be facts, statistics, opinions, previsions collected from intern and extern sources. Data without a context are noise (Nowicki and Staniszkis, 2002).

Decomposition – a process that divides any difficult problem into sub-problems and then enables to treat them individually (Booch, Jacobson, Rumbaugh, 2000).

Encapsulation - a paradigm that permits to communicate with the members of each class by specified interfaces.

Entity - the entity describes one and only one subject – it can be represented by one single table which contains distinct information about wells, sources, protection zones, and others. Each entity contains attributes, which define different characteristics of objects (IBM, 2003).

GeoSciML (Geoscience Markup Language) **-** an application schema of GML, built to store and exchange geoscientific information (Sen and Duffy, 2005).

Geospatial feature - the geospatial feature represents an abstraction of a phenomenon which belongs to the real world. It has geospatial attributes (geometric and topological) such as shape, extent, position, relation to other features. Information about a shape and a position of a feature is contained in the geospatial feature description. The shape and the position are expressed in coordinates in a Spatial Reference System (SRS). The change of the SRS influences the position and the shape of the feature. In geographic systems, geospatial features can be represented by vectors, in simple geometrical forms: points, lines and polygons or their collections. The geospatial feature is not the synonym of the geospatial object. The non-objects features are, for instance, a groundwater recharge area or an artesian basin.

Geospatial object - an instance of a class that is based on the object-oriented paradigm, coming from UML (OMG 01-09-67, 2001; Mark et al., 2001).

GML (Geography Markup Language) - an XML grammar written in XML Schema which provides a large variety of objects for describing features, co-ordinate reference systems, geometry, topology, time, units of measure and generalised values (Cox, 2001).

GWML (GroundWater Markup Language) – a GML application schema standard data format for exchanging data and information related to groundwater, under development (Boisvert, Brodeur, Brodaric, 2005).

Information - computer data organised and presented in a systematic form for their easy basic meaning understanding or data that are interpreted in one specific goal (Nowicki and Staniszkis, 2002).

Inheritance - or the “generalization-specialization” relationship, specifies that each super-class in the inheritance relationship delegates all its attributes, methods, and constraints to a child-class and it is one of the most important object-oriented paradigms.

ISO/TC211 (International Organization for Standardization, Technical Committee 211) **-** the ISO/TC211 Geographic information/Geomatics scope is focused on standardization in the field of digital geographic information (ISO/TC211: http://www.isotc211.org). It aims at establishing a structured set of standards for information on objects or phenomena directly or indirectly associated with a location relative to the Earth. According to the ISO/TC211 statement, geographic information standards may specify methods, tools, and services for data definition, description and management, data acquisition, processing, analysis, accessing, and visualisation.

Mereology - a branch of topology that deals with the issue of association of one feature with another as a part of it (Michalak, 2003 after Smith and Mark, 1998).

Mereotopology - a branch of topology that, when a spatial context is concerned, deals with the issue of association of one feature with another as a part of it (Michalak, 2003 after Smith and Mark, 1998).

Metadata - data about data (ISO 19115:2005). A metadata record is a file of information in different forms, nowadays usually presented as an XML document, which provides basic characteristics of a data or information resource. It provides the: who, what, when, where, why and how of the resource. Geospatial metadata can be used to document geoinformation resources in different formats, such as GIS files, or geospatial databases (FGDC, 2006, http://www.fgdc.gov/metadata). The ISO 19115 standard states that metadata give information about the identification, the extent, the quality, the spatial and temporal schema, spatial reference, and distribution of digital geographic data (ISO 19115, 2003).

Metamodel – a model that defines the language for expressing a model (ISO 19103:2005).

Markup Language - a set of annotations to text that describe how it is to be structured, laid out, or formatted. One of the examples is SGML (Standardized General Markup Language) with its two the most popular specializations: HTML (HyperText Markup Language) and XML (eXtensible Markup Language) (Wikipedia, 2008).

OGC (Open Geospatial Consortium, Inc) - an international industry consortium of 350 companies, government agencies and universities participating in a consensus process to develop publicly available interface specifications (OGC: http://www.opengeospatial.org/ogc). OpenGIS Specifications support interoperable solutions that "geo-enable" the Web, wireless and location-based services. The specifications empower technology developers to make spatial information and services accessible and useful to all kinds of applications.

O&M (Observations & Measurements) - the general models and XML encodings for sensor observations and measurements. O&M originated under OWS-1.1 and was significantly enhanced under the OWS-1.2, OWS-3, and OWS-4 testbed initiatives and is currently a Version 1.0 Implementation Specification (OGC 06-009r6, 2007).

Ontology - entities and relations for a domain of interest to a community of agents (ISO 19101-2, 2004).

Polymorphism – a characteristics that assures that different methods, such as “draw“ or “edit”, will be applied differently, according to the origin and to the type of the object instantiated from a class (Booch, Jacobson, Rumbaugh, 2000).

Profile - a customized UML models for particular domains and platforms. The Unified Modeling Language provides a generic extension mechanism for profiles that are defined using stereotypes, tagged values, and constraints that are applied to specific model elements, such as classes, attributes, operations, and activities (Wikipedia, 2008).

Role – a role that one class plays in a relationship with another classes.

Semantics – in philosophy, semantics is the study of meaning in communication, in informatics semantics is the study of meaning of data or a fragment of a program, or a structured recorded as a schema (Subieta, 1999).

Semantic type – a category of objects that share some common characteristics and are thus given an identifying type name in a particular domain of discourse (ISO 19136, 2005).

SensorML (Sensor Model Language) – the general models and XML schema for describing sensors and processes associated with measurement. SensorML originated under NASA funding and was significantly enhanced under OWS-1.1, OWS-1.2, OWS-3, and OWS-4 testbed initiatives and is now available as a Version 1.0 Implementation Standard (OGC 06-009r6, 2007).

SOS (Sensor Observation Service) **-** provides an API for managing deployed sensors and retrieving sensor data and specifically "observation" data. Whether from in-situ sensors (e.g., water monitoring) or dynamic sensors (e.g., satellite imaging), measurements made from sensor systems contribute most of the geospatial data by volume used in geospatial systems today (OGC 06-009r6, 2007).

Stereotype - new type of modeling element that extends the semantics of the metamodel (ISO 19103:2005).

SWE (Service Web Enablement) - the Open Geospatial Consortium Sensor Web Enablement standards enable developers to make all types of sensors, transducers and sensor data repositories discoverable, accessible and useable via the Web (OGC 06-009r6, 2007).

Tagged value – an explicit definition of a property as a name-value pair (ISO 19103:2005).

Topology - describes the relationships amongst related or neighbouring features such as points, lines or polygons (ISO 19104 DIS).

UML (Unified Modeling Language) - a graphical language for visualizing, specifying, constructing, and documenting the artifacts of a software-intensive system. The Unified Modeling Language offers a standard way to write a system's blueprints, including conceptual things such as business processes and system functions as well as concrete things such as programming language statements, database schemas, and reusable software components

(Booch, Jacobson, Rumbaugh, 2000). UML is extensible, offering the following mechanisms for customization: profiles and stereotype. The semantics of *extension by profiles* have been improved with the UML 1.0 major revision (Wikipedia, 2008).

Universe of discourse – a view of the real or hypothetical world that includes everything of interest (ISO 19102:2002).

WCS (Web Coverage Service) **-** the Open Geospatial Consortium service that supports electronic retrieval of geospatial data as "coverages" – that is, digital geospatial information representing space-varying phenomena (Wikipedia, 2008). A WCS provides access to potentially detailed and rich sets of geospatial information, in forms that are useful for client-side rendering, multi-valued coverages, and input into scientific models and other clients. The WCS may be compared to the OGC Web Map Service (WMS) and the Web Feature Service (WFS); like them it allows clients to choose portions of a server's information holdings based on spatial constraints and other criteria (OGC 07-067r5, 2008). Unlike the WMS [OGC 06-042], which portrays spatial data to return static maps (rendered as pictures by the server), the Web Coverage Service provides available data together with their detailed descriptions; defines a rich syntax for requests against these data; and returns data with its original semantics (instead of pictures) which may be interpreted, extrapolated, etc. – and not just portrayed. Unlike WFS [OGC 04-094], which returns discrete geospatial features, the Web Coverage Service returns coverages representing space-varying phenomena that relate a spatio-temporal domain to a (possibly multidimensional) range of properties.

WFS (Web Feature Service) **-** the Open Geospatial Consortium Interface Standard that provides an interface allowing requests for geographical features across the web using platform-independent calls (Wikipedia, 2008).

WMS (Web Map Service**) -** an International Standard that produces maps of spatially referenced data dynamically from geographic information. This International Standard defines a "map" to be a portrayal of geographic information as a digital image file suitable for display on a computer screen. A map is not the data itself. WMS-produced maps are generally rendered in a pictorial format such as PNG, GIF or JPEG, or occasionally as vector-based graphical elements in Scalable Vector Graphics (SVG) or Web Computer Graphics Metafile (WebCGM) formats (OGC 03-109r1, 2008).

XMML (eXploration and Mining Markup Language) **-** online data transfer for the exploration and mining industry. XMML is developed by 3D Visualisation and Geological Modeling in CSIRO Australian organisation (Commonwealth Scientific and Industrial Research Organization) (Cox, 2001).

XML (eXtensible Markup Language) – a partially self-documenting markup language. It allows for describing unambiguously its internal structure by, for instance, Document Type Definition DTD (*.dtd) or by XML Schema (*.xsd). The markup structure of an XML document can be validated automatically against such definitions or schemas (Wikipedia, 2008).

XSLT (eXtensible Stylesheet Language Transformations) - is an XML-based language used for the transformation of XML documents into other XML or "human-readable" documents. The original document is not changed; rather, a new document is created based on the content of an existing one. The new document may be serialized (output) by the processor in standard XML syntax or in another format, such as HTML or plain text. XSLT is most often used to convert data between different XML schemas or to convert XML data into HTML or XHTML documents for web pages, creating a dynamic web page, or into an intermediate XML format that can be converted to PDF documents (Wikipedia, 2008).

ANNEXES

ANNEX 1

```
<?xml version="1.0" encoding="UTF-8"?>
<gwml:PumpingTest gml:id="p1" xmlns:om="http://www.opengis.net/om/1.0" xmlns:sa=
"http://www.opengis.net/sampling/1.0" xmlns:swe="http://www.opengis.net/swe/1.0.1" xmlns:gml=
"http://www.opengis.net/gml" xmlns:cv="http://www.opengis.net/cv/0.2.1" xmlns:xlink=
"http://www.w3.org/1999/xlink" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xmlns:gsml="urn:cgi:xmlns:CGI:GeoSciML:2.0" xmlns:gwml="http://www.nrcan.gc.ca/xml/gwml/1"
xsi:schemaLocation="http://www.nrcan.gc.ca/xml/gwml/1 ..\gwml.xsd">
    <gml:description/>
    <gml:name codeSpace="walloon"/>
    <sa:sampledFeature xlink:href="urn:cgi:def:definition:unknown"/>
    <sa:relatedObservation>
        <om:Observation gml:id="PT1">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">PT1-DD</gml:name>
            <om:samplingTime>
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
            <om:procedure xlink:href="urn:gwml:procedure:pumptest:multiLevelPumpTest"/>
            <om:observedProperty>
                <swe:CompositePhenomenon gml:id="cp1" dimension="1">
                    <gml:name codeSpace="urn:ietf:rfc:2141">
urn:gwml:procedure:pumpTestWithLevels</gml:name>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:level"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:time"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:pumpRate"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:waterlevel"/>
                </swe:CompositePhenomenon>
            </om:observedProperty>
            <om:featureOfInterest xlink:href="urn:gwml:geologicUnit:unknown" xlink:role=
"urn:def:featureType:gwml:stratigraphy"/>
            <om:parameter>
                <!-- some parameters -->
            </om:parameter>
            <om:result>
                <swe:DataArray>
                    <swe:elementCount>
                        <swe:Count><swe:value>3</swe:value></swe:Count>
                    </swe:elementCount>
                    <swe:elementType name="Pump Test Record">
                        <swe:DataRecord>
                            <swe:field name="Time">
                                <swe:Quantity definition="urn:ogc:def:phenomenon:OGC:time">
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:hour"/>
                                </swe:Quantity>
                            </swe:field>
                            <swe:field name="Pump Rate">
                                <swe:Quantity definition=
"urn:ogc:def:phenomenon:OGC:pumpRate">
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:m3/h"/>
                                </swe:Quantity>
                            </swe:field>
                            <swe:field name="Draw down">
                                <swe:Quantity definition=
"urn:ogc:def:phenomenon:OGC:waterlevel">
```

```xml
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:m"/>
                                </swe:Quantity>
                            </swe:field>
                            </swe:DataRecord>
                            </swe:elementType>
                        <swe:encoding>
                            <swe:TextBlock decimalSeparator="." tokenSeparator="#08"
blockSeparator="#0A"/>
                        </swe:encoding>
                        <swe:values>
0   7.3 0
                        </swe:values>

                </swe:DataArray>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="PT2">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">PT2-DD</gml:name>
            <om:samplingTime>
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
            <om:procedure xlink:href="urn:gwml:procedure:pumptest:multiLevelPumpTest"/>
            <om:observedProperty>
                <swe:CompositePhenomenon gml:id="cp2" dimension="1">
                    <gml:name codeSpace="urn:ietf:rfc:2141">
urn:gwml:procedure:pumpTestWithLevels</gml:name>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:level"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:time"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:pumpRate"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:waterlevel"/>
                </swe:CompositePhenomenon>
            </om:observedProperty>
            <om:featureOfInterest xlink:href="urn:gwml:geologicUnit:unknown" xlink:role=
"urn:def:featureType:gwml:stratigraphy"/>
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                <!-- some parameters -->
            </om:parameter>
            <om:result>
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                    </swe:elementCount>
                    <swe:elementType name="Pump Test Record">
                        <swe:DataRecord>
                            <swe:field name="Time">
                                <swe:Quantity definition="urn:ogc:def:phenomenon:OGC:time">
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:hour"/>
                                </swe:Quantity>
                            </swe:field>
                            <swe:field name="Pump Rate">
                                <swe:Quantity definition=
```

```
"urn:ogc:def:phenomenon:OGC:pumpRate">
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:m3/h"/>
                                </swe:Quantity>
                            </swe:field>
                            <swe:field name="Draw down">
                                <swe:Quantity definition=
"urn:ogc:def:phenomenon:OGC:waterlevel">
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:m"/>
                                </swe:Quantity>
                            </swe:field>
                        </swe:DataRecord>
                        </swe:elementType>
                        <swe:encoding>
                            <swe:TextBlock decimalSeparator="." tokenSeparator="#08"
blockSeparator="#0A"/>
                        </swe:encoding>
                        <swe:values>
8   18.0    5.28
                        </swe:values>

                </swe:DataArray>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
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            <gml:description>Drawdown test</gml:description>
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                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
            <om:procedure xlink:href="urn:gwml:procedure:pumptest:multiLevelPumpTest"/>
            <om:observedProperty>
                <swe:CompositePhenomenon gml:id="cp3" dimension="1">
                    <gml:name codeSpace="urn:ietf:rfc:2141">
urn:gwml:procedure:pumpTestWithLevels</gml:name>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:level"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:time"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:pumpRate"/>
                    <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:waterlevel"/>
                </swe:CompositePhenomenon>
            </om:observedProperty>
            <om:featureOfInterest xlink:href="urn:gwml:geologicUnit:unknown" xlink:role=
"urn:def:featureType:gwml:stratigraphy"/>
            <om:parameter>
                <!-- some parameters -->
            </om:parameter>
            <om:result>
                <swe:DataArray>
                    <swe:elementCount>
                        <swe:Count><swe:value>3</swe:value></swe:Count>
                    </swe:elementCount>
                    <swe:elementType name="Pump Test Record">
                        <swe:DataRecord>
```

```
                            <swe:field name="Time">
                                <swe:Quantity definition="urn:ogc:def:phenomenon:OGC:time">
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:hour"/>
                                </swe:Quantity>
                            </swe:field>
                            <swe:field name="Pump Rate">
                                <swe:Quantity definition=
"urn:ogc:def:phenomenon:OGC:pumpRate">
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:m3/h"/>
                                </swe:Quantity>
                            </swe:field>
                            <swe:field name="Draw down">
                                <swe:Quantity definition=
"urn:ogc:def:phenomenon:OGC:waterlevel">
                                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:m"/>
                                </swe:Quantity>
                            </swe:field>
                        </swe:DataRecord>
                        </swe:elementType>
                        <swe:encoding>
                            <swe:TextBlock decimalSeparator="." tokenSeparator="#08"
blockSeparator="#0A"/>
                        </swe:encoding>
                        <swe:values>
16  24.6    14.19
                        </swe:values>

                </swe:DataArray>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="TR1">
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                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
            <om:procedure>
                <gwml:DependantCalculation>
                    <gwml:method codeSpace="">
urn:gwml:procedure:Calculation:transmissivity:Jacob</gwml:method>
                    <gwml:sourceObservation xlink:href="#PT1-DD"/>
                </gwml:DependantCalculation>
            </om:procedure>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:transmissivity"/>
            <om:featureOfInterest xlink:href="urn:gwml:Aquifer:810"/>
            <om:result>
                <gsml:CGI_Numeric>
                    <gsml:principalValue uom="m2.s-1">7.4E-04</gsml:principalValue>
                </gsml:CGI_Numeric>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
```

```xml
    <sa:relatedObservation>
        <om:Observation gml:id="TR2">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">TR2-DD</gml:name>
            <om:samplingTime>
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
            <om:procedure>
                <gwml:DependantCalculation>
                    <gwml:method codeSpace="">
urn:gwml:procedure:Calculation:transmissivity:Jacob</gwml:method>
                    <gwml:sourceObservation xlink:href="#PT1-DD"/>
                </gwml:DependantCalculation>
            </om:procedure>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:transmissivity"/>
            <om:featureOfInterest xlink:href="urn:gwml:Aquifer:810"/>
            <om:result>
                <gsml:CGI_Numeric>
                    <gsml:principalValue uom="m2.s-1">2.7E-04</gsml:principalValue>
                </gsml:CGI_Numeric>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="TR3">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">TR3-DD</gml:name>
            <om:samplingTime>
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
            <om:procedure>
                <gwml:DependantCalculation>
                    <gwml:method codeSpace="">
urn:gwml:procedure:Calculation:transmissivity:Jacob</gwml:method>
                    <gwml:sourceObservation xlink:href="#PT2-DD"/>
                </gwml:DependantCalculation>
            </om:procedure>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:transmissivity"/>
            <om:featureOfInterest xlink:href="urn:gwml:Aquifer:810"/>
            <om:result>
                <gsml:CGI_Numeric>
                    <gsml:principalValue uom="m2.s-1">3.8E-04</gsml:principalValue>
                </gsml:CGI_Numeric>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="TR4">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">TR4-DD</gml:name>
            <om:samplingTime>
```

```xml
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
            <om:procedure>
                <gwml:DependantCalculation>
                    <gwml:method codeSpace="">
urn:gwml:procedure:Calculation:transmissivity:Jacob</gwml:method>
                    <gwml:sourceObservation xlink:href="#PT2-DD"/>
                </gwml:DependantCalculation>
            </om:procedure>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:transmissivity"/>
            <om:featureOfInterest xlink:href="urn:gwml:Aquifer:810"/>
            <om:result>
                <gsml:CGI_Numeric>
                    <gsml:principalValue uom="m2.s-1">2.6E-04</gsml:principalValue>
                </gsml:CGI_Numeric>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="TR5">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">TR5-DD</gml:name>
            <om:samplingTime>
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
            <om:procedure>
                <gwml:DependantCalculation>
                    <gwml:method codeSpace="">
urn:gwml:procedure:Calculation:transmissivity:Jacob</gwml:method>
                    <gwml:sourceObservation xlink:href="#PT2-DD"/>
                </gwml:DependantCalculation>
            </om:procedure>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:transmissivity"/>
            <om:featureOfInterest xlink:href="urn:gwml:Aquifer:810"/>
            <om:result>
                <gsml:CGI_Numeric>
                    <gsml:principalValue uom="m2.s-1">2.9E-04</gsml:principalValue>
                </gsml:CGI_Numeric>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="TR6">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">TR6-DD</gml:name>
            <om:samplingTime>
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
```

```
            <om:procedure>
                <gwml:DependantCalculation>
                    <gwml:method codeSpace="">
urn:gwml:procedure:Calculation:transmissivity:Jacob</gwml:method>
                    <gwml:sourceObservation xlink:href="#PT3-DD"/>
                </gwml:DependantCalculation>
            </om:procedure>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:transmissivity"/>
            <om:featureOfInterest xlink:href="urn:gwml:Aquifer:810"/>
            <om:result>
                <gsml:CGI_Numeric>
                    <gsml:principalValue uom="m2.s-1">4.7E-04</gsml:principalValue>
                </gsml:CGI_Numeric>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="TR7">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">TR7-DD</gml:name>
            <om:samplingTime>
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
                <om:procedure>
                <gwml:DependantCalculation>
                    <gwml:method codeSpace="">
urn:gwml:procedure:Calculation:transmissivity:Jacob</gwml:method>
                    <gwml:sourceObservation xlink:href="#PT3-DD"/>
                </gwml:DependantCalculation>
            </om:procedure>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:transmissivity"/>
            <om:featureOfInterest xlink:href="urn:gwml:Aquifer:810"/>
            <om:result>
                <gsml:CGI_Numeric>
                    <gsml:principalValue uom="m2.s-1">3.0E-04</gsml:principalValue>
                </gsml:CGI_Numeric>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="TR8">
            <gml:description>Drawdown test</gml:description>
            <gml:name codeSpace="urn:gwml:obs">TR8-DD</gml:name>
            <om:samplingTime>
                <gml:TimePeriod>
                    <gml:beginPosition>2004-06-04</gml:beginPosition>
                    <gml:endPosition>2004-06-05</gml:endPosition>
                </gml:TimePeriod>
            </om:samplingTime>
        <om:procedure>
                <gwml:DependantCalculation>
                    <gwml:method codeSpace="">
urn:gwml:procedure:Calculation:transmissivity:Jacob</gwml:method>
                    <gwml:sourceObservation xlink:href="#PT3-DD"/>
```

```xml
                </gwml:DependantCalculation>
            </om:procedure>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:transmissivity"/>
            <om:featureOfInterest xlink:href="urn:gwml:Aquifer:810"/>
            <om:result>
                <gsml:CGI_Numeric>
                    <gsml:principalValue uom="m2.s-1">2.0E-04</gsml:principalValue>
                </gsml:CGI_Numeric>
            </om:result>
        </om:Observation>
    </sa:relatedObservation>
    <gwml:report xlink:href="http://www.inasep.be/reports?id=222" xlink:title="Rapport de la
commune de Fosses la Ville, captage de Banbois, délimitation des zones de prévention"/>
    <gwml:contact xlink:href="urn:ogc:def:responsibleParty:Walloon:GeologicaSGSBelgium"
xlink:title="Société Geologica SGS Belgium"/>
    <gwml:observationFeature xlink:href="urn:walloon:wells:A"/>
    <gwml:observationFeature xlink:href="urn:walloon:wells:B"/>
    <gwml:observationFeature xlink:href="urn:walloon:wells:C"/>
    <gwml:testWell>
        <gwml:WaterWell gml:id="FUNDPN02_31936">
            <gml:name codeSpace="Walloon">PIEZO PZBA4</gml:name>
            <sa:sampledFeature>
                <gwml:Aquifer gml:id="urn.gwml.aquifers.walloon.810">
                    <gml:description>Massif Schisto-Greseux du bassin de Dinant
</gml:description>
                    <gml:name codeSpace="urn:ietf:rfc:2141">
urn:gwml:hydrogeologicUnit:walloon:810</gml:name>
                    <gml:name codeSpace="walloon">810</gml:name>
                    <gml:boundedBy>
                        <gml:Envelope srsName="EPSG:9803">
                            <gml:pos/>
                            <gml:pos/>
                        </gml:Envelope>
                    </gml:boundedBy>
                    <gsml:observationMethod>
                        <gsml:CGI_TermValue>
                            <gsml:value codeSpace="gwml">mapping</gsml:value>
                        </gsml:CGI_TermValue>
                    </gsml:observationMethod>
                    <gsml:purpose>instance</gsml:purpose>
                    <gsml:occurrence>
                        <gsml:MappedFeature>
                            <gsml:observationMethod>
                                <gsml:CGI_TermValue>
                                    <gsml:value codeSpace="gwml">mapping</gsml:value>
                                </gsml:CGI_TermValue>
                            </gsml:observationMethod>
                            <gsml:positionalAccuracy>
                                <gsml:CGI_TermValue>
                                    <gsml:value codeSpace="gwml">undefined</gsml:value>
                                </gsml:CGI_TermValue>
                            </gsml:positionalAccuracy>
                            <!-- we define here what is the mapping support -->
                            <gsml:samplingFrame xlink:href="urn:ogc:mappingFrame:x"/>
                            <gsml:specification xlink:href="#e1"/>
                            <gsml:shape>
                                <gml:Polygon srsName="EPSG:9803">
```

```
                                    <gml:outerBoundaryIs>
                                        <gml:LinearRing>
                                            <gml:posList>
                                                <!-- coordinates of the polygon of the aquifer -->
                                            </gml:posList>
                                        </gml:LinearRing>
                                    </gml:outerBoundaryIs>
                                </gml:Polygon>
                            </gsml:shape>
                        </gsml:MappedFeature>
                    </gsml:occurrence>
                    <gwml:mediaType>porous</gwml:mediaType>
                </gwml:Aquifer>
            </sa:sampledFeature>
            <sa:position>
            <gml:Point srsName="EPSG:9808">
                    <!-- levée par géomètre -->
                    <gml:pos>172587.3 117252.3 255.34</gml:pos>
                </gml:Point>
            </sa:position>
            <gwml:wellStatus xlink:href="urn:x-ogc:def:nil:OGC:unknown"/>
           <gwml:referenceElevation uom="m">255.34</gwml:referenceElevation>
            <gwml:groundwaterAccessFeature>
                <gsml:Borehole gml:id="B-FUNDPN02_31936">
                    <gml:description>Borehole dug for water well</gml:description>
                    <gml:name codeSpace="Walloon">PZBA4</gml:name>
                    <sa:sampledFeature xlink:href="urn:cgi:def:definition:unknow"/>
                    <sa:relatedObservation>
                        <om:Observation gml:id="O3">
                            <gml:description>Earth Material</gml:description>
                            <om:samplingTime>
                                <gml:TimeInstant>
                                    <gml:timePosition>2007-05-30</gml:timePosition>
                                </gml:TimeInstant>
                            </om:samplingTime>
                            <om:procedure xlink:href=
"urn:gwml:procedure:penetrometer:3405.102XX"/>
                            <om:observedProperty xlink:href=
"urn:ogc:def:phenomenon:CGI:2007:earthMaterial"/>
                            <om:featureOfInterest xlink:href="urn:gwml:geologicUnit:unknown"
xlink:role="urn:def:featureType:gwml:stratigraphy"/>
                            <om:result>
                                <cv:CV_DiscreteCoverage>
                                    <cv:domainExtent xlink:href="#B1-shape"/>
                                    <cv:rangeType/>
                                    <cv:element>
                                        <cv:CV_GeometryValuePair>
                                            <cv:geometry>
                                                <cv:CV_DomainObject>
                                                    <cv:spatialElement>
                                                        <gml:LineString srsName=
"#B-FUNDPN02_31936-shape" srsDimension="1">
                                                            <gml:pos>0</gml:pos>
                                                            <gml:pos>1</gml:pos>
                                                        </gml:LineString>
                                                    </cv:spatialElement>
                                                </cv:CV_DomainObject>
```

```xml
                                            </cv:geometry>
                                            <cv:value xsi:type="gsml:EarthMaterial">
                                                <gsml:UnconsolidatedMaterial>
                                                    <gml:description>sable argileux, ocre et
morceaux centimétrique de psammites</gml:description>
                                                    <gml:name>sable argileux</gml:name>
                                                    <gsml:purpose>definingNorm</gsml:purpose>
                                                    <gsml:consolidationDegree>
                                                        <gsml:CGI_TermValue>
                                                            <gsml:value codeSpace=
"urn:cgi:classifierScheme:IUGS:consolidationTerms">UNCONSOLIDATED</gsml:value>
                                                        </gsml:CGI_TermValue>
                                                    </gsml:consolidationDegree>
                                                    <gsml:lithology>
                                                        <gsml:ControlledConcept gml:id="RCS4">
                                                            <gml:name codeSpace=
"urn:ietf:rfc:2141">urn:cgi:classifier:IUGS:RCS:MSDR</gml:name>
                                                            <gsml:identifier codeSpace="">t
</gsml:identifier>
                                                            <gsml:name xml:lang="en"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">clayey sand</gsml:name>
                                                            <gsml:name xml:lang="fr"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">sable argileux</gsml:name>
                                                            <gsml:vocabulary xlink:href=
"urn:cgi:classifierScheme:IUGS:RCS"/>
                                                        </gsml:ControlledConcept>
                                                    </gsml:lithology>
                                                </gsml:UnconsolidatedMaterial>
                                            </cv:value>
                                        </cv:CV_GeometryValuePair>
                                    </cv:element>
                                    <cv:element>
                                        <cv:CV_GeometryValuePair>
                                            <cv:geometry>
                                                <cv:CV_DomainObject>
                                                    <cv:spatialElement>
                                                        <gml:LineString srsName=
"#B-FUNDPN02_31936-shape" srsDimension="1">
                                                            <gml:pos>1</gml:pos>
                                                            <gml:pos>8</gml:pos>
                                                        </gml:LineString>
                                                    </cv:spatialElement>
                                                </cv:CV_DomainObject>
                                            </cv:geometry>
                                            <cv:value xsi:type="gsml:EarthMaterial">
                                                <gsml:UnconsolidatedMaterial>
                                                    <gml:description>siltites brunes
</gml:description>
                                                    <gml:name>siltite</gml:name>

<gsml:color><gsml:CGI_TermValue><gsml:value codeSpace="Walloon">brun
</gsml:value></gsml:CGI_TermValue></gsml:color>
                                                    <gsml:purpose>definingNorm</gsml:purpose>
                                                    <gsml:consolidationDegree>
                                                        <gsml:CGI_TermValue>
                                                            <gsml:value codeSpace=
"urn:cgi:classifierScheme:IUGS:consolidationTerms">UNCONSOLIDATED</gsml:value>
```

```
                                                        </gsml:CGI_TermValue>
                                                    </gsml:consolidationDegree>
                                                    <gsml:lithology>
                                                        <gsml:ControlledConcept gml:id=
"RCS4A">
                                                            <gml:name codeSpace=
"urn:ietf:rfc:2141">urn:cgi:classifier:IUGS:RCS:MSDR</gml:name>
                                                            <gsml:identifier codeSpace="t">
identifier</gsml:identifier>
                                                            <gsml:name xml:lang="en"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">siltites</gsml:name>
                                                            <gsml:name xml:lang="fr"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">siltite</gsml:name>
                                                            <gsml:vocabulary xlink:href=
"urn:cgi:classifierScheme:IUGS:RCS"/>
                                                        </gsml:ControlledConcept>
                                                    </gsml:lithology>
                                                </gsml:UnconsolidatedMaterial>
                                            </cv:value>
                                        </cv:CV_GeometryValuePair>
                                    </cv:element>
                                    <cv:element>
                                        <cv:CV_GeometryValuePair>
                                            <cv:geometry>
                                                <cv:CV_DomainObject>
                                                    <cv:spatialElement>
                                                        <gml:LineString srsName=
"#B-FUNDPN02_31936-shape" srsDimension="1">
                                                            <gml:pos>8</gml:pos>
                                                            <gml:pos>11</gml:pos>
                                                        </gml:LineString>
                                                    </cv:spatialElement>
                                                </cv:CV_DomainObject>
                                            </cv:geometry>
                                            <cv:value xsi:type="gsml:EarthMaterial">
                                                <gsml:UnconsolidatedMaterial>
                                                    <gml:description>argile brun-ocre avec
débris de psammites altérées</gml:description>
                                                    <gml:name>argile</gml:name>

<gsml:color><gsml:CGI_TermValue><gsml:value codeSpace="Walloon">brun-ocre
</gsml:value></gsml:CGI_TermValue></gsml:color>
                                                    <gsml:purpose>definingNorm</gsml:purpose>
                                                    <gsml:consolidationDegree>
                                                        <gsml:CGI_TermValue>
                                                            <gsml:value codeSpace=
"urn:cgi:classifierScheme:IUGS:consolidationTerms">UNCONSOLIDATED</gsml:value>
                                                        </gsml:CGI_TermValue>
                                                    </gsml:consolidationDegree>
                                                    <gsml:lithology>
                                                        <gsml:ControlledConcept gml:id=
"RCS4B">
                                                            <gml:name codeSpace=
"urn:ietf:rfc:2141">urn:cgi:classifier:IUGS:RCS:MSDR</gml:name>
                                                            <gsml:identifier codeSpace="t">x
</gsml:identifier>
                                                            <gsml:name xml:lang="en"
```

```
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">clay</gsml:name>
                                                            <gsml:name xml:lang="fr"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">argile</gsml:name>
                                                            <gsml:vocabulary xlink:href=
"urn:cgi:classifierScheme:IUGS:RCS"/>
                                                        </gsml:ControlledConcept>
                                                    </gsml:lithology>
                                                </gsml:UnconsolidatedMaterial>
                                            </cv:value>
                                        </cv:CV_GeometryValuePair>
                                    </cv:element>
                                    <cv:element>
                                        <cv:CV_GeometryValuePair>
                                            <cv:geometry>
                                                <cv:CV_DomainObject>
                                                    <cv:spatialElement>
                                                        <gml:LineString srsName=
"#B-FUNDPN02_31936-shape" srsDimension="1">
                                                            <gml:pos>11</gml:pos>
                                                            <gml:pos>19</gml:pos>
                                                        </gml:LineString>
                                                    </cv:spatialElement>
                                                </cv:CV_DomainObject>
                                            </cv:geometry>
                                            <cv:value xsi:type="gsml:EarthMaterial">
                                                <gsml:UnconsolidatedMaterial>
                                                    <gml:description>siltites brunes
</gml:description>
                                                    <gml:name>siltite</gml:name>

<gsml:color><gsml:CGI_TermValue><gsml:value codeSpace="Walloon">brun
</gsml:value></gsml:CGI_TermValue></gsml:color>
                                                    <gsml:purpose>definingNorm</gsml:purpose>
                                                    <gsml:consolidationDegree>
                                                        <gsml:CGI_TermValue>
                                                            <gsml:value codeSpace=
"urn:cgi:classifierScheme:IUGS:consolidationTerms">UNCONSOLIDATED</gsml:value>
                                                        </gsml:CGI_TermValue>
                                                    </gsml:consolidationDegree>
                                                    <gsml:lithology>
                                                        <gsml:ControlledConcept gml:id=
"RCS4C">
                                                            <gml:name codeSpace=
"urn:ietf:rfc:2141">urn:cgi:classifier:IUGS:RCS:MSDR</gml:name>
                                                            <gsml:identifier codeSpace="t">x
</gsml:identifier>
                                                            <gsml:name xml:lang="en"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">siltites</gsml:name>
                                                            <gsml:name xml:lang="fr"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">siltite</gsml:name>
                                                            <gsml:vocabulary xlink:href=
"urn:cgi:classifierScheme:IUGS:RCS"/>
                                                        </gsml:ControlledConcept>
                                                    </gsml:lithology>
                                                </gsml:UnconsolidatedMaterial>
                                            </cv:value>
                                        </cv:CV_GeometryValuePair>
```

```
                                    </cv:element>
                                    <cv:element>
                                        <cv:CV_GeometryValuePair>
                                            <cv:geometry>
                                                <cv:CV_DomainObject>
                                                    <cv:spatialElement>
                                                        <gml:LineString srsName=
"#B-FUNDPN02_31936-shape" srsDimension="1">
                                                            <gml:pos>19</gml:pos>
                                                            <gml:pos>32</gml:pos>
                                                        </gml:LineString>
                                                    </cv:spatialElement>
                                                </cv:CV_DomainObject>
                                            </cv:geometry>
                                            <cv:value xsi:type="gsml:EarthMaterial">
                                                <gsml:Rock>
                                                    <gml:description>Grès gris-jaune,
parfois bleuté, fracturé saturé à partir de 20m</gml:description>
                                                    <gml:name>Sanstone</gml:name>

<gsml:color><gsml:CGI_TermValue><gsml:value codeSpace="Walloon">gris-jaune
</gsml:value></gsml:CGI_TermValue></gsml:color>
                                                    <gsml:purpose>definingNorm</gsml:purpose>
                                                    <gsml:consolidationDegree>
                                                        <gsml:CGI_TermValue>
                                                            <gsml:value codeSpace=
"urn:cgi:classifierScheme:IUGS:consolidationTerms">INDURATED</gsml:value>
                                                        </gsml:CGI_TermValue>
                                                    </gsml:consolidationDegree>
                                                    <gsml:lithology>
                                                        <gsml:ControlledConcept gml:id=
"RCS4D">
                                                            <gml:name codeSpace=
"urn:ietf:rfc:2141">urn:cgi:classifier:IUGS:RCS:MSDR</gml:name>
                                                            <gsml:identifier codeSpace="t">x
</gsml:identifier>
                                                            <gsml:name xml:lang="en"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">sandstone</gsml:name>
                                                            <gsml:name xml:lang="fr"
codeSpace="urn:cgi:classifierScheme:IUGS:RCS">grès</gsml:name>
                                                            <gsml:vocabulary xlink:href=
"urn:cgi:classifierScheme:IUGS:RCS"/>
                                                        </gsml:ControlledConcept>
                                                    </gsml:lithology>
                                                </gsml:Rock>
                                            </cv:value>
                                        </cv:CV_GeometryValuePair>
                                    </cv:element>
                                </cv:CV_DiscreteCoverage>
                            </om:result>
                        </om:Observation>
                    </sa:relatedObservation>
                    <sa:shape>
                        <gml:LineString srsDimension="3" srsName="EPSG:9808">
                            <gml:pos>172587.3 117252.3 255.34</gml:pos>
                            <gml:pos>172587.3 117252.3 223.34</gml:pos>
                        </gml:LineString>
```

```xml
                    </sa:shape>
                    <sa:length uom="m">32</sa:length>
                    <gsml:collarLocation><gsml:BoreholeCollar>
                        <gsml:location><gml:Point srsName="9808"><gml:pos>172587.3 117252.3
255.34</gml:pos></gml:Point></gsml:location>
                    </gsml:BoreholeCollar>
                    </gsml:collarLocation>
                    <gsml:indexData>
                        <gwml:WellBoreholeDetails>
                            <gsml:operator xlink:href="urn:cgi:unknown"/>
                            <gsml:driller xlink:href="urn:cgi:unknown"/>
                            <gsml:dateOfDrilling>2008-05-30</gsml:dateOfDrilling>
                            <gsml:drillingMethod>direct push</gsml:drillingMethod>
                            <gsml:startPoint>natural ground surface</gsml:startPoint>
                            <gsml:nominalDiameter uom="m">0.3</gsml:nominalDiameter>
                            <gsml:inclinationType>vertical</gsml:inclinationType>
                            <gwml:drillingFluid xlink:href=
"urn:ogc:def:definition:drillingFluid:unknown"/>
                        </gwml:WellBoreholeDetails>
                    </gsml:indexData>
                </gsml:Borehole>
            </gwml:groundwaterAccessFeature>
        </gwml:WaterWell>
    </gwml:testWell>
    <gwml:pumpingTestType><gsml:CGI_TermValue>
        <gsml:value codeSpace="Walloon">multiLevelPumpingTest</gsml:value>
    </gsml:CGI_TermValue></gwml:pumpingTestType>

</gwml:PumpingTest>
```

ANNEX 2

```xml
<?xml version="1.0" encoding="UTF-8"?>
<gwml:WaterWell gml:id="W1" xmlns:om="http://www.opengis.net/om/1.0" xmlns:sa=
"http://www.opengis.net/sampling/1.0" xmlns:swe="http://www.opengis.net/swe/1.0.1" xmlns:gml=
"http://www.opengis.net/gml" xmlns:cv="http://www.opengis.net/cv/0.2.1" xmlns:xlink=
"http://www.w3.org/1999/xlink" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xmlns:gsml="urn:cgi:xmlns:CGI:GeoSciML:2.0" xmlns:gwml="http://www.nrcan.gc.ca/xml/gwml/1"
xsi:schemaLocation="http://www.nrcan.gc.ca/xml/gwml/1 ..\gwml.xsd">
    <gml:description>Test of water level encoding on a water well</gml:description>
    <gml:name codeSpace="gwml">W1</gml:name>
    <sa:sampledFeature xlink:href="urn:gwml:def:hydrogeologicUnit:aquifer:SomeAquiferX"/>
    <sa:relatedObservation>
        <!-- observation included in this section -->
        <om:Observation gml:id="WL1">
            <gml:description>Water level taken during summer field work</gml:description>
            <gml:name codeSpace="urn:gwml:obs">WL1</gml:name>
            <om:samplingTime>
                <gml:TimeInstant>
                    <gml:timePosition>
                    2007-07-15
                    </gml:timePosition>
                </gml:TimeInstant>
            </om:samplingTime>
            <om:procedure xlink:href="urn:gwml:procedure:piezometricProbe:foogleMeter2000" />
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:gwaterLevel" />
            <om:featureOfInterest xlink:href="#W1"/>
            <om:result xsi:type="gml:MeasureType" uom="m">34.67</om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <!-- observation included in this section -->
        <om:Observation gml:id="WL2">
            <gml:description>Water level taken during fall revisit</gml:description>
            <gml:name codeSpace="urn:gwml:obs">WL2</gml:name>
            <om:samplingTime>
                <gml:TimeInstant>
                    <gml:timePosition>
                    2007-09-23
                    </gml:timePosition>
                </gml:TimeInstant>
            </om:samplingTime>
            <om:procedure xlink:href="urn:gwml:procedure:piezometricProbe:foogleMeter2000" />
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:gwaterLevel" />
            <om:featureOfInterest xlink:href="#W2"/>
            <om:result xsi:type="gml:MeasureType" uom="m">23.44</om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:relatedObservation>
        <om:Observation gml:id="WL3">
            <gml:description>Measure taken during winter </gml:description>
            <gml:name codeSpace="urn:gwml:obs">WL3</gml:name>
            <om:samplingTime>
                <gml:TimeInstant>
                    <gml:timePosition>
                    2007-12-27
                    </gml:timePosition>
                </gml:TimeInstant>
            </om:samplingTime>
```

```
            <om:procedure xlink:href="urn:gwml:procedure:piezometricProbe:foogleMeter2000"/>
            <om:observedProperty xlink:href="urn:ogc:def:phenomenon:OGC:gwaterLevel"/>
            <om:featureOfInterest xlink:href="#W2"/>
            <om:result xsi:type="gml:MeasureType" uom="m">36.22</om:result>
        </om:Observation>
    </sa:relatedObservation>
    <sa:surveyDetails xlink:href="urn:x-ogc:def:nil:OGC:unknown"/>
    <sa:position><gml:Point srsName="EPSG:4326">
            <gml:coordinates cs="," decimal="." ts="">-79.35493,44.63142</gml:coordinates>
        </gml:Point></sa:position>
    <gwml:wellStatus xlink:href="urn:x-ogc:def:nil:OGC:unknown"/>
    <gwml:referenceElevation uom="m">220.9019</gwml:referenceElevation>
    <gwml:contact xlink:title="custodian" xlink:href="urn:x-ngwd:contact:custodian:test"/>
    <gwml:construction xlink:href="urn:x-ogc:def:nil:OGC:unknown"/>
    <gwml:groundwaterAccessFeature xlink:href="urn:gwml:borehole:XA-99843"/>
</gwml:WaterWell>
```

ANNEX 3

```xml
<?xml version="1.0" encoding="UTF-8"?>
<gml:Bag xmlns:swe="http://www.opengis.net/swe/1.0.1" xmlns:gml="http://www.opengis.net/gml"
xmlns:xlink="http://www.w3.org/1999/xlink" xmlns:xsi=
"http://www.w3.org/2001/XMLSchema-instance" xsi:schemaLocation=
"http://www.nrcan.gc.ca/xml/gwml/1 ..\gwml.xsd">
    <gml:member>
        <swe:CompositePhenomenon gml:id="walloon.measured.components" dimension="1">
            <gml:name codeSpace="urn:ietf:rfc:2141">urn:walloon:geochemistry:components
</gml:name>
            <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:bromide"/>
            <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:silicium"/>
            <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:conductivity"/>
            <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:pH"/>
            <swe:component xlink:href="urn:ogc:def:phenomenon:OGC:nitrates"/>
        </swe:CompositePhenomenon>
    </gml:member>
    <gml:member>
        <swe:DataRecord>
            <!-- data record to repeat here -->
            <swe:field name="Bromure">
                <swe:Quantity definition="urn:ogc:def:phenomenon:OGC:bromide" gml:id="br">
                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:mgL-1"/>
                </swe:Quantity>
            </swe:field>
            <swe:field name="Silice">
                <swe:Quantity definition="urn:ogc:def:phenomenon:OGC:silicium" gml:id="si">
                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:mgL-1"/>
                </swe:Quantity>
            </swe:field>
            <swe:field name="conductivity">
                <swe:Quantity definition="urn:ogc:def:phenomenon:OGC:conductivity" gml:id="K">
                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:uScm-1"/>
                </swe:Quantity>
            </swe:field>
            <swe:field name="pH">
                <swe:Quantity definition="urn:ogc:def:phenomenon:OGC:pH" gml:id="pH">
                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:none"/>
                </swe:Quantity>
            </swe:field>
            <swe:field name="nitrate">
                <swe:Quantity definition="urn:ogc:def:phenomenon:OGC:nitrate" gml:id="NO3">
                    <swe:uom xlink:href="urn:ogc:def:uom:OGC:mgL-1"/>
                </swe:Quantity>
            </swe:field>
        </swe:DataRecord>
    </gml:member>
</gml:Bag>
```

```xml
<?xml version="1.0" encoding="UTF-8"?>
<gwml:WaterWell gml:id="LUXIBOUT" xmlns:om="http://www.opengis.net/om/1.0" xmlns:sa=
"http://www.opengis.net/sampling/1.0" xmlns:swe="http://www.opengis.net/swe/1.0.1" xmlns:gml=
"http://www.opengis.net/gml" xmlns:cv="http://www.opengis.net/cv/0.2.1" xmlns:xlink=
"http://www.w3.org/1999/xlink" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xmlns:gsml="urn:cgi:xmlns:CGI:GeoSciML:2.0" xmlns:gwml="http://www.nrcan.gc.ca/xml/gwml/1"
xsi:schemaLocation="http://www.nrcan.gc.ca/xml/gwml/1 ..\gwml.xsd">
    <gml:description>Puit à Vielsalm</gml:description>
    <gml:name codeSpace="walloon">LUXIBOUT</gml:name>
    <!--massif shisto-greseux de l'Ardenne-->
    <!-- ================================== -->
    <sa:sampledFeature>
        <gwml:Aquifer gml:id="urn.cgi.aquifer.wallon.805">
            <gml:description>Massif Schisto-Greseux de l'Ardenne</gml:description>
            <gml:name codeSpace="urn:ietf:rfc:2141">urn:gwml:hydrogeologicUnit:walloon:805
</gml:name>
            <gml:name codeSpace="walloon">805</gml:name>
            <gml:boundedBy>
                <gml:Envelope srsName="EPSG:9803">
                    <gml:pos/>
                    <gml:pos/>
                </gml:Envelope>
            </gml:boundedBy>
            <gsml:observationMethod>
                <gsml:CGI_TermValue>
                    <gsml:value codeSpace="gwml">mapping</gsml:value>
                </gsml:CGI_TermValue>
            </gsml:observationMethod>
            <gsml:purpose>instance</gsml:purpose>
            <gsml:occurrence>
                <gsml:MappedFeature>
                    <gsml:observationMethod>
                        <gsml:CGI_TermValue>
                            <gsml:value codeSpace="gwml">mapping</gsml:value>
                        </gsml:CGI_TermValue>
                    </gsml:observationMethod>
                    <gsml:positionalAccuracy>
                        <gsml:CGI_TermValue>
                            <gsml:value codeSpace="gwml">undefined</gsml:value>
                        </gsml:CGI_TermValue>
                    </gsml:positionalAccuracy>
                    <gsml:samplingFrame xlink:href="urn:ogc:mappingFrame:x"/>
                    <gsml:specification xlink:href="#e1"/>
                        <gsml:shape>
                        <gml:Polygon srsName="EPSG:9803">
                            <gml:outerBoundaryIs>
                                <gml:LinearRing>
                                    <gml:posList>
                                        <!-- coordinates of the polygon of the aquifer -->
                                    </gml:posList>
                                </gml:LinearRing>
                            </gml:outerBoundaryIs>
                        </gml:Polygon>
                    </gsml:shape>
                </gsml:MappedFeature>
            </gsml:occurrence>
            <!-- this describes the relation between the aquifer and its host rocks -->
```

```
            <gsml:part>
                <gsml:GeologicUnitPart>
                    <gsml:role codeSpace="gwml">aquiferHost</gsml:role>
                    <gsml:proportion>
                        <gsml:CGI_TermValue>
                            <gsml:value codeSpace="gwml">completly</gsml:value>
                        </gsml:CGI_TermValue>
                    </gsml:proportion>
                    <gsml:containedUnit xlink:href="urn:walloon:geologicUnit:ardenne"/>
                </gsml:GeologicUnitPart>
            </gsml:part>
            <gwml:mediaType>mixed</gwml:mediaType>
        </gwml:Aquifer>
        <!-- =================== -->
    </sa:sampledFeature>
    <sa:relatedSamplingFeature>
        <!-- observation included in this section -->
        <sa:SamplingFeatureRelation>
            <sa:role>specimen</sa:role>
            <sa:target>
                <sa:Specimen>
                    <gml:description>specimen of water pumped from the well</gml:description>
                    <gml:name codeSpace="walloon">calypso00_26806</gml:name>
                    <!-- what is sampled is the groundwater body held in the #805 aquifer -->
                    <sa:sampledFeature xlink:href="urn:walloon:GroundWaterBody:805"/>
                    <sa:relatedObservation>
                        <!-- geochemistry goes here -->
                        <om:Observation>
                            <gml:name codeSpace="urn:gwml:obs">calypso00_26806_1</gml:name>
                            <om:samplingTime>
                                <gml:TimeInstant>
                                    <gml:timePosition>
                    2007-05-30
                    </gml:timePosition>
                                </gml:TimeInstant>
                            </om:samplingTime>
                            <!-- must check lab -->
                            <om:procedure xlink:href="urn:gwml:procedure:labo:X"/>
                            <om:observedProperty xlink:href=
"walloon_geochem.xml#walloon.measured.components"/>
                            <om:featureOfInterest xlink:href=
"urn:walloon:GroundWaterBody:805"/>
                            <om:result>
                                <gwml:GroundwaterAnalysisResult gml:id="calypso00_26806_1-R1">
                                    <gml:description>First result when the well has been
drilled</gml:description>

                                    <gml:name codeSpace="walloon">calypso00_26806_1-R1
</gml:name>

                                    <gwml:member>
                                        <gwml:ResultElement>
                                            <gwml:parameter xlink:href=
"urn:ogc:def:phenomenon:OGC:pH"/>

                                            <gsml:CGI_Numeric>
                                                <gsml:value uom="">5.9</gsml:value>
                                            </gsml:CGI_Numeric>
                                        </gwml:ResultElement>
                                    </gwml:member>
```

```
                                    <gwml:member>
                                        <gwml:ResultElement>
                                            <gwml:parameter xlink:href=
"urn:ogc:def:phenomenon:OGC:conductivity"/>
                                            <gsml:CGI_Numeric>
                                                <gsml:value uom="uSi.cm-1">27</gsml:value>
                                            </gsml:CGI_Numeric>
                                        </gwml:ResultElement>
                                    </gwml:member>
                                    <gwml:member>
                                        <gwml:ResultElement>
                                            <gwml:parameter xlink:href=
"urn:ogc:def:phenomenon:OGC:silicium"/>
                                            <gsml:CGI_Numeric>
                                                <gsml:value uom="mg.L-1">5.4</gsml:value>
                                            </gsml:CGI_Numeric>
                                        </gwml:ResultElement>
                                    </gwml:member>
                                </gwml:GroundwaterAnalysisResult>
                            </om:result>
                        </om:Observation>
                    </sa:relatedObservation>
                    <sa:materialClass>water</sa:materialClass>
                    <!-- CEE type complete analysis -->
                    <sa:samplingMethod xlink:href="urn:walloon:samplingMethod:c4b"/>
                    <sa:samplingTime>
                        <gml:TimeInstant>
                            <gml:timePosition>1996-12-09</gml:timePosition>
                        </gml:TimeInstant>
                    </sa:samplingTime>
                </sa:Specimen>
            </sa:target>
        </sa:SamplingFeatureRelation>
    </sa:relatedSamplingFeature>
    <!-- Another sample -->
    <!-- ===================================== -->
    <sa:relatedSamplingFeature>
        <!-- observation included in this section -->
        <sa:SamplingFeatureRelation>
            <sa:role>specimen</sa:role>
            <sa:target>
                <sa:Specimen>
                    <gml:description>specimen of water pumped from the well</gml:description>
                    <gml:name codeSpace="walloon">calypso00_13619</gml:name>
                    <!-- what is sampled is the groundwater body held in the #805 aquifer -->
                    <sa:sampledFeature xlink:href="urn:walloon:GroundWaterBody:805"/>
                    <sa:relatedObservation>
                        <!-- geochemistry goes here -->
                        <om:Observation>
                            <gml:name codeSpace="urn:gwml:obs">calypso00_13619_1</gml:name>
                            <om:samplingTime>
                                <gml:TimeInstant>
                                    <gml:timePosition>
                    2004-06-07
                    </gml:timePosition>
                                </gml:TimeInstant>
                            </om:samplingTime>
```

```
                            <!-- must check lab -->
                            <om:procedure xlink:href="urn:gwml:procedure:labo:Y"/>
                            <om:observedProperty xlink:href=
"walloon_geochem.xml#walloon.measured.components"/>
                            <om:featureOfInterest xlink:href=
"urn:walloon:GroundWaterBody:805"/>
                            <om:result>
                                <gwml:GroundwaterAnalysisResult gml:id="calypso00_13619_1-R1">
                                    <gml:description>First result when the well has been
drilled</gml:description>
                                    <gml:name codeSpace="walloon">calypso00_13619_1-R1
</gml:name>
                                    <gwml:member>
                                        <gwml:ResultElement>
                                            <gwml:parameter xlink:href=
"urn:ogc:def:phenomenon:OGC:pH"/>
                                            <gsml:CGI_Numeric>
                                                <gsml:value uom="">5.62</gsml:value>
                                            </gsml:CGI_Numeric>
                                        </gwml:ResultElement>
                                    </gwml:member>
                                    <gwml:member>
                                        <gwml:ResultElement>
                                            <gwml:parameter xlink:href=
"urn:ogc:def:phenomenon:OGC:conductivity"/>
                                            <gsml:CGI_Numeric>
                                                <gsml:value uom="uSi.cm-1">40</gsml:value>
                                            </gsml:CGI_Numeric>
                                        </gwml:ResultElement>
                                    </gwml:member>
                                    <gwml:member>
                                        <gwml:ResultElement>
                                            <gwml:parameter xlink:href=
"urn:ogc:def:phenomenon:OGC:silicium"/>
                                            <gsml:CGI_Numeric>
                                                <gsml:value uom="mg.L-1">5.1</gsml:value>
                                            </gsml:CGI_Numeric>
                                        </gwml:ResultElement>
                                    </gwml:member>
                                    <gwml:member>
                                        <gwml:ResultElement>
                                            <gwml:parameter xlink:href=
"urn:ogc:def:phenomenon:OGC:nitrates"/>
                                            <gsml:CGI_Numeric>
                                                <gsml:value uom="mg.L-1">5.2</gsml:value>
                                            </gsml:CGI_Numeric>
                                        </gwml:ResultElement>
                                    </gwml:member>
                                    <gwml:member>
                                        <gwml:ResultElement>
                                            <gwml:parameter xlink:href=
"urn:ogc:def:phenomenon:OGC:bromide"/>
                                            <gsml:CGI_Numeric>
                                                <gsml:qualifier>lessThan</gsml:qualifier>
                                                <gsml:value uom="mg.L-1">0.05</gsml:value>
                                            </gsml:CGI_Numeric>
                                        </gwml:ResultElement>
```

```xml
                                    </gwml:member>
                                </gwml:GroundwaterAnalysisResult>
                            </om:result>
                        </om:Observation>
                    </sa:relatedObservation>
                    <sa:materialClass>water</sa:materialClass>
                    <!-- CEE type complete analysis -->
                    <sa:samplingMethod xlink:href="urn:walloon:samplingMethod:c4b"/>
                    <sa:samplingTime>
                        <gml:TimeInstant>
                            <gml:timePosition>1996-12-09</gml:timePosition>
                        </gml:TimeInstant>
                    </sa:samplingTime>
                </sa:Specimen>
            </sa:target>
        </sa:SamplingFeatureRelation>
    </sa:relatedSamplingFeature>
    <sa:surveyDetails xlink:href="urn:x-ogc:def:nil:OGC:unknown"/>
    <sa:position><gml:Point srsName="EPSG:9803">
            <gml:coordinates cs="," decimal="." ts="">265260 108120</gml:coordinates>
        </gml:Point></sa:position>
    <gwml:wellStatus xlink:href="urn:x-ogc:def:nil:OGC:unknown"/>
    <!-- elevation measurement method should be listed in metadata -->
    <gwml:referenceElevation uom="m">-9999</gwml:referenceElevation>
    <gwml:contact xlink:title="user" xlink:href="urn:x-ngwd:contact:user:ac_gouvy"/>
    <gwml:construction xlink:href="urn:x-ogc:def:nil:OGC:unknown"/>
    <gwml:groundwaterAccessFeature xlink:href="urn:gwml:borehole:"/>
</gwml:WaterWell>
```