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A synthesis of hydraulic conductivity measurements of the subsurface in Northeastern Belgium.

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ABSTRACT. Since the late 1970's, the Belgian Nuclear Research Centre (SCK•CEN) has been collecting hydrogeological parameters from the subsurface in NE-Belgium in the framework of radioactive waste disposal studies, which are now managed by ONDRAF/NIRAS, the Belgian agency for radioactive waste and enriched fissile materials. In this paper, the hydro-stratigraphy of the Campine hydrogeological system is described and the hydraulic conductivity data collected by SCK•CEN, complemented with data from other sources (drinking water companies, universities, government services) are synthesized and analyzed according to the measurement method that was used to determine them. This results in parameter ranges based on all available measurements for each hydrogeological layer, ranging from the Quaternary until the Ledo-Paniselian-Brusselian aquifer system, which are compared to representative literature ranges. Besides parameter ranges based on all available measurements, the most important result of this study are parameter ranges that are useful for groundwater flow modelling.

KEYWORDS: hydraulic conductivity, groundwater modelling ranges, aquifers above and below the Boom Clay

1. Introduction

In order to quantitatively describe groundwater flow, the hydraulic properties of sediments, such as hydraulic conductivity and storage coefficients, are necessary input parameters for the groundwater flow equation (Domenico & Schwarz, 1998). The most important parameter from a perspective of modelling groundwater flow is the (saturated) hydraulic conductivity K [LT^{-1}], since this parameter together with the hydraulic gradient allows quantifying groundwater flow according to Darcy's Law (Darcy, 1856).

Hydrogeological data and more in particular hydraulic conductivity data have been collected in NE-Belgium (Campine region) by various institutions and for different purposes. The Belgian Nuclear Research Centre (SCK•CEN) has been collecting hydrogeological data in the Campine for more than 30 years in the framework of radioactive waste disposal studies (summarized in Vandersteen et al., 2013). The collected data are related to two main disposal programs carried out by ONDRAF/NIRAS: the deep disposal program (category B&C waste: high and intermediate long-lived radioactive waste), and the surface disposal program cAt (category A waste: low and intermediate short-lived waste). The surface disposal program focuses on the vicinity of the Mol-Dessel site, providing locally more detailed information. The deep disposal program, owing to its main interest in the Boom Clay as a potential host formation, involves a larger and deeper study domain. The study area is delineated by the presence of the Boom Formation in Belgium (Fig. 1) and its assumed role in the regional groundwater system. Hydraulic conductivity data is collected from the Quaternary aquifer systems until the Ledo-Paniselian-Brusselian aquifer system. Deeper layers are not considered as no or very few hydraulic conductivity data are available from these layers in NE-Belgium.

Besides SCK•CEN, hydraulic parameters in the Campine area have also been collected by a number of institutions for commercial (groundwater extraction) and research goals. Several pumping tests in the Neogene aquifer were commissioned by the main drinking water company in the Campine area. Data on the deep aquifers below the Boom Clay are scarce and mostly related to the outcrops of the respective formations. Pumping tests here have been done mainly by universities or by the drinking water company. Large parts of the 'external' data have been summarized by Wemaere & Marivoet (1995) and by the VMM (Vlaamse Milieumaatschappij) (2010).

The objective of this study is to synthesize, analyse and discuss available information on measured hydraulic conductivity of the Campine subsurface such that the data can be used in a relatively fast and straightforward way by other researchers and groundwater modelling experts.

2. Data collection methods

Various methods exist for measuring the hydraulic conductivity (K) of aquifers, which can be subdivided into two categories: direct measurements and indirect measurements. Direct measurements involve measuring flow through a sample (in the

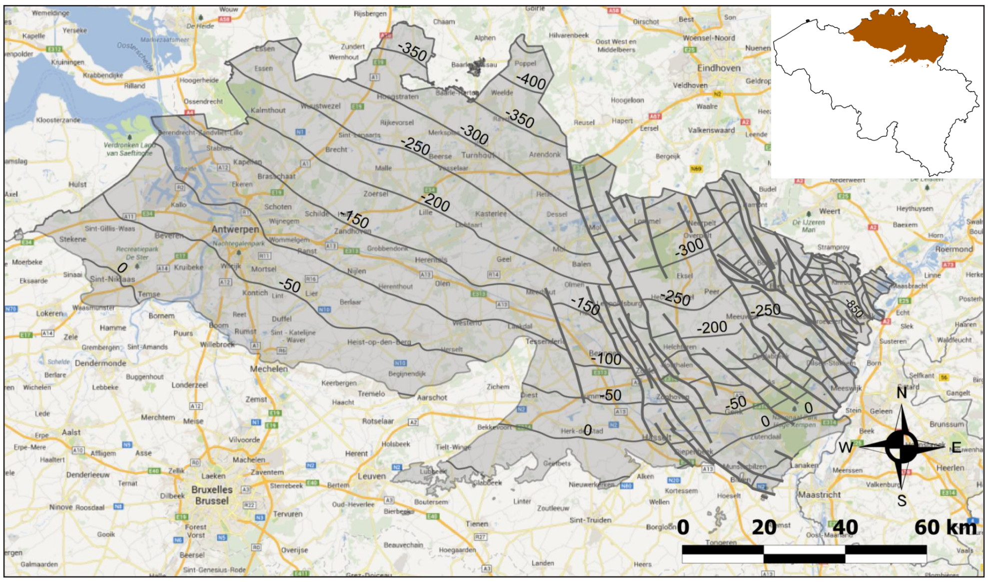


Figure 1. Extent and depth of the base (in m TAW; Tweede Algemene Waterpassing) of the Boom Formation in Belgium (based on interpretations of the Geological Survey of Belgium (Vancampenhout, 2004; Welkenhuysen et al., 2012)). Faults cross-cutting the Boom Formation are shown by NW-SE trending lines; they belong to the Roer Valley Graben system. A map of Belgium with the location of the Boom Formation is shown in the upper right corner.

laboratory) or towards a well screen (in the field). In the former case, K measurements are performed on sediment samples taken from boreholes or outcrops. These laboratory measurements are representative only at the scale of the sample. Pumping tests and slug tests are conducted in situ using piezometers or wells and injecting or extracting water. Indirect measurements derive K from other measured sediment properties, such as the grain size distribution, or geophysical measurements (borehole logs or cone penetration testing). This section describes the main uncertainties of the different measurement techniques that were used for determining hydraulic conductivity in the dataset used in this study.

2.1. Direct measurement methods: pumping tests, slug tests and permeameter tests

In situ pumping tests are particularly fit to produce effective K-values representative of a relatively large aquifer volume. They somewhat average the effects of small-scale variability in K and are compatible with the scale of the groundwater flow model. In the hereafter presented hydraulic conductivity dataset, two main types of in situ pumping tests were performed – the step drawdown test and the constant discharge test with recovery (Kruseman & de Ridder, 1994) – and several interpretation methods were applied for each of these tests. They comprise analytical methods as well as numerical groundwater flow modelling. Besides (long-term) pumping tests, requiring one pumping well and one or more observation wells, also single-borehole tests were performed, as they do not require observation wells, which can be very costly, especially in the deep aquifers. However, these tests may provide more biased K estimates, since the effects of the well construction and screen cannot be excluded and have to be estimated in order to filter them out. Also the area for which the K value is representative is much smaller. Different analytical methods can be used to interpret pumping tests (Kruseman & de Ridder, 1994). Besides using an analytical solution for the well flow, pumping tests can also be interpreted using a numerical groundwater flow model. Hydraulic conductivity values for different layers are then estimated by fitting the calculated to measured drawdown evolution (inverse modelling). If the conceptual model is correct, the hydraulic conductivity values estimated by calibrating the groundwater flow model are less biased than the values derived using analytical methods since they take into account the assumed geometry and conditions under which the test was performed. However, uncertainties may arise because of parameter insensitivity and conceptual model uncertainty.

Details on design, performance and analysis of slug tests can be found in Butler (1997). Slug tests cannot be regarded as a substitute for conventional pumping tests. From a slug test, for instance, it is only possible to determine the characteristics of a small volume of aquifer material surrounding the well, and this volume may have been disturbed during well drilling and construction. The analytical method of Hvorslev (1951) is probably the most used for interpretation of a slug test.

A description of the permeameter test can be found in Klute & Dirksen (1986). The main disadvantage of the method is related to the limited size of the samples: the measurement is not representative for large volumes of an aquifer. Disturbance by the sampling methods itself is also a possible issue. On the other hand, when applied to densely sampled cores, it can provide a good measure of the heterogeneity of the subsurface material.

2.2. Indirect measurement methods: grain size measurements, cone penetration testing, air permeameter measurements and geophysical measurements

Grain-size analysis is one of the cheapest methods to obtain hydraulic conductivity predictions and can still be performed on disturbed core samples. However, this method can suffer from large uncertainties (Vienken & Dietrich, 2011). The parameters usually required to calculate the hydraulic parameters are derived from the cumulative curve of the grain-size. The hydraulic conductivity is then calculated by means of experimental formulae. For the cAt project, Rogiers et al. (2012a) used an approach based on artificial neural network ensemble to predict hydraulic conductivity with multiple grain-size fractions as data input, and to provide reasonable uncertainty estimates using the GLUE methodology.

The cone penetration test (CPT) is a method used to determine the geotechnical engineering properties of soils and delineate soil stratigraphy. Rogiers et al. (2012b) used CPT data in combination with site-specific K data (laboratory measurements) to generate various concepts of parameterization of the Kasterlee Clay in the vicinity of the Mol-Dessel site. The main advantage of this method is that geotechnical data have a very high resolution and are suitable for studying small-scale heterogeneity in the subsurface.

Air permeameter measurements are small-scale measurements used to assess in situ the air permeability of porous media, such as soils and sediments, which is subsequently transferred into saturated hydraulic conductivity using well-defined transfer functions (Rogiers et al., 2013). Amongst others, the most important prerequisite is that the water content should be small enough to allow air being sucked from the exposure into the permeameter. Like permeameter measurements, the method is not representative of large sediment volumes. However, when applied to high-resolution sampling grids, it can provide a good measure of the heterogeneity of the porous material.

The MDT single probe, which is a geophysical measurement technique, allows measuring a pressure response induced by extraction (or injection) of a given volume of water from (into) a borehole. The hydraulic conductivity is calculated from the pressure record in time and the known volume of extraction (or injection). Only a small radius of the formation is investigated by this method and therefore, one measurement cannot be taken as representative for the whole formation.

The previous description illustrates that the applied measurement method not only influences the precision, but also determines the representativeness of the measurement. As it is our intention to give guidelines on representative hydraulic conductivity measurement ranges for certain hydrogeological layers, this has to be taken into account. When used for large-scale modelling purposes for example, K-values from pumping test data are more representative than small-scale permeameter test data. However, small-scale data can give an indication on the heterogeneity of the aquifer, which can be used as additional information for the modeller. Therefore, in this paper, we subdivide - for each considered hydrogeological unit - the available hydraulic conductivity measurements according to the measurement method that was used. Included in our analysis is a comparison with available literature ranges for the area, coming from the VMM (2008a and 2008b) and the SAFIR 2 report (ONDRAF/NIRAS, 2001). The VMM assigned hydraulic conductivity ranges to each hydrogeological unit for the different groundwater systems in Flanders, based on their internal database of K-values. The ranges we compare with in this paper come from the Central Campine System (VMM, 2008a) for the hydrogeological layers above the Boom Clay, and from the Brulandkrijt System (VMM, 2008b) for the hydrogeological layers below the Boom Clay. The SAFIR 2 report (ONDRAF/NIRAS, 2001) summarizes the technical and scientific knowledge that was acquired within the period 1990 – 2000 by the B&C research program developed by ONDRAF/NIRAS for the disposal of high- and intermediate level radioactive waste in clays. In this report, best estimates and ranges were derived for the hydraulic conductivity of the large hydrogeological entities in the Campine, based on the available measurement data at SCK•CEN. These ranges were based on all available K-measurements, disregarding the measurement method. However, considerable new information has been gathered since then. The analysis presented in this paper discusses and provides complementary valuable information on existing hydraulic conductivity literature ranges.

3. Hydrogeological structure of the subsurface in NE-Belgium

In this paper, we distinguish between a shallow aquifer system (unconfined and semi-confined) and a deep aquifer system (confined) in NE-Belgium. The shallow aquifer system comprises the hydrogeological system above the Boom Clay, while the deep aquifer system refers to the confined hydrogeological system

HYDRO-STRATIGRAPHY HCOV coding Unit	Sub-unit	Basic-unit	LITHO-STRATIGRAPHY FORMATION + Code	Member + Code	Main lithology	CHRONO-STRAT.
Quaternary aquifer systems (0100)	Embankments (0110)				various	QUATERNARY
	Dunes (0120)				sand	
	Polder sediments (0130)				clay	
	Alluvial covers (0140)				clay	
	Covering layers (0150)				sand	
	Pleistocene sediments (0160)				sand	
	Meuse- and Rhine deposits (0170)				gravel	
Campine aquifer system (0200)	Sediments north of the Feldbiss fault (0210)		KIEZELOOLIET Kz		sand/clay	QUATERNARY AND NEOGENE (PLIOCENE) NEOGENE
	Campine clay-sand complex (0220)	Turnhout Clay (0221) Beerse Sands (0222) Rijkevorsel Clay (0223)			sand/clay	
	Pleistocene and Pliocene aquifer (0230)	Brasschaat and/or Merksplas Sands (0231)	MERKSPLAS Me		sand	
			BRASSCHAAT Bs	Hemeldonk BsHd Schorvoort BsSv Malle BsMa	sand	
		Mol Sands (0232)	MOL Ml	Rees MlRe Russendorp MlRu Maatheide MlMh Maat MlMa Donk MlDo	sand	NEOGENE MIO-PLIOCENE
		Sandy top of Lillo (0233) Poederlee Sands and/or sandy top of Kasterlee (0234)	LILLO Li POEDERLEE Pd KASTERLEE Kl		sand	
	Pliocene clayey layer (0240)	Clayey part of Lillo and/or of the Lillo-Kattendijk transition (0241)	KATTENDIJK Kd		clay	
		Clayey transition between Diest and Kasterlee Sands (0242)				
	Miocene aquifer system (0250)	Kattendijk Sands and/or lower Sands of Lillo (0251)			sand	
		Diest Sands (0252)	DIEST Di	Deurne DiDn Dessel DiDe	sand	
		Bolderberg Sands (0253)	BOLDERBERG Bb	Opitter BpOp Genk BpGe Houthalen BpHo	sand	
		Berchem and/or Voort Sands (0254)	BERCHEM Bc VOORT Vo	Antwerpen BcAb Voort VoVo	sand sand	
		Veldhoven Clay (0255)		Veldhoven VoVe	clay	PALAEOGENE OLIGOCENE
		Eigenbilzen Sands (0256)	EIGENBILZEN Eg		sand	

Table 1. Detailed hydro-, litho-, and chronostratigraphy of the shallow aquifer system in Belgium (based on HCOV (Meyus et al., 2000) and the Tertiary lithostratigraphic table (ALBON, 2010)).

below the Boom Clay, whereby the latter can be considered as a low-permeable barrier. The division between shallow and deep aquifer system in NE-Belgium is explained in detail in Vandersteen et al. (2013), and is based on modelling and conceptual knowledge on groundwater flow in this area, mainly relating to boundary conditions, water balance calculations and piezometric records. The unconfined parts of the deep aquifer system situated close to the Boom Clay outcrop are included in our analysis for reasons of completeness.

The hydrogeological units division in this paper is based on the HCOV (Hydrogeologische Codering Ondergrond Vlaanderen) system (Meyus et al., 2000), which is a generally

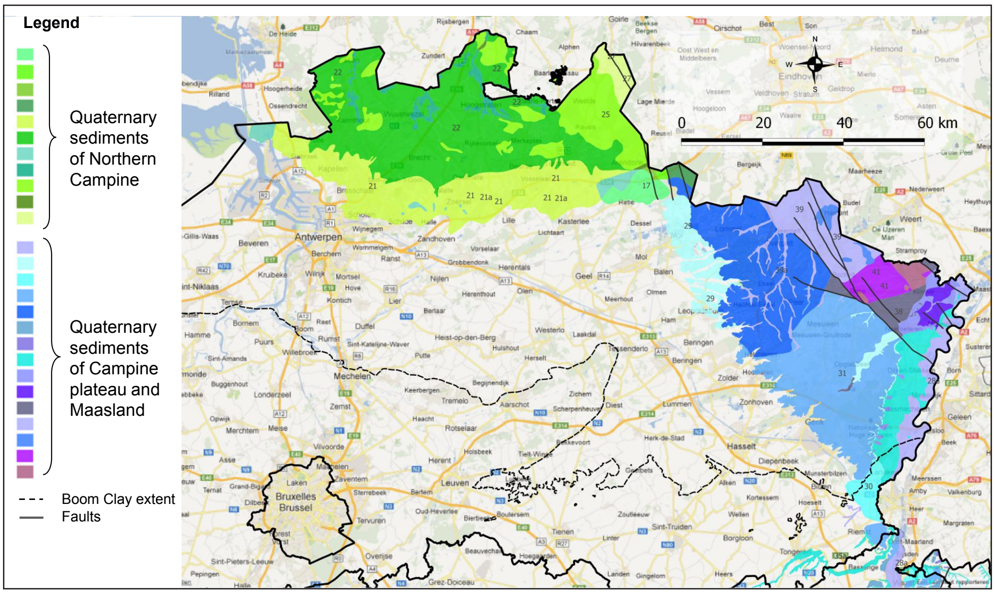


Figure 2. Hydrogeologically significant Quaternary sediments. The sediment profile types of the Northern Campine (greenish colours) correspond roughly to the Campine complex (HCOV 0220), the sediment profile types of the Campine plateau and the Maasland (bluish colours) correspond to the Maas and Rhine deposits (HCOV 0170) and to the sediments north of the Feldbiss fault (HCOV 0210). Based on the Quaternary geological map of Databank Ondergrond Vlaanderen.

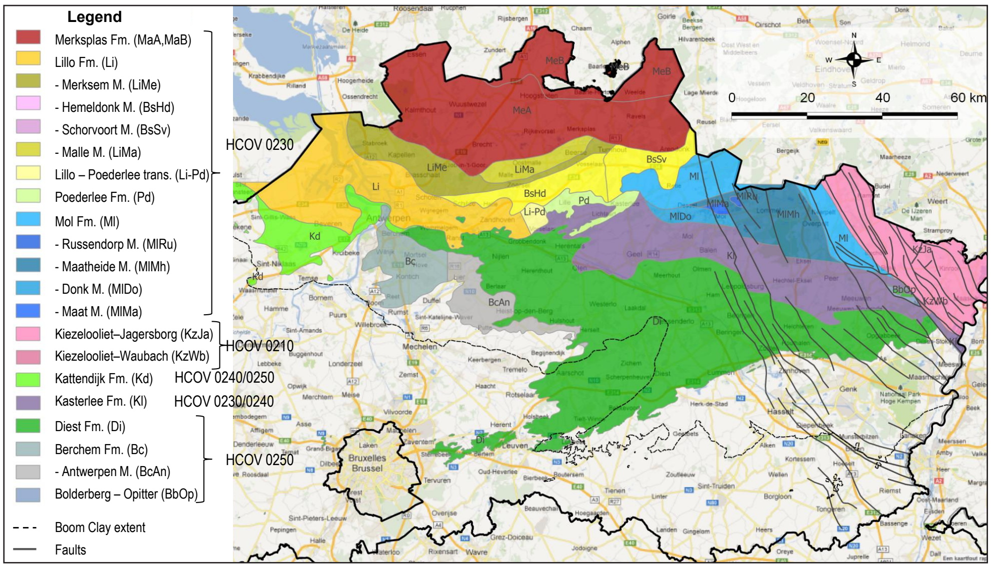


Figure 3. Tertiary lithostratigraphic units forming the shallow aquifer system. Based on the Tertiary geological map of Databank Ondergrond Vlaanderen.

accepted Flemish hydrogeological terminology. For improving clarity of the text, references to the detailed hydrostratigraphy, lithostratigraphy and chronostratigraphy of the subsurface are included in this paper.

3.1 Shallow aquifer system

The shallow aquifer system comprises the Quaternary aquifer systems (HCOV 0100) and the Campine aquifer system (HCOV 0200). The detailed hydro-, litho- and chronostratigraphy of these systems are given in Table 1.

Unlike all other HCOV units, the Quaternary aquifer systems (HCOV 0100) do not represent a single continuous water conducting feature; they rather group all Quaternary sediments in Flanders. In the Campine region, there are parts of the main Quaternary HCOV unit covering the Campine aquifer system (embankments – HCOV 0110, alluvial covers – HCOV 0140, covering layers – HCOV 0150 and Meuse- and Rhine deposits – HCOV 0170). These fragments form a single aquifer with the underlying Campine aquifer system, which makes is difficult to describe them separately. Moreover, because of their proximity to the surface, they are often unsaturated or partly saturated. Some continuous Quaternary layers are included in the Campine aquifer system, i.e. sediments north of the Feldbiss fault (HCOV 0210) and the Campine clay-sand complex (HCOV 0220) (Fig. 2).

The Campine aquifer system (HCOV 0200) consists of a sequence of sandy layers of Quaternary and Tertiary age, alternated with locally occurring clayey layers. The Campine aquifer system has an average thickness of about 100 m, ranging from a few meters at the Boom Clay outcrop to a maximum thickness of over 600 m in the Roer Valley Graben (north-east Campine). This hydrogeological unit is subdivided into 5 different subunits (Fig. 3): the Kiezeloöliet Formation (HCOV 0210), the Campine clay-sand complex (HCOV 0220), the Pleistocene and Pliocene aquifer (HCOV 0230), the Pliocene clayey layer (HCOV 0240) and the Miocene aquifer system (HCOV 0250). Most units of the Campine aquifer system extend to the north of the Boom Clay outcrop line. The only exception is the Diest Sands, which cut through the Boom Clay in the central part of the Campine (Fig. 3).

HYDRO-LITHOSTRATIGRAPHY			LITHO-STRATIGRAPHY			CHRONO--STRATIGRAPHY	
HCOV coding Unit	Sub-unit	Basic-unit	FORMATION + code	Member + code	Main lithology		
Boom aquitard (0300)		Clayey part of Eigenbilzen (0301)		Boeretang		OLIGOCENE	RUPELIAN
		Putte Clay (0302)		Putte BmPu	clay		
		Terhagen Clay (0303)		Terhagen BmTe			
		Belsele-Waas Clay (0304)		Belsele Waas BmBw			
Oligocene aquifer system (0400)	Kerniel Sand (0410)		BILZEN Bi	Kerniel BiKe	sand		
	Kleine-Spouwen Clay (0420)			Kleine Spouwen BiKs	clay		
	Ruisbroek-Berg aquifer (0430)	Berg Sands (0431)		Berg BiBe	sand		
		Kerkom Sands (0432)	BORGLOON Bo	Kerkom BoKe			
		Alden Biezen Clayey Sands (0433)		Alden Biesen BoOb	sand		
		Boutersem Sands (0434)		Boutsersem BoBt			
		Ruisbroek Sands (0435)	ZELZATE Zz	Ruisbroek ZzRu	sand		
	Tongeren aq. (0440)	Henis Clay (0441)		Henis BoHe	clay		
		Watervliet Clay (0442)		Watervliet ZzWa			
	Lower-Oligocene aquifer system (0450)	Neerrepen Sands (0451)	St. H. HERN Sh	Neerrepen ShNe			
		Grimmertingen Sand-Clay (0452)		Grimmer-tingen ShGr	sand		
		Bassevelde Cl. Sand (0453)		Bassevelde ZzBa			
Bartonian aquitard system (0500)		Onderdijke Clay (0501)	MALDEGEM Ma	Onderdijke MaOd	clay	EOCENE	LUTETIAN-BARTONIAN
		Buisputten Sand (0502)		Buisputten MaBu	sand		
		Zomergem Clay (0503)		Zomergem MaZo	clay		
		Onderdaele Sand (0504)		Onderdaele MaOn	sand		
		Ursel and/or Asse Clay (0505)		Ursel MaUr/ Asse MaAs	clay		
Ledo-Paniseliaan-Brusseliaan aquifer system (0600)	Wemmel – Lede aquifer (0610)			Wemmel MaWe	sand		
			LEDE Ld		sand		
	Brussels Sands (0620)		BRUSSEL Br		sand		
	Upper Paniselian Deposits (0630)		AALTER Aa		sand, sandy cl.		
	Lower Paniselian sandy Deposits (0640)		GENTBRUGGE Ge	Vlierzele GeVl sand			

Table 2. Detailed hydro-, litho- and chronostratigraphy of the deep aquifer system in Belgium (based on HCOV (Meyus et al., 2000) and the Tertiary lithostratigraphic table (ALBON, 2010)).

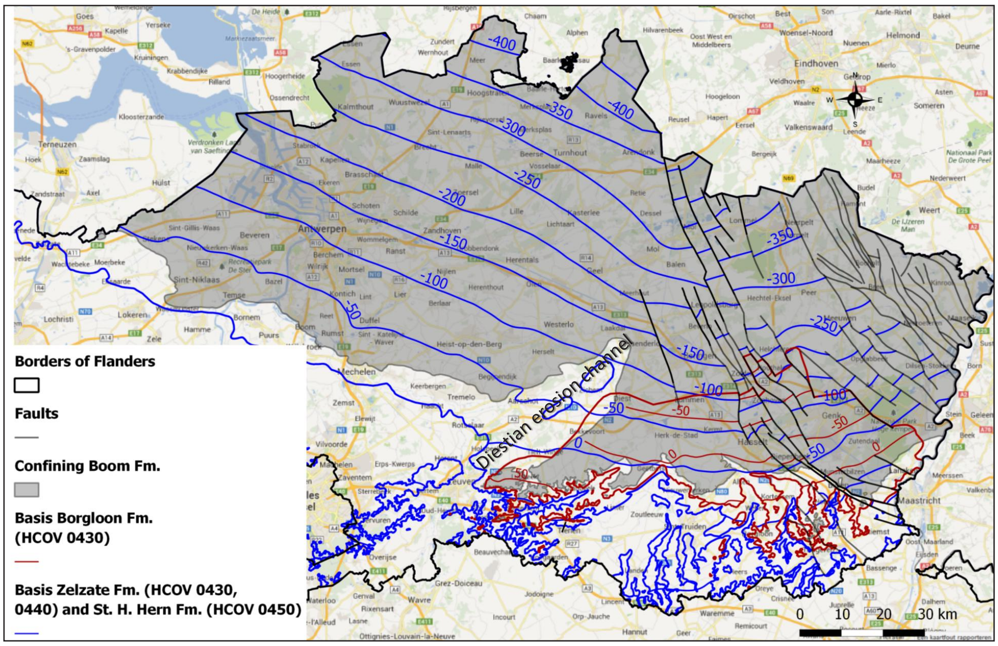


Figure 4. Basis of Borgloon, Zelzate and St. H. Hern Formations defining the lower boundary of the Oligocene aquifer system (HCOV 0400). Based on interpretations of the Geological Survey of Belgium (Vancampenhout, 2004, Welkenhuysen et al., 2012).

3.2 Deep Aquifer System

The deep aquifer system, defined in section 3 as the hydrogeological system below the Boom Clay in NE-Belgium, includes a large part of the strata of the Campine subsurface. The hydrogeological knowledge of this system is, however, relatively poor. This is largely due to its relatively large depth and limited use as a groundwater resource which is the result of the decaying groundwater quality towards the north and west. This study is limited to the upper aquifers and aquitards of the deep aquifer system, including the Boom aquitard (HCOV 0300), the Oligocene aquifer system (HCOV 0400), the Bartonian aquitard system (HCOV 0500) and the Ledo-Paniselian-Brusselian aquifer system (HCOV 0600). Table 2 shows the detailed description of the hydro-, litho- and chronostratigraphy of the considered layers of the deep aquifer system.

The Boom aquitard (HCOV 0300) subcrops in the entire Campine area. The Boom Formation dips to the north-east, its base reaching a maximum depth of about -400 meter TAW near the northern Belgian border (Fig. 1). In the Roer Valley Graben, the base of the Boom aquitard can locally reach much larger depths. The thickness is between 20 and 50 meters in the outcrop zone, reaching more than 130 meters towards the northern Belgian border. The Boom aquitard has been eroded in the Diestian erosion channel that subsequently became filled with marine sands from the Diest Formation.

The Oligocene aquifer system (HCOV 0400) is formed – in the western part - by sediments of the Formation of Zelzate and in the eastern part by sediments of the Formations of Sint-Huibrechts-Hern, Borgloon and Bilzen (Fig. 4). The base of the Oligocene aquifer system dips to the north reaching a maximum depth of approximately -450 meter TAW near the northern Belgian border. Towards the east of the Campine, the Oligocene aquifer system is disturbed by north-west - south-east oriented faults, causing a vertical downward shift of the aquifer system towards considerable depths. These faults also cause an increase in the thickness of the sediments which reaches up to 50 meters here, while the overall thickness of the sediments is restricted to a few tens of meters in the western part of the study area. The Oligocene aquifer system consists of sandy clay and clayey sands with, in between, thin discontinuous clay layers.

The Bartonian aquitard system (HCOV 0500) is formed by low-permeable clay layers alternating with more permeable

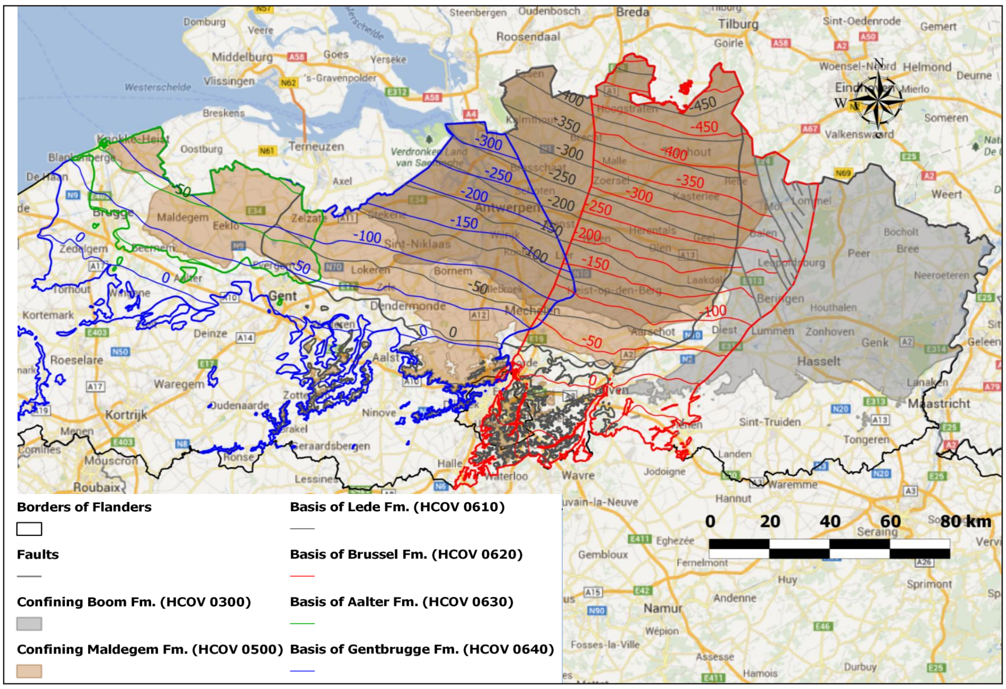


Figure 5. Basis of Lede, Brussel, Aalter and Gentbrugge Formations forming the Ledo-Paniselian-Brusselian aquifer system (HCOV 0600). Based on interpretations of the Geological Survey of Belgium (Vancampenhout, 2004).

sandy layers of the Maldegem Formation. The extent of the Maldegem Formation is given in Fig. 5. This aquitard system is absent in the province of Limburg. Its base dips to the north reaching a maximum depth of more than 450 meter. Its thickness is 50 meters at the most.

The Ledo-Paniselian-Brusselian aquifer system (HCOV 0600) is absent in the largest part of the province of Limburg. It consists of the Formations of Lede (in the west), Brussels (in the east), Aalter (in the west, outside of the Campine) and the upper part of the Formation of Gentbrugge (Vlierzele Sands, only present in the west of the Campine near Antwerp) (Fig. 5). On top, at the base of the Maldegem Formation, the Wemmel Sands are present. The base of the aquifer system dips to the north reaching a maximum depth of approximately 500 meter. The aquifer system is covered by the Bartonian aquitard system in the west of the study area and by the Oligocene aquifer system in the east of the study area. The aquifer has a fairly constant thickness of approximately 50 meters throughout the study area. The Ledo-Paniselian-Brusselian aquifer system mainly consists of fine to coarse glauconitic and calcareous sands, containing limestone benches and locally thin marl and clay lenses.

4. Hydraulic conductivity data of the Campine underground

4.1. Hydraulic conductivity of the shallow aquifer system units

The sandy sediments of the shallow aquifer system feature a relatively high hydraulic conductivity. They represent the most important source for groundwater supply in Flanders. The aquitards within the shallow aquifer system are not regionally continuous. Many well spatially distributed hydraulic conductivity measurements are available. The number of measurements decreases however with depth, whereas only a limited number of measurements are available for the deepest, not exploited units (Voort, Eigenbilzen). A large concentration of hydraulic conductivity measurements is found in the vicinity of the Mol-Dessel site, where a detailed site-characterization took place in 2008 (Beerten et al, 2010, Wouters & Schiltz, 2012) in the framework of the planned surface disposal site (cAt project). Different measurement techniques have been used at this location to investigate the hydraulic properties and its heterogeneity. In the rest of the Campine, the concentration of measurements is far less dense and the measurement techniques mainly consist of granulometric analyses, and occasionally a pump- or slug test. A summary of hydraulic conductivity ranges available for the shallow aquifer system units is given in Table 3, based on available data from SCK•CEN (measured values), supplemented with data from other sources, summarized in the VMM database (2010) and in Wemaere & Marivoet (1995). Besides a column with a summary of all measured values, giving an indication on the heterogeneity of the unit, an additional column is given with recommended ranges for groundwater modelling, mainly based on large-scale pumping test measurements.

Because of the presence of various deposits forming the Quaternary aquifer systems (HCOV 0100), a very large variability in hydraulic properties can be observed (Table 3). The largest values are found in the gravely Meuse- and Rhine deposits (HCOV 0170) in the east (hydraulic conductivity values up to 6047 m/d). The VMM data range (2008a) is very narrow compared to the range based on all measured data. Based on the pumping test values, a range for use in groundwater modelling for HCOV 0170 is derived (Table 3) between 31 and 6047 m/d. Due to lack of more detailed data, ranges for other sub-units could not be derived.

In the Campine clay-sand complex (HCOV 0220), the horizontal hydraulic conductivity was determined mainly from granulometric analyses and a limited number of pumping and slug tests and air permeameter measurements. Only pumping test measurements are available for the vertical hydraulic conductivity. The hydraulic conductivity ranges given in Fig. 6 are relatively narrow for all horizontal hydraulic conductivity measurements of the sandy layers. On the contrary, the range of the vertical hydraulic conductivity measurements of the clayey layers is much wider. This can be related to the pumping test interpretation, which is difficult in poorly permeable and mixed (fine and coarse) sediments. The literature ranges from SAFIR 2 (ONDRAF/NIRAS, 2001) and the Central Campine System of the VMM (2008a) are well within the measured ranges.

As pumping test data are the most representative for the whole aquifer, we derive hydraulic conductivity ranges from these data. We consider a horizontal hydraulic conductivity - K_h - range

HCOV unit		All measured values [m/d]		Groundwater modelling range [m/d]		Literature values [m/d]	
		K_h	K_v	K_h	K_v	K_h	K_v
Quaternary aquifer systems (0100)		1.2×10^{-4} – 6047		31 – 6047 (only for HCOV 0170)		1 – 10†	
Campine clay-sand complex (0220)		1.9 – 22.4	2.5×10^{-5} – 0.03	3.5 – 22.4	2.5×10^{-5} – 0.03	2.6 – 17.3§ 5 - 15†	2.6×10^{-5} – 0.03§
Pleistocene and Pliocene aquifer (0230)	Entire	0.07 – 46.1		0.1 – 46.1		0.86 – 51.84§ 0.5 - 46†	
	Brass./Merk. (0231)	6.3 – 46.1				6 - 46†	
	Mol (0232)	0.16 – 44.4				0.5 - 30†	
	Top Lillo (0233)	2.5 – 21.9				5 - 18†	
	Poed./Kast. (0234)	0.07 – 13.0				0.6 – 10†	
Pliocene clayey layer (0240)		5.7×10^{-4} – 23.8	1.68×10^{-4} – 11.4	5.7×10^{-4} – 0.82	1.68×10^{-4} – 7.6	0.04 – 0.5§ 0.02 – 0.2†	
Miocene aquifer system (0250)	Entire	2.4×10^{-5} - 104.5		0.05 - 104.5		2.6 – 34.6§	
	Kattendijk (0251)	4.7 – 14.8		< 14.8		4 - 20†	
	Diest (0252)	0.09 – 54.9		1.1 – 54.9		0.2 - 35†	
	Bolderberg (0253)	6.0 – 104.5		6.0 – 104.5			
	Berchem/Voort (0254)	2.4×10^{-5} – 18.8		0.02 - 18.5		0.03 – 18†	
	Eigenbilzen (0256)	6×10^{-6} – 3.0		< 3.0		0.2 - 3†	

§SAFIR 2 (ONDRAF/NIRAS, 2001); †VMM (2008a)

Table 3. Summary of hydraulic conductivity values in the shallow aquifer system units.

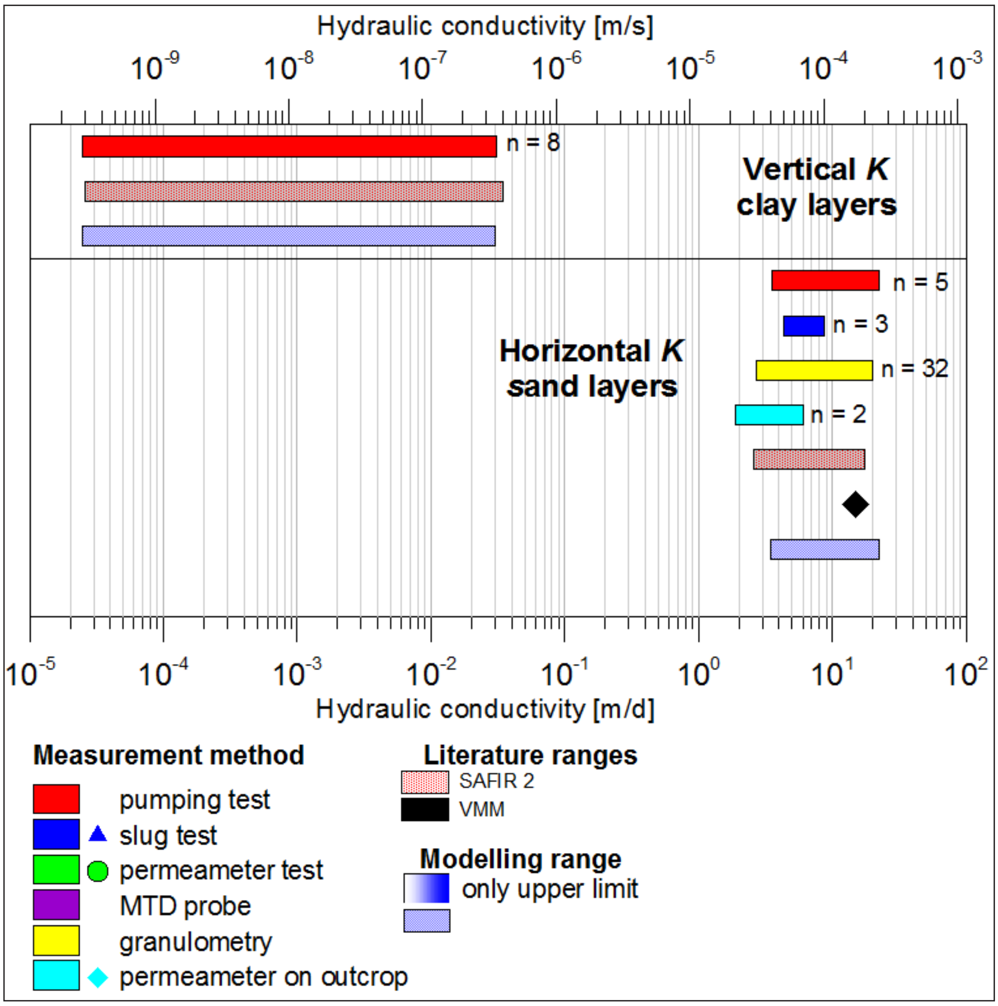


Figure 6. Hydraulic conductivity measurement ranges for the Campine clay-sand complex (HCOV 0220), together with the number of measurements (n), including the proposed ranges for use in groundwater modelling. Ranges from other sources include the Central Campine System (VMM, 2008a) and SAFIR 2 (ONDRAF/NIRAS, 2001).

between 3.5 and 22.4 m/d most suitable for use in groundwater modelling (Table 3, Fig. 6). For the vertical hydraulic conductivity K_v, the recommended modelling range lies between 2.5×10^{-5} and 0.03 m/d. These K_h- and K_v-ranges are very close to the ranges determined using all measurement methods.

Hydraulic conductivity ranges for both the undifferentiated

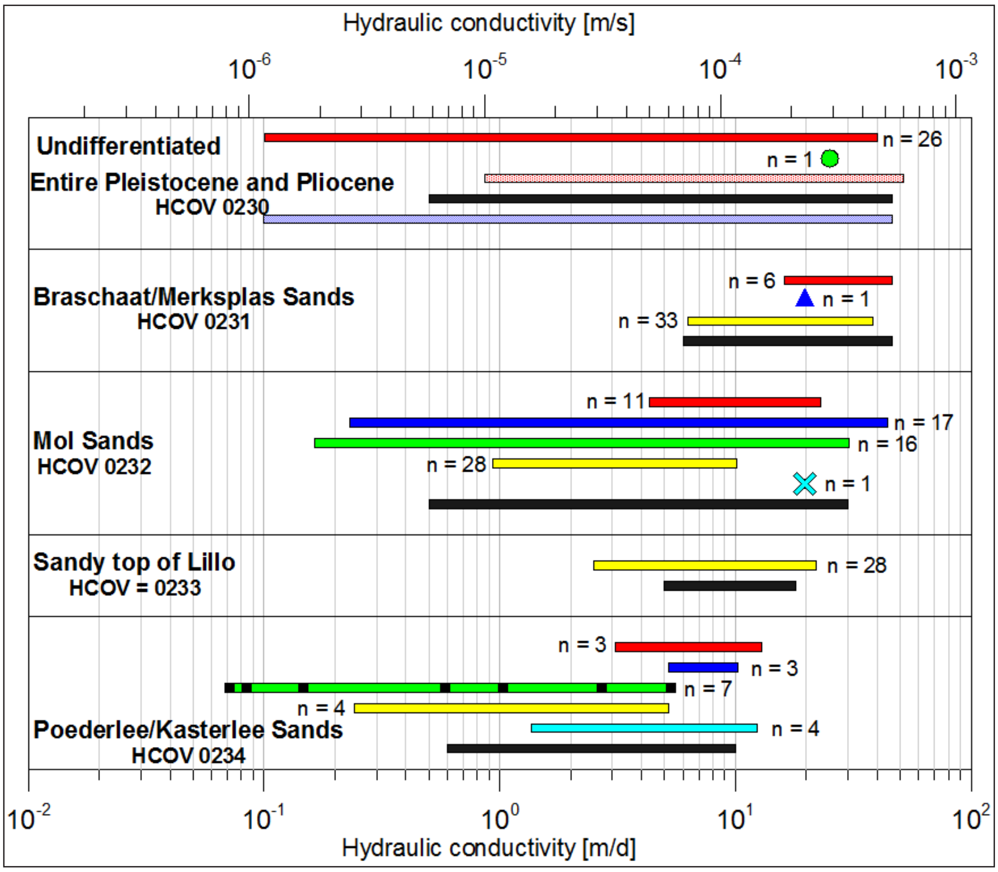


Figure 7. Horizontal hydraulic conductivity measurement ranges for the Pleistocene and Pliocene aquifer (HCOV 0230), together with the number of measurements (n), including the proposed ranges for use in groundwater modelling. Ranges from other sources include the Central Campine System (VMM, 2008a) and SAFIR 2 (ONDRAF/NIRAS, 2001). Same legend as in Fig. 6.

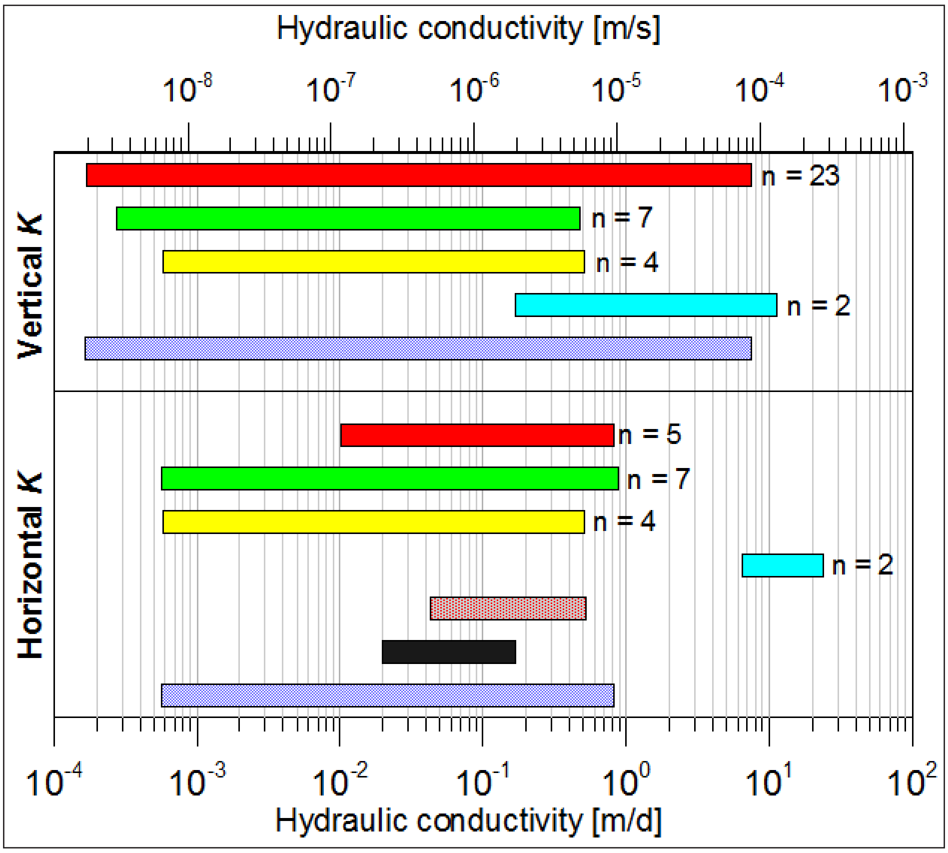


Figure 8. Hydraulic conductivity ranges for the Pliocene clayey layer (HCOV 0240) in the study area for different measurement methods, including the proposed ranges for use in groundwater modelling. Ranges from other sources are also given (Central Campine System (VMM, 2008a) and SAFIR 2 (ONDRAF/NIRAS, 2001). Same legend as in Fig. 6.

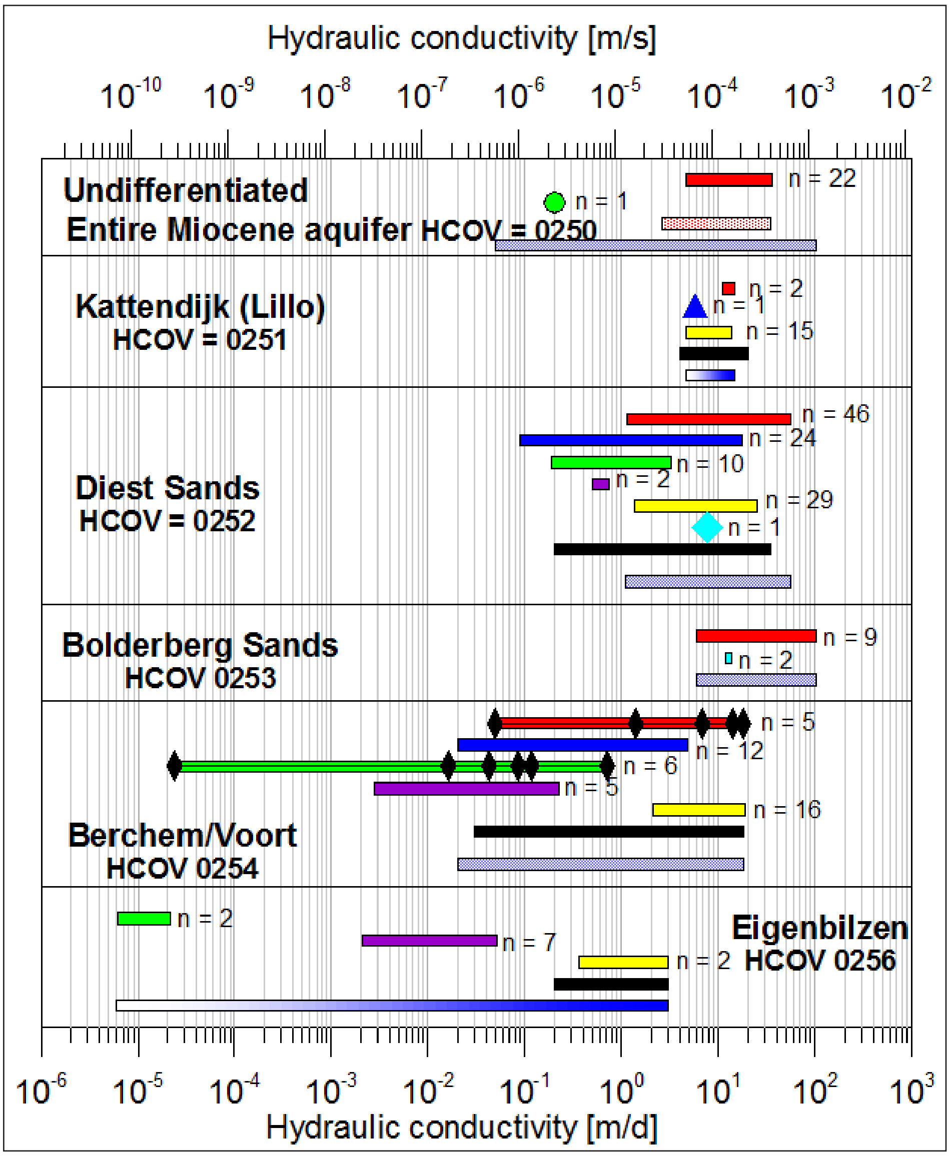


Figure 9. Horizontal hydraulic conductivity ranges for the Miocene aquifer system in the study area for different measurement methods, including the proposed ranges for use in groundwater modelling. Separate measurements are denoted by black diamonds. Ranges from literature are also given (Central Campine System (VMM, 2008a) and SAFIR 2 (ONDRAF/NIRAS, 2001). Same legend as in Fig. 6.

unit and the different sub-units of the Pleistocene and Pliocene aquifer (HCOV 0230) are shown in Fig. 7. In the Mol Sands (HCOV 0232) and the Poederlee/Kasterlee Sands (HCOV 0234), the heterogeneity in the small-scale measurements (slug tests in former and permeameter data in both) is considerable. For the Brasschaat/Merksplas Sands (HCOV 0231) and the sandy top of Lillo (HCOV 0233), information on the *K*-values is scarce, as mostly less reliable data from granulometry are available for these units. The maximum hydraulic conductivity value tends to decrease from the top of the aquifer (Brasschaat/Merksplas Sands) towards the bottom (Poederlee/Kasterlee Sands). Ranges from SAFIR 2 (ONDRAF/NIRAS, 2001) and the VMM (2008a) for the entire aquifer and VMM (2008a) ranges for the subunits are well within the range of all measured values. Taking into account the pumping test values, we consider a horizontal hydraulic conductivity range between 0.1 and 46.1 m/d most suitable to use in conceptual groundwater modelling. As the pumping data for the different sub-units are scarce and because of the large range in pumping test data for the undifferentiated aquifer, we don't consider separate ranges for the different sub-units to use in conceptual groundwater models.

Hydraulic conductivity ranges for the Pliocene clayey layer (HCOV 0240) are given in Fig. 8. Similar ranges are obtained for the hydraulic conductivity measurements in vertical and horizontal direction. Moreover, the measured ranges are rather wide, spanning over three or more orders of magnitude. Because of the aquitard structure, documented by Beerten et al. (2010) and by Wouters & Schiltz (2012), in the eastern part of the Campine as a succession of clay and sand layers varying in each documented borehole, it is difficult to identify a representative measurement value. The small volume measurements (permeameter tests, granulometry) represent either the sandy layers or the clayey layers. Although the pumping tests theoretically represent the entire layer, they have only limited validity. Different pumping tests performed in the vicinity of Mol in the framework of the cAt project (Meyus & Helsen, 2012) could only estimate the upper bound *K* values, as no drawdown was observed across this formation. The true hydraulic conductivity could therefore be considerably lower. The air permeameter value is larger than most values obtained by the other methods. This is probably due to the fact that this measurement was taken at the outcrop of a weathered formation (Rogiers et al., 2013).

Ranges from SAFIR 2 (ONDRAF/NIRAS, 2001) and the VMM (2008a) for the entire Pliocene clayey layer are within the measured ranges, the latter being however considerably wider than the literature ranges. However, as already stated before, one has to be careful with the pumping test values and also the permeameter values, which are not representative of the whole layer. Ranges for use in large-scale groundwater models, are based on the upper bounds of the pumping test values (table 3, Fig. 8) and the lower bound values using all measurement methods, i.e. $1.68\times10^{-4} < K_v < 7.6$ m/d and $5.7\times10^{-4} < K_h < 0.82$ m/d.

Hydraulic conductivity ranges for different sub-units of the Miocene aquifer (HCOV 0250) are shown in Fig. 9. The deepest layers within this aquifer - Berchem/Voort (HCOV 0254) and Eigenbilzen (HCOV 0256) - feature lower hydraulic conductivity values than the upper layers. In these two units, the permeameter tests generally yield lower values than slug tests or pumping tests, which is probably a consequence of their limited representative volume and an indication of the aquifer's heterogeneity.

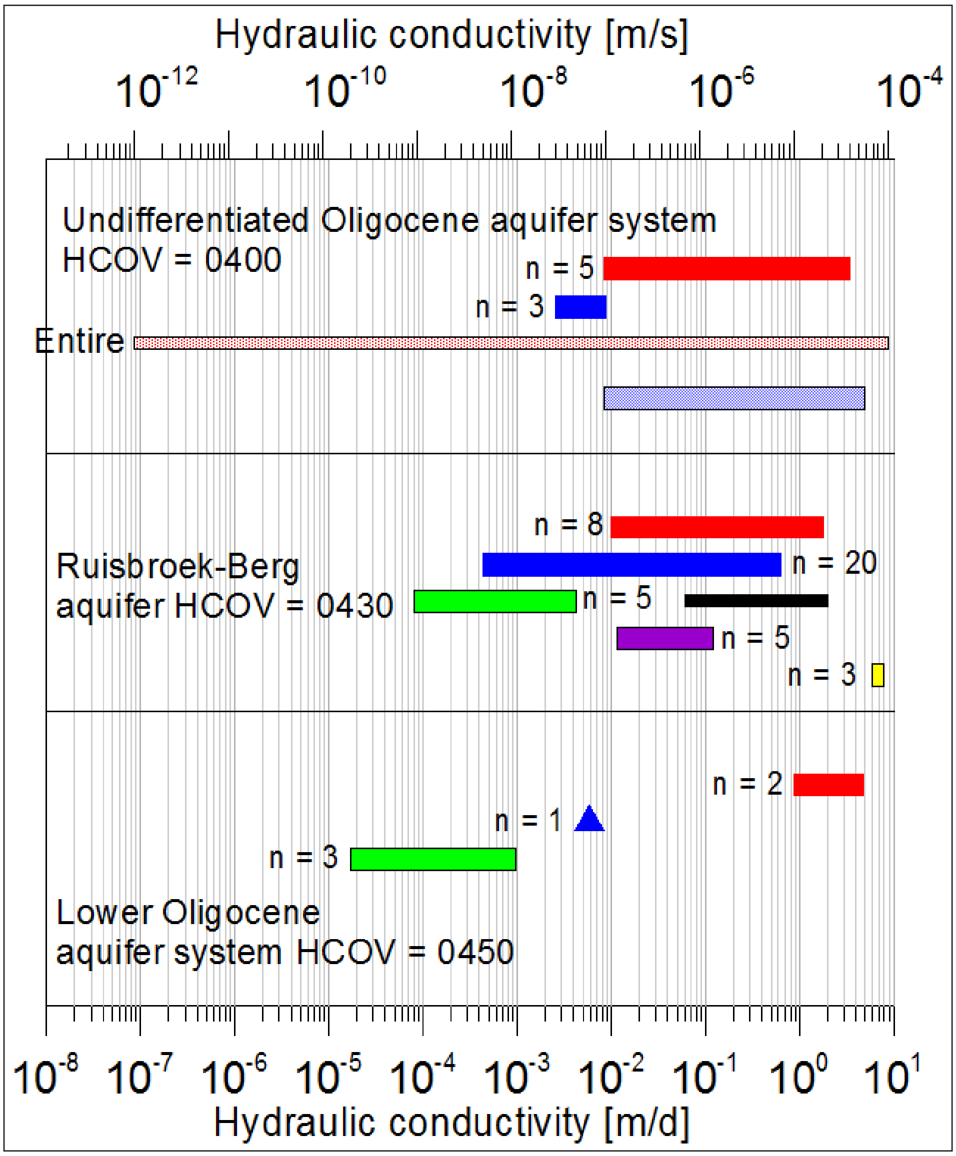
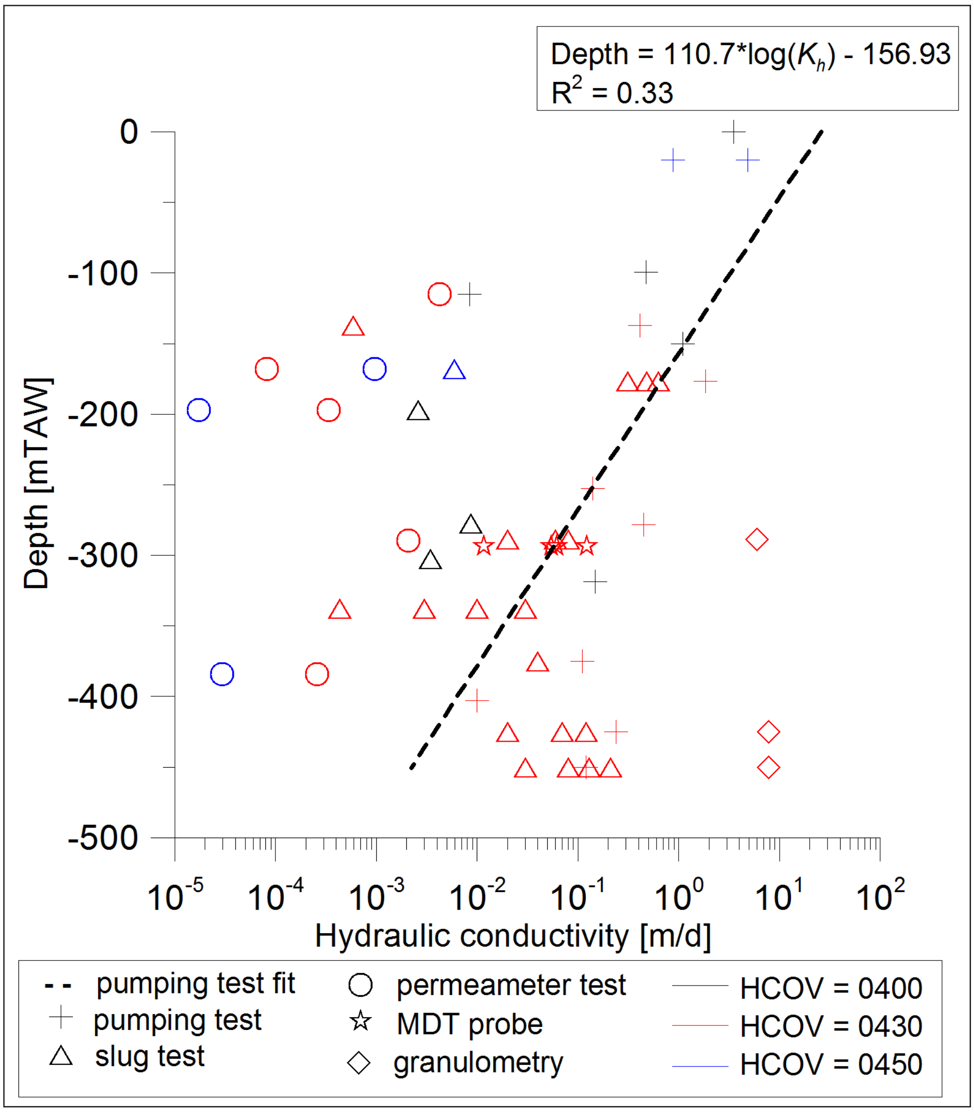


Figure 10. Horizontal hydraulic conductivity ranges for the Oligocene aquifer system (HCOV 0400) using different measurement methods, showing the number of measurements per method (n), including the proposed range for use in groundwater modelling. Ranges from other sources include values documented in Brulandkrijt System (VMM, 2008b) and SAFIR 2 (ONDRAF/NIRAS, 2001). Same legend as in Fig. 6.

Figure 11. Measured horizontal hydraulic conductivity [m/d] against measurement depth for the Oligocene aquifer system. The pumping test data are fitted using a linear function of log(K_h) versus depth.



Ranges from SAFIR 2 (ONDRAF/NIRAS, 2001) for the entire Miocene aquifer are rather narrow compared to the current measurement ranges for the different sub-units. Ranges from the VMM (2008a) for the different sub-units correspond well with the measured ranges, except for the Berchem/Voort (HCOV 0254) and Eigenbilzen Formations (HCOV 0256), where some measurement values from the MDT-probe and permeameter tests lie far below the values from VMM. Recommended *K*-ranges for use in groundwater models were derived as follows (Fig. 9):

For the entire Miocene, we take the range of all available pumping test data (0.05 < K_h < 104.5 m/d), while for the sub-units Diest Sands (HCOV 0252) and Bolderberg Sands (HCOV 0253) we take the range of pumping test data belonging to each sub-unit, respectively 1.1 < K_h < 54.9 m/d and 6.0 < K_h < 104.5 m/d. The range of the undifferentiated Miocene most probably corresponds to values from the Diest Sands as this is the most important aquifer of the Miocene;

For the Kattendijk Sands (HCOV 0251), we only consider an upper limit, derived from all measurements as few pumping test data are available and the granulometry data most likely give values in the upper hydraulic conductivity range: K_h < 14.8 m/d. For the Berchem/Voort Sands (0254), the upper and lower limits of the pumping test and the slug test data are chosen when determining a parameter range for use in groundwater models, as the number of pumping test measurements is limited to 5, resulting in 0.02 < K_h < 18.5 m/d. For the Eigenbilzen Formation (HCOV 256), we only consider an upper limit derived from the granulometry data as no pumping test data are available and the granulometry data most likely give values in the upper hydraulic conductivity range: K_h < 3 m/d.

4.2. Hydraulic conductivity of the deep aquifer system units

In the Campine subsurface the amount of knowledge on the hydraulic properties of the deep aquifer system units decreases with depth. Most information has been gathered on the Boom Clay and the units immediately below it: Oligocene aquifer system, Bartonian aquitard and Ledo-Paniselian-Brusselian aquifer system. As the units deepen towards the north-east, the available measurements lie usually close to the unit's outcrops at limited depths.

A summary of hydraulic conductivity ranges available for the deep aquifer system units is given in Table 4, based on available data from SCK•CEN, supplemented with data from other sources, summarized in the VMM database (2010) and in Wemaere & Marivoet (1995).

An extended synthesis of the available data on the hydraulic conductivity of the Boom aquitard (HCOV 0300) was done by Yu et al., 2013. Throughout the years, the Boom Clay hydraulic conductivity *K* has been determined in several ways and at several scales (Yu et al., 2013): laboratory experiments (permeameter, percolation experiments), small-scale and large-scale in situ tests at the HADES Underground Research Facility in Mol. The results of the various lab-experiments and in situ measurements in Mol at different scales (summarized in Yu et al., 2013) yielded consistent hydraulic conductivity values.

The regional variability of the Boom Clay hydraulic conductivity was studied by regional borehole investigations in the Campine area, including the Doel, Zoersel, Mol, Weelde and Essen boreholes (Yu et al., 2013; Jeannée, 2012). For each borehole, the vertical and horizontal hydraulic conductivity were measured experimentally using laboratory experiments on clay cores which were sampled over the entire Boom Clay profile at

Table 4. Summary of hydraulic conductivity values in the deep aquifer system units.

HCOV unit		Measured values [m/d]		Groundwater Modelling range [m/d]		Literature values [m/d]	
		K_h	K_v	K_h	K_v	K_h	K_v
Boom aquitard (0300)	Entire Boom aquitard	1.1×10^{-6} – 4.1×10^{-5}	2.4×10^{-7} – 6.9×10^{-6}	1.1×10^{-6} – 4.1×10^{-5}	2.4×10^{-7} – 6.9×10^{-6}	10^{-7} – 10^{-5}†	
	Boeretang (0301)	4.3×10^{-7} – 3.0×10^{-6}	2.4×10^{-7} – 1.5×10^{-6}	4.3×10^{-7} – 3.0×10^{-6}	2.4×10^{-7} – 1.5×10^{-6}		8.6×10^{-8} - 8.6×10^{-6} §
	Putte + Terhagen (0302, 0303)	4.3×10^{-7} – 1.5×10^{-6}	2.0×10^{-7} – 6.5×10^{-7}	4.3×10^{-7} – 1.5×10^{-6}	2.0×10^{-7} – 6.5×10^{-7}	2.6×10^{-7} – 8.6×10^{-7} §	6×10^{-8} - 6×10^{-7} §
	Belsele-Waas (0304)	1.7×10^{-6} – 2.9×10^{-4}	5.8×10^{-7} – 6.7×10^{-5}	1.7×10^{-6} – 2.9×10^{-4}	5.8×10^{-7} – 6.7×10^{-5}		8.6×10^{-8} – 8.6×10^{-5} §
Oligocene aquifer system (0400)	entire/undifferentiated aquifer (0400)	1.16×10^{-6} – 7.8 (without HCOV 0440)		8.5×10^{-3} – 4.9 (without HCOV 0440)		10^{-7} – 8.64§	
	Ruisbroek-Berg aquifer (0430)	8.2×10^{-5} – 7.8				0.06 – 2†	
	Tongeren aquitard (0440)	1.2×10^{-6} - 2×10^{-4}	7.9×10^{-7} - 2.8×10^{-5}				
	Lower Oligocene (0450)	1.7×10^{-5} – 4.9					
Bartonian aquitard system (0500)	sandy (0502, 0504)	2.3×10^{-4} – 0.13				10^{-6} – 1.7†	
	clayey (0501, 0503, 0505)	7.3×10^{-8} – 6.2×10^{-5}	1.1×10^{-7} – 1.1×10^{-4}	7.3×10^{-8} – 6.2×10^{-5}	1.1×10^{-7} – 1.1×10^{-4}	10^{-8} – 10^{-4} †	
Ledo-Paniselian-Brusselian aquifer system (0600)	unconfined	0.8 – 75.0		0.8 – 75.0		0.6 – 6.7† 0.864 – 43.2§	
	semi-confined	0.4 – 6.5		0.4 – 6.5		0.864 – 43.2§	
	confined	2.1×10^{-5} – 0.4		< 0.4		4.32×10^{-5} – 0.432§	

§SAFIR 2 (ONDRAF/NIRAS, 2001); †VMM (2008b)

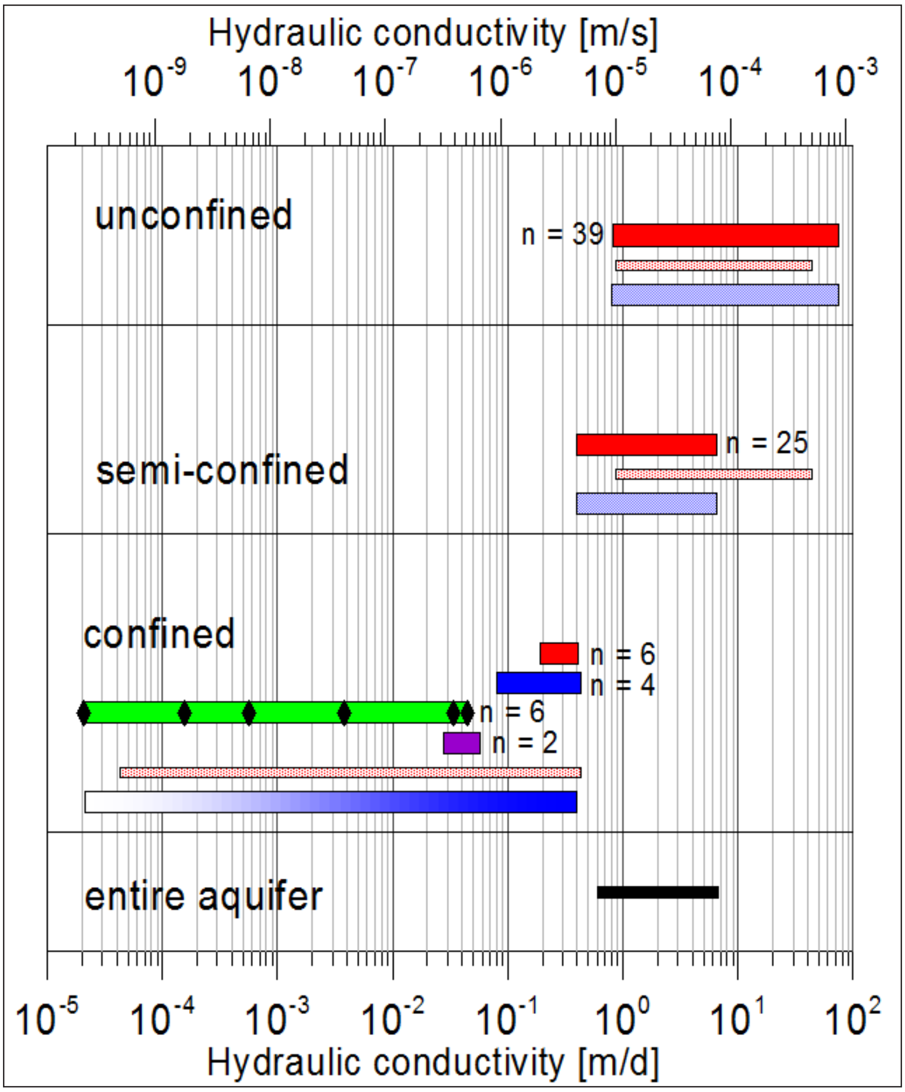


Figure 12. Horizontal hydraulic conductivity ranges for confined, semi-confined and unconfined parts of the Ledo-Paniselian-Brusselian aquifer system (HCOV 0600) using different measurement methods, showing the number of measurements (n), including ranges for use in groundwater modelling. Separate measurements are given with black diamonds. Ranges from other sources include VMM (2008b) and SAFIR 2 (ONDRAF/NIRAS, 2001). Same legend as in Fig. 6.

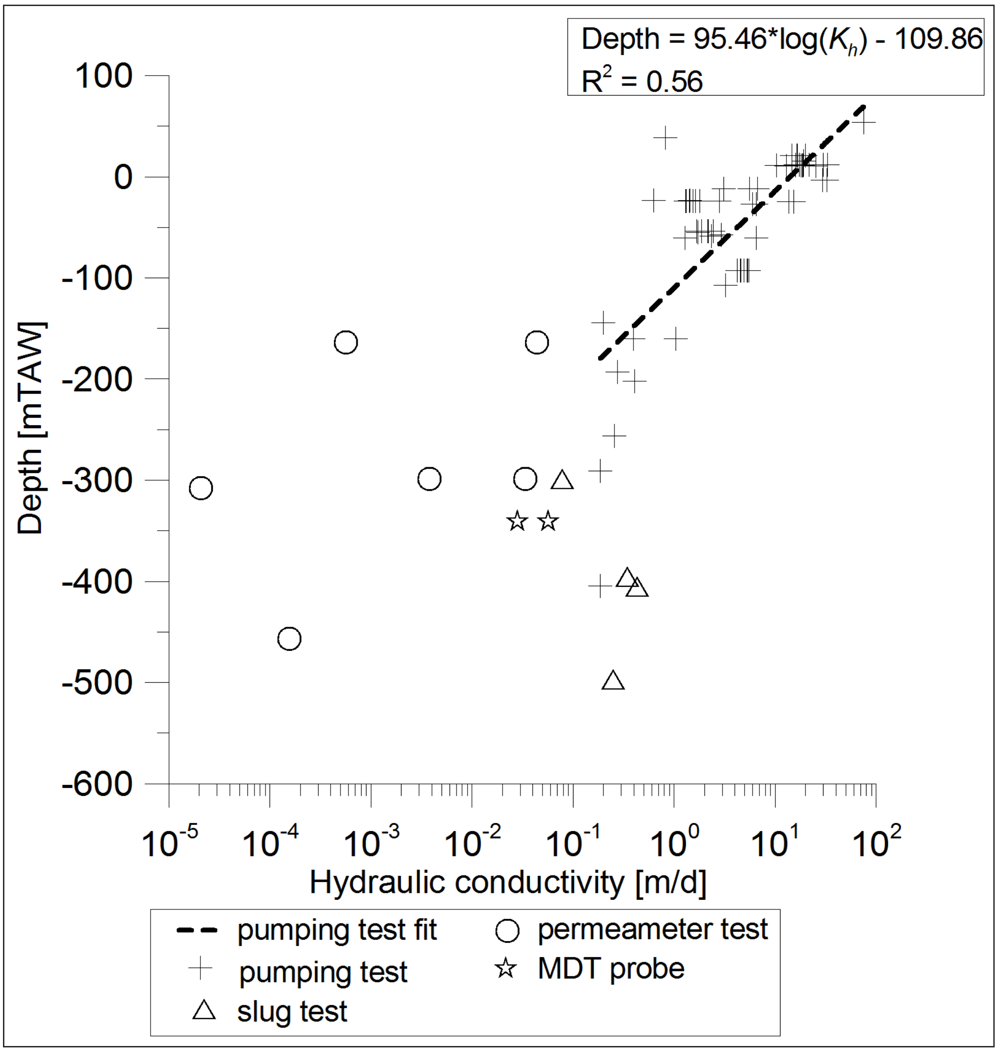


Figure 13. Measured horizontal hydraulic conductivity [m/d] against measurement depth for the Ledo-Paniselian-Brusselian aquifer system. The pumping test data are fitted using a linear function of $\log(K_h)$ versus depth.

a vertical spatial resolution of 1-2 m. The measurement ranges calculated from these cored boreholes are shown in Table 4. Measurement ranges are in good accordance with VMM (2008b) and SAFIR 2 (ONDRAF/NIRAS, 2001) ranges. As for the Boom Clay consistent hydraulic conductivity values were obtained in Mol using different measurement techniques, we consider the ranges derived from the regional boreholes using laboratory measurement techniques as ranges to use in groundwater modelling.

The Oligocene aquifer system (HCOV 0400) is quite heterogeneous. It is often referred to as the Ruisbroek-Berg aquifer because of the rather more permeable nature of these two aquifers, belonging respectively to the Zelzate and Bilzen Formations. In the Campine, the Oligocene aquifer system is generally little exploited, mainly due to its low transmissivity and its increased salinity towards the north-west of the region (De Craen et al., 2012). However, towards the outcrop of the Boom Clay, some important groundwater abstractions are present.

Hydraulic conductivity ranges for different parts of the Oligocene aquifer system are shown in Fig. 10: the Ruisbroek-Berg aquifer (HCOV 0430) and the Lower Oligocene aquifer system (HCOV 0450). Low hydraulic conductivity values of the Tongeren Aquitard (HCOV 0440; Watervliet Clay (HCOV 0442) in particular) are not included as only three (permeameter) K_h-values (and K_v-values) are available for the latter unit (1.2×10^{-6}, 3.4×10^{-6} and 2×10^{-4} m/d respectively). The measurements are organized according to the sub-unit (if available) and according to the measurement method that was used. The HCOV 0400 unit (undifferentiated Oligocene aquifer) includes measurements that were not assigned to any particular unit. There are no large differences between the measured ranges of the different layers within the aquifer system. The pumping tests are mainly single-borehole tests, which are less reliable than multiple-well tests. Ranges documented in SAFIR 2 (ONDRAF/NIRAS, 2001) are very broad compared to measurement ranges. The presence of very low values in the SAFIR 2 range indicates inclusion of the aquitard values of the Watervliet Clay (HCOV 0442), which were filtered out in this analysis. The VMM-range (2008b) includes mainly high values. In general, permeameter tests yield lower values than slug tests or pumping tests. This is probably an indication of considerable heterogeneity within the Oligocene aquifer system.

Previous modelling studies at SCK•CEN assumed a decrease of hydraulic conductivity with depth for the deep aquifers (Gedeon & Wemaere, 2009; Vandersteen et al., 2012), resulting from increased compaction of the sediments with depth. This assumed depth-dependency of the hydraulic conductivity was explored in Fig. 11 for the Oligocene aquifer system. The reference depth used here is the base of the aquifer system at the location of the measurement. Considering all measurement data, horizontal hydraulic conductivity data show a broad range with no clear trend with depth. However, when fitting the pumping test data using a linear function of $\log(K_h)$ against depth, a decrease in horizontal hydraulic conductivity with depth is detected, with a correlation coefficient between measured and fitted data R^2 = 0.33.

As only limited pumping test data are available, ranges for use in groundwater models are only determined for the entire Oligocene aquifer system (Table 4), not including the clayey HCOV 0440 unit: $8.5\times10^{-3} < K_h < 4.9$ m/d. From the pumping test data, it was found that there is presumably a decrease with depth of the hydraulic conductivity.

The succession of sands and clays in the Bartonian aquitard system (HCOV 0500) forms a hydraulic barrier between the Oligocene aquifer system and the Ledo-Paniselian-Brusselian aquifer system. The heterogeneous components cause an important spatial variation in the representative hydraulic properties of this aquitard system. Only a limited number of horizontal hydraulic conductivity measurements for the sandy layers (HCOV 0502, 0504) are available for this unit (6 values derived from permeameter tests and one value from a pumping test). The horizontal hydraulic conductivity value in the unconfined part, based on a pumping test (K_h = 0.13 m/d), is considerably higher than the values in the confined parts coming from laboratory measurements. Due to limited data amount, no conclusion regarding a K value trend with depth could be made. For the clayey layers (HCOV 0501, 0503, 0505), 9 measurements are available from permeameter tests. The range of the measured K_v values (Table 4) is in good agreement with the range proposed by the VMM (2008b), while the range on the measured K_h values is smaller than the VMM range: the latter is stretched towards lower values, while the upper-range values are similar. As only very limited data are available, no reliable ranges for use in groundwater modelling are derived for the sandy layers, while for the clayey layers, we adopted the measurement range as a range for use in groundwater modelling ($1.1\times10^{-7} < K_v < 1.1\times10^{-4}$ m/d) under the assumption that – similar to the Boom Clay – small-scale permeameter data can give a good indication on the large-scale hydraulic conductivity for these clayey layers. However, because of the low number of measurements for such a complex clayey system, caution is advised when using these measurement ranges.

The Ledo-Paniselian-Brusselian aquifer system (HCOV 0600) is one of the main aquifers in NE-Belgium, with numerous pumping wells located south of the rivers Demer and Dijle. More to the north, the water is too salty to be used as drinking water. Hydraulic conductivity ranges for different parts of the Ledo-Paniselian-Brusselian aquifer system are summarized in Fig. 12. Here, the measurements are subdivided according to their location in the unconfined, semi-confined or confined parts of the aquifer system and the measurement method. The hydraulic conductivity measurements are mostly available in the unconfined parts of the aquifer (areas where both confining Formations of Boom and Maldegem are absent). In general, values in the unconfined parts are higher than values in the confined or semi-confined parts (near the outcrop) of the aquifer system, which is most likely due to compaction of the sediments at larger depth. Note that in the confined parts of the aquifer, different measurement methods were used to obtain the hydraulic conductivity (slug tests, pumping test, MDT-probe and permeameter tests), while in the unconfined and semi-confined parts, only pumping tests are available. The range of the measurements in the confined part spreads over four orders of magnitude in the permeameter test data, while the measured values are well distributed within the range. This most probably indicates local heterogeneity of the aquifer. The pumping tests in the deeper parts of the aquifer are mainly single-borehole tests,

HCOV Unit			Range groundwater modelling [m/d]		Reliability assessment for range [m/d]	
Unit	Sub-unit	Basic unit	K_h	K_v	K_h	K_v
Quaternary aquifer Systems (0100)	Meuse- and Rhine deposits (0170)		31 – 6047		good	
Campine aquifer System (0200)	Campine clay-sand complex (0220)		3.5 – 22.4	2.5×10^{-5} – 0.03	Good (based on the sandy layers)	- fair - Wide range, possibly related to difficulties in pumping test interpretation
	Pleistocene and Pliocene (0230)		0.1 – 46.1		- good - decrease in K_h from top to bottom of aquifer	
	Pliocene Clayey layer (0240)		5.7×10^{-4} – 0.82	1.68×10^{-4} – 7.6	- fair - unreliable result of pumping test	
	Miocene (0250)	entire	0.05- 104.5		good	
		Kattendijk (0251)	< 14.8			
		Diest (0252)	1.1 – 54.9			
		Bolderberg (0253)	6.0 – 104.5			
		Berchem/Voort (0254)	0.02 - 18.5			
		Eigenbilzen (0256)	< 3.0		- fair - only upper bound based on granulometry data	
Boom Aquitard (0300)		entire Boom aqt.	1.1×10^{-6} – 4.1×10^{-5}	2.4×10^{-7} – 6.9×10^{-6}	good, although based on small-scale laboratory tests	
		Boeretang (0301)	4.3×10^{-7} – 3.0×10^{-6}	2.4×10^{-7} – 1.5×10^{-6}		
		Putte + Terhagen (0302, 0303)	4.3×10^{-7} – 1.5×10^{-6}	2.0×10^{-7} – 6.5×10^{-7}		
		Belsele-Waas (0304)	1.7×10^{-6} – 2.9×10^{-4}	5.8×10^{-7} – 6.7×10^{-5}		
Oligocene aquifer system (0400)	sandy part (without HCOV 0440)		8.5×10^{-3} – 4.9		- good - possible decrease of K_h with depth: Depth = 110.7*log(K_h) – 156.93 (depth in m TAW; K_h in m/d)	
Bartonian aquitard (0500)	clayey part		7.3×10^{-8} – 6.2×10^{-5}	1.1×10^{-7} – 1.1×10^{-4}	- fair - based on limited amount of small-scale permeameter tests	
Ledo-Paniselian-Brusselian aquifer system (0600)	unconfined		0.8 – 75.0		good	
	semi-confined		0.4 – 6.5		good	
	confined		< 0.4		- good - only upper bound value (lack of pumping data in deeper parts of aquifer) - decrease of K_h with depth (valid for depth > -300 m TAW): Depth = 95.46*log(K_h) –109.86 (depth in m TAW; K_h in m/d)	

Table 5. Summary of groundwater modelling ranges for the different aquifers including a reliability assessment.

which are less reliable than multiple-well tests. The ranges from SAFIR 2 (ONDRAF/NIRAS, 2001) are in good agreement with the measurement ranges. Ranges from the VMM (2008b) are only appropriate for the unconfined and semi-confined parts.

The assumed depth dependency of the hydraulic conductivity data is further explored in Fig. 13. The reference depth used here is the base of the aquifer system at the location of the measurement. The hydraulic conductivity data from the pumping tests were fitted against depth (Fig. 13). Until a depth of -200 m, a linear decrease of log(K_h) with depth with a correlation coefficient R^2 = 0.56 was found. For larger depths, the hydraulic conductivity does not show a clear decrease with depth. However, pumping data are scarce at these depths. Measurements from permeameter tests in general yield lower values in a broad range showing no clear trend with depth. This indicates rather the aquifer heterogeneity than the depth dependency.

Ranges for use in groundwater modelling are derived for the unconfined and semi-confined parts of the aquifer based on the available pumping test data (Table 4, Fig. 12), respectively $0.8 < K_h < 75$ m/d and $0.4 < K_h < 6.5$ m/d. For the confined parts of the aquifer, only an upper bound value is given as pumping test data are limited, especially in the deeper parts of the aquifer $K_h < 0.4$ m/d. From the pumping test data, it was found that there is decrease with depth of the hydraulic conductivity at least until a depth of -200 m.

4.3. Discussion on ranges for use in groundwater modelling

The summary of the obtained ranges for use in groundwater modelling supplemented with an assessment on their reliability is given in Table 5.

For the hydrogeological layers above the Boom aquitard, we were able to derive reliable ranges for most HCOV sub-units, except for the Quaternary aquifer systems (HCOV 0100) and the clayey layers of the Campine aquifer system (Campine clay-sand complex HCOV 0220 and Pliocene clayey layer HCOV 0240). For the Quaternary aquifer systems, we could only give ranges for the Meuse and Rhine deposits (HCOV 0170). However, as these Quaternary aquifer systems are often unsaturated or partly saturated, their relevance for groundwater modelling is in many cases not very large. For the heterogeneous clayey layers above the Boom aquitard (HCOV 0220 and HCOV 0240), the deduced values are less reliable mainly because of difficulties in pumping test interpretation in these layers. For the Miocene aquifer system (HCOV 0250), representing the most important aquifer of the Neogene, reliable ranges could also be found for most basic units, except for the Eigenbilzen unit (HCOV 0256).

For the Boom aquitard and the deeper hydrogeological layers, reliable ranges could be derived for the large units, except for the Bartonian aquitard system (HCOV 0500), where only less-reliable *K*-values could be deduced for the clayey part and no ranges could be given for the sandy layers, because of lack of measurement data. For the Oligocene aquifer system (HCOV 0400), reliable ranges could be derived for the sandy part, excluding the Tongeren aquitard (HCOV 0440), for lack of measurement data in the latter. Considering the available pumping test values, a possible decreasing K_h-value with depth was found for this aquifer.

For the Ledo-Paniselian-Brusselian aquifer system (HCOV 0600), reliable values for different parts of the aquifer could be derived: unconfined, semi-confined and confined. However, for the latter, only an upper bound value was given because of lack of data in the deeper parts of the aquifer. It was found that the K_h values are decreasing with depth in this aquifer system.

As a conclusion, we can state that for the aquifers above the Boom Clay reliable ranges are available at a detailed scale that can be used as initial values in groundwater models. For the more clayey layers, the deduced ranges are less reliable. For the deeper aquifers below the Boom aquitard, data are scarcer and reliable ranges could only be derived for large aquifer entities. Information on *K*-values on more clayey parts (HCOV 0440, 0500) and on the sandy parts of the Bartonian aquitard system (HCOV 0500) is very scarce.

5. Conclusions

The hydro-stratigraphy of the Campine hydrogeological system is described in detail and summarizes the available measured hydraulic properties of each hydrogeological layer, ranging from the Quaternary until the Ledo-Paniselian-Brusselian aquifer system. The measurement ranges are compared to the ranges from the SAFIR 2 scientific summary report on the disposal of high- and intermediate level radioactive waste in clays, and the ranges of the Central Campine and the Brulandkrijt Groundwater Systems of the Flemish Environmental Agency (VMM). For the Neogene aquifer, numerous hydraulic property data are available in the vicinity of the nuclear zone of Mol-Dessel. However, at a regional scale, much less data have been collected so far. For the Oligocene and Ledo-Paniselian-Brusselian aquifer systems, data with a good spatial spread are available in the Campine region. However, the number of data decreases with increasing depth.

Besides parameter ranges taking into account all measurement methods, ranges were derived for use (as initial values) in groundwater modelling. These ranges were mainly derived based on the pumping test data as these are the most compatible with groundwater flow modelling. The other measurement methods provide additional information, in the sense that they give an indication on the heterogeneity of the aquifer. For the aquifers above the Boom Clay, reliable ranges are available at a detailed scale that can be used as initial values in groundwater models. For the more clayey layers, reliable *K*-values are scarce. For the deeper aquifers below the Boom Clay, data are scarcer and reliable ranges could only be deduced for large aquifer entities. A relationship of hydraulic conductivity versus depth was suggested for the Oligocene and the Ledo-Paniselian-Brusselian aquifer system. Information on *K*-values of the Bartonian aquitard (HCOV 0500) is very scarce.

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