Environmental Modelling & Software 43 (2013) 109–123

Contents lists available at SciVerse ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

An object-oriented hydrogeological data model for groundwater projects

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ARTICLE INFO

Article history:
Received 19 June 2012
Received in revised form
19 December 2012
Accepted 29 January 2013
Available online 6 March 2013

Keywords:
Hydrogeological information
Data modelling
Model standardization
Unified modeling language

ABSTRACT

Geological and hydrogeological data are expensive to obtain in the field but are crucial for specific hydrogeological studies, from hydrogeological water balances to groundwater flow modelling and contaminant transport, or for more integrated environmental investigations where groundwater plays a role. In this context, hydrogeological data are collected, transformed and exchanged at different scales, from local to international levels and between numerous institutions ranging from environmental consulting companies to the national and international environmental administrations. To guarantee that these exchanges are possible and meaningful, a clear structure and meta-information on applied hydrogeological data models is required. To make one step towards seamless management of groundwater projects, a new hydrogeological data model has been developed: $H^g{}_2O$. It is described using object-oriented paradigms and it follows the recommendations of the International Organization for Standardization (ISO/TC211), the Open Geospatial Consortium (OGC), and the European Geospatial Information Working Group. Hydrogeological features are organized in packages of spatial feature datasets. The observations and measurements related to these features are organized in a separate package. A particular focus is on specialized hydrogeological field experiments such as hydraulic and tracer tests. Two first implementations in the proprietary desktop ArcGIS environment and in the open source web-based Web2GIS platform are presented, focussing on their respective standards support.

1. Introduction

Geological and hydrogeological data are acquired and used in diverse hydrogeological studies driven by scientific investigations and exploitation schemes, ensuring groundwater resources protection and sustainable exploitation. Since geological and hydrogeological data are expensive to obtain in the field, there is a need for their efficient management and delivery. The latter should be ensured at different scales: from local to international levels, between numerous institutions ranging from environmental consulting companies to the national and international environmental administrations (Wojda et al., 2010a,b), using the most appropriate tools. Since most geological and hydrogeological information is Earth-relative, they are geospatial by nature and geomatics technology presents the most appropriate tools for hydrogeological data and information structuring, management and exploitation.

Nowadays, hydrogeological information is mainly stored in digital form, facilitating their availability, transparency and exchange (Michalak, 2003). While there are efficient databases for managing hydrogeological data at the local level (data owners and users), there is however no unique hydrogeological data model used by the various interested parties in today multidisciplinary, cross-border and multi-language environment, specific to groundwater resources management. This heterogeneity of formats makes it difficult to communicate and to exchange hydrogeological data (Michalak and Leśniak, 2003).

The problem of system and data interoperability is not only applicable to the hydrogeological domain, but it is valid in the realm of environmental data management, where a lot of data sources need to be consulted and provide input for complex environmental models. Such interdisciplinary systems and model components can be connected and made interoperable following different approaches such as Environmental Modelling Frameworks (David et al., 2012). This can also be achieved, applying a service-oriented paradigm, where a collection of distributed components communicate through a commonly defined web service interface (Goodall et al., 2011; Gregersen et al., 2007).

To enable data interoperability from multiple and heterogeneous data sources, a Spatial Data Infrastructure (SDI) needs to be

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http://dx.doi.org/10.1016/j.envsoft.2013.01.015

deployed. Environmental data should be modelled using widely accepted formalisms such as entity-relationship or object-oriented paradigms (Pinet, 2012). While generic geospatial data querying and transport can be accomplished through generic mechanisms and a global schema, every environmental domain needs to be addressed by a specific and adapted domain schema. Many domain standards exist already and can be found at OGC Network Resources (http://www.ogcnetwork.net/node/210). Nevertheless, at present there is no widely applied hydrogeological data standard. As a consequence, the hydrogeological community needs standardization to improve interoperability leading to efficient management and delivery of hydrogeological information.

In this context, a new logical hydrogeological data model is presented, contributing to the standardization of hydrogeological information. This model is compliant with the recommendations from the European Geospatial Information Working Group (Vogt, 2002). It is described using a series of Unified Modelling Language (UML) diagrams, using object-oriented paradigms, and following the recommendations of the International Organization for Standardization Technical Committee 211 (ISO/TC211), and the Open Geospatial Consortium (OGC). Hydrogeological features are grouped within feature classes and organized in packages of spatial feature datasets. The observations and measurements related to these features are organized in a separate package, which follows the Observations and Measurements discussion documents (Cox, 2003) and standards (OGC Observations and Measurements, 07-022r1, 2007). The first implementation of the model was made in the ArcGIS desktop environment, building 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*" (Wojda et al., 2006). The second implementation was made in a Web2GIS web-based environment offering on-line tools for model conception, database implementation and visualisation (Laplanche, 2006).

The first part of the paper provides a review of existing geological and hydrogeological data models based upon modern data modelling approaches and methods. Subsequently, the new hydrogeological data model $H^g{}_2O$ is introduced. Relationships between hydrogeological features are presented, followed by a description of related observations and measurements. In particular, an innovative data model for hydrogeological field experiments such as hydraulic tests and applied tracer tests is described. Implementation of the model in different platforms is shown and achieved data interoperability between presented solutions is discussed. The conclusions propose further developments as well as the possible contribution of $H^g{}_2O$ data model to an emerging international groundwater information exchange standard such as GroundWater Markup Language (GWML).

2. Hydrogeological data modelling background

Several existing hydrogeological data models, briefly described here-after, were the source of the object-oriented model developed in this study.

The HydroCube data model was developed at the University of Liège for the Walloon Region in Belgium to cover a full set of hydrogeological concepts and features, allowing effective hydrogeological project management (Wojda et al., 2010b). It is described by a formalized entity-relationship diagrammatic notation. The first model implementation was performed in the MS Access environment. The implemented 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, by spatially-enabled databases. The data stored in these structures might be analysed by any geoprocessing tool and eventually displayed by mapping clients. In 2010, the logical model was migrated into the ORACLE environment to enable multi-user instances. Both implementations have been enriched with fully functional user interfaces.

The Guidance document on the implementation of the GIS elements in the European Water Framework Directive (WFD) presents several solutions for groundwater data modelling in the scope of resource management and reporting (Vogt, 2002). The corresponding data model described using the UML (Unified Modeling Language, OMG, 2012) notation, proposes a general framework and guidelines for an implementation of WFD according to the geomatics principles. However, it does not provide a holistic model for hydrogeological data.

The WaterStrategyMan project proposed a generic data model which enables describing a water resource system in terms of water availability, demand, infrastructure, and administrative structures (ProGEA S.r.l, 2004) in the framework of water resources management.

International standards and on-going projects concerning encoding and exchange of geospatial information have also been taken into account for developing the new hydrogeological model. In particular, the "*Geographic 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) and "*GroundWater Markup Language – GWML*" (Boisvert and Brodaric, 2012) have been analysed. In further phases, the "*Observations and Measurements – O&M*" described by Observation schema (OGC Observations and Measurements – Part 1 – Observation schema, 07-022r1, 2007) and Sampling Features (OGC Observations and Measurements – Part 2 – Sampling Features, 07-002r3, 2007) have also been investigated. Last but not least, an interesting international standard OpenMI (The Open Modelling Interface) has been explored (OpenMI Association, 2012).

GML is an XML grammar written in XML Schema providing a large variety of objects for describing features, co-ordinate reference systems, geometry, topology, time, and units of measure. 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 industry sector. GeoSciML is as an on-going standardization for geoscientific information exchange format, mainly for structural geology (geological units), sampling features (boreholes), geologic vocabulary, and earth materials.

GWML is specifically being developed for the exchange of hydrogeological data. First real-data tests have been carried out in Canada in the national context. Then, through the OGC Groundwater Interoperability Experiment, the GWML model and emerging WaterML2.0 were tested at the international level (OGC® Groundwater Interoperability Experiment, Final report, 10-194r3). The experiment was aimed to advance the exchange of groundwater data, more particularly well characteristics and groundwater levels, between Canada and the USA. The authors of $H^g{}_2O$ presented in this paper took part in on-line discussions on the GWML development and in a workshop organised in Quebec City in Canada in February 2009. These technical considerations were mainly focused on whether the well feature is to be considered as a separate feature or not, on hydrogeological systems elements (such as WaterBody) and on groundwater type classifications. Furthermore, a possible use and extension of O&M proposing a generic conceptual model and encoding for observations and measurements was discussed in the context of groundwater resources and time series.

It is important to mention CUAHSI WaterML 1.0 and its further development into WaterML 2.0 under the OGC Standards Working Group. The 1.0 specification available since October 2009 (Valentine and Zaslavsky, 2009) offered a standard for encoding of the semantics of hydrologic observation discovery and retrieval in the context of water data services. The 2.0 specification currently under development, a candidate Open Geospatial Consortium encoding standard for the representation of in-situ hydrological observations data, will offer a standard information model for the representation of in-situ water observations data, with the intent of allowing the exchange of such data sets across information systems (OGC® WaterML 2.0: Part 1 Timeseries, 10-126r2, 2012). However, WaterML 1.0 was focused mainly on hydrological issues and WaterML 2.0 was not available while working on the present paper.

Finally, the OpenMI enables data exchange between different environmental domain models at run-time. Data exchange can be accomplished between OpenMI-enabled software components, linked in any combination of models, databases, analytical and visualisation tools (Gregersen et al., 2007; Moore et al., 2010). However, this initiative applies to higher-level data exchange between models and does not treat about implementation of specific conceptual or logical data models.

To conclude, the H^g_2O is not meant to replace the development of the GWML or WaterML2.0. The hydrogeological model was developed in parallel and naturally some of the main elements are common. However, the H^g_2O model was developed mainly in the European context, following the recommendations of European Directives. As one of its strongest and innovative points, the hydrogeological model complements the GWML offering a milestone in the domain of hydrogeological field experiments such as hydraulic and tracer tests, proposing an O&M structured concept of data storage and exchange.

3. Description of the hydrogeological data model

Recently, object-oriented modelling techniques have become a geoscientific standard. They permit convergence across different domains leading towards interoperability. Seamless data exchange between different domains and projects are becoming possible using available web transformation services and pre-defined exchange protocols, on the condition that the models are unambiguously described in feature catalogues or by application schemas. In the broad environmental domain, some efforts have arisen recently in order to exchange or to publish geospatial data (Horsburgh et al., 2009). Unfortunately, apart from the hydrogeological data models identified in the previous point, little work has been accomplished in the hydrogeological domain. To fill this gap and to follow the integration trend, the following model has been proposed, implemented and tested.

During the development of H^g_2O, the following requirements have been considered:

- (1) usability in the international context,
- (2) usability in the multi-user and multi-purpose context (Integrated Water Resource Management),
- (3) easiness to map the model onto international standards and to transform the data.
- (4) further development of already existing and implemented solutions,
- (5) further development of the conceptual model of hydrogeological field experiments proposed by the HydroCube project,
- (6) usability in the artificial recharge context for semi-arid and arid zones,

Resulting from these requirements, the following design choices have been adopted:

- UML has been chosen as internationally recognized standard, used by ISO and OGC (responding to the requirements 1, 2, 3, 4),
- the H^g_2O model develops specific hydrogeological feature classes and it imports some general classes and their attributes from GML/GeoSciML/O&M to guarantee correct mapping onto standards, schema transformation and future data exchanges within the Web-based environment and Service-oriented architectures (responding to the requirements 1, 2, 3, 4, 5),

XML has been chosen to exchange geospatial data (responding to the requirements 1, 2, 6). The H^g_2O classes have been described in the following packages: AbstractFeatures, GroundwaterFeatures, Hydrogeology, and Observations&Measurements.

3.1. Abstract features

The AbstractFeatures package contains abstract classes which are common to different parts of the model (Fig. 1). It defines the

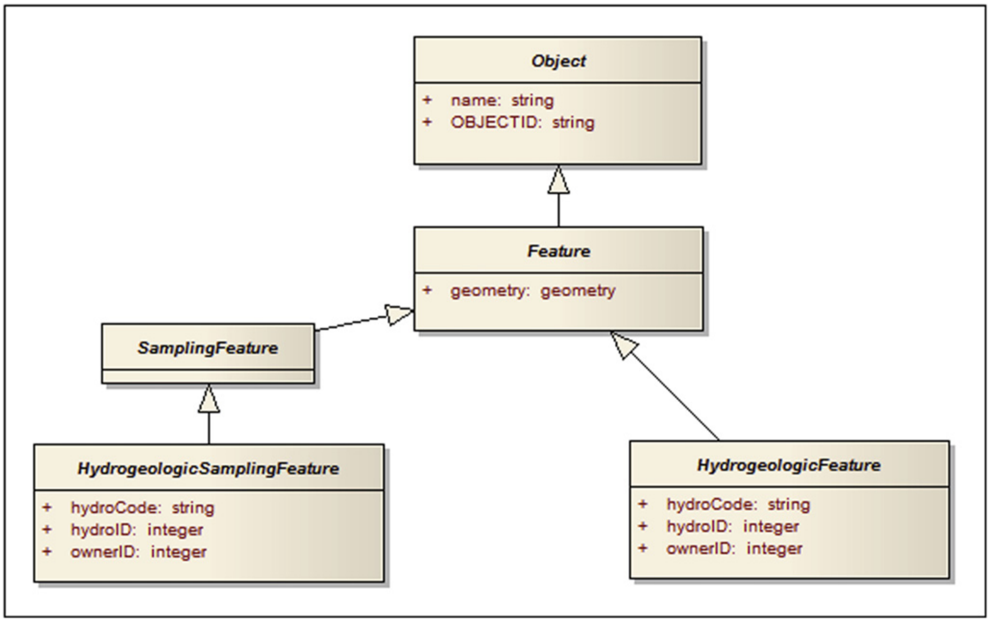


Fig. 1. Abstract features of H^g_2O.

non-spatial *Object* class with its mandatory OBJECTID attribute defining a unique and mandatory identifier of every instance generated by any class across the model. It may be mapped onto gml:id property, although the latter is optional. Then, the spatial class *Feature* with a single attribute defining the geometry of any geospatial feature, being an equivalent of gml:AbstractGeometry property. It can represent any geometry type such as point, curve or polygon.

The *Feature* class is extended by two abstract features, namely: *SamplingFeature* and *HydrogeologicFeature*. The *SamplingFeature* class, equivalent to the SamplingFeature class from the O&M sampling feature model (OGC Observations and Measurements, 05-087r4), is used primarily for handling observations of any kind in the data model, with a specialized *HydrogeologicSamplingFeature* class, defined as "a natural or constructed structure that allows access to groundwater or where the groundwater system can be observed or measured" (National Groundwater Committee, 1999). This specialized class can be used for handling information of two kinds: data on the monitoring of hydrogeological conditions by observations and measurements, and data on groundwater exploitation (extracted or injected volumes of groundwater). The *HydrogeologicFeature* class represents any hydrogeologic geospatial feature which is not used for making observations. It can be seen as a specialization of the GeologicFeature from GeoSciML representing "a conceptual feature that is hypothesized to exist coherently in the world", (GeoSciML, 2008). *HydrogeologicSamplingFeature* and *HydrogeologicFeature* are the two main abstract components of 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. HydroID stands for a unique identifier of any hydrogeologic (sampling) feature instantiated by the hydrogeological data model. This unique identifier is created, managed and used internally. On the contrary, a global unique identifier (OBJECTID) of "any object" is propagated to all the objects and features of the model and can be used externally to identify an object instance regardless its type. HydroCode is inherited from the Water Framework Directive guidance model, where the principles of the European structured coding are given (Vogt, 2002). OwnerID identifies the owner of the hydrogeological feature.

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 (Fig. 2). These specific 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 complete the description of hydrogeological sampling features, two sub-packages have been defined, namely "Construction elements" and "Borehole". In the first sub-package a series of construction elements, defined as a man-made module of a groundwater feature that improves access to groundwater, is designed: casing, screens, seals gravel, packs and pumps.

The "borehole" sub-package was designed to deal with geological and hydrogeological data retrieved from the underground, which are necessary to correctly characterize and interpret hydrogeological environments. The module has partially been based on the GeoSciML "borehole" model. However, in $H^{g}{}_{2}O$ a clear distinction is made between a borehole, used for sampling of the geological environment and a well serving for sampling or exploitation of the water content of the hydrogeological environment.

In the GeoSciML, the borehole is considered as the generalized term for any narrow shaft drilled in the ground, either vertically or

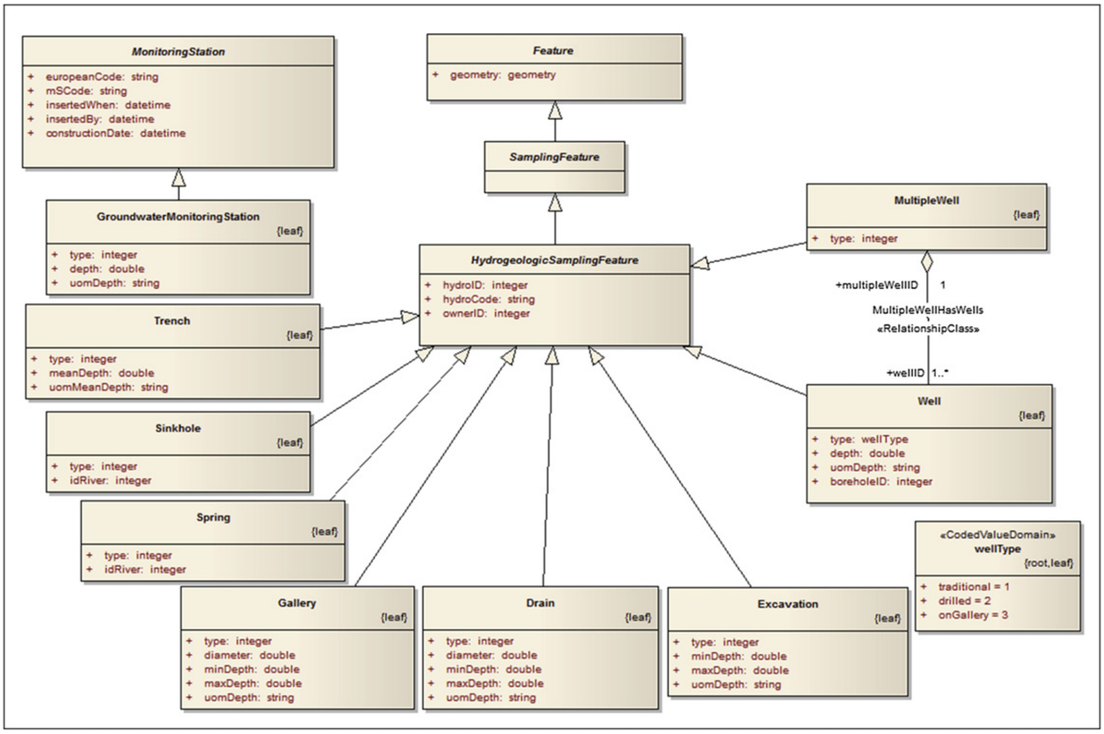


Fig. 2. Sampling feature classes derived from the HydrogeologicSamplingFeature abstract super class. To monitor the groundwater status and to appropriately manage this information, the EC WFD makes an explicit distinction between Surface Water Monitoring and Groundwater Monitoring (Vogt, 2002). In the hydrogeological data model, respective classes have been imported and the GroundwaterMonitoringStation class is indicated.

horizontally used to sample geological environment. The Borehole class is a specialization of the SamplingCurve class and the Profile class, both equivalent to those in the O&M model (OGC Observations and Measurements, 05-087r4). By contrast, the hydrogeological data model assumes that the well is a natural or constructed structure that allows access to groundwater or where the groundwater system can be observed or measured. It is a specialization of the HydrogeologicalSamplingFeature class and it is used to sample or to exploit a groundwater body located in an aquifer. An association is established between the well and a borehole to express the fact that a well is located at the borehole (Fig. 3).

3.3. Observations and measurements

To manage raw hydrogeological data such as time series of piezometric heads and field measurements or observations, a specific: “Observations&Measurements” package has been developed. It is an adaptation of the HydroCube (Wojda et al., 2010a,b) based on the OGC documents (OGC Observations and Measurements: 03-022r3 and 05-087r4), candidates for an International Standard 07-022r1 (2007). In ISO terms, the model presented in this paper does not pretend to be fully conformant to the O&M standard. Instead, it proposes a simplified approach based on the O&M elements, a solution convenient for the hydrogeological community and easy to implement in different GIS environments used across research institutes and environmental administrations. Furthermore, if an interoperable data exchange is required, it is easy to map the presented solution directly onto the O&M model because naming convention and model logics are preserved and indicated where appropriate.

3.3.1. Single observation or measurement

The Observations&Measurements package allows the organization of different kinds of measurements such as piezometric levels, water volumes or water geochemistry (Fig. 4).

In accordance with the OGC (Observations and Measurements, 05-087r4) and Fowler (1998), an observation is an act or event through which a number, term or other symbol is assigned to a phenomenon. Thus, in the context of geomatics, the Observation class is considered as a specialization of the Event class, with a result and an associated value describing the observed phenomenon. An observation binds the result to the feature that is being observed. These classes might be mapped to the O&M (05-087r4) classes of the same name. The abstract Observation class can be realized through specialized children classes, such as PiezometricHeadLevelMeasurement or GeochemistryMeasurement.

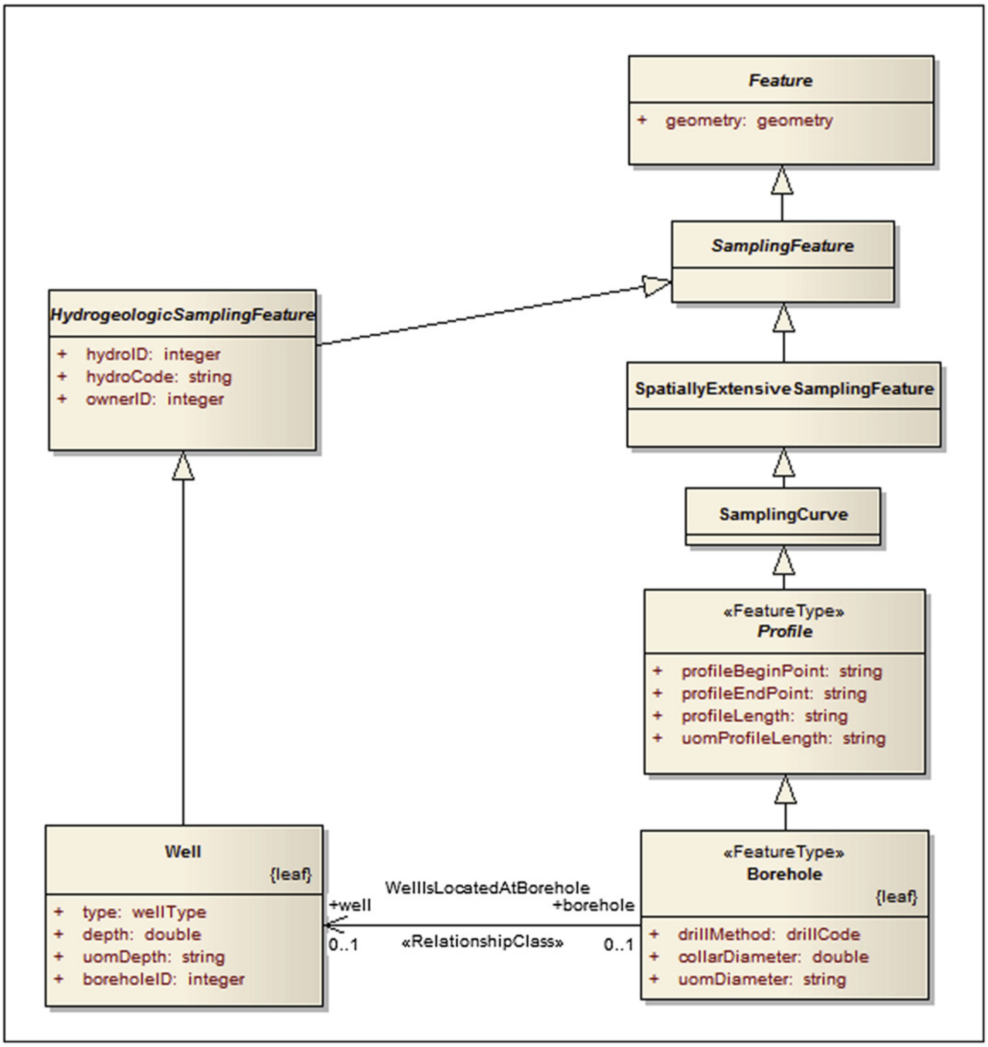


Fig. 3. The Borehole sub-package implemented in the hydrogeological data model, based on the XMML/GeoSciML borehole profile proposal. The Borehole class enables to store Lithological codes. It is associated with the Well class.

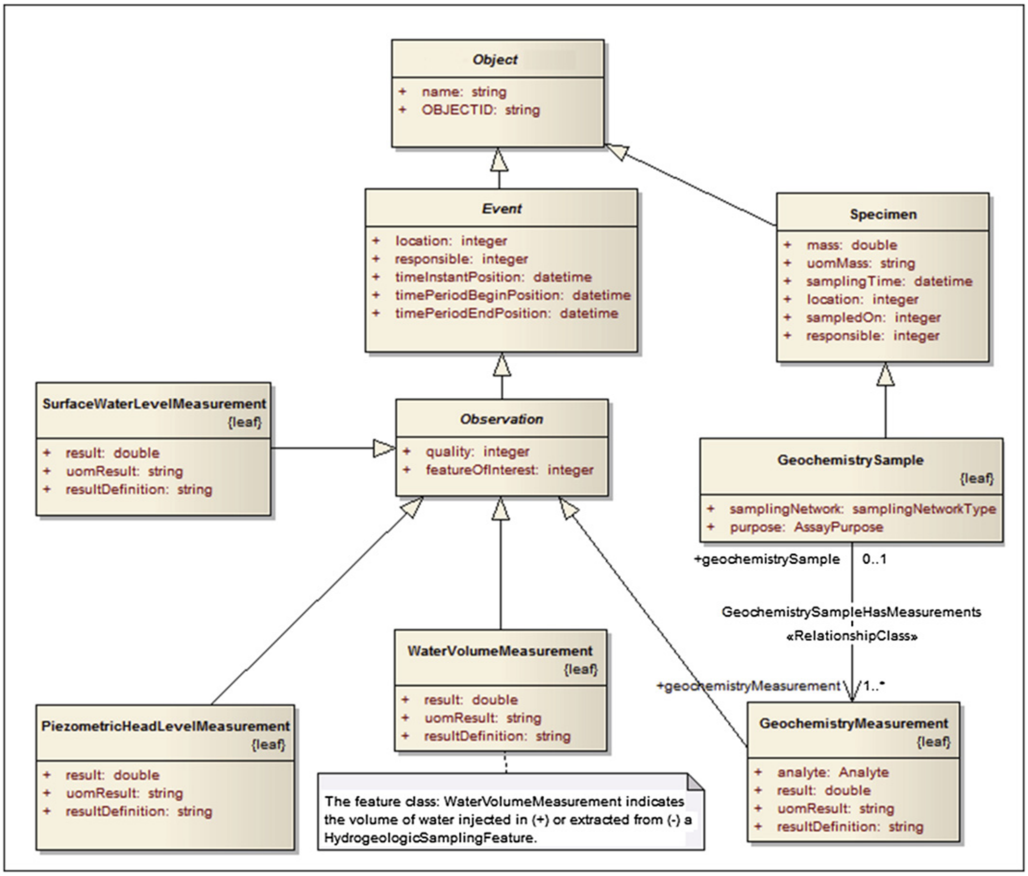


Fig. 4. Observations and measurements classes derived from the AbstractObservation class.

The Event, Observation and different specialized measurement classes have the following attributes listed in Table 1.

The following convention has been adopted for the storage and transfer of geochemistry measurements. Each measurement is performed on a specimen, where the specimen represents a finite volume of some physical material sampled from a specific location. This class can be mapped onto the O&M Specimen class. For the purpose of the work presented in this paper, a GeochemistrySample class, being an extension of the Specimen class, has been created to store specific information on groundwater samples and associated water chemistry measurements. The GeochemistrySample class inherits from the Specimen class and adds the following attributes (Table 2).

Table 1
Event, AbstractObservation and specialized measurements classes attributes.

Attribute	Definition
Event	
location	Location of data acquisition system or sensor
responsible	Person or organisation in charge of the observation
timeInstantPosition	Observation time
timePeriodBeginPosition	Observation time start
timePeriodEndPosition	Observation time end
Observation	
quality	Description of the type of the observation (surface water level, piezometric level etc)
featureOfInterest	A proximate sampling feature such as a well that ultimately samples an aquifer
Specialized measurement classes	
result	A result of the observation or measurement
uomResult	The unit of measure for the particular measurement
resultDefinition	A definition of the structure of the obtained result

3.3.2. Observation collection and array

Any spatial analysis performed to understand the hydrogeological environment needs to be carried out based on spatial and temporal observations and measurements. From a data modelling point of view, such collections of observations can be of two types: heterogeneous or homogeneous.

A collection of heterogeneous observations is a convenient “bag” for grouping a set of observations which descriptions are largely independent of each other. For instance, different observations and measurements can be performed during a field investigation, such as piezometric levels measured in different wells, surface water levels or groundwater samples collected for geochemistry analyses, where different physical and geochemical parameters can be measured.

By contrast, an array of homogeneous observations can be defined by the ObservationArray class. It associates a sequence, in time or

Table 2
GeochemistrySample class with its attributes.

Attribute	Definition
GeochemistrySample	
mass	Geochemistry sample mass
uomMass	Unit of measure of the geochemistry sample mass
sampleTime	Sampling time
location	Sampling location
sampledOn	Sampled medium

space, of observations concerning one phenomenon, such as piezometric levels measured in different wells during one field survey, or tracer concentration measured at different times. Homogeneity of observations is reflected by the fact that the value of the property *observablePhenomenon* (for instance a groundwater table) is unique for all members (OGC Observations and Measurements: 03-022r3 and 05-087r4). The *observablePhenomenon* attribute is therefore associated with the Observation Array and inherited by all its members. The ObservationArray class is a specialisation of the ObservationCollection class to which it adds the attributes shown in Fig. 5. The ObservationCollection and ObservationArray classes map onto O&M (03-022r3) classes of the same name preserving the same concepts.

3.3.3. Hydrogeological field experiments

More complex hydrogeological parameters can be obtained by performing advanced field experiments under controlled conditions, such as pumping and tracer tests. These experiments produce large amounts of geospatial data that are difficult to handle and to analyse. To provide assistance for data management, retrieval and interpretation a model has been developed, based on a three-phase generic approach described here-after.

First, information on the experimental setup is required, describing the field equipment (wells used and piezometers, pumping devices, monitoring points, sensors) and the experimental conditions (pumping rate and location, injected tracer quantity). Second, during the experiment, observations retrieved at different locations in space and time (drawdown curves, tracer breakthrough) have also to be stored. Finally, any interpretation, together with information on the interpretation method and results should also be stored. Table 3 illustrates this for hydraulic tests and tracer tests respectively. The definitions of the specific hydrogeological terms enumerated below are not provided in this paper. They may be found in on-line or any other external specialized resources.

3.3.3.1. Hydraulic tests. In the case of hydraulic tests (Fig. 6), the experimental setup consists of the main water well where water is pumped or injected and a set of observation wells/piezometers where the aquifer reaction is monitored (piezometric variations). The main well can also be considered as a monitoring well. The experimental conditions such as pumping or injection-rate profile at the main well, or piezometric head level measurements and drawdown values measured at the observation points are registered and grouped within an observation array. Information on interpretation frameworks together with their results estimating the aquifer properties such as hydraulic conductivity, transmissivity, storativity, specific yield and depression-cone radius can be stored in the HydraualicTestInterpretation class.

The HydraulicTest class is related to the ObservationCollection by the [0..1] to [1..1] association HydraulicTestHasObservationCollection. In doing so, one hydraulic test is linked to its observations collection, containing a set of observations taken in different observation points, such as pumping well, piezometers, observation wells, etc. An observation collection is associated with different measurements such as WaterVolumeMeasurements and PiezometricHeadLevelMeasurements at the observation points.

The InterpretationOfObservation class extends the Observation class with the interpretation *technique* attribute, which value comes from a coded value domain.

The ObservationCollection class is related to the HydraulicTestInterpretation class by a [1] to [0…*n*] relationship “ObservationCollectionHasHydraulicTestIntepretations”. The latter is a child

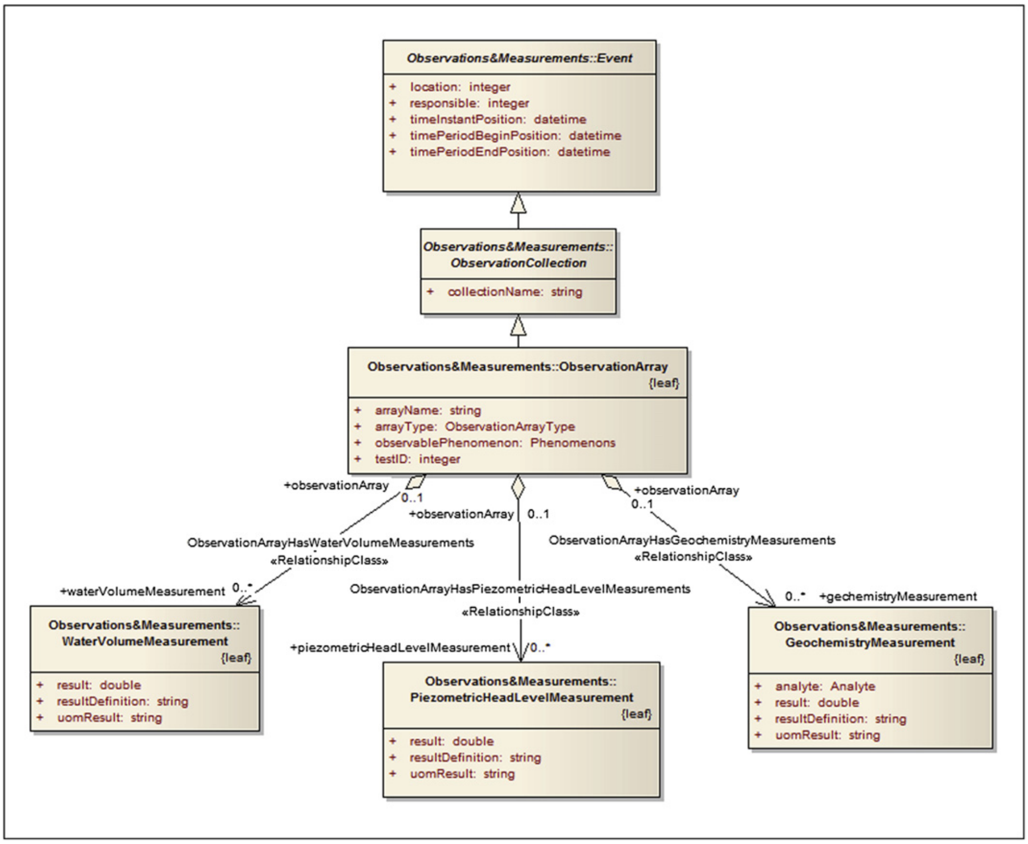


Fig. 5. Observation Array for a specialized collection of observations, where the observable property on the members is constant.

Table 3
Main groups of data of hydrogeological field experiments.

		Hydraulic test	Tracer test
Experimental setup and test conditions	Equipment/sensors tested well/point	Pumping/injection well ID	Injection point ID
	Monitoring points	Observation wells IDs	Observation wells IDs, spring IDs …
	Stress profile	Injection/pumping rate profile	Tracer injection profile (quantity, concentration)
Observations and measurements		Drawdown curves	Concentration variations
Interpretations		Transmissivity Hydraulic conductivity Storativity *Others*	Effective porosity Longitudinal dispersivity Transverse dispersivity *Others*

class of the abstract class “InterpretationOfObservation”. It extends it with the attributes listed in Table 4.

3.3.3.2. Tracer tests. For the tracer tests, the experimental setup consists of a location where the tracer is injected and a set of observation points (piezometers, wells, springs) where tracer recovery is monitored (tracer concentration evolution). In the case of single-well tracer tests, the injection point and the monitoring point correspond to the same well.

Table 4
HydraulicTestInterpretation class attributes and their definitions.

Attribute	Definition
HydraulicTestInterpretation	
hydraulicConductivity	Interpreted hydraulic conductivity
transmissivity	Interpreted transimissivity
storativity	Interpreted storativity
specificYield	Interpreted specific yield
depressionConeRadius	Indicates the depression-cone maximal radius interpreted from the hydraulic test results
observationCollecitonID	Indicates the observation collection to which the interpretation is associated

The experimental conditions such as nature and quantity of the injected tracer, the tracer injection profile (i.e. tracer injection volume, duration and flush rate), the tracer concentration evolution at different monitoring points are stored as related observations and measurements and may be grouped into an observation array. Different interpretations of the tracer test can be performed by analytical or numerical simulation tools. They are stored in the TracerTestInterpretation class which contains both the estimates of aquifer properties (such as effective porosity or dispersivity) and the information on the interpretation technique (Fig. 7).

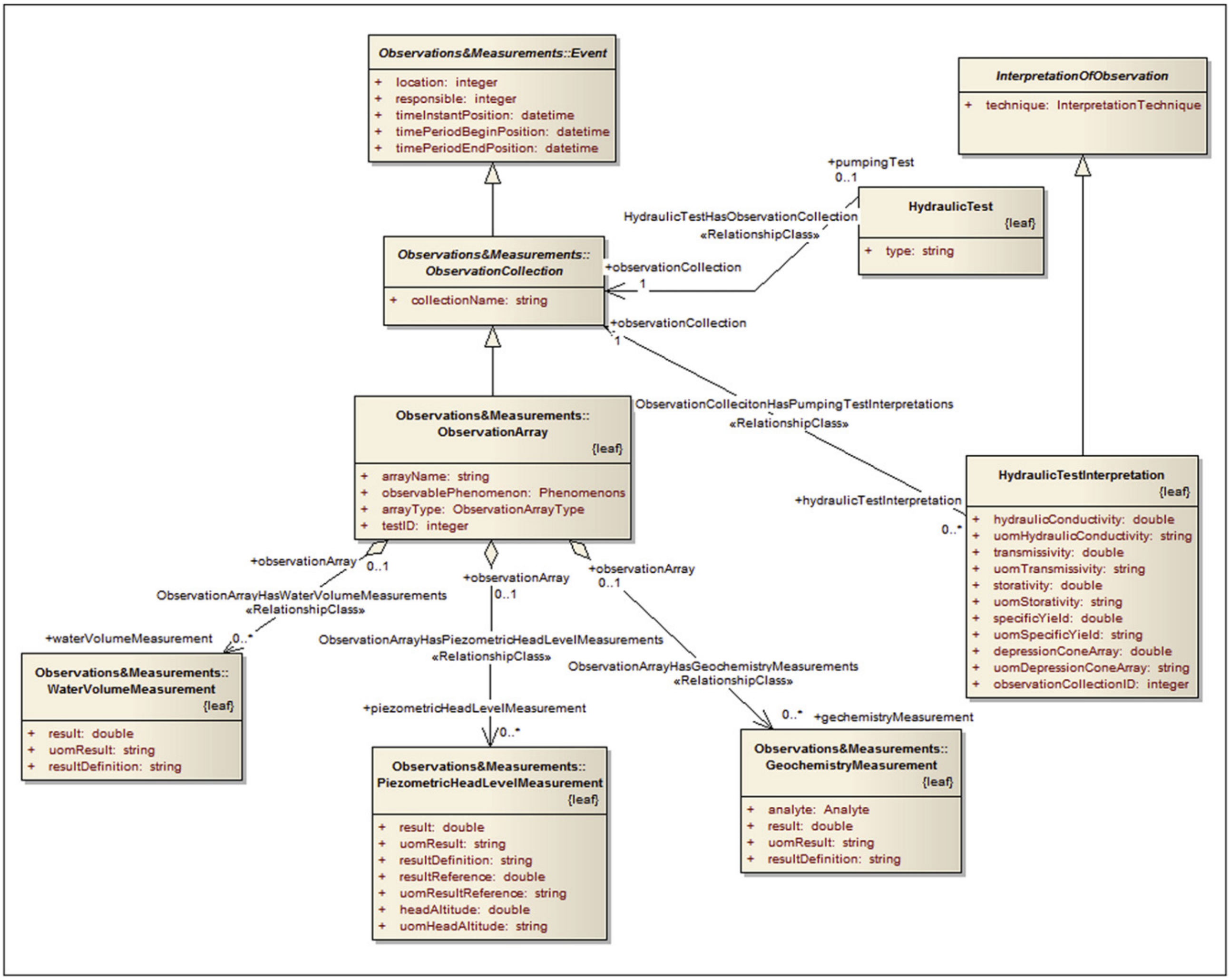


Fig. 6. The hydraulic test class together with its related classes. The hydraulic test class is defined as a specialization of the Event class and extends it with several additional attributes.

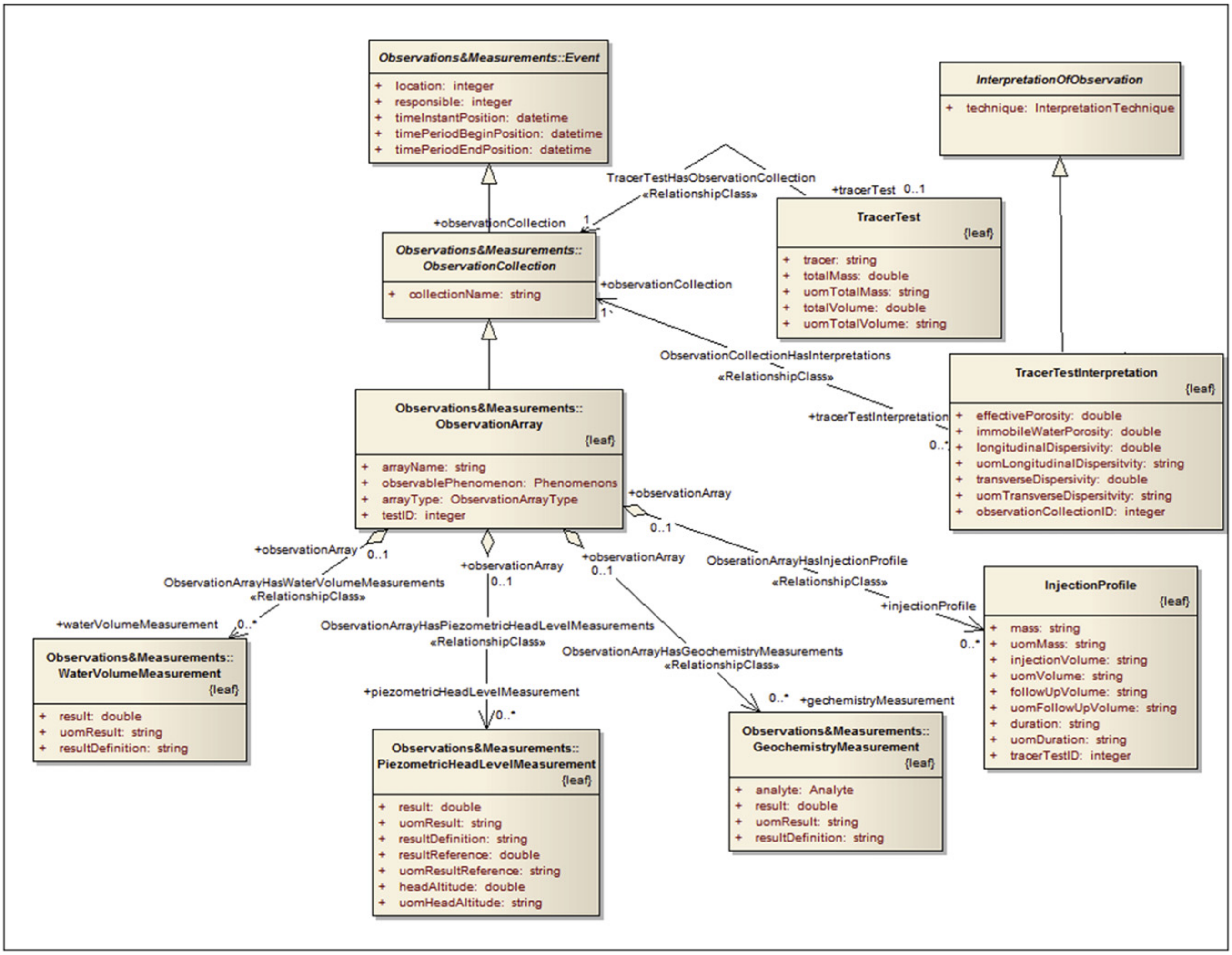


Fig. 7. Data model illustrating hydrogeologic tracer test class and other related classes. The tracer test class is defined as a specialization of the Event class and extends it with several additional attributes.

In the data model, there are four major subclasses: ObservationCollection, TracerTest, InjectionProfile, and InterpretationOf Observation (Fig. 7). The TracerTest class and the InjectionProfile class extend the Observation abstract class and add the attributes listed in Table 5.

Table 5
TracerTest and InjectionProfile attributes.

Attribute	Definition
TracerTest	
tracer	Type of the injected tracer
totalMass	Mass of the injected tracer
uomTotalMass	Unit of measure for the mass
totalVolume	Injected volume of diluted tracer
uomTotalVolume	Unit of measure of the volume
InjectionProfile	
mass	Mass of the injected tracer per time period defined in the Event Class
uomMass	Unit of measure the tracer mass
injectionVolume	Tracer injection volume per time period defined in the Event Class
uomVolume	Unit of measure for the injected volume
duration	Tracer injection duration
uomDuration	Unit of measure for the injection duration
followUpVolume	Tracer flush volume per time period defined in the Event Class
uomFollowUpVolume	Unit of measure of the follow-up volume
tracerTestID	Tracer test ID

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

An ObservationCollection instance can be associated with different tracer test interpretations, encoded in the TracerTest Interpretation class. The latter contains hydrogeological parameters interpreted using different methods, and it extends the InterpretationOfObservation abstract class with the following attributes, Table 6.

Table 6
Tracer test interpretations class with its attributes.

Attribute	Definition
TracerTestInterpretation	
effectivePorosity	Porosity available to flow interpreted from the tracer test
longitudinalDispersivity	Longitudinal dispersivity interpreted from the tracer test
transverseDispersivity	Transverse dispersivity interpreted from the tracer test
uomDispersivity	Unit of measure for dispersivity interpreted from the tracer test
observationCollecitonID	Unique identifier of the Observation collection, from which all interpretations have been made

4. Model implementations and their interoperability

In order to show the versatility and flexibility of the object-oriented hydrogeological data model, two pioneer implementations have been carried out in two different software environments: the proprietary desktop ArcGIS software and the open source, free, web-based system Web2GIS (Laplanche, 2006). The implementations consisted of a physical model development, database structure generation, populating with hydrogeological data and finally using these data to perform spatio-temporal queries. The following sub-sections present major steps, constraints and conclusions that were drawn after this implementational phase.

4.1. Implementation in ArcGIS – Geospatial database

$H^{g}{}_{2}O$ has been implemented in the ArcGIS desktop software and used as a common spatial database amongst the FP6 EC GABARDINE project partners developing a Decision Support System in the framework of Integrated Water Resources Management (Rusteberg et al., 2012). For this implementation purpose, the $H^{g}{}_{2}O$ adapted UML model was based on the ESRI template and its conversion to the database schema was accomplished automatically using CASE tools (Wojda et al., 2006). However, the ArcGIS implementation platform has imposed several constraints, amongst which the specific framework for the model development and restricted name domains. Furthermore, abstract classes can generate instances and all the associations between classes could only be established at the lowest inheritance level. 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; ISO, 19103; ISO, 19109), where every feature has a geometric property set to a point location, a line string in space or a bounded area (Sen and Duffy, 2005).

To verify the robustness of the first implementation, the geospatial database was successfully populated with real hydrogeological data coming from the GABARDINE project test sites located in Portugal, Spain and Israel. The data consisted in spatial features such as wells and boreholes to test their associations, groundwater bodies and performed geochemistry measurements to investigate on groundwater quality, as well as piezometric head measurements to explore mid and long term trends depending on groundwater exploitation schemes. More exhaustive description and details can be found in Wojda (2009) and in Rusteberg et al. (2012).

Since the hydrogeological field experiments module is one of the model novelties, it was additionally tested with an independent set of data. The ArcGIS implemented database was populated with tracer test data, coming from a real case-study conducted in the Bovenistier experimental site, located in the Hesbaye aquifer, in the eastern part of Belgium (Brouyère, 2001; Brouyère et al., 2004), where among other experiments, tracers tests were performed under radially converging flow conditions, between a piezometer Pz CS and a pumping well PC (Fig. 8).

Further Figs. 9–11 focus on the eosin yellowish tracer test only. Eosin yellowish was injected in the Pz CS, while the PC was pumped at 1.2 m^3/h pumping rate to recover the tracer. The experimental conditions and the measurements taken during the experiment were encoded in the database. Based on that, an XML file to exchange data was automatically generated. Its structure was based on the Geodatabase schema (Fig. 9), where each file is divided, the first part describing the data structure based strictly on the

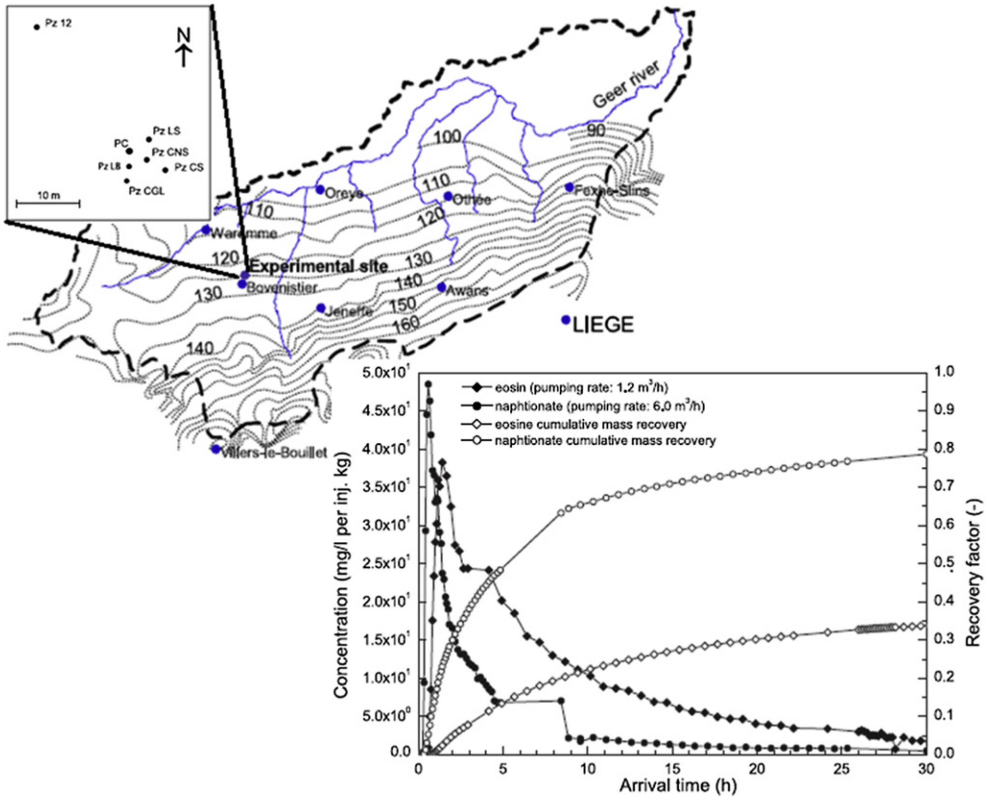
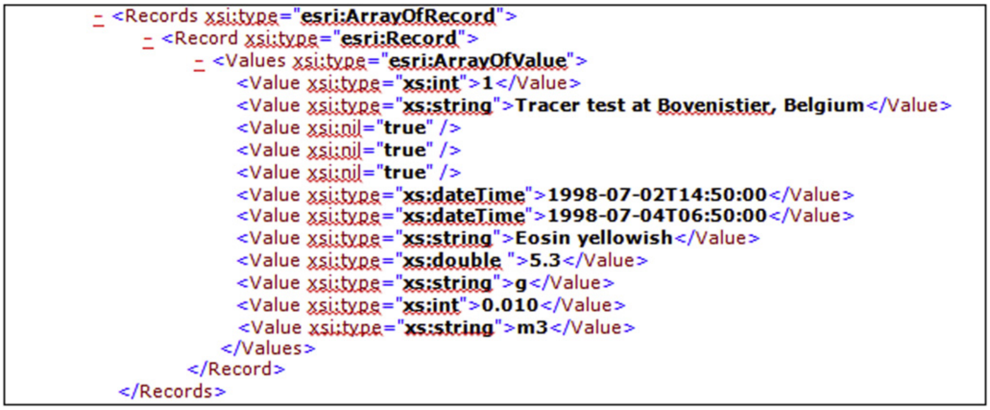


Fig. 8. Location of the Bovenistier experimental site where, among other experiments, tracers tests were conducted. Piezometric map of the Hesbaye acquifer is depicted. At the bottom-right corner: the measured breakthrough curves and mass recovery are shown at the pumping well PC for different tracers.



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  - <Records xsi:type="esri:ArrayOfRecord">
    - <Record xsi:type="esri:Record">
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          <Value xsi:type="xs:int">1</Value>
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        </Values>
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```

Fig. 9. A tracer test (unique identifier = 1) at Bovenistier in Belgium is described by the injected tracer type, starting and ending times of hydrogeological field experiment and the diluted tracer volume. The unique identifier of this test is then reported in an appropriate Observation Collection, composed of observation array specializations and tracer test interpretations.

```
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            <Value xsi:type="xs:string">5.3</Value>
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            <Value xsi:type="xs:string">0.010</Value>
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            <Value xsi:type="xs:string">h</Value>
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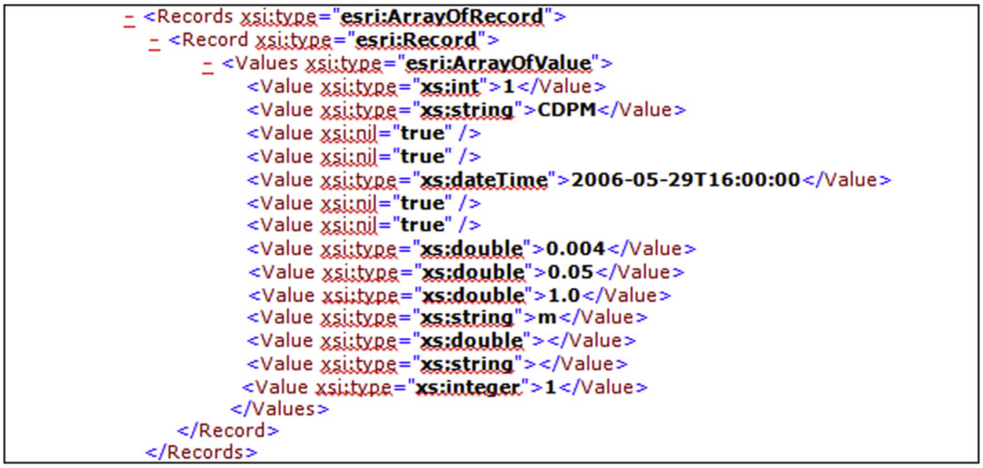
    </Records>
  </Data>
```

Fig. 10. In the injection point (Pz CS, which unique identifier = 1) eosin yellowish was injected. The starting time and the end of observations time are given for the tracer test. The injection was performed in one step, followed by a water flush to push the tracer towards the observation well, where pumping at 1.2 m^3/h was performed (PC). Every step is characterized, according to the defined schema, by: its duration (time start/end), injected mass and volume, follow-up water-volume and its duration.



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- <Records xsi:type="esri:ArrayOfRecord">
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       <Value xsi:type="xs:integer">1</Value>
      </Values>
    </Record>
  </Records>
```

Fig. 11. Tracer test interpretation results, using "classical dual porosity model" (CDPM) approach (Brouyère et al., 2008). The interpretation results describe an interpretation time, a code for interpretation technique, interpreted values of effective or immobile water porosity, longitudinal and transverse dispersivity, and internal observation array code.

implemented data model, and the second using this schema to store hydrogeological data.

The next example presents the tracer injection profile and a water flush (Fig. 10).

The fourth example illustrates the interpretation of the tracer test results (Fig. 11).

This successful implementation showed that the specific hydrogeological field experiments data were clearly encoded in a transparent way according to the established data model. This enabled the geospatial data comprehensive and interoperable exchange between interested parties.

4.2. Implementation in Web2GIS

To evaluate the feasibility of the model implementation and use in an open source web-based environment the Web2GIS platform: an Open Source free system developed in the Geomatics Unit of the University of Liège (Laplanche, 2006) has been considered. 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. This modular solution promotes the use and a practical implementation 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, and finally, data users. To follow the ISO/TC211 standard on feature cataloguing (ISO 19110, 2005), a specialised feature catalogue was created in the Web2GIS environment using the Cataloguing Module (1) comprising definitions of feature types, attributes and associations.

A conceptual model was created in the Conceptual Modelling Module (2), using the UML notation for standard application design, following the ISO 19109 (2005) describing the rules for applications schema. The database application was hereby fully documented before its final implementation (Fig. 12).

In an additional phase of conceptual model development, mandatory or forbidden topological relationships have been established between spatial features (Fig. 13). This functionality is important to correctly manage the topological relationships between spatial features, for instance, a groundwater well should be located at a borehole.

Once this phase was accomplished, an instance of a database was automatically generated from the UML model, using in-built Implementation Module functions (3). The database was populated with data. To explore spatial data, the user may use the Cartographic Module (4) for spatial data visualisation and simple querying. This module is based on the Open Source MapServer software and its PHP library PhpMapScript (Laplanche, 2006). The user can display and query PostGIS non-spatial data or spatial tables, and use the following OGC standard services: Web Feature Services (WFSs) and Web Map Services (WMS). Finally, appropriate user rights were setting-up in the Privilege Administration Module (5).

The implementation of the hydrogeological model in the Web2GIS environment shows that it is feasible to implement the hydrogeological data model in a web-based environment built upon and promoting ISO/TC211 and OGC standards. Furthermore, the generated spatial database fed with hydrogeological field data was successfully explored through standardised WMS and WFS, by viewing a map and by querying features in a GIS client. Spatial features such as boreholes, wells and groundwater bodies are correctly rendered in the map and it is possible to query them and appropriate associations such as piezometric head level measurements showed up.

4.3. Achieved interoperability

Interoperability between different implementations has also been investigated, driven by the following case-study. Nitrate concentration measurements performed in different observation wells located in a groundwater body have to be analysed for reporting. Data used in this interoperability study are available from two different sources: a geodatabase implemented in the ArcGIS system and a PostGIS database equivalent to the one managed by the Web2GIS application, both based strictly on the previously described $H^g{}_2O$ model.

First, visualisation of the groundwater bodies and the related observation wells is performed. Data are made available through a standardized Web Feature Service (WFS) serving geospatial data directly from the PostGIS database. In this case, the following $H^g{}_2O$ model feature classes are involved: GroundwaterBody and Well, together with their parent classes.

Second, a query is launched to select all observation wells where nitrate concentration measurements are available. A direct relationship is established between the Well feature class (by the OBJECTID primary identifier) served by WFS, the GeochemistrySample class (by the sampledOn foreign key) and the GeochemistryMeasurement (by a featureOfInterest foreign key) served by the ArcGIS geodatabase.

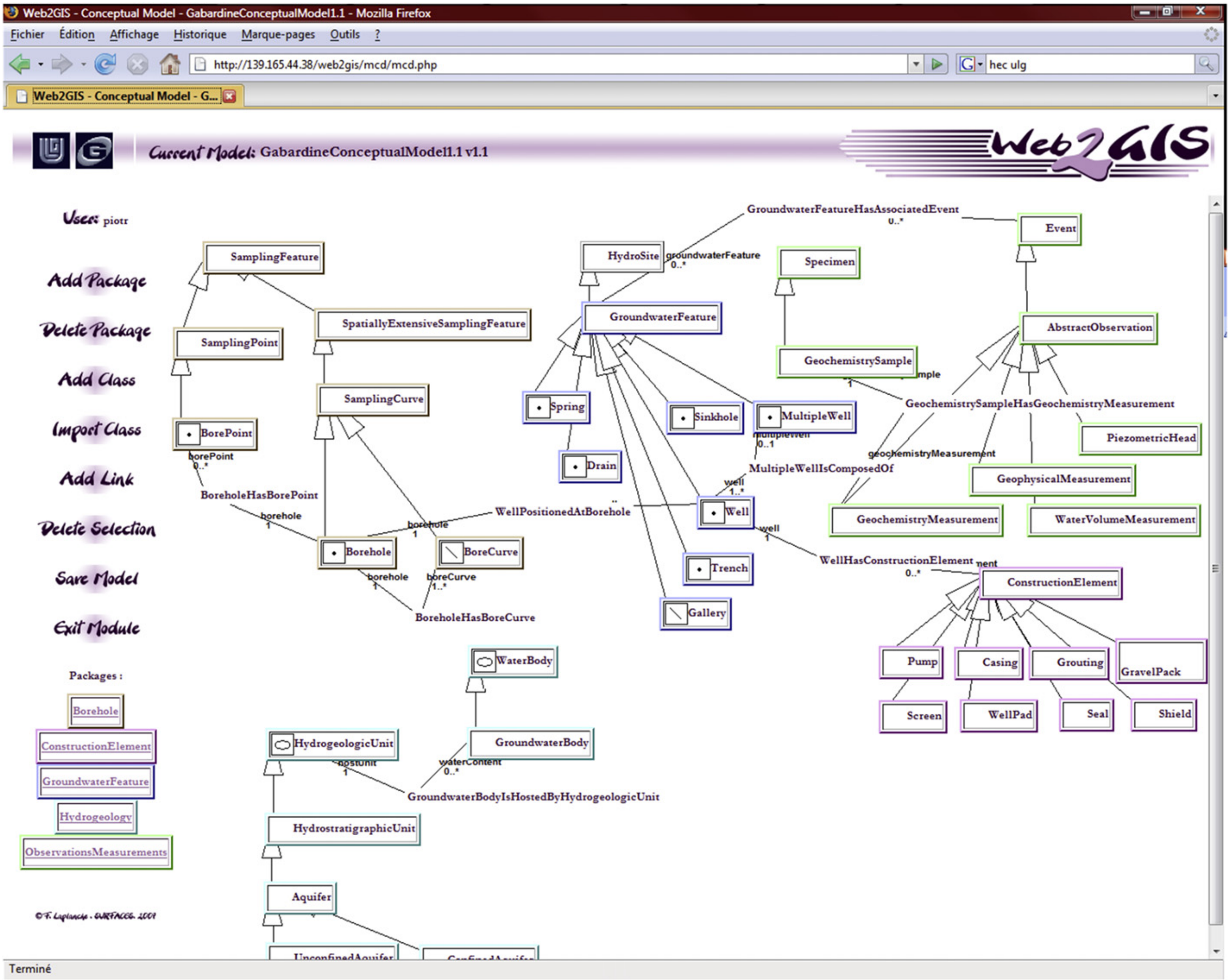


Fig. 12. Conceptual Modelling Module: Hydrogeological data model presented in the Web2GIS implementation. Packages are identified by their colour codes, each package contains imported feature types and their associations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

This requires the use of other classes from the $H^{g}_{2}O$ model, namely: Event, Observation, GeochemistryMeasurement together with Specimen and GeochemistrySample.

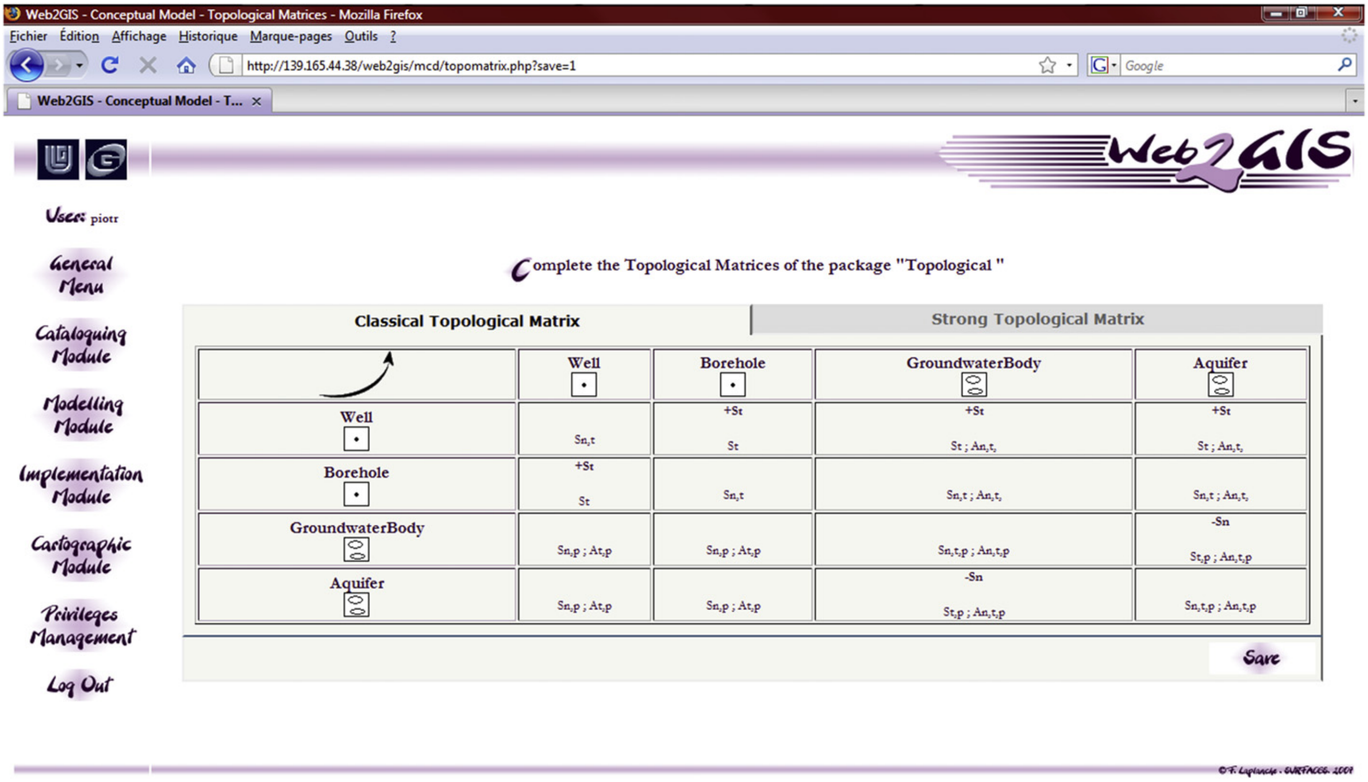
At the end, the geospatial data are plotted in one map and appropriate symbols are used to differentiate nitrate concentration classes measured in the different observation wells (Fig. 14).

The interoperability case-study is successful. Both data sources are easily accessible and the related geospatial information is understandable. Setting-up relationships between features classes accessible through WFS and feature classes stored in the ArcGIS geospatial database is possible and straightforward since the data structure and the identifiers policy are identical for both implementation platforms. As a consequence, no additional schema mapping is necessary to reach interoperability.

5. Discussion and conclusions

The main objective of this research was to develop an innovative hydrogeological data model, used at the local-regional level and internationally, thereby contributing to the standardization process in the domain. To reach this objective, particularities of hydrogeological information have been identified and characterized in a wider context of geospatial information modelling and exchange. The analysis of available data models shows that the hydrogeological community needs more complete and universal data models. However, these currently heterogeneous models need to converge and their structures must be standardised to enable seamless data exchange mechanisms. Following these requirements, the $H^{g}_{2}O$ hydrogeological data model was proposed. It offers an innovative object-oriented approach, based on standardized solutions promoted through the geomatics community and domain standards from ISO and OGC. A particular attention was put on a specific hydrogeological field experiments module, focussing on hydraulic and tracer tests, following the OGC Observations and Measurements approach.

$H^{g}_{2}O$ is designed using an object-oriented approach in UML notation, currently the most appropriate development methodology in the context of geospatial information exchange together with ISO/TC211 standards and OGC norms. The pioneer model implementations and tests with hydrogeological data were successfully performed in desktop ArcGIS and web-based Web2GIS environments. The implementation platforms ability to support internationally recognised standards has also been investigated. The following conclusions have been drawn. The ArcGIS



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

Fig. 13. 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 borehole feature, or a GroundwaterBody feature has to be hosted by an aquifer feature (non-superimposition is forbidden, while partial or total superimpositions are allowed).

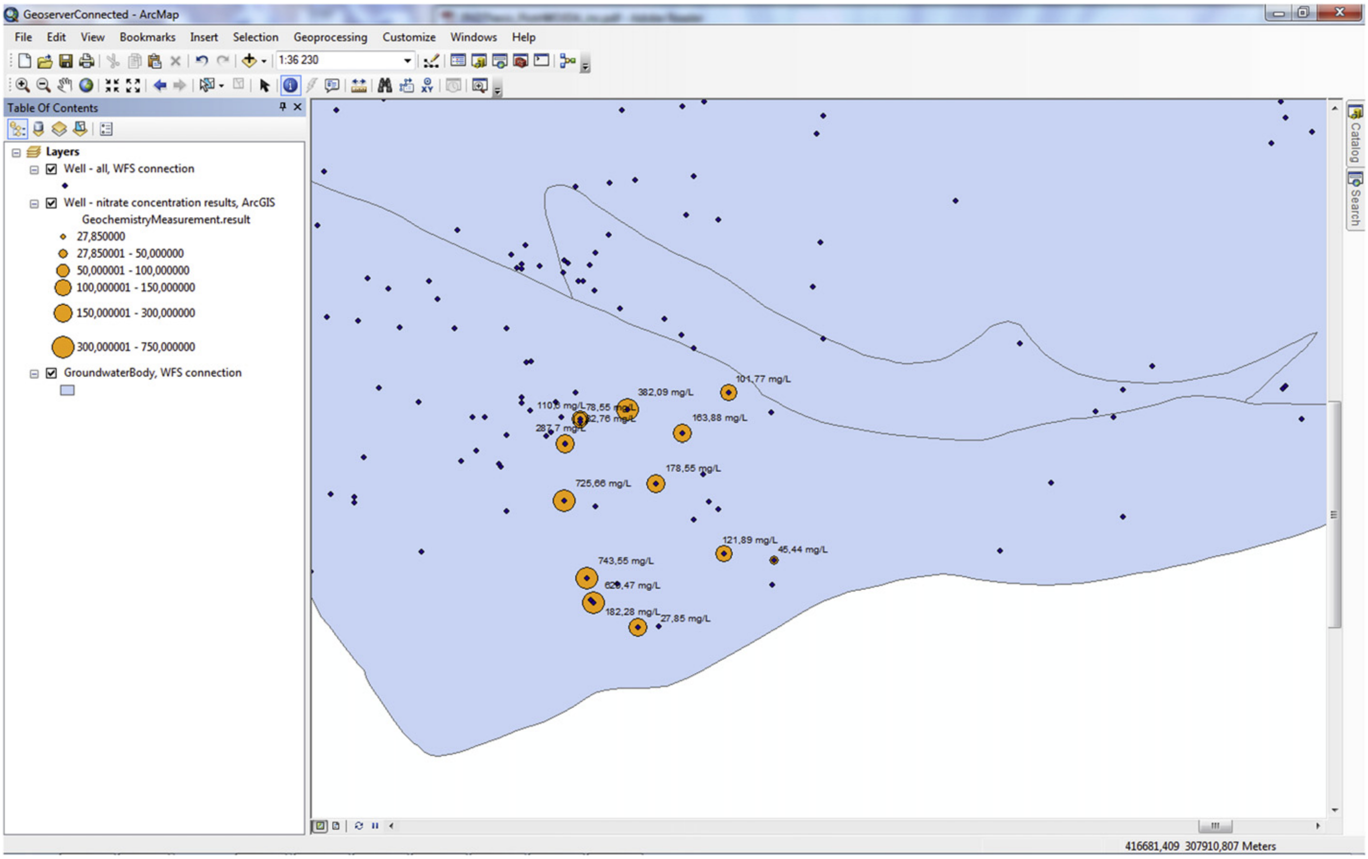


Fig. 14. Nitrate concentration measurements [mg/L] in the groundwater body. An ArcGIS client connected to a PostGIS database through a WFS and to a geospatial database internally. Both database models are strictly based on H²O model, which enhances querying and visualisation of spatial data.

environment provides a very poor support for some of the object-oriented principles such as inheritance. It does not support the ISO/TC211 or OGC standards in the conceptual and implementational phases. Nevertheless, it does offer very good interfaces for geospatial data management and a possibility to exchange geospatial data through XML. On the contrary, the Web2GIS environment gives appropriate tools for the creation of ISO compliant Feature Catalogue and Conceptual Model. It fully supports the object-oriented principles and it proposes soundness and direct geospatial database implementation. Last but not least, the interoperability case-study shows that using the same data model implemented on different platforms, it is easy to visualise, query and analyse geospatial data available through WFS and WMS together with geospatial data available from a proprietary system implementation.

The $\mathrm{H^{g}_{2}O}$ model complements the existing models offering a milestone in the domain of hydrogeological field experiments, proposing an O&M structured concept of data storing and exchange. This simplified approach makes it appropriate for direct use by the hydrogeological community and makes it easy to implement in different GIS environments used across research institutes and environmental institutions.

In the medium term perspective the $\mathrm{H^{g}_{2}O}$ model can be fully derived from GML (Geography Markup Language) as its application schema, extending the existing GML constructs by additional and specific feature classes proposed in this paper. This step would enable the possibility to store and exchange spatio-temporal hydrogeological data at international level in an ISO-standardized way. However, this work may be accomplished better by a wider geomatics and hydrogeological community in close cooperation with the OGC and within the INSPIRE framework.

Acknowledgements

This work was supported by the European Union FP6 STREP Project nb. 518118-1 GABARDINE under the thematic priority sustainable development, global change and ecosystems. We are grateful to F. Laplanche from the professor J-P. Donnay Geomatics Unit of the University of Liège for an extensive support during the Web2GIS implementation. We are also indebted to Eric Boisvert and Boyan Brodaric for their valuable discussions and insights, Simon Kay for an English review, and three anonymous reviewers for their helpful comments.

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