
HydroCube: an entity-relationship hydrogeological data model

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Abstract Managing, handling and accessing hydrogeological information depends heavily on the applied hydrogeological data models, which differ between institutions and countries. The effective dissemination of hydrogeological information requires the convergence of such models to make hydrogeological information accessible to multiple users such as universities, water suppliers, and administration and research organisations. Furthermore, because hydrogeological studies are complex, they require a wide variety of high-quality hydrogeological data with appropriate metadata in clearly designed and coherent structures. A need exists, therefore, to develop and implement hydrogeological data models that cover, as much as possible, the full hydrogeological domain. A new data model, called HydroCube, was developed for the Walloon Region in Belgium in 2005. 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. The model stores data relating to the project locality, hydrogeological equipment, and related observations and measurements. In particular, it focuses on specialized hydrogeological field experiments such as pumping and tracer tests. This logical data model uses entity-relationship diagrams and it has been implemented in the Microsoft Access environment. It has been enriched with a fully functional user interface.

Keywords Hydrogeological data · Entity-relationship · Database · Groundwater management · Belgium

Introduction

Recently, decision makers and professionals in environmental sectors have witnessed a great change in data and information management. Data should be accessible to and shared between multiple institutions such as administrations, water suppliers, research organisations, and consulting companies because there is a growing interest in hydrogeological data and information availability. Efficient cooperation and information exchange are necessary at different levels, between field specialists, regional watershed- and basin-responsible parties, and international managers. Reliable analyses require high-quality data with appropriate metadata (Batcheller 2008). It is also important to have access to individual research projects, whose results should be disseminated or integrated into larger national information structures. Furthermore, the hydrogeological community requires holistic approaches and all the necessary hydrogeological information and concepts should allow for management of projects in their entirety. Information management and sharing is very complex and requires common designs, standards and methodologies. Unambiguous data structuring can be achieved by elaborating and implementing hydrogeological data models. Geomatics is the discipline of knowledge and technology that models, acquires, stores, analyses and displays spatial data regarding the Earth. It provides a framework and tools that can be used to make hydrogeological information modelling and sharing possible. As a consequence of the recent changes in

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information carriers and new needs for seamless data exchange, existing hydrogeological data models have to be adapted and sometimes completely redesigned. Ultimately, such models should be implemented into open-source solutions, conforming to emerging Geography Markup Language (GML) technologies (Wojda 2009, Wojda et al. 2010). However, a first step in that direction is to build a holistic model for hydrogeological data management.

In this context, a new formalized logical model of hydrogeological data, HydroCube, is proposed here. The main objective of the HydroCube model is to respond to the requirements identified during discussions with groundwater professionals, end-users, university teams and other institutions in the Walloon Region of Belgium. The HydroCube model promotes an innovative “project-based” approach that deals with any hydrogeological project as a whole. This includes data about the project locality, previous hydrogeological studies, and contact people, and also information on available natural and man-made groundwater access features together with their associated quantity and quality observations and measurements. HydroCube also presents 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) their interpretation.

The HydroCube data model is described by a series of normalized entity-relationship diagrams. Entities are identified and 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. The logical model also defines permissible value domains such as code-list entities. Furthermore, the need for hydrogeological data availability and transfer between different universities and the administration required a convergence in applied data models. HydroCube can become a standard for data encoding and synchronisation amongst users in different locations via structured protocols. Technically, the data for each project can be stored in one database instance, or data can be differentiated by unique identifiers, where each identifier is composed of a defined prefix and an automatic number.

The HydroCube logical model has been implemented through a physical model under the HydroCube database in Microsoft (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 implementation platform choice was driven by the requirements of the financing institution.

The first part of the article 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 geometry-based classification of hydrogeological entities, topological links, and the pioneer data model dealing with hydrogeological field experiments. More details on entities, attributes and their data types are also provided in electronic supplementary material (ESM). The user-interface functionalities are then presented. The

conclusion proposes new directions for further developments of hydrogeological data models, respecting international standards and norms.

Driving concepts and existing data models

A review of existing projects and databases was performed prior to the work on HydroCube. Five from the most interesting hydrogeological projects are technically described hereafter. The HYGES hydrogeological database, a precursor of HydroCube, was developed in the Walloon Region, Belgium (Gogu et al. 2001) based on entity-relationship diagrams. It is a geographic information system (GIS)-based database offering facilities to model groundwater flow and contaminant transport, for groundwater vulnerability assessment and for the management of regional groundwater resources at the basin level, using both a relational database management system and a GIS.

The H+ database, developed in the framework of the ERO program (French Environmental Research Observatory), allows for data gathering from a network of hydrogeological sites (de Dreuzey et al. 2006). Its flexible conceptual model is described by an enhanced entity-relationship notation. H+ proposes entities for storing data coming from different experiments or surveys. It is enriched with a fully-functional web-based user interface. However, its generic structure, proposed as a template, does not describe a conceptual data model for specific tests. Moreover, storage of non-spatial data needs further development.

The Basin of Mexico Hydrogeological Database (BMHDB) includes data on climatological, borehole and run-off variables, providing information for the development of hydrogeological models (Carrera-Hernández and Gaskin 2008). It also allows 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.

The Australian National Groundwater Data Transfer Standard, developed by the National Groundwater Committee Working Group on the National Groundwater Data Standards (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 ESRI’s ArcHydro data model, developed at the University of Texas at Austin (USA) (Strassberg 2005) attempts to extend the ArcHydro model (Maidment 2002) to represent groundwater systems. It uses specific notation 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 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, with the exception of H+, these models do not allow for storage of hydrogeological data coming from field tests such as pumping tests and tracer tests, or the management of topological relationships (for instance spatial relationships between an exploitation well and its protection zone). All these projects can be considered as interesting first steps and sources of ideas for further development, but they must be extended or adapted in order to respond to current needs.

In development of the HydroCube logical data model, 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. 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 becomes necessary to extend or enrich the model, one may pass to another notation such as object-oriented modelling, using formalized mapping techniques. It was assumed that comprehension and implementation of any object-oriented model would require advanced knowledge and could only be addressed by specialists in geomatics. On the contrary, the HydroCube model addresses the users who are interested in a holistic project-based data management system that is better focused on applied hydrogeology and field test data.

HydroCube: the Walloon Region hydrogeological data model

This section describes the most important or innovative elements of the logical data model. For the sake of completeness, other more conventional components of the data model can be found in the ESM and in Wojda (2009). First, the main hydrogeological entities are presented, including topological relationships. Second, an innovative database structure for specialized hydrogeological tests such as pumping and tracer tests, is described in detail. Finally, the user-interface functionalities are summarised briefly.

Main hydrogeological entities

The HydrogeologicalFeature is the central entity of the data model (Fig. 1). 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. In Figs. 1, 2, 3, 4 and in the ESM figures, mandatory primary identifiers are underlined and indicated with the letter M. Foreign identifiers keep the same name, as from the original table they come from. The value of the attribute itself during encoding is physically copied by the user interface.

Following the convention on geometric classification of primitive features (GM_Primitive) and the conventional

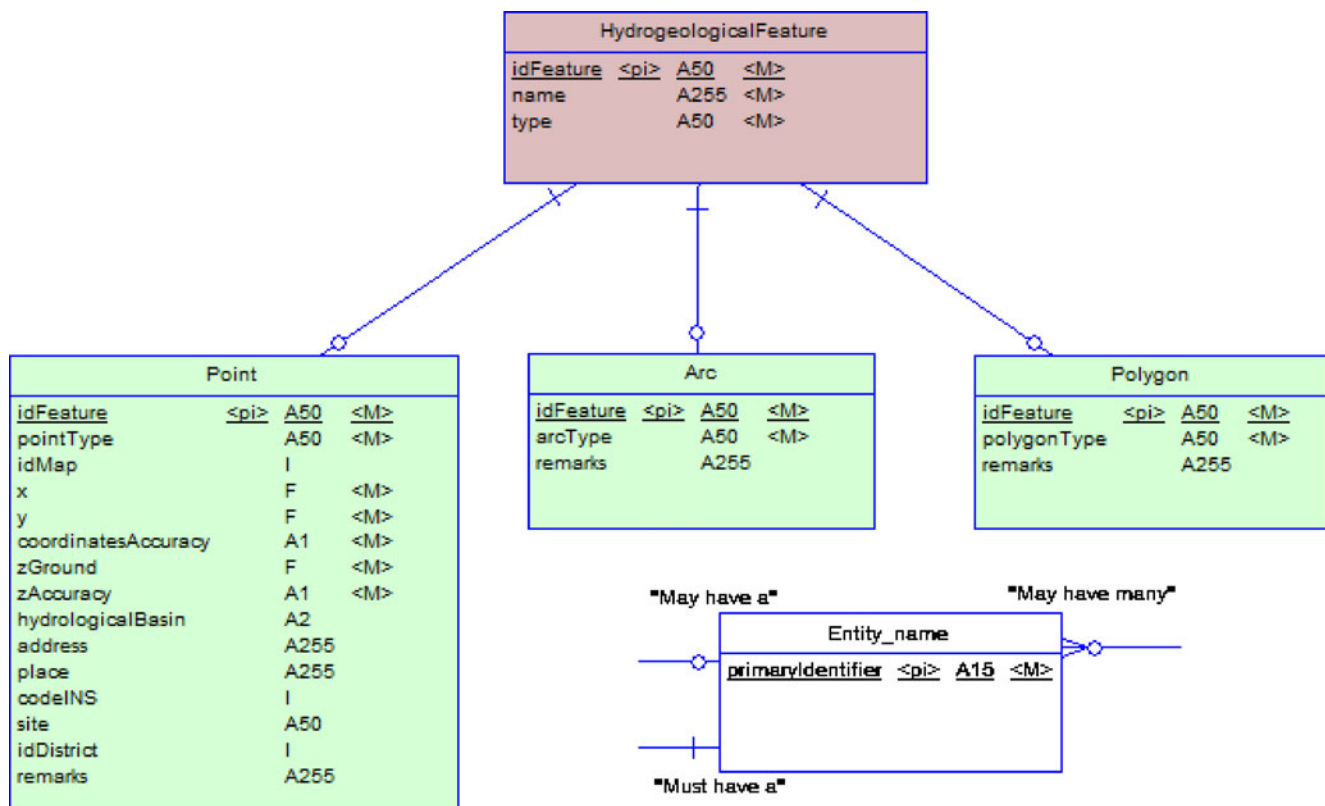


Fig. 1 Basic entities of the HydroCube model. Data types and symbols notation for all the figures: *A(x)* characters (number); *I* Integer (it can also be a primary identifier from a dictionary); *F* float; *SF* short float; *DT* date and time; *MBT* Multibyte; *BL* Boolean; *<pi>* primary identifier; *<M>* mandatory value. *Commas* equate decimal points

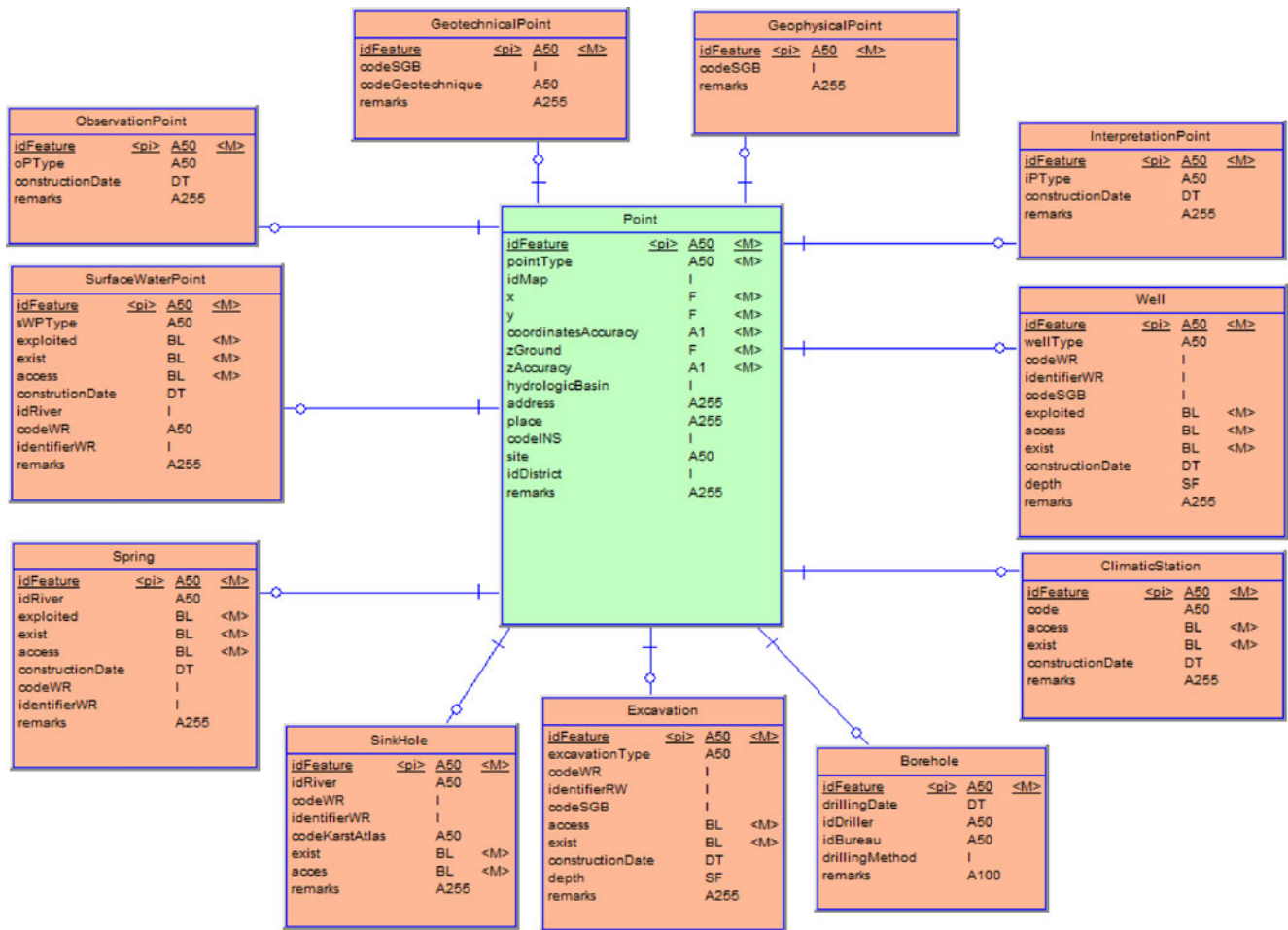


Fig. 2 Entity-relationship diagram of point-type feature entities

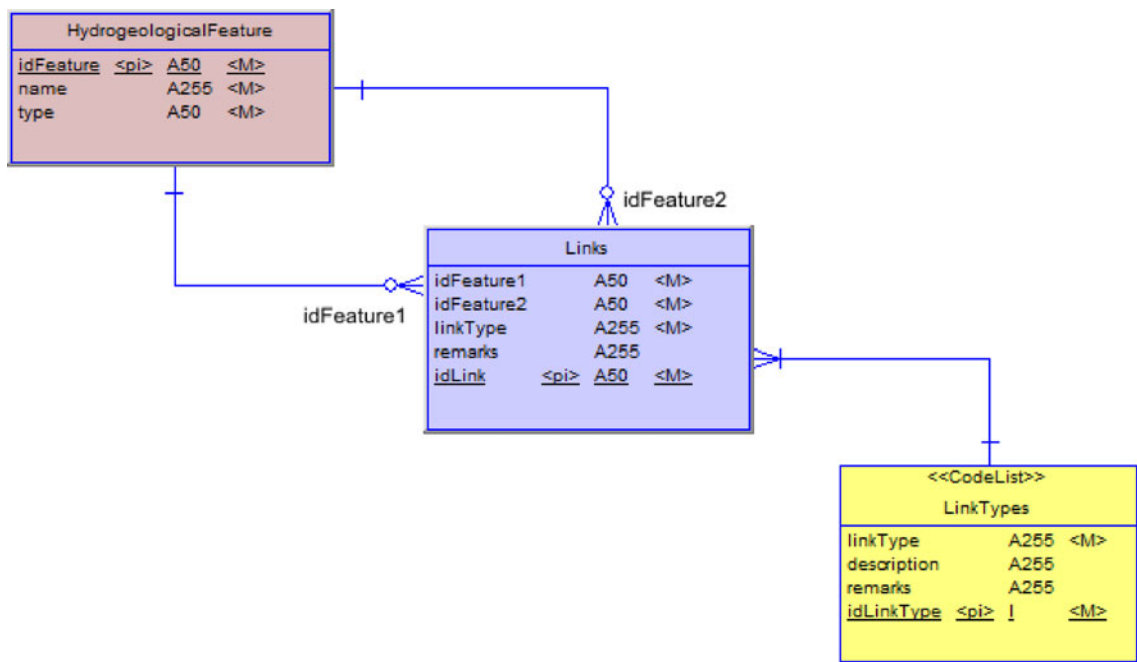


Fig. 3 Links entity and related hydrogeological features

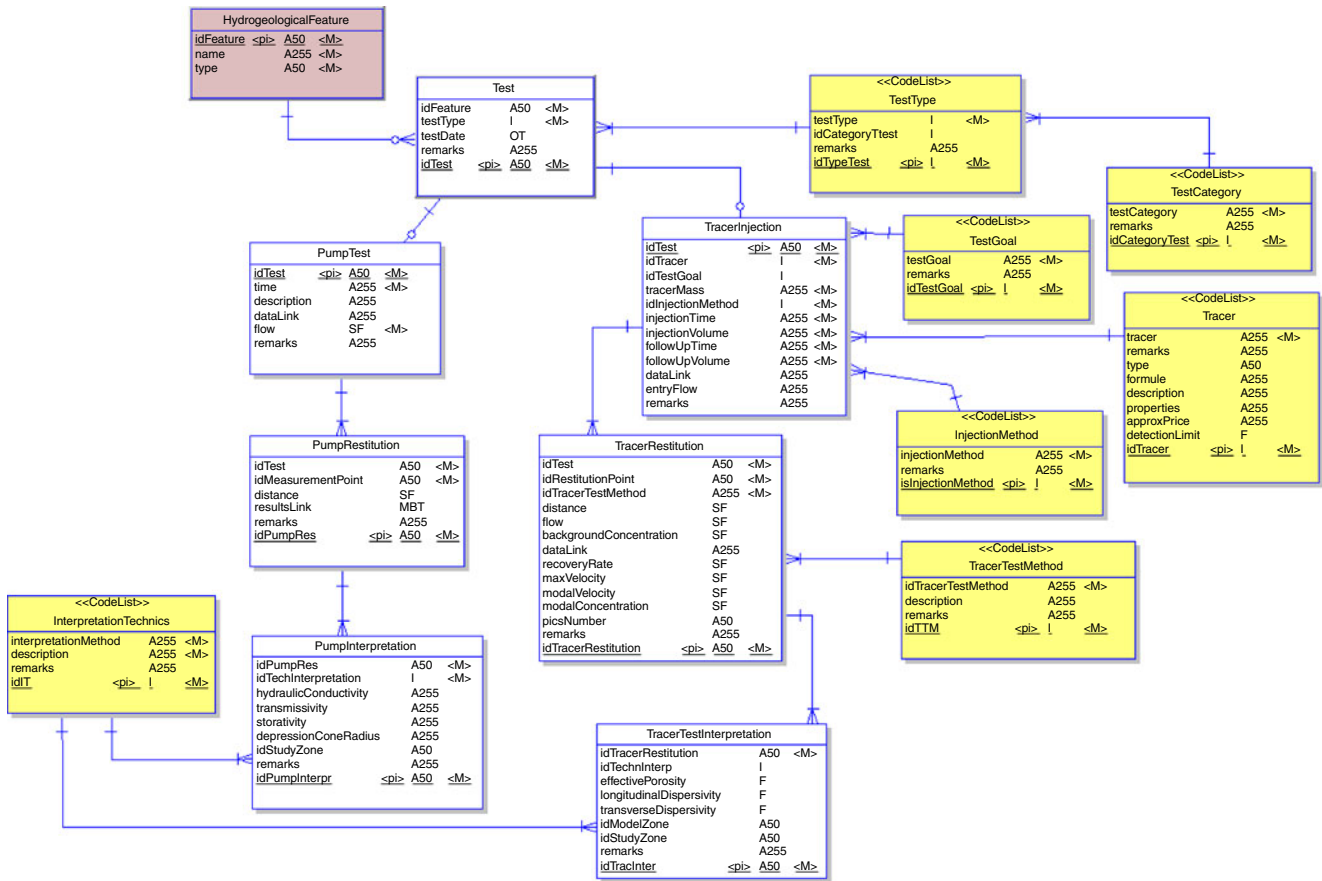


Fig. 4 Entity-relationship diagram of test sub-model for pumping tests and tracer tests

GIS geometry-first approach, used also in the ‘Guidance Document for Implementing the GIS Elements of the Water Framework Directive’ (Vogt 2002), the hydrogeological entities of HydroCube are classified according to their basic geometric characteristics (Fig. 1). This solution presents a geometry-centric data model where all the elements are represented by points, lines, and polygons, all being one-dimensional (1D) or two-dimensional (2D) features. The proposed HydroCube model deals directly with the geometry of Point-type entities, 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. Only the point entity is presented here. The arc and polygon entities with their specific related hydrogeological features and defined attributes are presented in the ESM (see figures 1 and 2 ESM 1).

The most important point attributes are the type of the point (well, spring, surface water observation point, etc.), the geographic coordinates with a description of their accuracy, and the postal address. The point entity may have one of 11 specialized hydrogeological features, namely SurfacePoint, Sinkhole, Spring, Borehole, Well, Excavation, InterpretationPoint, ObservationPoint, GeotechnicalPoint, GeophysicalPoint and ClimaticStation (Fig. 2).

Topological relationships 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. The project may include information about the study zone together with hydrogeological features such as springs 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 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 a groundwater intake location and its protection zones based on pollutant transfer times, 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 features such as wells, piezometers, rivers, springs constituting the monitoring network for a regional groundwater investigation.

Observations and measurements

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 on piezometric levels, groundwater fluxes and groundwater geochemical properties. In this context, the HydroCube model defines specific entities for well equipment (figure 3; ESM 1), groundwater chemistry data (figure 4; ESM 1), and piezometric head measurements with an example of encoding (figure 5; ESM 1).

However, more complex hydrogeological parameters can only be obtained by performing advanced field experiments such as pumping tests and tracer tests. Field experiments usually produce large amounts of data that are sometimes difficult to handle and to analyse. In order to facilitate the management, retrieval, and interpretation of such data, an advanced model has been developed (Fig. 4), based on a three-phase generic framework which can be described as follows. First, the experimental setup and the experimental conditions of each field test are described. Information on the experimental setup consists of the exact location of the test, and available hydrogeological features used to perform the test such as wells, piezometers, or sensors. Information on the experimental conditions includes 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 a 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.

For pumping tests, information is stored about the experimental device, which usually consists of a main pumping well and several surrounding observation wells and piezometers. The experimental conditions include the pumping-rate profile associated with the pumping well. Time series of piezometric head levels and drawdown values measured during the pumping test are stored in relation to 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 tests, the experimental setup consists of 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 with the injection point, and on tracer recovery associated with each observation point. Tracer injection conditions consist of the nature and quantity of the injected tracer, on a description of the injection profile (i.e. injection volume, duration and flush rate) and possibly on the concentration evolution in the injection well (Brouyère et al. 2005). Information on tracer recovery includes, among others, the tracer test

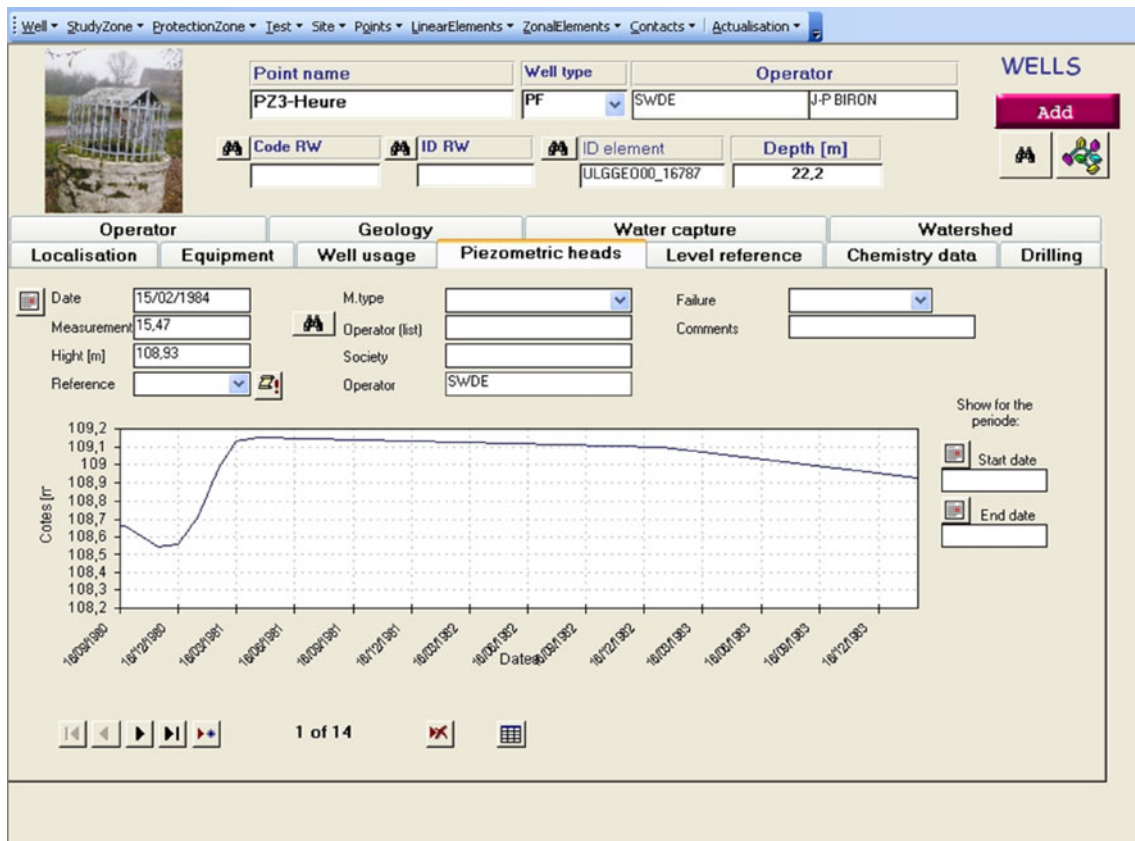


Fig. 5 Well form with the *piezometric heads* tab, which allows the user to view measurements for a chosen period of time

method, tracer background concentration and the distance between the injection point and the recovery point. The tracer test entity can also store interpretations of the results obtained using analytical or numerical simulation tools.

Interface to HydroCube

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. Moreover, the use of user interfaces prevents errors while introducing data, i.e. pre-coded permissible value lists facilitate encoding. Complex search queries also give reliable and complete results, improving data reliability and re-use.

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, which allows encoded 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 (Fig. 5).

The HydroCube interface provides specific query forms that allow the use of one or several search criteria and can combine them for more advanced queries on the hydrogeological data stored in the database. The query forms allow the user 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, based on localisation attributes such as one particular region/map or based on radial functions (Fig. 6). More complex spatial queries can however be performed using external GIS software.

Data visualisation can be performed using several visualisation tools included in the HydroCube user interface. Any data previously encoded in the HydroCube database can also be exported to either MS Excel or MS Word. Other electronic data deliverables can be developed using standard MS tools. Specialized field forms can also be produced for use in the field during experiments and surveys (Fig. 7). Such field forms allow compilation of all the available information about existing wells and piezometers prior to additional measurements in the field.

Choose one or more criteria for a point feature search

POINT NAME

COORDINATES

Min Max (m)

X 150000 195000

Min Max (m)

Y 100000 120000

Geocentric

X center Y center Array [m]

POINT TYPE

Point type

well/piezo/x/groundw

WATERSHED

Watershed

MAP

Geologic/Hydrogeologic map

IGN map

LOCATION

Former location

ZIP code

GROUNDWATER BODY

Groundwater body

OWNER

OPERATOR

DEPARTMENT (INS code)

INC code

Selected points:	Point name	Point type	X	Y	Z	Locality
12	PZ3	well/piezo/x/groundw	153140	119270	170	Presles
	Solvay PZ3	well/piezo/x/groundw	162340	119440	176,12	Hemiprinne-lez-Florennes
	Pz3-CARMEUSE-Hemiprinne	well/piezo/x/groundw	163191,2	102748,3	242,95	Monalmé
	PZ3-Monalmé	well/piezo/x/groundw	164653,2	106937,4	263,94	Florennes
	PZ3-Berthe	well/piezo/x/groundw	168017	104112	263,36	Mettet
	SWDE PZ3-METTET	well/piezo/x/groundw	168637	110001,8	255	Biesmerée
	SWDE PZ3-Biesmerée	well/piezo/x/groundw	173047,4	109536,1	236,55	
	Grand Fond Pz3	well/piezo/x/groundw	180000	113357		
	Bioul Pz3	well/piezo/x/groundw	180010	113350		Bioul
	Pz3-Lustin	well/piezo/x/groundw	186341	119300		Lustin
	PZ3-Pieuré d'Anseremme	well/piezo/x/groundw	187337,4	103056		Anseremme
	PZ3-Thynes-Lisogne	well/piezo/x/groundw	192938,7	106881,3		

SEARCH

Delat selection

OK Annuler

Fig. 6 Query form for point-type hydrogeological features allows users 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 are displayed in a list form and can be visualized in detail for a chosen feature or exported into the MS Excel file, or can be transferred into the field note form

Field Note

ID HydroCube: DIXSOU00_26403	WR code: 5223003	IGN: Thuin
Name: <u>LOBBES G2</u>	WR ID: 3912	IGN: 522
Type: puits/piezo/Xeso		
Well type: PGAL		H/G map: Merbes-le-Château/Thuin
Use:		H/G map: 52/1-2

X: 143488	Address: CHAPELLE AUX CHARMES	Accessible: <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/>
Y: 117894		Existe: <input type="checkbox"/> <input type="checkbox"/> <input type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/>
Precision: L	Locality:	Exploited: <input type="checkbox"/> <input type="checkbox"/> <input checked="" type="checkbox"/>
Z ground:	Depth [m]:	Classified:
Precision:		

Comments:

Available Observations Measurements:

Constr. date:

Chemistry:

Counter:

Piezometry:

Pump:

Geology:

Equipment:

Intake volumes:

Owner:

Society: S.W.D.E.- SOCIETE WALLONNE DE

Address:

INS:

Activity:

ZIP code: 4800

Website

Contact S.W.D.E.- SOCIETE

Type: administration
publique (non
distribution)

Telephone:

Code 70

Fax

e-mail:

Operator:

Society: S.W.D.E.

Address:

INS:

ZIP Code:

Website

Contact

Telephone:

Fax

email:

Start:

End:

Field piezometry head measurements:

Date:

Reference level:

Measurement:

Piezometric head altitude:

Comments:

Fig. 7 The *Field Note* form facilitates the preparation phase for field work. Once the HydroCube database is queried through a search form, the user can export information into the *Field Note* form, where additional measurements or remarks can be noted

Conclusions

HydroCube proposes a new logical model of hydrogeological data, described using entity-relationship diagrams. The model contains a full range of hydrogeological features encountered in a project, classified into points, arcs or polygons according to their geometric attributes. The model includes location, equipment, installations, measurements and related observations, in particular pumping tests and tracer tests which can be related spatially. 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 since 2005 by around 30 people for hydrogeological data management in many real studies by different universities as well as in administrative projects in the Walloon Region. The model has received data continuously from different local and regional projects such as the hydrogeological mapping of the Walloon Region (Bouezmarni et al. 2006), large-scale groundwater modelling projects (Orban et al. 2004), the European Union (EU) FP6 AquaTerra Project (Batlle Aguilar et al. 2007), and groundwater vulnerability mapping (Popescu et al. 2004). For the HydroCube model and database being used in the Walloon Region, rules have been defined for data encoding, and for semi-automatic periodic centralisation through data-exchange files.

Every data-exchange file contains updated or added data for one period in exactly the same logical model as HydroCube, which has greatly improved data transcription. These files are then uploaded and data are automatically transferred to the central database. The latter is then redistributed to all the users through FTP protocols (20 MB zip-compressed file). Furthermore, the feedback from using HydroCube yielded improvements to the database itself, as well as to the user interface. For instance, new entities have been added to assure compatibility with the EU Water Framework Directive (2000/60/EC) and the Groundwater Framework Directive (2006/118/EC).

The MS Access implementation platform ensures 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, upon the request of the financing institution, migration to the ORACLE environment has already been performed. The ORACLE data model is identical to the HydroCube logical model, and it reuses its user interface. Therefore, there is a larger possibility of adding new functionalities and electronic data deliverables.

Further work on the hydrogeological data model involves the development of an object-oriented form, using UML notation and XML schema. This work has been performed in the scope of the EU FP6 Project GABARDINE, focusing on groundwater artificial recharge based on alternative sources of water (Wojda et al. 2006). The UML methodology will enrich the model with additional functionalities such as different entities behaviour, according to their specific types, additional topological relationship rules, and clearer constraints, which can be used during data encoding and transfer to avoid errors (Wojda et al. 2010). 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 (Chia-Hsin et al. 2009). 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 et al. 2005).

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