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MODELLING OF DENSITY DEPENDENT GROUNDWATER FLOW IN THE SOUTH-WESTERN BELGIAN COASTAL PLAIN

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Abstract

The Belgian coastal plain provides an excellent opportunity to study the development of fresh water lenses. Aquifer heterogeneity and human interference such as land reclamation determine the distribution of fresh and salt-water. Before the land reclamation the Belgian coastal plain was a tidal flat and the groundwater reservoir was mainly filled with salt-water. From around 1100 AD, with the completion of land reclamation, this salt-water was replaced by fresh-water leading to the now observed groundwater quality distribution. The heterogeneous distribution of peat, clay, silt and sand influences the general flow and distribution of fresh and salt-water along with the drainage pattern and results in the development of fresh-water lenses. These fresh-water lenses were surveyed in the polder 'Noordwatering Veurne' situated on the west bank of the IJzer river in the western Belgian coastal plain. Data of a preliminary field survey and literature data were combined to make a 3D groundwater flow model of the area using the MOCDENS3D code. This model shows the 3D development of fresh-water lenses in a heterogeneous aquifer.

Keywords: fresh water lens, 3D modelling, water quality distribution, polder area

Introduction

Sediments of the Belgian coastal plain are of Quaternary age and consist of alternations of clay, sand, silt and peat deposited and formed in tidal flat environment. This leads to a heterogeneous groundwater reservoir having, together with important human interference, its influence on the nowadays observed distribution of fresh and salt-groundwater. Between 7500 and 5500 BP a mud flat environment, in which mud and salt marsh deposits formed, was present in the Belgian coastal plain. Tidal channels and gullies were incised in mainly clastic deposits (sand and clay) with local peat layers. From 5500 BP on, peat growth became more important because of a lower rate of sea level rise. Peat development locally continued to

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about 2000 BP. This was ended by renewed invasion of the sea in the coastal plain. Again, mud flat environments with many tidal channels and gullies developed. During this evolution, the groundwater reservoir was almost completely filled with salt-water. Evidence of human activity in the coastal plain is found from Roman times onward. Dikes were built as probably as early as the 10th century AD around some tidal channels. They served to protect the reclaimed land from influence of the sea. Also a dense network of drainage channels was constructed in the reclaimed areas. From the beginning of the 12th century most of the coastal plain was reclaimed. From then on only fresh-water could enter the groundwater reservoir and the older salt-water was gradually replaced with this fresh-recharge-water. Thereby, fresh-water is found in lenses in the former tidal channels and gullies and salt-water in the adjacent areas. This has different reasons. First, the former tidal channels and gullies consist of permeable sandy deposits whereas the adjacent areas consists of less permeable clay, silt and or peat deposits. Secondly, the tidal channel deposits are generally (± 1 to 2 meter) higher in relief, principally due to the different compaction properties of the sediments. Therefore, the term tidal channel ridge is often used. Finally, due to the difference in drainage intensity between the tidal channel ridges and the adjacent areas, which is already a consequence of the constitution of their subsoil and of their elevation, the tidal channel ridges are less intense drained than the adjacent less permeable areas.

Because of its Quaternary geological history and the amount of (hydro)geological data available (e.g. a map showing the depth of the 1500 mg/L total dissolved solids (TDS) contour line for the entire coastal plain presented by De Breuck et al. (1974) and numerous other local studies) the Belgian coastal plain provides an excellent opportunity to study the development of fresh water lenses. Recent work consisted of surveying the groundwater quality around a major tidal channel ridge in the eastern Belgian coastal plain (Vandenbohede and Lebbe, 2000). A 2D density dependent groundwater flow model of this channel was made (Vandenbohede and Lebbe, 2002a; Vandenbohede, 2003) showing the development of water quality distribution in and around the channel. In this work water quality evolution and groundwater flow in and around fresh-water lenses is studied using a 3D density dependent numerical model. The influence of drainage channels will also be shown.

Study area and field work

The study area is located in the western Belgian coastal plain (Figure 1). It is bounded in the east and the south by the Ijzer river. The groundwater reservoir consists of Quaternary sand, silt, clay and peat deposits bounded below by Paleogene deposits of the Kortemark Member (Formation of Tielt) and the Aalbeke Member (Formation of Kortrijk). These are clay and siltous sediments. A number of old Quaternary tidal channels run through the study area. Their subsoil consists of permeable sandy deposits. Adjacent deposits are less permeable silt, clay and peat sediments.

Linster (2003) made fieldwork to supplement literature and the archival data of the area. Seven rotary drillings were performed. Four wells were grouped on a tidal channel ridge allowing the performance of a pumping test. Geophysical borehole measurements were made in all wells. Therefore, a focussed electromagnetic induction tool (EM39, Geonics©) was used. The EM39 is especially designed for use in wells encased with electrical non-conductive materials. EM39 measures the electrical conductivity of the surrounding soil within a distance ranging from 20 to 100 cm from the well axis while being insensitive to

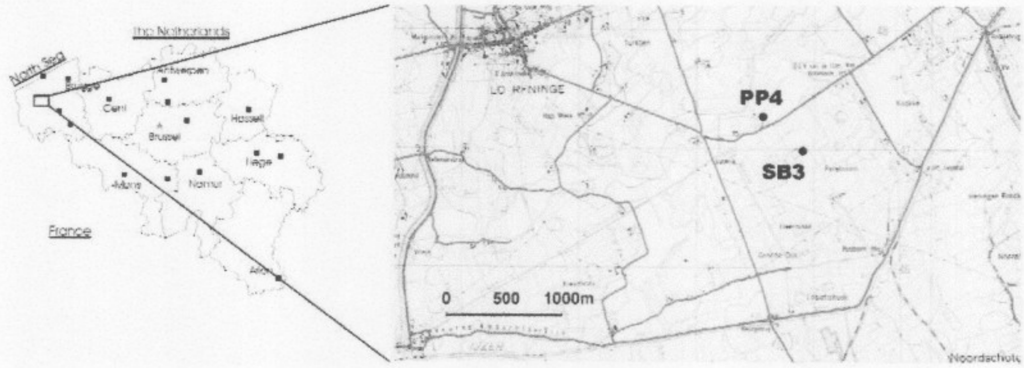

Figure 1. Localisation of the study area.

conductivity of the borehole fluid and disturbed material situated near the well axis. The vertical resolution is 20 centimetres. This makes it an excellent tool to study the distribution of fresh and salt-water around observation wells. More detailed discussion of the EM39-tool can for instance be found in McNeil (1986) and Vandenbohede and Lebbe (2002b). Moreover, measured electrical conductivities can be easily recalculated to total dissolved solids content (TDS) of the pore water (Van Meir and Lebbe, 2002). Figure 2 shows two examples of EM39 measurements in PP4 and SB3. PP4 is located on a tidal channel ridge. Low electrical conductivities are measured indicating that the groundwater reservoir is filled with fresh water. Based on EM39 measurements, a mean TDS of 1000 mg/L is derived for PP4. Large conductivities below –3 mTAW are due to the Paleogene clayey and silteous deposits and do thus not reflect pore water chemistry. SB3 is situated in the adjacent less permeable sediments. High conductivities are measured meaning that the sediments are filled with salt-water. Based on EM39 measurements, a mean TDS of 14000 mg/L is derived.

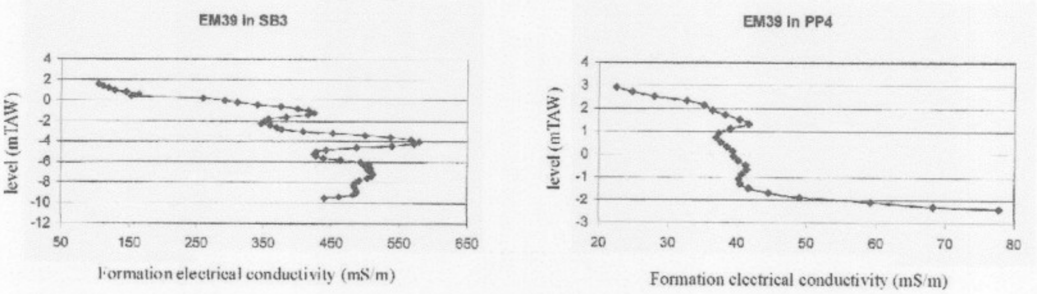

Figure 2. EM39 measurements in PP4 and SB3 (Linster, 2003).

A pumping test was performed on the tidal channel ridge aiming to derive its hydraulic conductivity. The pumping test was interpreted using the inverse numerical model of the HYPARIDEN program package (Lebbe, 1999). A horizontal hydraulic conductivity of 4.09 m/d and a vertical conductivity of 0.31 m/d were deduced.

3D simulation with MOCDENS3D

MOCDENS3D (Oude Essink, 1998, 2001) is used here. It is based on the three-dimensional solute transport computer code MOC3D (Konikow et al., 1996), but adapted for density differences. To simulate the flow, the groundwater reservoir is discretized in 64 columns and 53 rows, each with a width of 50 meters. So, the dimensions of the modelled area are 3.2 by 2.65 kilometres. Twelve layers with a thickness of 1,5 meter are used. The finite-difference grid contains thus 40704 cells.

Distinction is made between the permeable tidal channels and adjacent less permeable sediments. To do this for the modelled area, results of recent fieldwork (Linster, 2003), literature data and the soil map were used. Sandy deposits are present from layer one to the layer just above the Paleogene deposits in the old tidal channels. Its horizontal and vertical hydraulic conductivity was derived with the pumping test. The adjacent less permeable layers were schematised as follows: clay layer (model layer 1), peat layer (layers 2 and 3) and clay (layers 4 to layer above the Paleogene sediments); its horizontal hydraulic conductivities are respectively 0.38 m/d, 0.13 m/d and 0.10 m/d. Anisotropy or the ratio of horizontal to vertical conductivity is 50. Depth and occurrence of the two members of the Paleogene deposits were derived from the geological map (Jacobs and De Ceukelaire, 2002) supplemented by the recent fieldwork. Horizontal conductivity of the Kortemark and Aalbeke Member are respectively 0.08 m/d and 0.0066 m/d and their anisotropy is put equal to 50.

The water table forms the upper boundary. The lower boundary is an impermeable one and is situated in the Paleogene deposits. The IJzer river forms in the east and south a constant head boundary in the first three layers. The constant head is 3.14 mTAW being the mean water level of the river (mTAW is the Belgian ordnance datum referring to mean low low water level, about 2.3 m below mean sea level). East and south boundaries for the other layers are impermeable ones. North and west boundaries are also impermeable. Recharge is 56 mm/year on the former tidal channels and 5.6 mm/year on the adjacent areas. Two major drainage channels cross the study area. Additionally, a dense network of smaller drainage channels is present. This drainage system was included using MODFLOW's drainage package. The drainage level of major channels is 2 mTAW and 2.25 mTAW for the smaller channels.

With the start of the simulation, the groundwater reservoir is completely filled with salt-water (TDS = 27000 mg/L). This reflects the situation before the land reclamation. Thereafter, only fresh-water can recharge and this fresh-water replaces the salt-water. The start of the simulation is set at 1100 AD after which the influence of the sea is considered minimal. The longitudinal dispersivity is 0.2 m and the horizontal and vertical transverse dispersivity are respectively 0.02 m and 0.01 m. Effective porosity is 0.38. These are based on experiences with similar models in the Belgian coastal plain. A total period of 900 years is simulated.

Discussion

Figure 3 shows a cross-section along column 25. Two major drainage channels are found in this cross-section, one in the northern part of the cross-section and one between the two tidal channels. During the first 400 years of the simulation the tidal channels salt-water is gradually replaced by fresh-recharge-water.

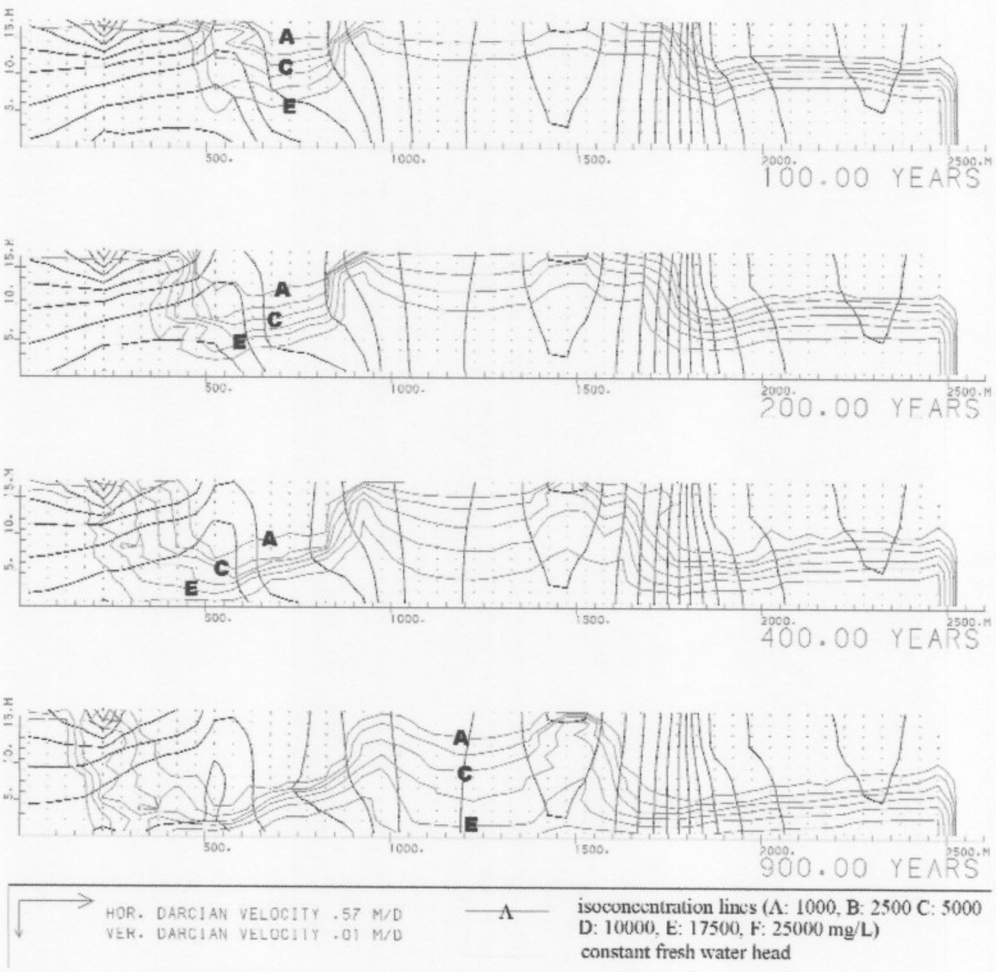

Figure 3. North-south cross-section along column 25 after 100 (1200 AD), 200 (1300 AD), 400 (1500 AD) and 900 (2000 AD) year simulation time. Lines of constant fresh water head are indicated together with isoconcentration lines and groundwater flow and its velocity using arrows.

This is not the case in the less permeable adjacent areas. In these zones salt-water is found up until today. Therefore fresh-water lenses are found in both the former tidal channels. This was also observed with the EM39 measurements. Groundwater velocities are also much faster in the former tidal channels and its immediate surroundings than in the adjacent less permeable deposits. Of note is the influence of the two major drainage channels. The drainage channel present between the two tidal channel ridges makes that the interface between fresh and salt-water is pushed upwards toward it. Salt-water is thus found shallower under the drainage channel than in its vicinity. Otherwise, a second drainage channel is present just north of a former channel ridge. This channel attracts fresh-water that recharges on the tidal channel ridge. Therefore, the less permeable sediments between the former tidal channel and the drainage channel are partially freshened.

Figure 4 shows a cross-section along row 17. Two tidal channel ridges with less permeable sediments in between are present in this cross-section. The eastern channel ridge illustrates the development of a typical fresh-water lens. Fresh-water recharges on the channel ridge and flows out on the transition between it and the adjacent area with less permeable sediments. The main flow direction in the centre of the fresh water lens is downward. An important drainage channel is present on the western channel ridge. Because of the drainage flow is directed towards the drainage channel in its immediate surroundings. This interferes with the development of the fresh-water lens. Therefore, an upconing of salt-water under the drainage channel is found. Notice also that the normal flow cycle in a fresh-water lens, downward flow in the centre and an upward flow along the edges, is here reversed.

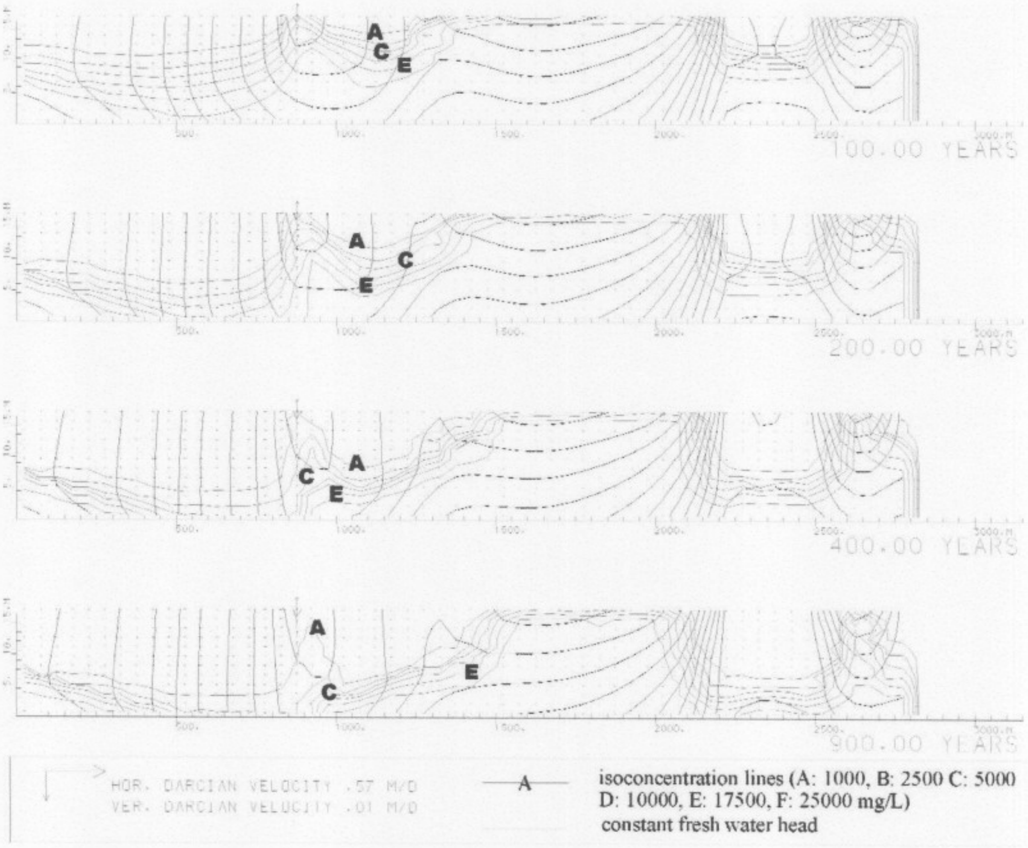

Figure 4. West-east cross-section along row 17 after 100 (1200 AD), 200 (1300 AD), 400 (1500 AD) and 900 (2000 AD) year simulation time. Lines of constant fresh water head are indicated together with isoconcentration lines and groundwater flow and its velocity using arrows.

Figure 5 shows water quality distribution, hydraulic head and groundwater flow in layer 2 after 900 years. This is thus the current situation just underneath the water table. Influence of lithology is obvious. Fresh-water is present in the channel ridges and salt and brackish-water in between. Groundwater flow velocities are largest in the tidal channel ridges and almost negligible small in the adjacent areas. The main drainage channels also influence flow. For instance, there is an important flow towards a drainage channel in the north-western quadrant of the model area. Fresh-water flows towards this channel in the permeable channel ridges circumventing the less permeable parts of the groundwater reservoir.

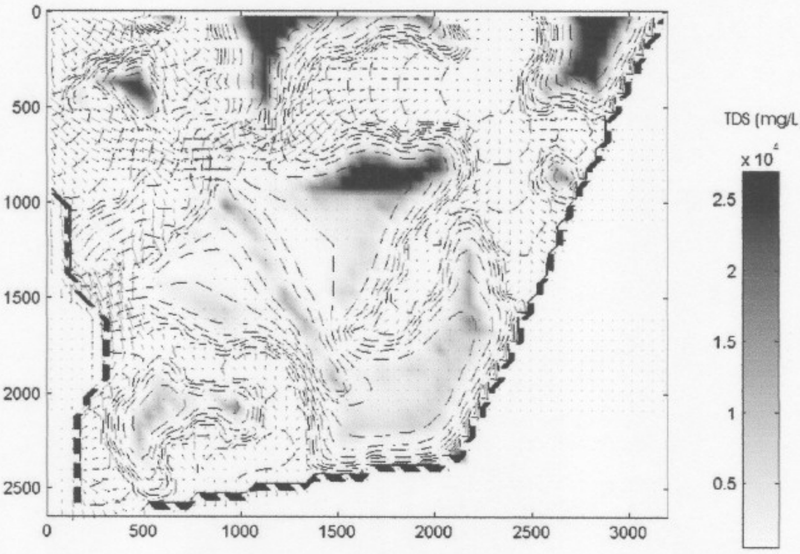

Figure 5. Water quality distribution, hydraulic heads (contour lines every 20 cm) and groundwater flow in layer 200 after 900 years (2000 AD).

Conclusion

In the Belgian coastal plain, the distribution of fresh and salt-water is influenced by the heterogeneity of the Quaternary groundwater reservoir (complex distribution of clay, silt, sand and peat) and by human intervention (land reclamation). Before the land reclamation, the groundwater reservoir was almost completely filled with salt-water. Afterwards, this salt-water was replaced by fresh-recharge-water. This led to the development of fresh-water lenses in the more permeable former tidal channels. Salt-water present between these channel ridges has not been replaced yet. This distribution was observed with geophysical borehole measurements (EM39) and the evolution was simulated with a 3D mathematical model using the MOCDENS3D code. The model also illustrated the influence of the drainage channels. An upconing of salt-water is present under drainage channels. In another case where the drainage channel is situated in the less permeable sediments close to a tidal channel ridge, fresh-water recharging on the channel ridge flows towards this drainage channel.

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