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ORIGINAL ARTICLE

Jan Cools
Yves Meyus
Solomon Tuccu Woldeamlak
Okke Batelaan
Florimond De Smedt

Large-scale GIS-based hydrogeological modeling of Flanders: a tool for groundwater management

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J. Cools (✉) · Y. Meyus
S. T. Woldeamlak · O. Batelaan
F. De Smedt
Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
E-mail: jan.cools@soresma.be
Tel.: +32-9-2616338
Fax: +32-9-2616301

J. Cools
Soresma, Poortakkerstraat 41, 9051 Ghent, Belgium

Abstract For the implementation of the European Union Water Framework Directive (WFD), technological and scientific support are required. This paper presents a methodology to support a first step of the implementation of WFD, which is the delineation of groundwater bodies. The methodology consists of (1) the development of a complete and generally-accepted hydrogeological classification system for Flanders, named the HCOV code, (2) the development of a geographic information systems (GIS)-managed borehole database, and (3) the development of aquifer and aquitard models by means of a solid modeling approach. For each unit of the hydrogeological classification code for Flanders unit, GIS maps are generated for the three basic characteristics of hydrogeological layers: extent, base level and thickness, such that combined, the volume and extent of a hydrogeological layer is unambiguously defined. This GIS-based hydrogeological database has become a useful tool for groundwater management purposes and to provide the input for groundwater modeling.

Keywords Hydrogeological modelling · GIS borehole database · Aquifer models · Aquitard models · Belgium

Abbreviations WFD: Water framework directive · CIS: Common implementation strategy of WFD · GIS: Geographic information systems · HCOV: Hydrogeological classification code for Flanders · IRBD: International river basin district · AMINAL: Environmental authority for Flanders · EU: European union · DEM: Digital elevation model · FGM: Flemish groundwater model

Introduction

The European Union Water Framework Directive (WFD) (2000/60/EC), further abbreviated as WFD, enforces an integrated approach to achieve at least a 'good status' for all European water bodies by 2015. The implementation of the WFD requires mixing of legal requirements with issues of technical feasibility, scientific knowledge, and socio-economic aspects which require intensive multi-stakeholder consultations (Quevauviller et al. 2005). A Common Implementation Strategy (CIS) consisting of the priorities for 2005–2006 is endorsed by the water directors in 2004 (European Communities 2004). In this paper a methodology is presented to support a first step of the implementation of WFD, which is the delineation of groundwater bodies, as the basic units for management and monitoring. Unlike for surface water bodies, the WFD guidance document 'on the identification of water bodies' (European Communities 2003) gives only a few recommendations on how to delineate groundwater bodies. The only criterion which must be followed is that the chemical and quantitative status of groundwater should be described unambiguously. Legislative details on groundwater protection are to be included in a separate groundwater 'daughter' directive. The proposed directive, which is currently under negotiation, will enforce Member States to monitor and evaluate groundwater quality on the basis of common criteria and to identify and reverse trends in groundwater pollution. Another priority in the CIS is the development of a common geographic information systems (GIS) format as a means to improve the exchange of spatial data in the context of reporting into the "Water Information System for Europe" (WISE). This system does not aim to replace existing GIS used by member states, but rather to harmonize national data into a format that could serve as a reference dataset thus allowing EU-wide mapping.

Meanwhile, Scaldit (2004) reported for the International River Basin District (IRBD) of the Scheldt river that member states use different methods to delineate groundwater bodies. The diversity is mainly characterized by a difference in the level of aggregation of hydrogeological units, and the choice of delineation for less permeable and less productive aquifers. In principle, all non-water bearing layers should be removed from the list of groundwater bodies. In practice, Scaldit (2004) reports that most less permeable layers as well as heterogeneous and fragmented aquifers are associated with neighboring or underlying aquifers such that these are ignored.

For Flanders, the northern region of Belgium and located in the IRBD of the Meuse and the Scheldt river, groundwater bodies are identified along hydrogeological boundaries and will therefore not coincide with surface water bodies. Thereby, a methodology is developed consisting of (1) the development of a complete and generally-accepted hydrogeological classification system for Flanders, named the hydrogeological classification code for Flanders (HCOV) code, (2) the development of a GIS-managed borehole database and (3) the development of aquifer and aquitard models by means of a solid modeling approach. Finally, for each HCOV unit, GIS maps are generated for the three basic characteristics of the hydrogeological units: extent, base level and thickness, such that combined, the volume and extent of a hydrogeological unit is unambiguously defined.

The Flemish water authority, Environmental Authority for Flanders (AMINAL), has subdivided the aquifers into several smaller groundwater bodies based on hydrogeological, hydrographical and pressure related criteria. In total 42 groundwater bodies are identified, 32 within the Scheldt IRBD and 10 within the Meuse IRBD. To optimize the reporting obligations to the EU, the groundwater bodies allocated to the Scheldt IRBD are clustered in six independent groundwater systems. For management considerations, aquifers are arbitrarily cut-off at the boundary of the IRBD to identify two groundwater bodies. Although the identification and delineation of the groundwater bodies is based on the work presented in this paper, these final steps will not be discussed. On this topic, more information can be found in the reports of Scaldit (2004) and the International Meuse Commission (2005).

Study area

The study area, shown in Fig. 1, covers three countries and three regions: France, the Netherlands, and Belgium with its three regions: Brussels, Wallonia and Flanders. The total size of the study area is 21.066 km^2 and completely encloses Flanders. The transboundary approach in this project has facilitated the characterization of the IRBD of the Scheldt (Scaldit 2004) and Meuse river (International Meuse Commission 2005).

A cross-section through the study area, shown in Fig. 2, shows the typical complex stratigraphy with alternating aquifers and aquitards, pinchouts, fragmented layers, and outcropping layers. Continuous units show a north-east directed trend.

The hydrogeological code for Flanders

Traditionally, chronostratigraphical classification is used to delineate geological formations, but for hydrogeological purposes, research institutes and drinking water companies in Belgium developed their own classification system. However, these codes are incomplete as they were developed only for specific objectives. Due to the lack of a complete and widely accepted hydrogeological classification for Flanders, a new hydrogeological code, named the HCOV code, is set up in the framework of the development of the Flemish groundwater model (Meyus et al. 2001).

Each HCOV unit represents a hydrogeological layer and is characterized by a four digit number and its associated description. HCOV consists of three hierarchical levels to allow for different levels of detail: main units (xx00), subunits (00x0) and basic units (000x). An overview of the 14 main units is given in Table 1. Table 2 shows an extract of the three hierarchical levels for HCOV code '0600', the Ledo–Paniselian–Brusselian aquifer system.

In the HCOV code, different chronostratigraphical strata, with quasi-similar hydrogeological properties are joined into one hydrogeological unit. For instance, sand layers deposited in consecutive time periods but with quasi-similar conductivities and water storage capacities are classified as one hydrogeological unit. On the other hand, alternating clayey and sandy depositions of the

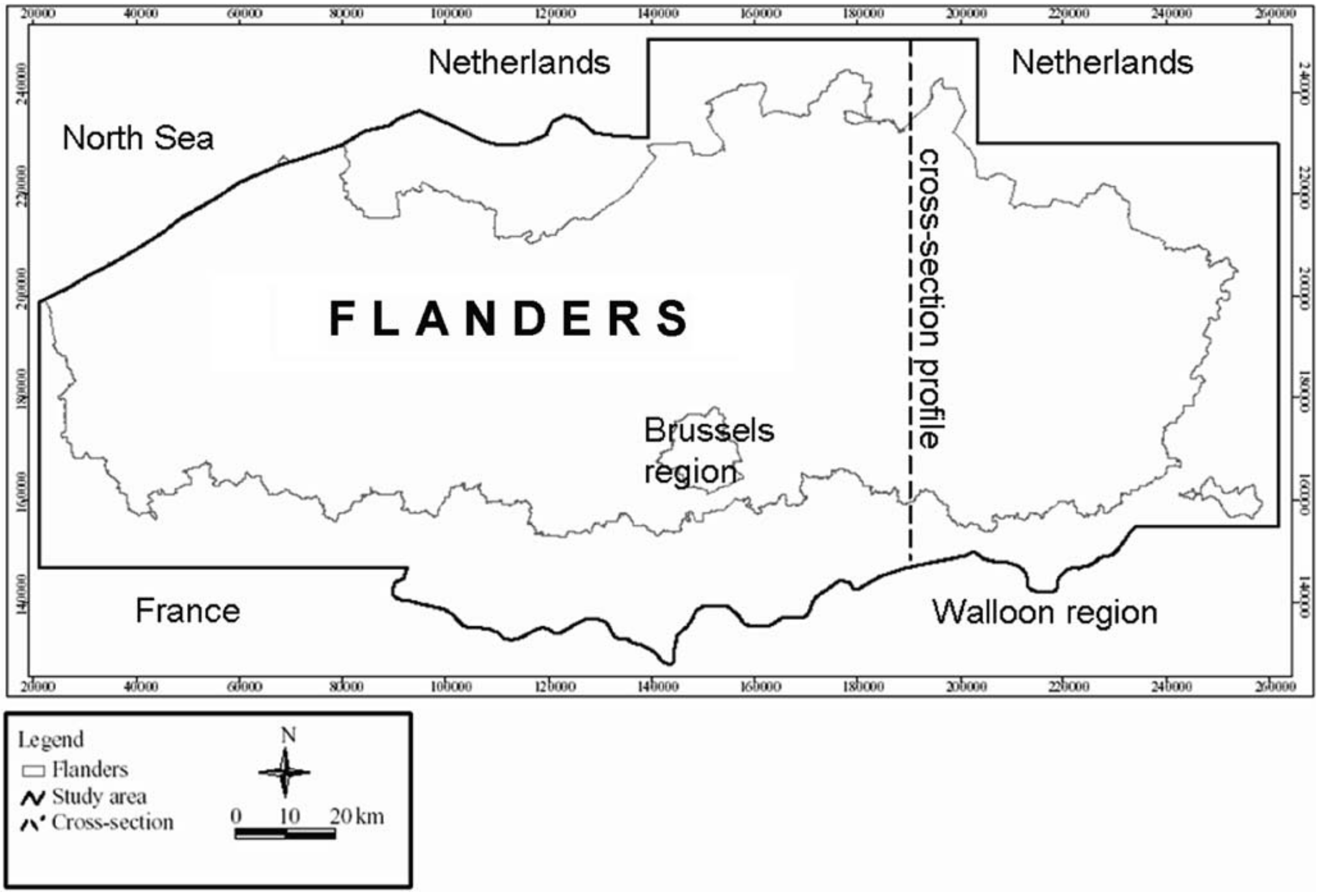

Fig. 1 The study area encloses Flanders; the *line* indicates the location of the cross-section

same era are subdivided into several hydrogeological units. Although, the HCOV code is not stratigraphically based, the units are ordered chronologically. HCOV code '0100' e.g. is assigned to quaternary depositions, whereas Paleozoic rock is coded '1300'. Except for code '0100' (quaternary aquifer systems) which groups several local, more or less unconnected depositions of quaternary age, all other units are spatially continuous.

The HCOV code is intended to be used for the delineation and management of groundwater bodies by the Flemish water authority (Coördinatiecommissie Integraal waterbeleid 2004). As the HCOV code is based on natural boundaries of aquifers and aquitards, it is most applicable to identify groundwater bodies. To include stress-related criteria, the HCOV code has been extended by the water authority firstly to cover the subdivision of aquifers in a phreatic, confined, brackish, freshwater, and vulnerable areas, and secondly to incorporate aquifers arbitrarily cut-off at the boundary of the IRBD (Coördinatiecommissie Integraal waterbeleid 2004).

Harmonizing geological data

A hydrogeological database for Flanders can only be of practical use for groundwater management if trans-boundary data are considered. Besides an inventory of data in Flanders, available data is collected as well in the five surrounding regions and countries. Data is collected from different institutions, such as water companies, environmental agencies, consulting companies, etc. However, each institute or company uses its own system

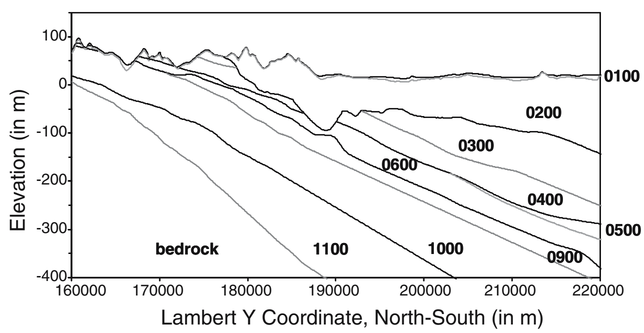

Fig. 2 Typical cross-section through the study area, HCOV codes are used as a legend

Table 1 Main units of the HCOV hydrogeological code

Geological era	HCOV main units	Description
	0000	Undetermined
Quaternary	0100	Quaternary aquifer systems
Tertiary	0200	Campine aquifer system
	0300	Boom aquitard
	0400	Oligocene aquifer system
	0500	Bartoon aquitard system
	0600	Ledo–Paniselian–Brusselian aquifer system
	0700	Paniselian aquifer system
	0800	Yperian aquifer
	0900	Yperian aquitard system
	1000	Paleocene aquifer system
Mesozoic	1100	Cretaceous
	1200	Jurassic–Trias–Perm
Paleozoic	1300	Paleozoic

of classification, methods of profile description and geological interpretation. Consequently, these various sources have strong dissimilarities in data format (analogue or digital), detail and accuracy of the geological description, time of sampling (some in the late nineteenth century) and accuracy in digitalisation and conversion of old (late 1980s) digital databases. The translation of the existing borehole logs into the HCOV code is therefore not straightforward. In total, 9,000 borehole logs were collected, harmonized and entered in the DOV (*Databank Ondergrond Vlaanderen*) database. To assess the reliability of the data, metadata is added to the database whenever possible. Metadata can furthermore be used for browsing, archiving and querying of the database and is useful to update the database when new insights in hydrogeology, borehole logs or classification systems become available. DOV is made available on internet by the Flemish administration (http://www.dov.vlaanderen.be) and is described by Cools et al. (2002). In a next step, shown in Fig. 4, the borehole database is linked to GIS and for each HCOV unit converted to a set of scatter points by means of the 'horizons' method (Fig. 3, Lemon and Jones 2003). Although Lemon and Jones (2003) refer to a 'horizon' as the top of a geologic unit in a depositional sequence (bottom–up), in this paper a 'horizon' refers to the base of a hydrogeological unit in a top–down sequence. In the groundwater modelling system GMS (EMS-I, 2005), the horizon method is currently implemented. A similar methodology is used in the Netherlands for the development of the Regional Geohydrological Information System REGIS (NITG-TNO 2000).

The existing geological maps show strong dissimilarities in scale, data format (analogue or digital), level of detail, methodology of interpolation and availability of additional folios. The new geological maps of Flanders, the Netherlands and France are on scale 1/50,000, whereas the maps of Wallonia are on 1/25,000, and the old Belgian maps on scale 1/40,000. Often, additional folios with isohyps and isopachs contour lines are available. Isohyps maps are contour lines of equal depth (in m above sea level), whereas isopachs are contour lines of equal thickness (in metre). All available maps and folios were digitized, re-scaled in GIS and converted into the HCOV-code to allow harmonization of the data. In a next phase, shown in Fig. 4, the scatter points are combined with the digitized contour maps to interpolate a surface for each HCOV unit which form the basis for the aquifer and aquitard models.

Developing aquifer and aquitard models

To develop a GIS model of the main aquifers and aquitards, a solid model of the whole stratigraphy is required. A solid is a 3-D layer in GIS and corresponds to a hydrogeological unit. With a properly constructed set of solids, the boundaries all match precisely without voids or overlaps (Lemon and Jones 2003). Hereby, the top of the underlying unit is completely equal to the base of the unit itself. Thus, the volume and extent of a solid is unambiguously defined. Although 3-D techniques for aquifer modeling exist, e.g. in the GMS software (EMS-I, 2005), Artimo et al. (2003) and Herzog et al. (2003), a 3-D visualization is not required by WFD. Hence, 2-D GIS maps are generated for the three basic characteristics of the solids: extent, base level and thickness. The methodology used to develop aquifer and aquitard models is visualized in Fig. 5.

Extent maps give the outer boundary or extent of the HCOV unit (in polygon vector format), either at the surface or in the underground. An extent map equals

Table 2 Extract of the three hierarchical levels of the HCOV code (example code '0600')

Main units		Subunits		Basic units	
0600	Ledo–Paniselian–Bruselian aquifer system	0610	Wemmel-Lede aquifer	0611	Sand of Wemmel
				0612	Sand of Lede
		0620	Sand of Brussels	–	Sand of Brussels
		0630	Sediments of upper-Paniselian	0631	Sands of Aalter and Oedelem
				0632	Sandy clay of Beernem
		0640	Sandy sediments of lower-Paniselian	–	Sand of Vlierzele and Aalterbrugge

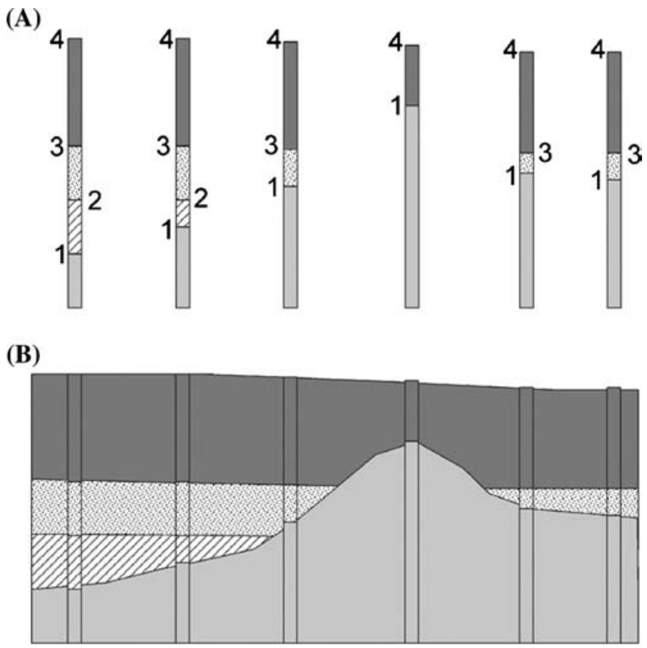

Fig. 3 Horizons concept: **a** horizons assigned to contacts on boreholes, and **b** resulting solids (Lemon and Jones 2003)

the isopach contour line of 0 m. Base level maps are comparable to digital elevation models (DEM). Instead of topography, the base of aquifers or aquitards is modelled. Thickness maps represent the spatially distributed thickness of a hydrogeological unit. For the Ledo–Paniselian–Brusselian aquifer system (HCOV

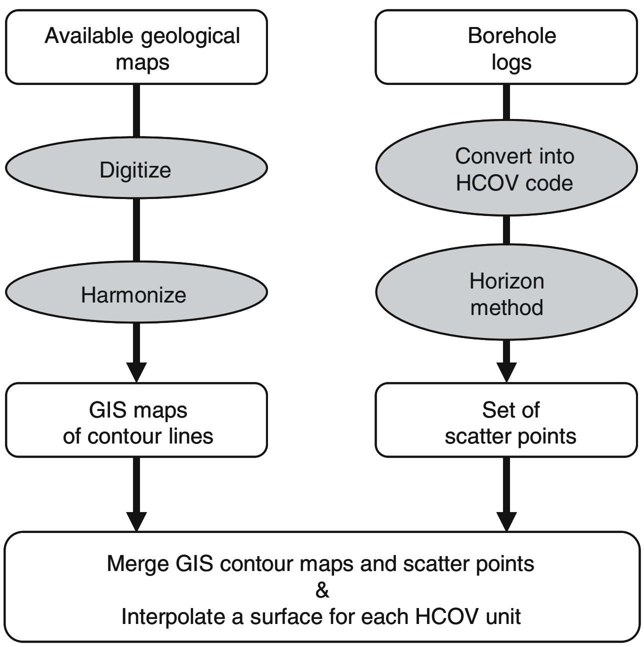

Fig. 4 Flowchart for harmonization of geological data

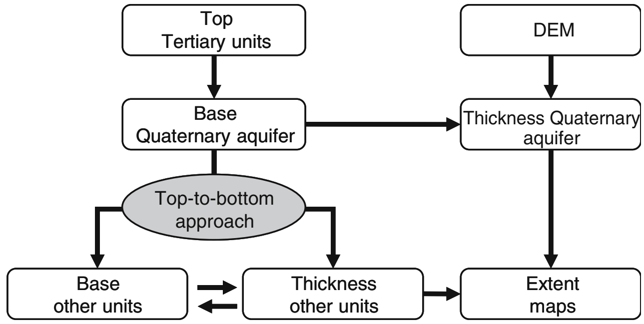

Fig. 5 Flowchart for developing aquifer and aquitard models

code '0600'), the extent, base level and thickness maps are presented respectively in Figs. 6, 7, and 8.

Complexities occur in the development of aquifer and aquitard models where data is lacking or contradictory data exists. In the latter case, e.g. when the total thickness of the main unit appears to be smaller than the sum of thicknesses of its subunits, decisions have to be taken whit respect to which data to use, to discard, to adjust, to replace, or to smooth. In case of lacking data, questions arise on which interpolation and interpretation techniques to use. To support these decisions, following guidelines have been established:

Firstly, the newest version of the official geological maps, its isohyps and isopachs maps are considered most reliable.

Secondly, data of one source, rather than an interpolation of two different maps is preferred since each map is the result of expert-knowledge and/or measurements resulting in a certain subjectivity.

Thirdly, the hierarchy in the HCOV code has to be preserved: the total thickness of all subunits should be equal to the respective thickness of the main units. Likewise, the extent of a main unit is the union of extents of its subunits.

Fourthly, a fixed relation exists between the thickness and base of a unit. The thickness added to the base of a unit should exactly equal the top of that unit.

Modeling the fixed relation between of thickness and base

In a solid modelling approach and in order to ensure the hierarchy of the HCOV code, thickness cannot be generated regardless of a unit's base and vice versa. Unlike Lemon and Jones (2003) and the borehole-to-solid tool in GMS, a top to bottom order is used instead of a bottom-up approach. In this way, the very detailed information available in the DEM and hydrogeological data for the uppermost and most important units can be preserved. Since for the deeper units, the least information is available, errors induced for each unit by the solid

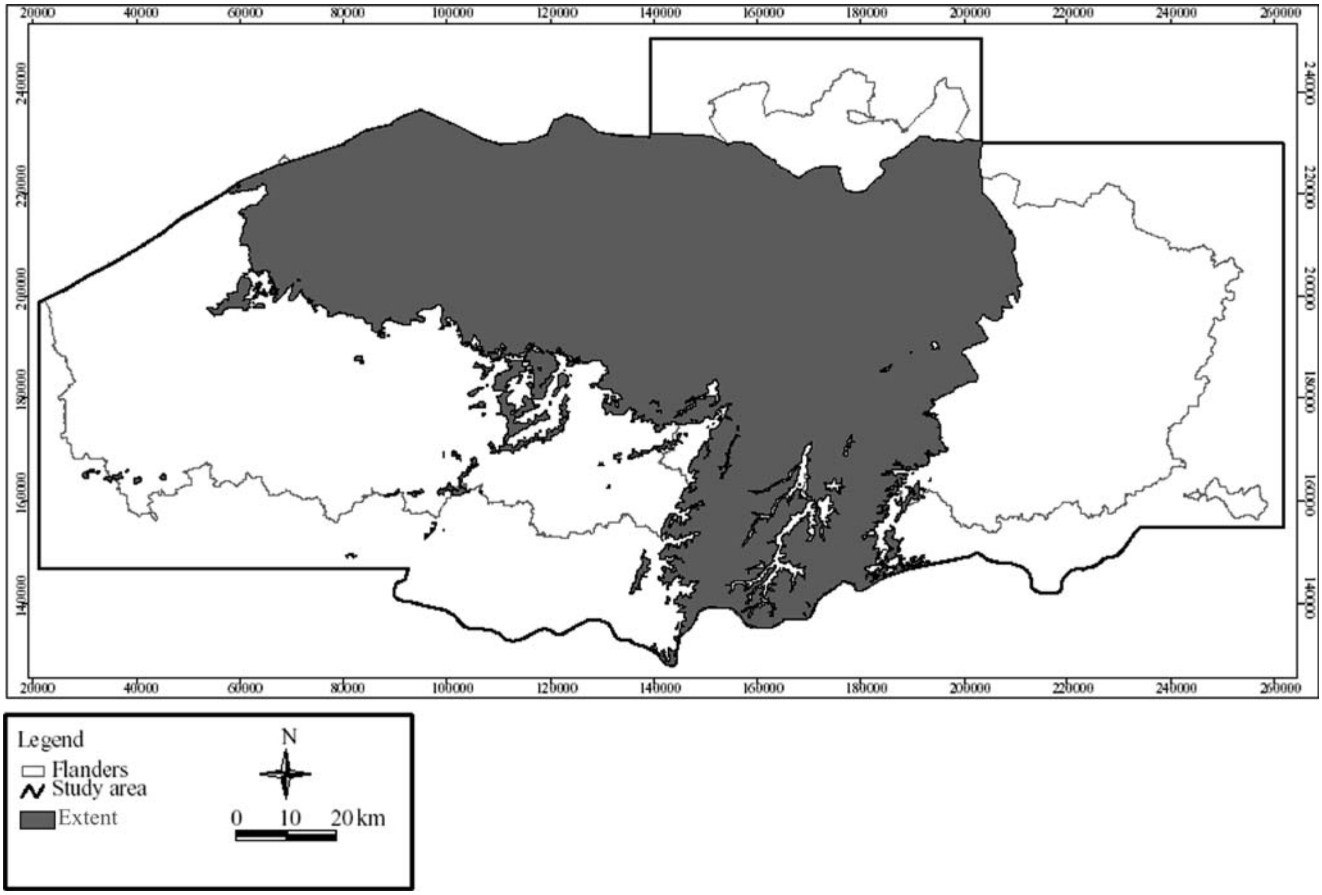

Fig. 6 Occurence map of the Ledo–Paniselian–Brusselian aquifer system (HCOV code '0600')

modelling approach can best be propagated to the most uncertain units, which are the deeper ones. In a top-to-bottom approach thickness can be calculated sequentially as the difference of the top and base of a hydrogeological units. However, sometimes it is less clear which units to substract, as the interface can be made up of more than one, discontinuous units. Hence, as a solution 'scoop maps' are generated. Herewith, values are assigned to raster cells in two ways: in the area of extent of a unit, a scoop map is identical to the top of that unit, whereas in the remainder of the study area, the top of the previously calculated top, i.e. the top of the unit just lying above, is assigned. The solid model of the underground can be compared with a box of ice cream in which the initial ice cream surface is equal to the earth's surface. The main unit computed first is scooped out of the box. The remaining ice cream surface is the scoop map. Only where a unit is present, a part is scooped out and only the raster map cells in that area are changed. Next, the second main unit is scooped out and the procedure is repeated until the bedrock. Afterwards, the main units are subdivided into its subunits. Scoop maps are therefore used as intermediate GIS-data to calculate spatially-distributed base and thickness maps.

However, for Flanders, the top–down approach is only followed from the top of the tertiary sediments. The latter is available for Flanders in GIS format. Bearing in mind that the latter is identical to the base of the quaternary aquifer systems, the modelling approach for units of the quaternary aquifer systems differs from the approach for older (and deeper) units. At the time of research of this project, an accurate, highly detailed DEM was not available for the whole study area. As the Quaternary units in the study area are characterized in close relation with the topographic relief and given that the thickness of these units is sufficiently measured, it was decided to model the quaternary aquifer by means of its thickness instead of its base level. In this case, the available isopach maps and point data are interpolated to obtain a thickness map. Base level maps are then derived from the thickness maps by substracting the thickness map from the topography. For deeper units, below the tertiary surface, the interface between two units is described more accurately than the thickness. Once the base and thickness layers are estimated for all main units, GIS maps are generated for the subunits and

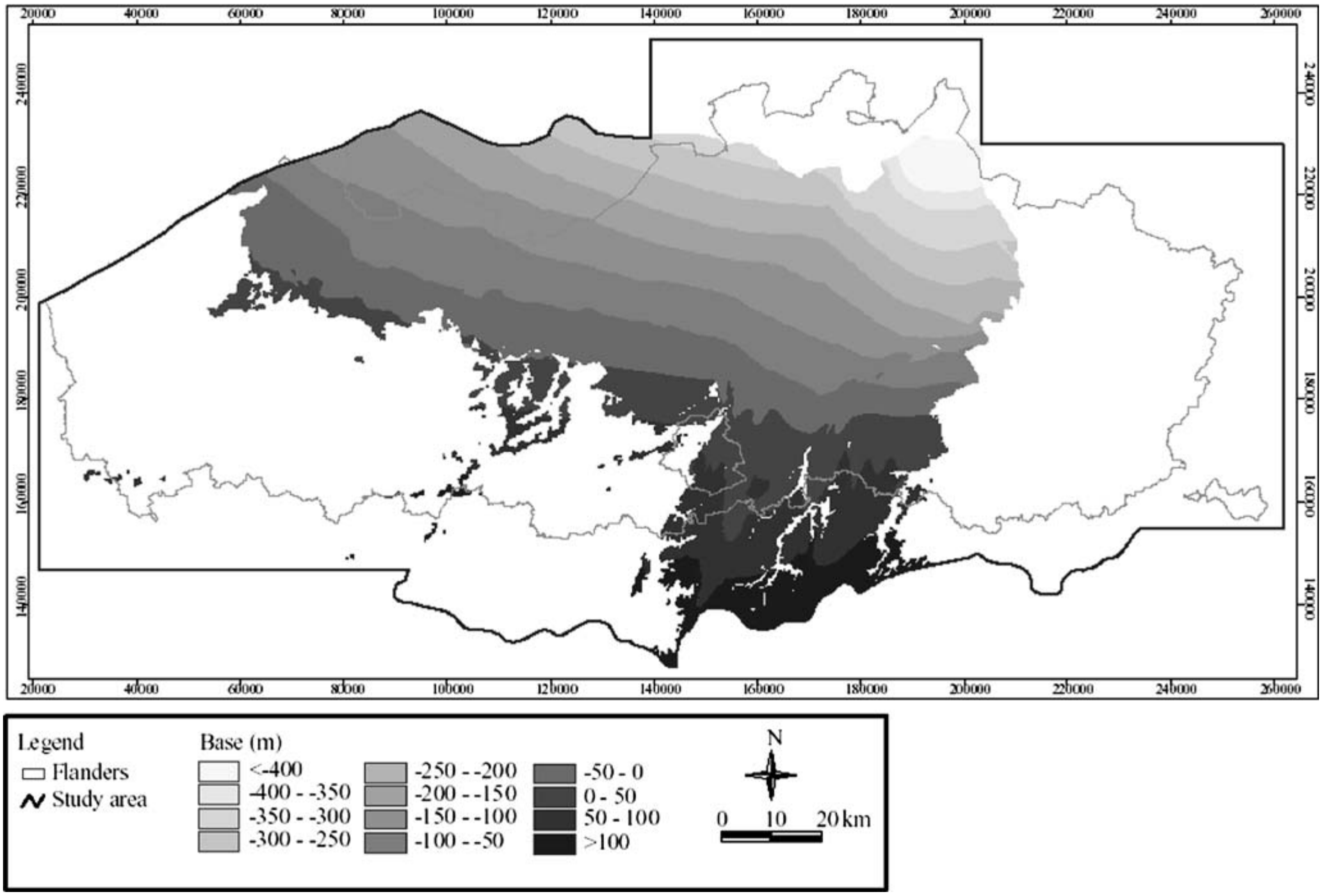

Fig. 7 Base level map of the HCOV unit of the Ledo–Paniselian–Brusselian aquifer system (HCOV code '0600')

afterwards for the basic units. In this way, the hierarchy of the HCOV code is preserved.

Input data for the Flemish groundwater model

The aquifer and aquitard models described in this paper serve as an input data for the flemish groundwater model (FGM), a regional groundwater model covering the whole of Flanders. For each of the six clustered groundwater bodies, a regional groundwater model is under construction. With respect to the 'quantitative status', as mentioned in the WFD, the FGM is to be used for four major applications.

Firstly, the groundwater bodies have currently been identified on a preliminary basis. As the WFD requires that, in a next phase, groundwater bodies need to be delineated based on water divides and flow lines, the FGM will provide the required data to do so.

Secondly, FGM will be a tool to concretize the objective to achieve a 'good quantitative status'. The WFD states that a balance between abstraction and groundwater recharge has to be ensured. Thereby, only that portion of the overall groundwater recharge not needed to sustain the ecology is allowed to be abstracted.

Thirdly, groundwater dependent terrestrial ecosystems need to be identified. At present, groundwater dependent ecosystems are simply assigned to a particular groundwater body. However, the FGM allows to identify which ecosystem is dependent on which groundwater body. For this purpose, Batelaan et al. (2003) developed a methodology to map groundwater dependent terrestrial ecosystems, groundwater discharge areas, and by means of particle tracking, the corresponding recharge zones and groundwater system.

Fourthly, to achieve the good quantitative status, a program of measures needs to be developed. The FGM allows to simulate the impact of potential restoration measures on the groundwater resources. Thus, the groundwater system including the identification of infiltration and discharge zones needs to be known.

A similar study on a small-scale river basins in Wallonia (southern region of Belgium), is described by Gogu et al. (2001). These investigators use a hydrogeological GIS database in their vulnerability assessment studies and numerical modeling for groundwater flow and contaminant-transport studies. Henriksen et al. (2003)

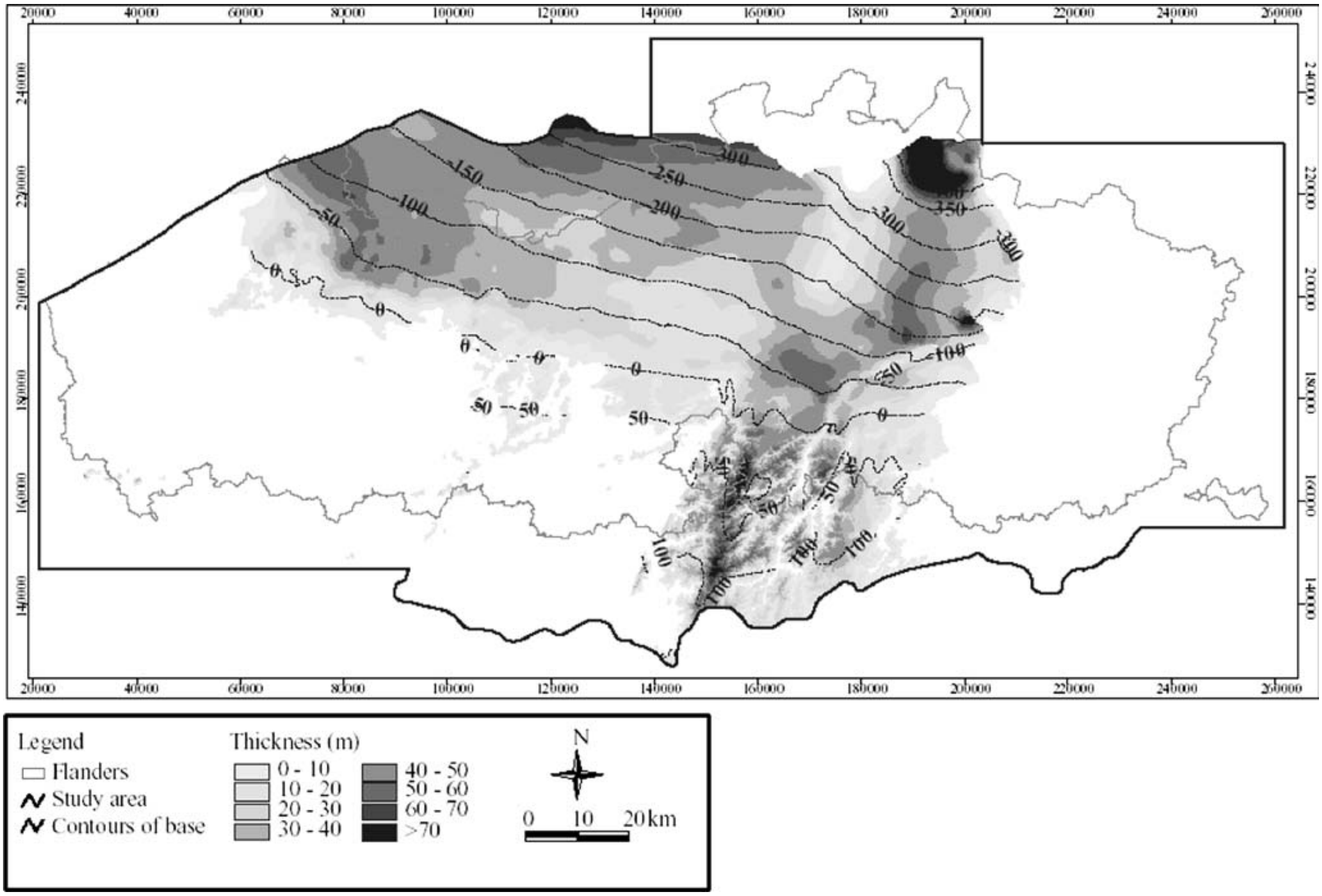

Fig. 8 Thickness map of the HCOV unit of the Ledo–Paniselian–Brusselian aquifer system (HCOV code '0600')

and Sonnenborg et al. (2003) constructed an integrated groundwater/surface hydrological model for Denmark with a 1 km^2 raster map. In the Netherlands, as well, the national groundwater models NAGROM (RIZA 1996) and LGM (Pastoors 1992) were for these purposes developed. In the United States, regional, surface water-groundwater models are described e.g. in Sophocleous et al. (1999) and Sophocleous and Perkins (2000).

Conclusions

In this paper, a methodology is elaborated in support of the first step of the implementation of the EU WFD, which is the delineation of groundwater bodies, as the basic units for management and reporting. The methodology consists of (1) the development of a complete and generally-accepted hydrogeological classification system for Flanders (HCOV code), (2) the development of a GIS-managed borehole database and (3) the development of aquifer and aquitard models by means of a solid modeling approach. Finally, for each HCOV unit, GIS maps are generated for the three basic characteristics of the hydrogeological units: extent, base level and thickness, such that combined, the volume and extent of a hydrogeological unit is unambiguously defined.

With respect to integrated groundwater management, insight in large-scale transboundary groundwater systems is required. A major challenge therefore is to harmonize the vast amount of data originating from different sources into a unique GIS borehole database and unique representation of a complex stratigraphy. Hence, conversion tables between the different systems of classification are needed as well as decision criteria when data is lacking or contradictory. The need therefore exists for decision-supportive technological tools. To achieve the objectives of the WFD, scientists and water managers have a joint responsibility.

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