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On the validity of modeling concepts for (the simulation of) groundwater flow in lowland peat areas – case study at the Zegveld experimental field

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Abstract

The groundwater flow models currently used in the western part of The Netherlands and in other similar peaty areas are thought to be a too simplified representation of the hydrological reality. One of the reasons is that due to the schematization of the subsoil, its heterogeneity cannot be represented adequately. Moreover, the applicability of Darcy's law in these types of soils has been questioned, but this law forms the basis of most groundwater flow models.

With the purpose of assessing the typical heterogeneity of the subsoil and to verify the applicability of Darcy's law fieldwork was completed at a research site in the western part of The Netherlands. The assessments were carried for the so called Complex Confining Layer (CCL), which is the Holocene peaty to clayey layer overlying Pleistocene sandy deposits. Borehole drilling through the CCL with a hand auger was completed and revealed the typical heterogeneous character of this layer showing a dominance of muddy, humified peat which is alternated with fresher peat and clay. Slug tests were carried out to study the applicability of Darcy's law given that previous studies suggested the non validity for humified peat soils given by a variable hydraulic conductivity K with the hydraulic gradient. For higher humification degrees, the experiments indeed suggested a variable K , but this seems to be the result of the inappropriate use of steady-state formulae for transient experiments in peaty environments. The muddy peat sampled has a rather plastic nature, and the high compressibility of this material leads to transient behavior. However, using transient formulae, the slug tests conducted for different initial hydraulic heads showed that there was hardly any evidence of a variation of the hydraulic conductivity with the hydraulic gradient. Therefore, Darcy's law can be used for peat soils.

The heterogeneity of the subsoil and the apparent applicability of Darcy's law were taking into account for the detailed heterogeneous model that was prepared for the research site. A MODFLOW model consisting of 13 layers in which 4 layers represent the heterogeneous CCL was set up for an average year assuming steady state con-

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ditions and for the winter of 2009 to 2010 adopting transient conditions. The transient model was then extended for a whole hydrological year and for an eight year period with the objective of visualizing the flowpaths through the CCL. The results from these models were compared with a 10 layer model whereby the CCL is represented by a single layer assuming homogeneity. From the comparison of the two model types the conclusion could be drawn that a single layer schematization of the CCL produces flowpath patterns which are not the same but still quite similar to a 4 layer representation of the CCL. However, the single layer schematization results in a considerable underestimation of the flow velocity, and subsequently a longer travel time, through the CCL. Therefore, a single layer model of the CCL seems quite appropriate to represent the flow behavior of the shallow groundwater system, but would be inappropriate for transport modeling through the CCL.

1 Introduction

In the western part of The Netherlands there is a great need to understand the flow of groundwater in lowland peat areas and its interactions with surface water. Generally, in these areas, an aquitard consisting of peat and clay overlays a sandy Pleistocene aquifer. The aquitard or semi-permeable layer is often referred to as a Complex Confining Layer (CCL) (Bierkens (1994), Weerts (1996) and Dufour (2000)) due to its lithological and hydraulic heterogeneity. This layer which covers a large area of The Netherlands (around 1/3 of the country) plays an important role in the interactions of surface water and groundwater systems in the low lying parts of The Netherlands such as protecting groundwater from pollution.

The groundwater flow models currently used in peaty lowlands are likely a too simplified representation of the hydrological reality, because of the following two reasons:

1. The CCL is often represented as one model layer whereby different parameter values in this layer as a result of its heterogeneity are lumped together. In another

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2 Research site

The research site was located at an experimental field in the Zegveldbroek polder at approximately 2.5 km north of Zegveld, a small town in the province of Utrecht (Fig. 1). The site has the form of a parcel of land which is completely surrounded by ditches, and it has a surface area of 1.57 ha. The topography is very flat with land surface elevations averaging around -2.30 m below sea level. The grass covered soils receive a mean precipitation of 826 mm yr^{-1} and the potential mean evapotranspiration has been estimated at around 545 mm yr^{-1} . The precipitation surplus of about 280 mm yr^{-1} is recharging the shallow groundwater.

The CCL in the area is part of the Holocene layer. This CCL has a thickness of approximately 6 to 7 m. The lithology of the CCL is mainly dominated by peaty and clayey deposits which were deposited in an environment with slow moving meandering rivers where the peat grew in still waters at considerable distances from the main water courses and the clays originated from flood depositions. Clays of a marine origin are also present. Sand deposits occur as well and can be related to bed deposits of the ancient water courses. The Pleistocene below the Holocene consists of medium to coarse sandy deposits of considerable thickness (around 18 m). According to Bierkens (1994) and Weerts (1996) these sandy deposits, also referred to as the Kreftenheye Formation, were deposited during the Weichselian ice age and originated from braided river systems.

The research site is part of an area consisting of an extended network of ditches and canals to drain the polder areas in the winter season and to provide high groundwater tables during the dry summer. Thus, there is a strong interconnection between the groundwater and surface water. The organization responsible for water management in the area is the Water Board named Hoogheemraadschap de Stichtse Rijnlanden (HDSR).

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3 Field and laboratory work

To investigate the heterogeneity and anisotropy and the applicability of Darcy's law in groundwater flow modeling, a fieldwork program was defined and took place during the winter of 2009 to 2010. The fieldwork included drilling of two boreholes, about 150 m apart, through the CCL using a hand auger. Detailed sample descriptions of the collected soils were completed in the field. In addition, a geophysical survey was carried out in order to have more information on the aerial consistency of the layering detected during borehole drilling. The vertical electrical sounding (VES) method following the Schlumberger electrode layout was used.

Furthermore, slug tests were completed in 8 shallow boreholes to verify whether the hydraulic conductivity in the peat layers is constant or varies with the imposed hydraulic gradient. Through laboratory tests, the relation between the variability of the hydraulic conductivity and the decomposition degree of the peat layers would also be established. In the boreholes used for the slug tests peat samples were taken at different depths and the decomposition degree was determined according to the von Post method, the extracted carbon analysis technique and through the measurement of the absorbance (Price et al., 2005; Wang et al., 2004; Klavins et al., 2008).

Finally, time series of the groundwater levels were collected. The two boreholes penetrating through the CCL were equipped with piezometers. Other holes drilled up to the groundwater table and until halfway the CCL obtained piezometers as well. Pressure transducers installed in all the piezometers guaranteed a continuous set of time series of groundwater levels.

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4 Interpretation

4.1 Results of the field investigations

The soil descriptions showed a top layer of clayey and silty peat of around 1.5 m thickness. Below this layer the CCL consisted mainly of a highly moisturized, muddy material mixed with peat. In some places a lot of wood was present (Fig. 2). There were localized places where only peat was found. Below the mud layer, a peat layer mixed with mud and some wood was observed. Near the 5 m depth mark, a thin layer of clay was located in one of the boreholes, below a layer that consisted of a mixture of clay with peat (humic clay). At the depth of 6.3 to 6.5 m the sandy Pleistocene aquifer was found.

A cross sectional view through the CCL based on the soil descriptions at the two sites with both deeper and shallower boreholes indicates a continuity in lithology for most layers whereby the differences in layer thickness should be noted (see Fig. 3). However, not all the layers were found to be continuous as is demonstrated by the soil description of borehole 1, which had a muddy peat layer below the first layer that was not present at borehole 2. Underpinning this discontinuity is the isolated layer of peat detected in borehole 3 and the thin layer of clay that was observed in borehole 1. These layers are faded out at borehole 2. The substantial changes in lithology in the vertical direction and the discontinuity of layers in a lateral sense prove that the CCL is truly a very heterogeneous unit.

The geophysical VES measurement completed at the research site attained an investigation depth of about 20 m which is well into the sandy Pleistocene aquifer. The interpretation of the measurement allowed a 2-layer schematization of the CCL indicating layer thicknesses of 1.2 m and 6.5 m (see Fig. 4). These layers are thought to coincide with the first clayey/silty peat layer and the underlying mud and peat layer. The clay and clayey peat layers could not be differentiated due to the small thicknesses of these layers and to the fact that the latter layer contained a lot of peat. The resistivity contrast between the clay containing layers and the mud and peat layers was

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apparently small, which did not allow the interpretation of more layers. The third layer found in the measurement represents the sandy Pleistocene deposits. The VES interpretation shows that at this location in the middle of the research site the general lithological built up of the CCL is similar to the sites where the boreholes allowed a detailed layer description.

4.2 Validity of Darcy's law

The slug tests carried out at the research site to test the applicability of Darcy's law were first analyzed following methods based on steady state groundwater flow assuming a rigid system and negligible effects on the water table. The van Beers (1963) approach and the Hvorslev's method as suggested by Surridge et al. (2005) were selected. The steady state formula as formulated by Surridge can be expressed as follows:

$$K_h = -\frac{A}{Ft} \ln\left(\frac{h_t}{h_0}\right) \quad (1)$$

where K_h indicates the horizontal hydraulic conductivity (m d^{-1}), t is time (d), h_t (m) and h_0 (m) are respectively the head differences, caused by the removal of water, at time t and at the start of the test. The A and F are geometrical factors. Head differences are vertical distances measured between water levels during the test in the hole and the static water level in the soil. The formula shows that a plot of $\ln(h_t/h_0)$ against t produces a straight line since the other parameters in the expression are assumed to be constant.

Plots of $\ln(h_t/h_0)$ or level displacement against t for the research site do not produce straight lines at all sites. A curved line is shown for the slug test carried out in Borehole 5 where the tested material consisted of peat with a high degree of decomposition (Fig. 5). Several K_h values can be computed for different head differences (h_t/h_0) shown on the curve. This easily leads to the conclusion that Darcy's law is not applicable in peat areas since the K_h varies with the head differences in the system.

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Rather than contributing the phenomena to the non-applicability of Darcy's law, the “curved line behavior” could be attributed to the peat not being a rigid framework for groundwater flow. Peat is compressible and therefore a transient behavior of the soil can be expected during slug tests. The use of the traditional steady state formula should be avoided (Hinsby et al., 1992; Surridge et al., 2005) and instead transient formula have to be applied. Transient formulae to interpret slug tests in unconfined aquifers are hardly described in literature, but the KGS approach (Choi et al., 2008; Esling and Keller, 2009) and the Dax expression as suggested by Hinsby et al. (1992) can be considered.

The KGS approach is based on a semi-analytical model to estimate the storativity and the hydraulic conductivity of an unconfined aquifer for the transient situation. Dax simplified and approximated the transient Cooper method used for fully screened wells in confined aquifers for partially penetrating wells and applied this method to unconfined aquifers with delayed yield, assuming horizontal radial flow to the well. The Dax expression can be described as follows:

$$K_h = \frac{r_c^2 \cdot \ln(H_o/H_t)}{L \cdot t \cdot D(\alpha)} \quad (2)$$

where K_h is the horizontal conductivity (m d^{-1}), t is time (d), and H_t (m) and H_o (m) are head differences, following the injection of water, at time t and at the start of the test. The r_c and L are geo-metrical factors, and the $D(\alpha)$ is a variable also containing time t . The $D(\alpha)$ includes a term for the storativity S of the soil which represents the capacity for elastic storage depending on the compressibility of the material (Hinsby, 1992). The S can be obtained using the Cooper method when the unconfined aquifer is showing a delayed yield response.

Using steady state and transient formulae, K_h values were computed for the 8 shallow boreholes using a spreadsheet (Table 1). Level displacement against time t plots were prepared for all the holes. Five holes showed at least some “curvature” in the plot indicating compressible peat layers, but the other 3 holes produced “straight lines”

indicating sites where the soil material was apparently more rigid. The tests producing “curved lines” have been interpreted using the transient KGS and Dax methods, but for comparative reasons have also been analyzed using the steady-state van Beers and Hvorslev methods. The computed K_h values fall within the range of 0.1 to 1.6 m d⁻¹ which are normal values for peat land areas in The Netherlands (Weerts, 1996). The consistently lower values obtained with the KGS approach in relation to the Dax method may be due to the difficulty in determining accurate S values for the latter method.

A comparison can be made between the obtained K_h values, the compressibility at the site and the decomposition degree of the peat. The latter can be expressed using the von Post scale. The bore holes with higher conductivities and a higher compressibility interpreted with the transient KGS and Dax methods have a higher decomposition degree (Table 1: BH 5, 6, 9, 11, 12). Typically, these slug tests were carried out in well decomposed peat which has a muddy and plastic appearance containing besides peat also mineral components. The holes with lower conductivities and a more rigid soil analyzed with the steady state van Beers and Hvorslev formula have a relatively low decomposition degree (BH 7, 8, 10). These tests were carried out in more coherent soils made up of clay, silt and peat or where fresh, largely intact peat was found.

The inappropriate use of steady-state formula to interpret slug tests in compressible peat has led wrongly to the believe that Darcy’s law is not valid in these types of materials, but on the other hand full prove has also not been given that this most important law for groundwater can really be applied in peaty environments. In other words, is the hydraulic conductivity K_h really independent of the hydraulic gradient or hydraulic head differences in the groundwater flow system? Wayne et al. (1985) presented evidence of a higher hydraulic conductivity of well-decomposed peats with an increase in hydraulic gradient for steady-state experiments set up in the laboratory. However, the effect of the increase in hydraulic gradients was rather small (for a three-fold increase in gradient the hydraulic conductivity only increased by about 30%). The slug tests carried out for the current study were conducted for different initial hydraulic head differences. No trend was detected between the hydraulic conductivity and the magnitude of the head

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differences applied. Based on this information one is inclined to believe that Darcy's law with a constant K_h may not be entirely valid to describe groundwater flow in peaty environments, but that its application in analytical and numerical model computations is justified.

5 Modeling results

The groundwater modeling at the research site incorporates the heterogeneities of the Complex Confining Layer (CCL) which were disclosed from the fieldwork. The modeling results have been compared with the outcome of a simplified model whereby the CCL is represented as a single homogeneous layer. In this way the effect of heterogeneity on modeling results has been established. For the comparison calibrated models have been used keeping in mind the limitations attached to model verification following standard rules for model calibration (Konikow and Bredehoeft, 1992).

5.1 Conceptual model

5.1.1 Layer schematization

The heterogeneities in the CCL made it clear that a one layer schematization of the CCL is too simplified and at least a distinction has to be made between the muddy and peaty layers and the more clayey layers. Based on the cross section obtained from the drilling activities (Fig. 3), the schematization of the CCL in the model area included a representation by 4 model layers (Fig. 6). The alteration of sandy aquifers and clayey aquitards below the CCL were represented by another 9 model layers bringing the total number of layers to 13 (Fig. 7). The base of the aquifer system which is equivalent to the base of model layer 13 is located at a depth of about 310 m below surface in the so called Maassluis Formation. The model layer schematization below the CCL has been based on the layer set up of an existing well-calibrated regional model (Cheng, 2004).

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5.1.2 Boundary conditions

The groundwater model was not confined to the boundaries of the actual research site which measures 50 m by 300 m but was considerably larger having a size of 700 m by 900 m. At the boundaries groundwater level-controlled conditions were assumed for all the model layers. The selection of a larger model area than the research site can be explained by the introduction of errors at the boundaries. Measurement-based groundwater levels assigned to the boundaries will contain measurement and interpolation errors which will affect the model results especially at the margins of the model and less in the centrally located research site.

5.1.3 Groundwater balance

A groundwater balance can be defined for the entire model area including all model layers. The focus of attention in this paper is on the CCL and therefore the balance for this confining layer has been introduced as follows:

$$(Q_{\text{prec}} - Q_{\text{cap}}) + (Q_{\text{surf-in}} - Q_{\text{surf-out}}) + (Q_{\text{up}} - Q_{\text{down}}) = \frac{\Delta V_{\text{CCL}}}{\Delta t} \quad (3)$$

where Q_{prec} ($\text{m}^3 \text{d}^{-1}$) denotes the recharge at the groundwater table in the CCL as a result of precipitation, Q_{cap} ($\text{m}^3 \text{d}^{-1}$) expresses the capillary rise from the table, $Q_{\text{surf-in}}$ and $Q_{\text{surf-out}}$ ($\text{m}^3 \text{d}^{-1}$) refer to respectively the groundwater inflow and the outflow at the ditches, and the Q_{up} and Q_{down} ($\text{m}^3 \text{d}^{-1}$) are the vertical upward and downward flow exchanges between the CCL and underlying Pleistocene sandy aquifer. The term $\Delta V_{\text{CCL}}/\Delta t$ ($\text{m}^3 \text{d}^{-1}$) describes the change in water storage per time step Δt in the CCL. At the research area the flow through the CCL is downward which means that the Q_{up} can be neglected. A thorough analysis of phreatic groundwater levels in the CCL and piezometric levels for the sandy aquifer indicated this flow direction.

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5.2 Model code and data input

The selected code for the modeling at the research site was the well-known package PMWIN-MODFLOW which is based on Darcy's law. The grid for the MODFLOW model was designed with a constant cell size of 5 m by 5 m. This relatively small cell size relates to the small width of 50 m of the parcel of grass land forming the research site. In order to compute and calibrate the groundwater levels in this parcel bounded by ditches with sufficient accuracy, this small cell resolution was required.

5.2.1 Hydro-geological parameters

A Digital Elevation Model (DEM) with a resolution of 5 m by 5 m provided the information to input into the model the elevations of the land surface which varied between -1.9 up to 2.7 m below sea level. Based on fieldwork data, the elevations (of the top and bottom) of the model layers making up the CCL were inserted into the model. The bottom of the CCL varies between -8.4 m and 9.1 m below sea level. Borehole data of the database residing with the Institute of Applied Sciences (TNO) were interpolated to obtain adequate elevations of the model layers, corresponding with the sandy aquifers and clayey aquitards below the CCL.

Slug test experiments carried out during the fieldwork, permeameter laboratory tests completed by the Wageningen University and Research Centre, different literatures that discuss the permeability of the CCL (e.g. Weerts, 1996), and pumping tests carried out in nearby pumping stations for domestic water supply were considered in providing the data to set up the hydraulic conductivities and storage parameters for the different model layers. To satisfy anisotropic conditions, ratios between the horizontal and vertical hydraulic conductivities, varying from 1 to 5, were adopted for the peaty and clayey model layers in the CCL.

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5.2.2 Time and model boundary levels

Steady state and transient models were prepared for specific periods. The steady state model runs on the input of data for the year 1990. This year reflects average meteorological conditions and the model simulates average groundwater levels and flows (Cheng, 2004). The transient model was initially built for the input of 10-day averaged data for the winter period 2009 to 2010, but was extended at a later stage to simulate 4 and 8 yr simulation periods from either from 2002 or 2006 up to the spring of 2010. The extension was necessary in order to visualize the complete pathlines of water particles through the CCL and to be able to compute corresponding travel times.

Field-based measurements defined the boundary- and initial groundwater levels for the active modeling area. For the peaty layers with a phreatic response in the CCL the levels, ranging from -2.3 to 2.9 m below sea level, were obtained from so called GxG maps. The phreatic surface, which is rather irregular in the ditch and land parcel landscape of the model area, has been taken from these high resolution groundwater level maps. For the Pleistocene sandy aquifer and the deeper aquifers, the TNO database provided the levels for the model. The levels covered the range from -2.9 to 3.9 m below sea level. Since piezometric surfaces of the sandy aquifers are rather smooth, the levels for the model boundaries could reliably be estimated by interpolation of data available for the few boreholes present in the area.

5.2.3 Groundwater recharge and the surface water system

An unsaturated model for the root zone supplied the input data for groundwater recharge from precipitation. This model considering as main input parameters soil characteristics, precipitation and potential evapotranspiration, computes net recharge as the balance between downward recharge and capillary rise. Precipitation data for the rainfall station at the research area itself and evapotranspiration data from the De Bilt weather station were input into the unsaturated zone model and subsequently the corresponding net recharges were computed. For example, for the observation

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period selected for the steady model, the computed net recharge varied from a high of 2.3 mm d^{-1} to a low of -1.7 mm d^{-1} yielding a realistic average recharge value of 0.41 mm d^{-1} as model input.

The Water Board HDSR provided surface water information including data relating to the River Oude Meije and the extensive ditch system. The data comprise river and ditch characteristics like bed hydraulic conductances, open water levels and elevations of the bottom of these surface water courses. The open water levels at the river and ditches in the model area are controlled by HDSR and maintained at a fixed position for winter and summer conditions.

5.3 Sensitivity analysis and model calibration

The data input for the models was followed by a sensitivity analysis aiming to identify the parameters which have a large effect on modeling results including the computed phreatic and piezometric groundwater levels. The analysis showed that increases or decreases of 50% in the values for the hydraulic conductivity of the CCL and the groundwater recharge resulted in phreatic groundwater level changes of less than 0.1 m and piezometric groundwater level changes were even below 0.01 m. The hydraulic conductivity is a bit less sensitive than the recharge. The transient models require the input of storage parameters like the specific yield and this parameter is also sensitive. From a general point of view, however, the sensitivity of model parameters is not that large which could be attributed to the control which the open water levels at the ditches exert on the groundwater levels.

Taking into account the results of the sensitivity analysis the models were calibrated which meant that parameter values were changed in order to try to minimize the difference between the groundwater levels computed with the model and the groundwater levels measured in the field. Although the hydraulic conductivities are less sensitive than groundwater recharge the main model adjustments concerned the former parameter. The reason is that the values for the conductivities are believed to be less certain

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than the values for the recharge. During the actual calibration work with the steady state model the phreatic groundwater levels computed on the bases of a particular set of parameter values were compared with the field-based phreatic levels shown on the GxG maps. For the transient model computed phreatic and piezometric groundwater levels could be compared with groundwater levels measured during the fieldwork in the upper peaty layers of the CCL and in the sandy first aquifer. Model calibration resulted, for final mean absolute differences in computed and measured groundwater levels of less than 0.05 m, in particular in upgraded model conductivities ranging from 0.0001 m d⁻¹ for the clayey parts of the CCL up to 1.3 m d⁻¹ for the peaty layers (see Table 2).

5.4 Comparison of detailed and simplified models

Results of the calibrated detailed models with a heterogeneous CCL were compared with the outcomes of simplified models whereby the CCL is represented as a single homogeneous layer. To obtain a representative simplified model the upper four layers of the detailed model were merged into a single layer with equivalent values for parameters including the hydraulic conductivities and the effective porosity. The equivalent value for the horizontal conductivity was obtained from the total horizontal transmissivity of the CCL and was calculated as $K_h = 0.961 \text{ m d}^{-1}$. The equivalent vertical conductivity was elaborated from the total resistance across the CCL. Some aerial variation in resistance had to be taken into account leading to the computation of equivalent values with magnitudes of $K_{v1} = 0.0114 \text{ m d}^{-1}$, $K_{v2} = 0.0061 \text{ m d}^{-1}$ and $K_{v3} = 0.0013 \text{ m d}^{-1}$. For the equivalent porosity an average of the 4 model layers of 0.26 was considered. The assignment of equivalent values to the simplified model means that the unique effect of heterogeneity can properly be determined when comparing model results.

Model results that can be compared comprise pathlines and travel times. For either heterogeneous or homogeneous conditions, pathline plots demonstrate the different

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trajectories that water particles may have followed through the CCL and travel time computations indicate the time it takes a water particle to flow through the CCL to or from the sandy aquifer or the ditch system. In the peat areas in the western part of The Netherlands the dominant flow of the water particles may be either downward or upward. The prepared detailed and simplified models for the research area are representative for areas where groundwater flow is primarily directed in a downward direction. Additional hypothetical models have been prepared to study the path lines and travel times for typical upward flow through the CCL.

5.4.1 Typical downward flow through the CCL

Steady state model

Steady state models for the research area have been used to obtain pathlines and travel times for the typical case of downward flow through the CCL. The models assume that average hydrological conditions are maintained over a long time. The model results show that for both the heterogeneous and homogeneous cases the flow path of water particles are similar and the direction is almost vertically downward (Figs. 8 and 9). When the particles arrive in the sandy aquifer the flow becomes more horizontal. For the heterogeneous case the travel time of water through the saturated CCL was approximately 7 yr and for the homogeneous case a water particle was underway in the CCL for 9 yr. The longer travel time for the homogeneous case could be explained by the use of equivalent values for the hydraulic conductivities and effective porosities which influence the head distribution and affect the travel time in the CCL.

Transient model

Transient models that have been engaged to simulate pathlines and compute travel times did not assume the average state, but they did take into account seasonally varying hydrological conditions. Therefore, they allowed a more realistic computation of the

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pathline trajectories and travel times than the steady state model. The model outcomes emphasize that the flowpath of a water particle is directed downward (Figs. 10 and 11). However, in the heterogeneous case there is a larger tendency of a particle, entering the saturated CCL in spring, to end up in the ditch then for the homogeneous set up.

5 This has to do with the smaller velocities in the first clayey model layer for the heterogeneous case during the subsequent summer period when the flow exchange is from the ditch into the CCL. The particles are kept “within reach” of the ditches and may actually discharge into them through the second peaty model layer during the following winter season. Water particles entering in the autumn period may show an opposite behavior
10 and would tend to end up less in the ditches in the heterogeneous model than in the homogeneous case.

Confirming the results of the steady state model, the travel times calculated for the heterogeneous case are shorter than for the homogeneous model set up. For the former case the travel time through the saturated CCL is in the order of 4 yr and for the latter case the water particles have not even reached half way through the covering layer in this period. The travel times for the transient models are also less than for the steady models indicating that the differences in head distributions between the models play a prominent role. These differences can be attributed to the average hydrological conditions and constant water levels assumed for the steady simulation
15 and the seasonally varying conditions and levels adopted for the transient state.
20

5.4.2 Typical upward flow through the CCL

Transient hypothetical models have been used to generate pathline patterns and compute travel times for upward flow through the CCL. For comparative reasons, the absolute differences in phreatic and piezometric groundwater levels for the models were similar than for the models simulating downward flow. To visualize the flow through the CCL water particles had to be placed both at the water table and in the Pleistocene sandy aquifer. The model results indicate that a complex flow pattern develops
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culminating in a prominent outflow at the ditches (Figs. 12 and 13). Although upward flow is dominant also downward flow exists in the upper parts of the CCL. The heterogeneous case also clearly shows in the second peaty model layer and centrally between the ditches, the development of an area with nearly stagnant groundwater flow.

The travel times calculated for upward flow are comparable with those for downward flow. For the heterogeneous case the travel time for a water particle to move from the sandy aquifer into the ditch is in the order of 2 to 4 yr and when homogeneous conditions are considered the travel time to the ditch is longer, ranging from 5 to 8 yr. Not surprisingly, the travel times are shortest for particles that move upward in the CCL below the ditches. Particles that flow upward centrally between the ditches where the stagnant area is located take the longest time to finally reach the surface water system.

6 Conclusions

The shallow surface- and groundwater system in a typical peat lowland area in The Netherlands could successfully be analysed using a combination of fieldwork and modeling work. Uncertainties in modeling arising from the heterogeneity in peat soils and the applicability of Darcy's law could be eliminated through a proper model set up. The model itself provided useful information on the flowpath patterns and travel times of groundwater through the Complex Confining Layer (CCL) and the flow exchange with the ditch system.

The fieldwork and previous investigations (e.g. Weerts, 1996) indicated that the CCL indeed deserves its reputation of being a very complex layer. Borehole drilling revealed that both in the vertical and horizontal direction the CCL is heterogeneous. In the vertical direction layers of peaty and silty clay, mud and peat, clay and again peat succeed each other in a downward direction at the research site. The CCL rests on top of fine eolian sand which grades into coarser fluvial sands at lower levels. In the

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horizontal direction the various layers are continuous in many places, but also tend to wedge out offering additional complexity for groundwater flow.

Field slug tests indicated that an apparent variable K_h was observed for humified peat soils but this is thought to be due to the inappropriate use of steady state formula for transient experiments. Even though these expressions are normally used for transient slug tests, they were found to be inappropriate for this kind of peat soils. During the tests the humified peat soils introduce a large transient effect as a result of the compressibility of the peat and its plastic nature. On the other hand, the slug tests gave no clear evidence of the dependency of the hydraulic conductivity with the hydraulic gradient. In combination with earlier results from laboratory tests (Waine et al., 1985), the evidences proved that changes in the hydraulic gradient hardly affect the hydraulic conductivity and, therefore, Darcy's law can be used for peat soils. Based on interpreted elastic storativity values of the peat, varying from 0.0001 to 0.001, the hydraulic conductivity of the humified peat soil could be computed with an equation for transient conditions and a semi-analytical model yielding values in the range of 0.24 and 1.69 m d⁻¹.

The modeling work focused on the comparison of a detailed model for the peaty CCL and a model with aggregated parameters. The detailed model takes into account the heterogeneity of the CCL which is represented by 4 model layers and the aggregated model considers the CCL as an apparent homogeneous entity. The transient models run for an 8 yr simulation period proved to be adequate to visualize the pathline patterns in the CCL for downward flow in the research area and for upward flow encountered in other similar areas in the western part of The Netherlands. As a result of the similar hydrological conditions adopted at the boundaries of the CCL the flow line patterns for the model representing the heterogeneous case are quite similar to those generated by the model with a homogeneous CCL. Flow patterns made with the heterogeneous model tend to be more accurate when looking at flow details, for example when inspecting the flow exchange between the CCL and the surface water system.

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An interesting result from the modeling exercises are the indications of the travel times of water particles when flowing through the peaty CCL. In case the heterogeneity of the CCL is taken into account, the model computes travel times of water particles through the CCL which are considerably shorter than for the case whereby the Complex Confining Layer is represented by a single homogeneous model layer. Travel times downward or upward through the CCL for the heterogeneous model range between 2 to 4 yr whereas the model with homogeneity tends to compute times in the order 5 to 8 yr. The conclusion is that groundwater models that are based on the representation of the CCL with one homogeneous model layer are less suitable for assessments on groundwater transport where travel times play an important role. In particular when they are considered for the simulation of contaminant transport, models with a homogeneous CCL should not be used.

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Table 1. Horizontal hydraulic conductivity K_h (m d^{-1}) computed from the slug tests.

Borehole	van Beers	Hvorslev					Dax	KGS model	Decomp Degree vPost
		Δt_1	Δt_2	Δt_3	Δt_4	Δt_5			
BH5	1.60	1.66	0.86	0.67	0.47	0.22	1.69	1.00	H7
BH6	0.72	0.70	0.57				1.34	0.73	H5
BH7	0.11	0.10							H4
BH8	0.27	0.26							H4
BH9	0.67	0.58	0.34				0.69	0.45	H6
BH10	0.15	0.15							H4
BH11	0.56	0.52	0.44	0.42			1.00	0.48	H6
BH12	0.29	0.27	0.20				0.42	0.24	H7

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Table 2. Horizontal and vertical hydraulic conductivities for the model layers representing the CCL.

Layer/soil type	K_h (m d ⁻¹)	K_v (m d ⁻¹)
layer 1 – clay/silty peat	0.1	0.02
layer 2 – mud/peat	1.30	1.30
layer 3 – peaty clay	0.0024	0.0001, 0.0005, 0.001*
layer 4 – mud/peat	1.30	1.30

* In the clay layer, three different areas were found within the modelling boundaries with different K values.

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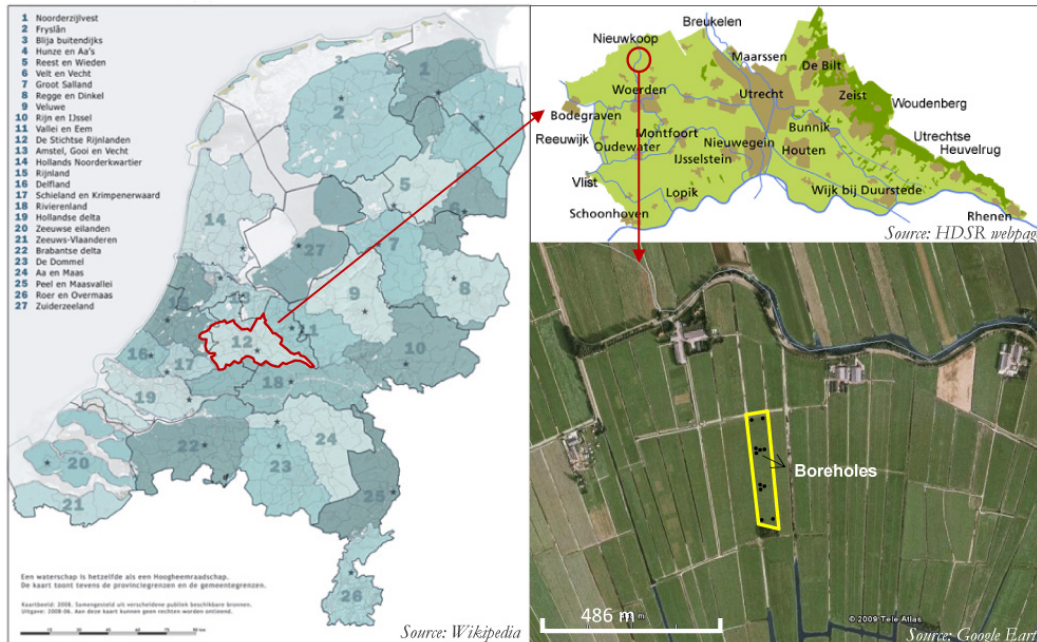


Fig. 1. Location of the research site in The Netherlands within the HDSR control area.

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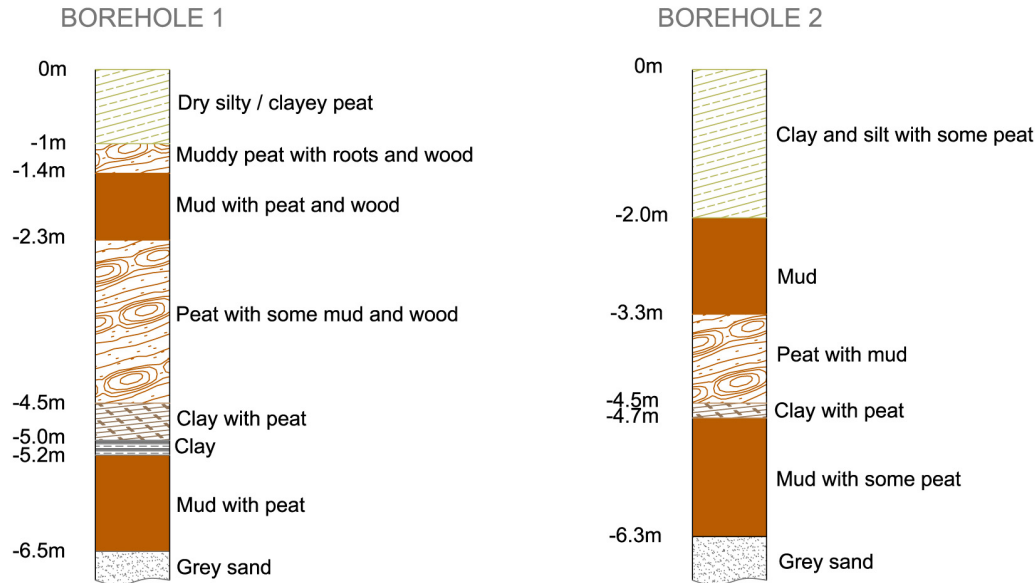


Fig. 2. Subsoil description of the deeper boreholes.

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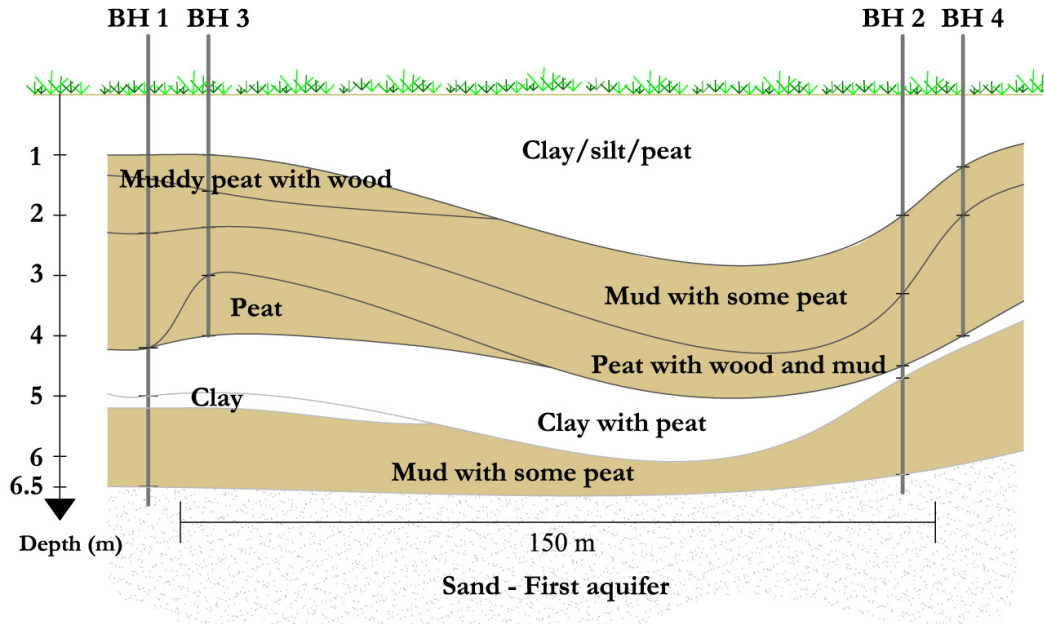


Fig. 3. Schematization of the CCL based on borehole descriptions.

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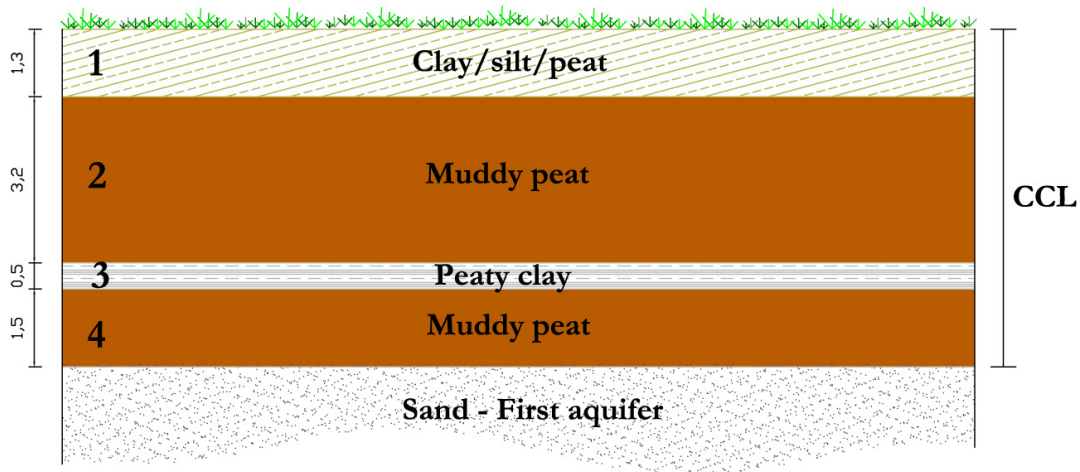


Fig. 6. Schematization of the CCL.

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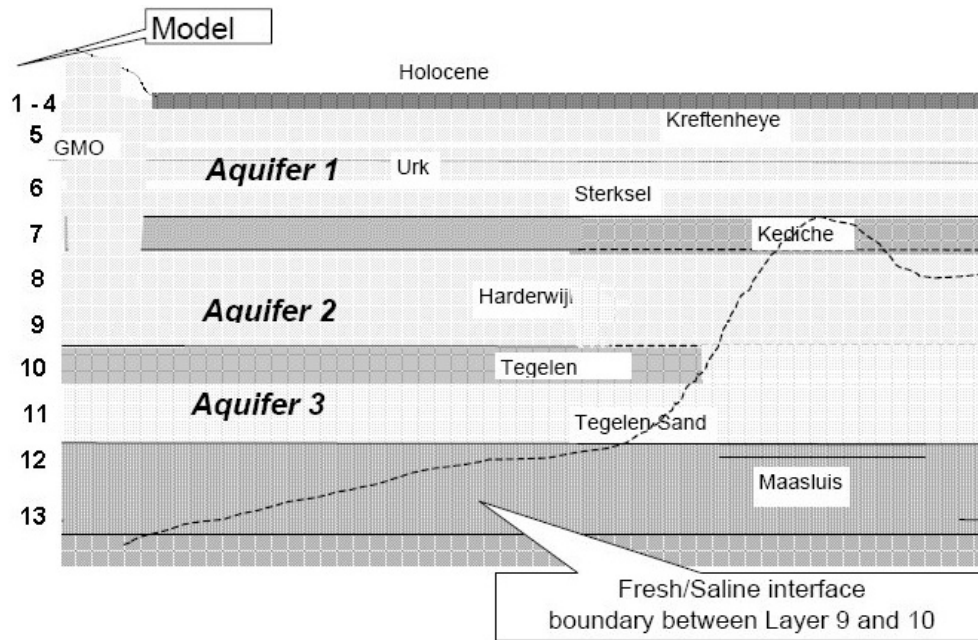


Fig. 7. Model layer schematization adopted from Cheng (2004).

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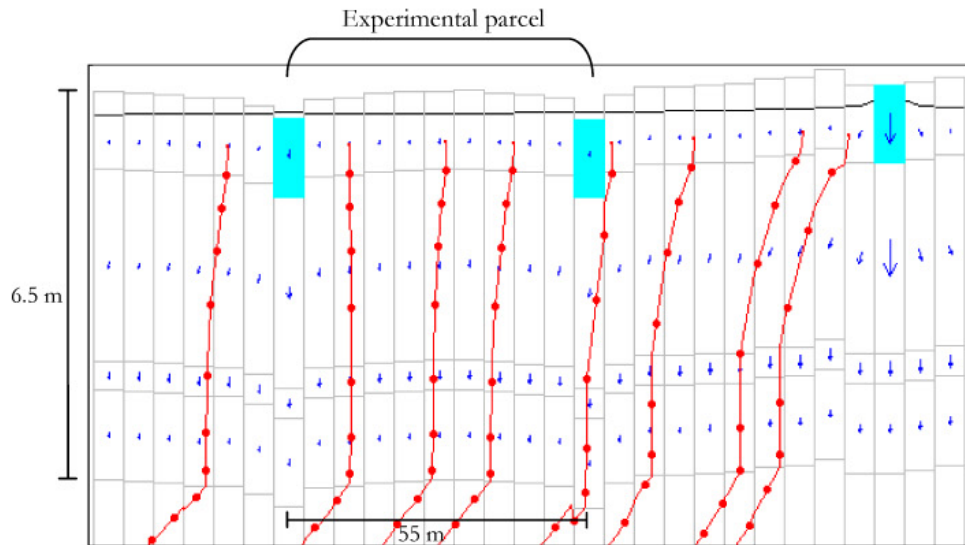


Fig. 8. Steady flow path lines for the heterogeneous case (lines are path lines; each dot represents one year).

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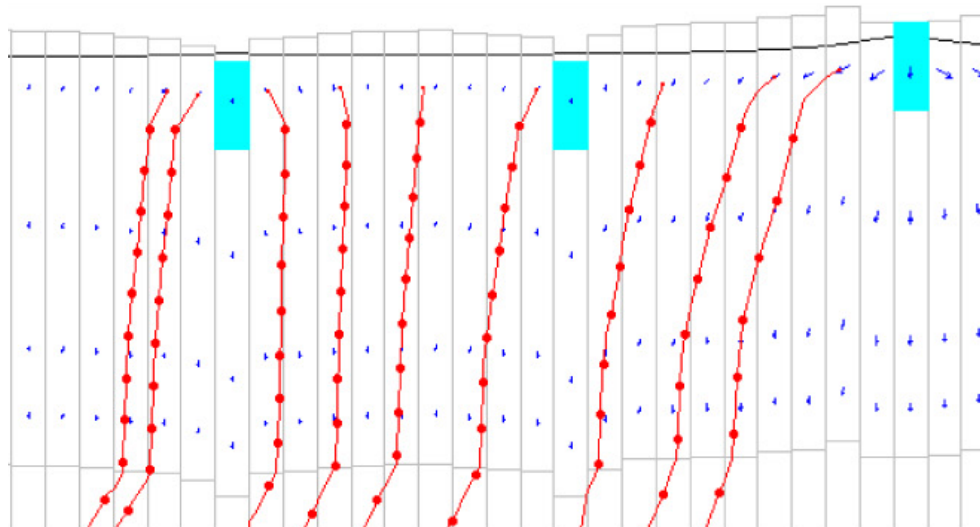
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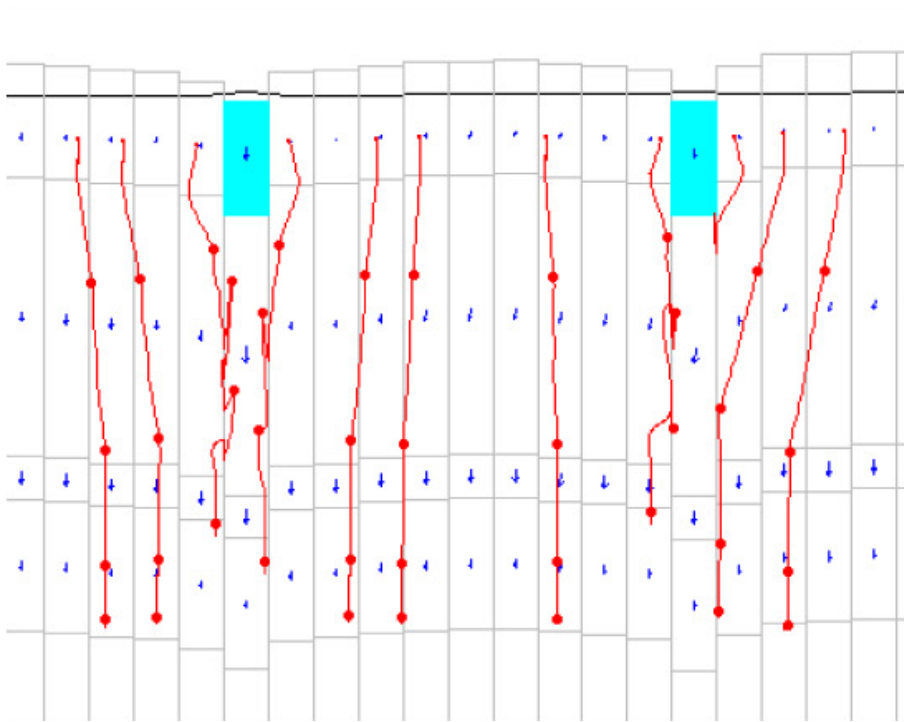


Fig. 10. Transient flow path lines for the heterogeneous case.

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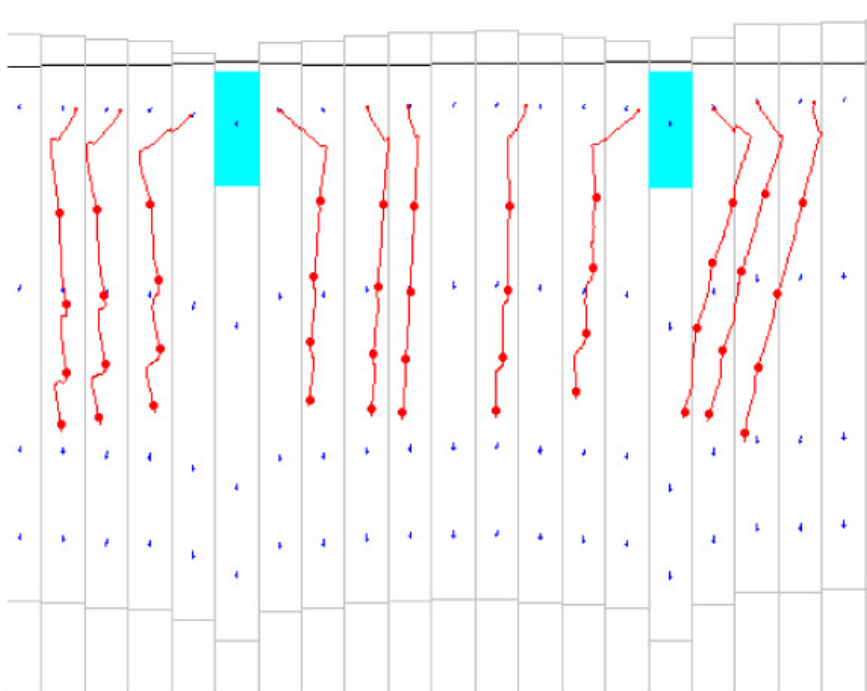


Fig. 11. Transient flow path lines for the homogeneous case (simulation runs from spring April 2006 to spring April 2010).

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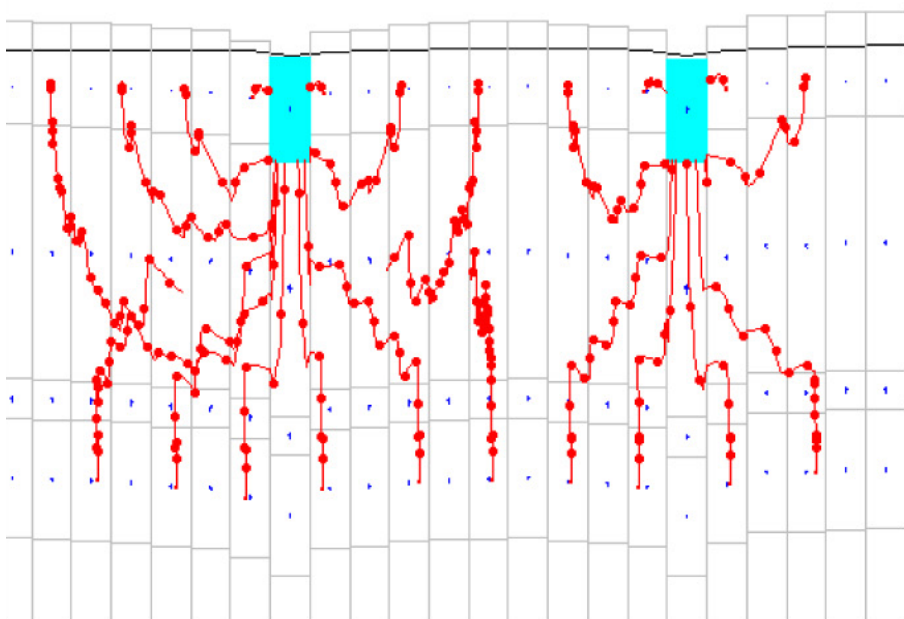


Fig. 12. Transient flow path lines for the heterogeneous case (dot every 4 months).

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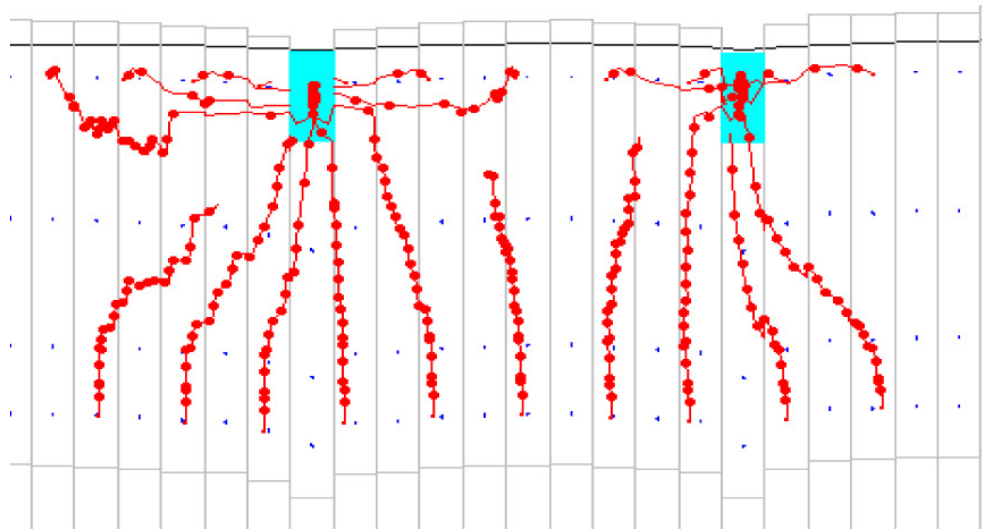


Fig. 13. Transient flow path lines for the homogeneous case (dot every 4 months).

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