Modeling Baseflow from an Alluvial Aquifer Using Hydraulic-Conductivity Data Obtained from a Derived Relation with Apparent Electrical Resistivity

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Abstract: In order to accurately quantify the water flux entering the Netherlands from Belgium via the Meuse River and its alluvial plain, the Belgian Ministry of Public Works has supported hydrological and hydrogeological studies in the area between the city of Liège (Belgium) and the Dutch border. The groundwater fluxes from the Albert Canal to the Meuse River and those passing around the weir-lock systems within the alluvial gravel deposits are not measured by the existing surface-water gauging system; therefore, detailed quantitative hydrogeological studies of the groundwater fluxes in these alluvial deposits were needed.

A detailed three-dimensional finite-element numerical model was used to compute these fluxes. Previous hydrogeological studies involving piezometers, pumped wells, and electrical soundings provided, respectively, data for potentiometric maps, local values of hydraulic conductivity, and more than 200 measurements of the apparent geoelectrical resistivity of the gravel deposits. From this data set, a new correlation between geoelectrical resistivity and hydraulic conductivity was used to define a spatially distributed set of hydraulic-conductivity values to be entered in the model.

Maps and measured potentiometric heads were used as references for the calibration of the model, and features of the model, such as layer geometry, external sink and source terms, and boundary conditions, were selected on the basis of all available information. Four non-horizontal layers were discretized as 2,356 elements.

On the basis of the model, the additional flow crossing to the Netherlands via the alluvial aquifer and the Meuse River is about 5.4 m^3/s during the summer.

Résumé: Afin de quantifier avec précision le flux d'eau entrant aux Pays-Bas depuis la Belgique, par la Meuse et sa nappe alluviale, le Ministère belge des Travaux Publics a financé des études hydrologiques et hydrogéologiques dans la région de Liège (Belgique) et de la frontière néerlandaise. Les flux d'eau souterraine depuis le canal Albert vers la Meuse et ceux passant par les systèmes d'écluses dans les graviers des alluvions ne sont pas mesurés par le dispositif existant de jaugeage des eaux de surface ; c'est pourquoi des études hydrogéologiques détaillées des flux souterrains dans ces nappes alluviales sont nécessaires.

Un modèle numérique détaillé, en 3 D, aux éléments finis, a été utilisé pour calculer ces flux. De précédentes études hydrogéologiques, s'appuyant sur des piézomètres, des pompages et des sondages électriques avaient respectivement fourni les données pour des cartes piézométriques, des valeurs locales de la transmissivité et plus de 200 mesures de résistivité apparente des dépôts de graviers. Cet ensemble de données a permis d'établir une nouvelle corrélation entre la résistivité électrique et la transmissivité, dans le but de définir une distribution spatiale des valeurs de transmissivité nécessaires au modèle.

Des cartes et des mesures de charges hydrauliques ont été utilisées comme références pour la calibration du modèle ; certaines caractéristiques du modèle, comme la géométrie des couches, les termes puits et source externes et les conditions aux limites, ont été choisies sur la base des informations disponibles. Quatre couches non horizontales ont été discrétisées en 2356 éléments.

Sur la base du modèle, le flux supplémentaire s'écoulant vers les Pays-Bas au travers de l'aquifère alluvial et de la Meuse est d'environ 5,4 m^3 /s en été.

Resumen: Para cuantificar adecuadamente el flujo de agua que entra a Holanda desde Bélgica a través del Río Mosa y su llanura aluvial, el Ministerio de Obras Públicas de Bélgica ha financiado estudios hidrológicos e hidrogeológicos en el área comprendida entre la ciudad de Lieja (Bélgica) y la frontera holandesa. Los flujos de agua subterránea desde el Canal Alberto al Río Mosa, así como los que pasan por los depósitos de gravas aluviales, sin llegar a entrar en el sistema de canalizaciones, no pueden registrarse con el sistema de medición superficial existente; por tanto, se necesitaban estudios hidrogeológicos cuantitativos de detalle para caracterizar estos flujos.

Se usó un modelo numérico tridimensional de elementos finitos para cuantificar estos flujos. Estudios previos, que incluían piezómetros, pozos de bombeo y prospección eléctrica proporcionaron, respectivamente, información sobre piezometría, valores locales de conductividad hidráulica y más de 200 medidas de la resistividad eléctrica aparente de los

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depósitos de gravas. A partir de esta base de datos, se usó una correlación entre los valores de resistividad eléctrica y conductividad hidráulica para definir la distribución espacial de los valores de conductividad hidráulica a usar en el modelo.

Los mapas y las medidas de alturas piezométricas se usaron como referencia en la calibración del modelo, y algunas características del modelo, como la geometría de las capas, fuentes y sumideros externos y condiciones de contorno, se seleccionaron a partir de toda la información disponible. Se discretizaron cuatro capas no horizontales, para un total de 2356 elementos.

A partir de los resultados del modelo, el flujo adicional que cruza hacia Holanda a través del acuífero aluvial y el Río Mosa, se estima en alrededor de 5.4 m^3/s durante el verano.

Introduction

In accordance with an agreement between The Netherlands and Belgium, the amount of water that enters The Netherlands along the valley of the Meuse River needs to be documented. Surface-water flow is monitored at a river gauge at Liège, Belgium, but quantitative estimates of groundwater flow in the alluvium need to be added to this amount.

In order to make these estimates, hydrogeological investigations were conducted with the support of the Ministry of Public Works of Belgium. Measurements of electrical resistivity were made and a relation established between resistivity and hydraulic conductivity. Additionally, source terms for groundwater were quantified; these included infiltration from precipitation and from the Albert Canal, and groundwater runoff from the adjoining hillsides. The distributions of hydraulic conductivity and source terms were incorporated with other data in a three-dimensional finite-element flow model to estimate groundwater flux.

Hydrogeological Conditions and Data Synthesis

Regional Geology

The study area is shown in *Figure 1*. Downstream of Liège, the bedrock underlying the alluvial deposits of the Meuse River valley is of Paleozoic age. In the Visé area, an anticline exposes Frasnian and Tournaisian-Visean limestones and dolomites. Highly developed karst occurs, and in places it affects areas greater than 1 Ha and to tens or hundreds of meters in depth. These paleokarst features are filled with overlying Namurian shales and siltstones, although these have been partially eroded during episodes of karst reactivation. On the limbs of the anticline, the Namurian shales, siltstones, and sandstones dip gently northward and southward. After the Hercynian orogeny, all these formations were peneplained and overlain by the Herve "smectite" of Late Cretaceous age. This hardened clayey and calcareous layer is 10-20 m thick and is itself overlain by chalky formations of Campanian and Maastrichtian age, which outcrop from north of Visé to Maastricht. Tertiary-age deposits have been almost completely eroded away, with the exception of limited remnants of Tongrian sand. These occur in areas where the underlying chalky formations are highly karstified.

During the Quaternary Period, the Meuse River created about ten terraces along its alluvial plain. At present, the river flows northward within a large alluvial plain (about 500-2,500 m wide) that is underlain by 10-15 m of loose fluvial silty to sandy gravel.

Geology and Hydrogeology of the Alluvial Plain

On the basis of a data set comprising about 1,500 information points (boreholes, wells, piezometers, cone-penetration tests, and seismic and electrical soundings), the following were compiled:

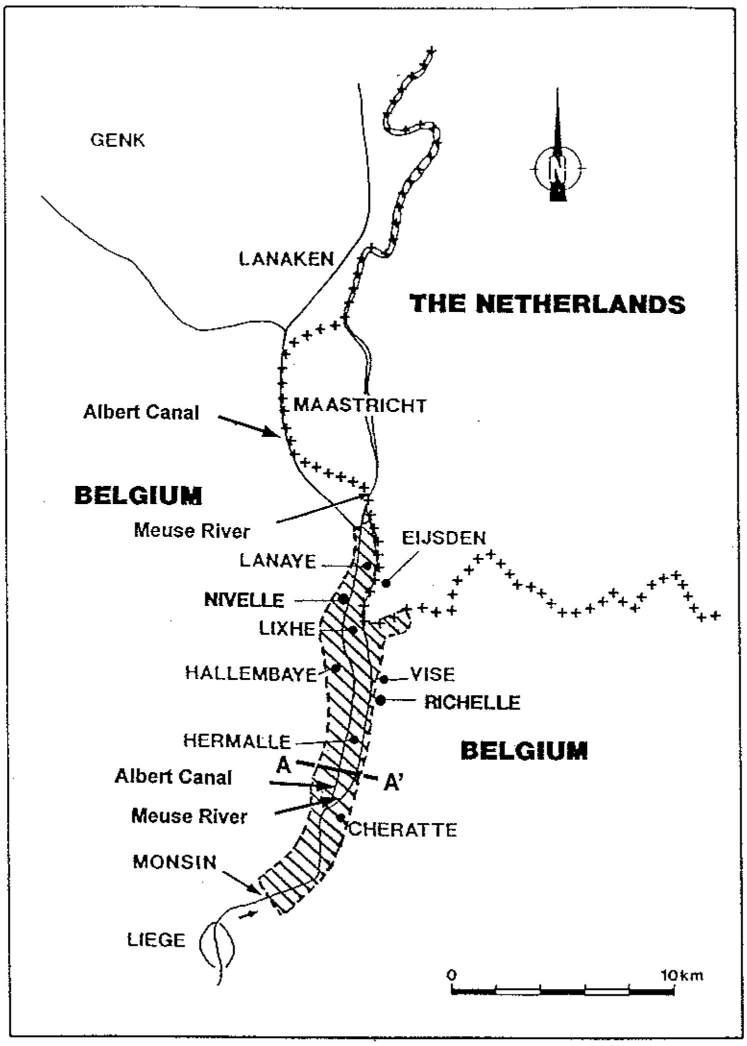
1) A map of the apparent resistivity of the gravel deposits, as shown in *Figure 2*;
2) Potentiometric maps; *Figure 3* is an example corresponding to a very dry season (July, 1989); and
3) 53 detailed geologic sections, transverse to the alluvial plain and located between Monsin (south) and Lanaye (north).

On the basis of these documents, the geology of the alluvial plain is summarized as follows (Dassargues and Lox, 1991):

- The alluvial deposits of the Meuse River are composed of gravel with highly variable amounts of silt and sand and overlain by fluvial loam. The thickness of the gravel deposits is 5-7 m. Numerous sandy beds and clay lenses occur. The overlying fluvial loam is 2-6 m thick. In some locations within the study area, artificial embankments as much as 7 m high have been built for industrial purposes.
- In the northern part of the area, the bedrock is composed of chalk of Cretaceous age (Lower Maastrichtian). This unit constitutes the Hesbaye aquifer (Dassargues et al., 1989), which overlies a clayey "smectite" layer.
- In the central part of the area, the bedrock consists of the "smectite" formation, which is underlain by Namurian weathered and fissured siltstone, often called schist. This schist is locally highly brecciated due to karst collapse in the underlying Visean limestone. Hydraulic conductivity of the schist is 10^{-6} - 10^{-5} m/s. The underlying limestone aquifer is partially artesian; the Namurian schist acts as the overlying confining bed.
- In the southern part of the area, Visean limestone crops out on the eastern side of the valley between Visé and Hermalle. Farther south, the Namurian schist underlies the alluvial plain, as shown in *Figure 4*.

The gravel deposits form a very good aquifer beneath the entire alluvial plain. This aquifer is recharged by direct infiltration of rainfall, interflow from the two sides of the valley, groundwater flux from interconnected aquifers, and leakage from surface-water bodies (i.e., the Albert Canal and some parts of the Meuse River).

The thickness of the gravel deposits depends on the amount of local erosional overdeepening that is associated with former gravel islands and braided channels. These granulometric and thickness variations are numerous and create zones where preferential groundwater flow occurs. The hydraulic conductivity



EXPLANATION

Study area in the alluvial plain between Liege (Belgium) and Maastricht (The Netherlands)

A— — —A' Line of section shown in *Figure 4*

Figure 1. Location of study area, Meuse River alluvial plain, Belgium.

of the gravel ranges from 5×10^{-3} - 1×10^{-1} m/s, depending on grain-size distribution and content of silt and sand. The results of pumping tests have confirmed the large transmissivity of the gravel, and chemical analyses of pumped waters have confirmed the important role of chalk and limestone in feeding the alluvial aquifer.

Hydraulic Works

In the study area of the alluvial plain, many civil works and installations strongly influence groundwater flow:

- *The Albert Canal.* The water level in the canal is maintained at 60 m above sea level (a.s.l.) by the Monsin weir (*Fig. 4*). The canal base is at 55 m a.s.l. on very pervious alluvial deposits. The potentiometric level in the alluvial aquifer is at the same level as, or below, the base of the canal. At its lowest, in the northern part of the study area, the level is 7.5 m below the base of the canal. Water thus leaks from the canal to the alluvial aquifer through the puddled-clay canal lining.
- *The impervious embankments.* These embankments and various drainage features along the Meuse River influence the relationship between river and aquifer, modifying hydraulic gradients and groundwater fluxes.
- *The weir-lock systems on the Meuse River.* These systems control discrete intermediate water levels, namely 60, 54.7, and 46 m a.s.l. The differences between the upper and lower levels induce groundwater flow in the alluvial aquifer; as a result, groundwater bypasses the weir-lock systems.

Determination of Hydraulic Conductivity

A fundamental relationship exists between hydraulic conductivity and electrical conductivity, owing to the common dependence of these parameters on the tortuosity and porosity of the porous medium (Bear, 1972). Researchers have attempted to quantify

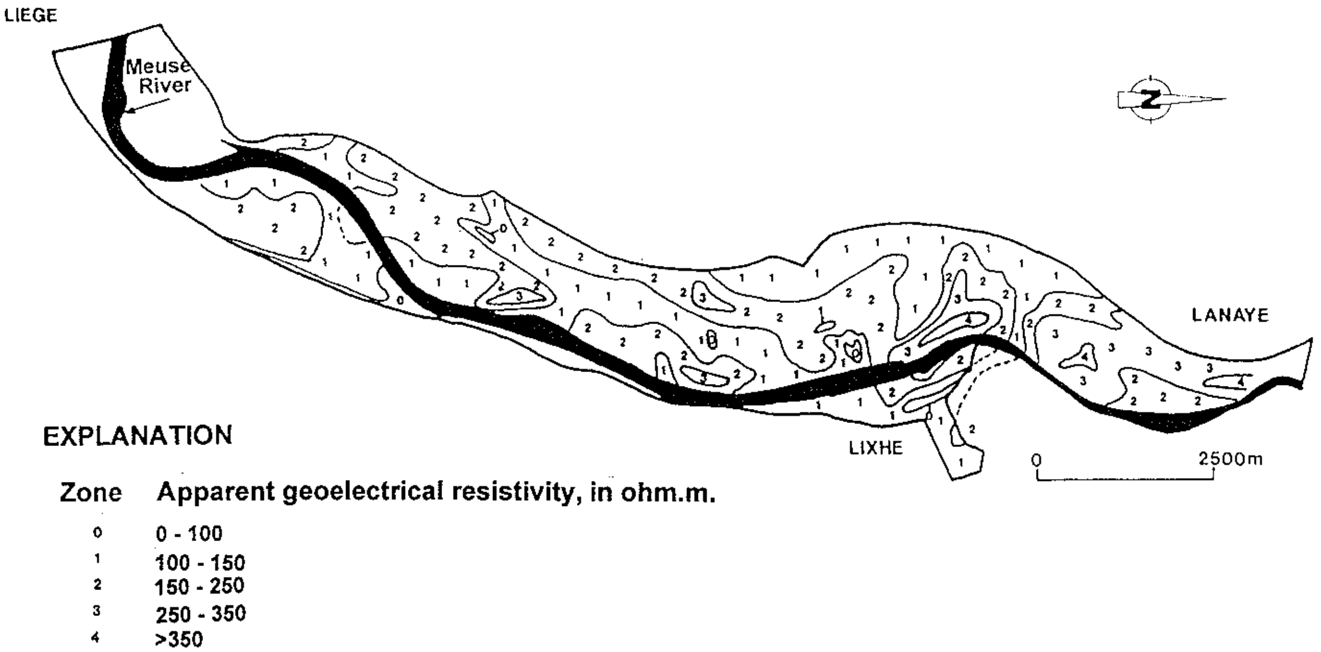


Figure 2. Distribution of apparent resistivity of the gravel deposits, as determined by electrical soundings (after Lox et al., 1990).

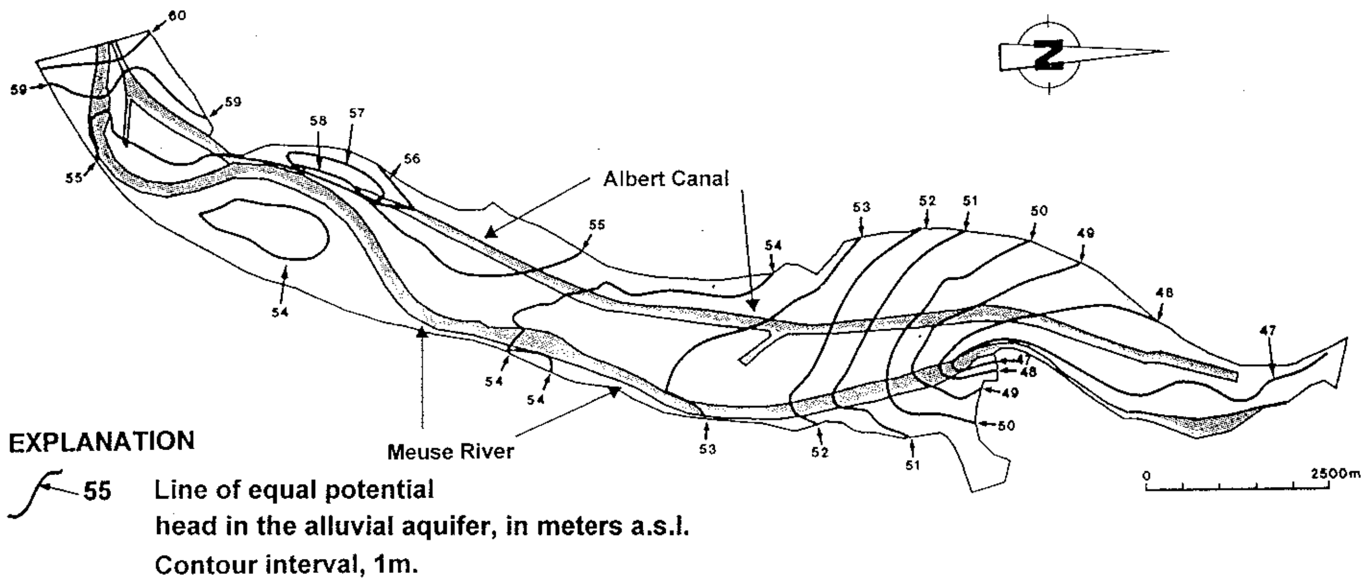


Figure 3. Reference potentiometric surface, corresponding to very dry conditions.

this relationship for fresh-water aquifers for decades, typically using a combination of borehole pumping tests and geoelectrical measurements. For example, see Kelly (1977) and Kosinsky and Kelly (1985) for glacial outwash sediments, using the results of Schlumberger electrical soundings; Heigold et al. (1979), Kwader (1985), and Huntley (1986) for granular porous media, using the results of electrical resistivity well-logging; and Ahmed and de Marsily (1987), using electrical resistivity data for co-kriging with permeability values. Results suggest that a broader, non-facies-specific generalization of each particular correlation law is not possible. All theoretical studies that have attempted to generalize relations between electrical and hydraulic conductivities have failed when applied to real cases.

The determination of hydraulic conductivity from geoelectrical data must thus be made on the basis of a complete and detailed understanding of the local sedimentological environment. In each studied case, a correlation must be identified from measured data, which can then be used to assist

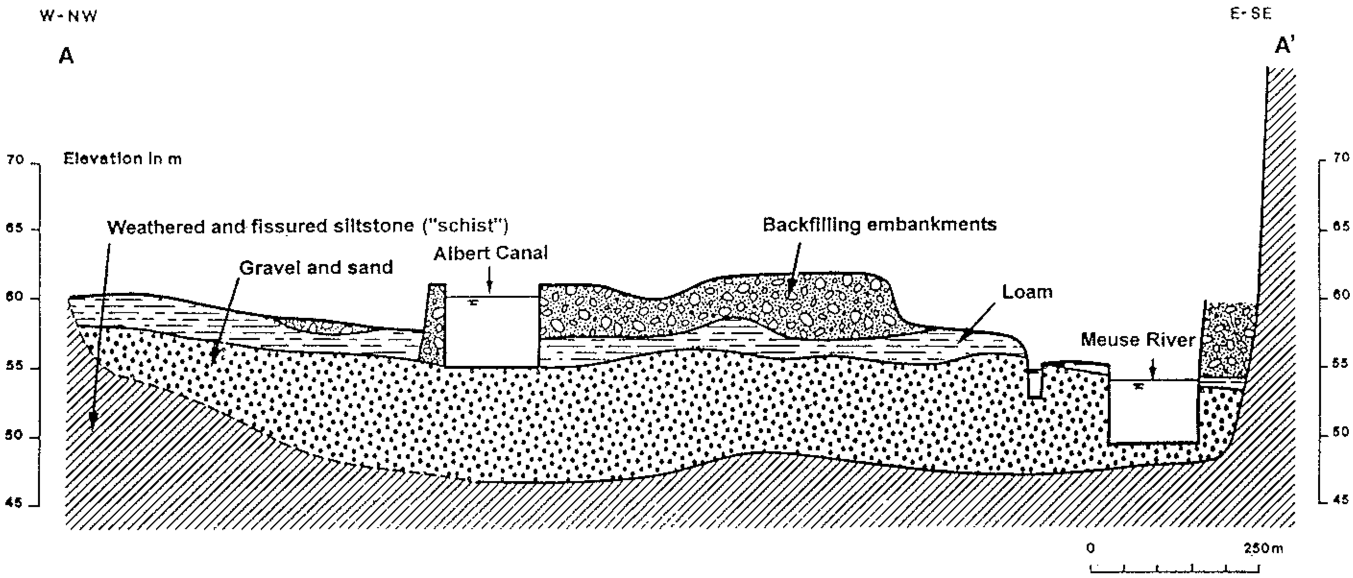


Figure 4. Geologic section across the Meuse River and Albert Canal. Line of section shown in *Figure 1*.

in interpolation of hydraulic-conductivity values between pumping-test locations.

Previous Correlation Studies

On the basis of all available data from the alluvial deposits of the Meuse River, Monjoie et al. (1987) and Haddouchi (1987) demonstrated a correlation between the apparent electrical resistivities of the saturated gravels and their hydraulic conductivities, as summarized in *Table 1*. From the map of apparent resistivity (*Fig. 2*), values of hydraulic conductivity (K_f) of the gravel were estimated throughout the whole alluvial plain, using this correlation.

Table 1. Relation between apparent resistivity and hydraulic conductivity, saturated gravels beneath the Meuse River alluvial plain near Liège (after Monjoie et al., 1987; and Haddouchi, 1987).

Zone	Apparent resistivity (ohm·m)	Hydraulic conductivity (m/s)
0	< 100	< 6 x 10^{-3}
1	100 - 150	6 - 7 x 10^{-3}
2	150 - 250	7 - 8 x 10^{-3}
3	250 - 350	0.8 - 1 x 10^{-2}
4	> 350	> 1 x 10^{-2}

New Correlation

For the case study described here, a data set was developed that consists of 22 values of hydraulic conductivity (K), derived from pumping tests, and about 220 values of apparent resistivity (ρ_A), derived from electrical sounding (Schlumberger) profiles. A new correlation was calculated by comparing pumping-test results with measured apparent resistivities in the saturated gravels in the immediate vicinity of these tests. All measured points were used to develop the relationship shown in *Figure 5*, except for those points that correspond to apparent resistivities greater than 325 ohm·m, which probably correspond to unsaturated gravels. Mean values of K or ρ_A) were used where the pumping tests or the electrical soundings provide a range of values rather than a unique value.

The data in *Figure 5* describe a parabolic curve rather than a line. Moreover, for a given value of ρ_A, the value of K can be ascertained with an uncertainty coefficient ranging from 1.0-2.5, mainly due to uncertainty in pumping-test interpretation. The parabolic regression was obtained by the least square method:

$$\log K = a + b(\rho_A) + c(\rho_A)^2 \qquad (1)$$

where $a = -4.797409$, $b = 0.02104219$, $c = -3.37441 \times 10^{-5}$, and $\rho_A \leq 300$ ohm·m (*Fig. 5*). The parabolic correlation coefficient, r, can be expressed as:

$$r = \sqrt{\frac{\sum[(\log K)^* - (\log K)_m]}{\sum[(\log K) - (\log K)_m]}} \qquad (2)$$

where $(\log K)^*$ = estimated value of log K using the parabolic correlation, and $(\log K)_m$ = mean value of log K.

The mean deviation from the parabola can be defined by:

$$\log \Delta = \frac{\sum |(\log K) - (\log K)^*|}{n} \qquad (3)$$

where n = number of observations. In this case, $r = 0.88$ and $\log \Delta = 6.4912\ 10^{-2}$. One can also write:

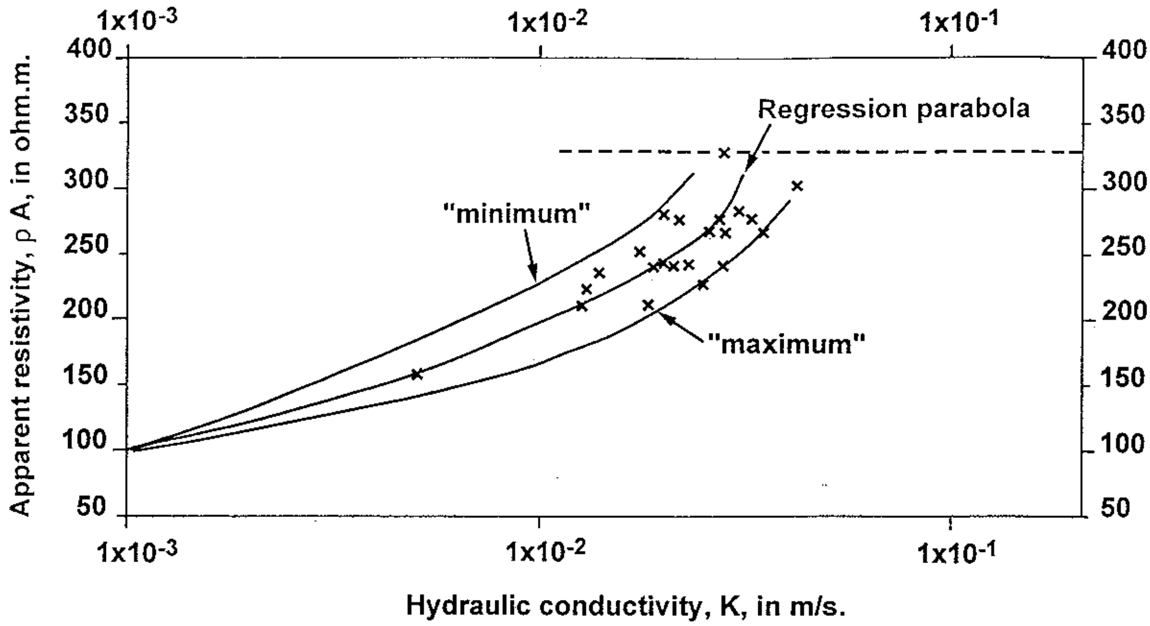


Figure 5. Relation between apparent resistivity and hydraulic conductivity, showing best-fit parabolic correlation and the extreme parabolas.

$$[(\log K)^* - \log \Delta] < (\log K) < [(\log K)^* + \log \Delta] \quad (4)$$

and

$$\frac{K}{\Delta} < K < K\Delta \quad (5)$$

where, in this case, $\Delta = 1.1612$.

The introduction of this constant variance into the computations is not recommended, because it would yield only a very rough approximation of reality. A preferred approach is to determine "extreme parabolas," including all the extreme values of the data set. In order to determine these parabolas, the following assumptions are made (*Fig. 5*):

1) The extreme parabolas have the same curvature as the correlation parabola;
2) The minimum point defined by $K = 1 \times 10^{-3}$ m/s and $\rho_A = 102$ ohm·m is on both parabolas;
3) The point defined by $K = 2.5 \times 10^{-2}$ m/s and $\rho_A = 225$ ohm·m is on the "maximum" parabola; and
4) The point defined by $K = 2 \times 10^{-2}$ m/s and $\rho_A = 280$ ohm·m is on the "minimum" parabola.

The first assumption (same curvature) implies that the second derivatives of the parabolic equations ($d^2(\log K)/d\rho_A^2 = 2c$) are equal. In this case, $c = -3.37441 \times 10^5$. The remaining unknowns (a and b) are then determined using the two prescribed points on each parabola. For each measured value of ρ_A, three values for the hydraulic conductivity were deduced (*Fig. 5*):

K_{min} = hydraulic conductivity obtained with the "minimum" parabola;
K_{mean} = "mean" hydraulic conductivity obtained with the best-fit correlation parabola; and
K_{max} = hydraulic conductivity obtained with the "maximum" parabola.

In practice, some corrections had to be applied in situations where the measured electrical resistivity represented both unsaturated and saturated gravels.

The data set of hydraulic-conductivity values obtained using the three parabolas was combined with the 22 values obtained from pumping tests. Three sets of hydraulic-conductivity data, corresponding to K_{min}, K_{mean}, and K_{max} are formed in this manner, and these can be mapped. The map of K_{mean} is shown in *Figure 6*.

Synthesis of the Available K Data

In summary, two sets of hydraulic-conductivity data were obtained:

1) Data from the former correlation, K_f; and
2) Data from the new correlation, K_{min}, K_{mean}, and K_{max}.

Each of these data sets was incorporated into a 3D finite-element numerical model of groundwater flow. The deduced values of K were employed in the elements that correspond to the gravels of the alluvial plain. For the other layers, hydraulic-conductivity values were assigned on the basis of the published values (Monjoie et al., 1987; Haddouchi, 1987).

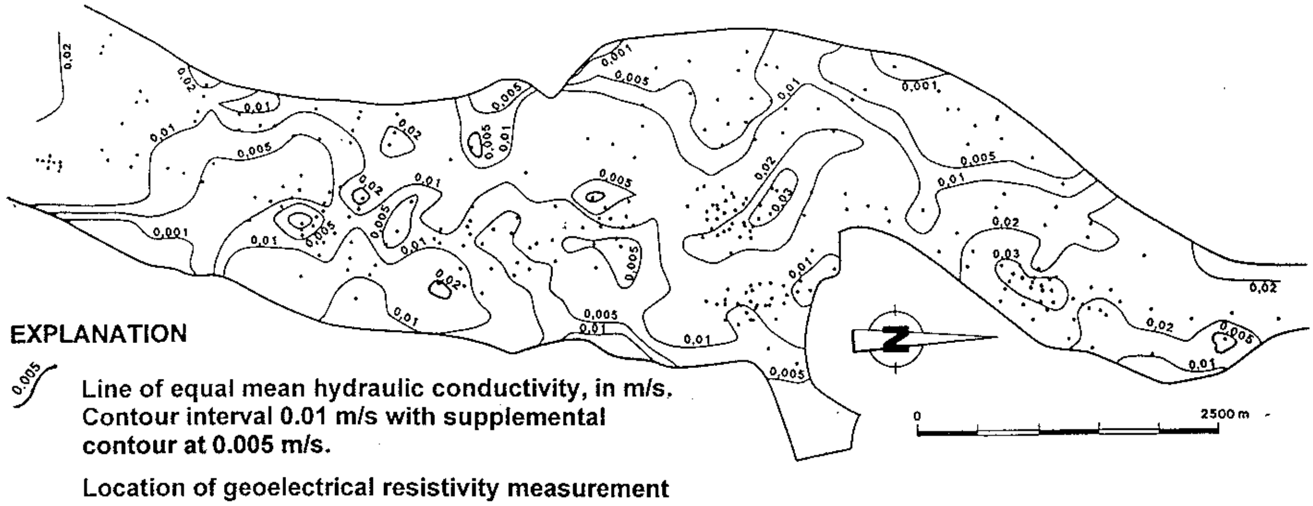


Figure 6. Distribution of mean hydraulic conductivity, obtained by application of the new parabolic correlation.

Numerical Simulations

The use of a Finite-Element-Method (FEM) code for simulating groundwater flow allows the construction of a model of very high geometrical complexity. The code also allows the known heterogeneities of the aquifer to be taken into account via the flexibility of the grid structure. In this study, the LAGAMINE code, developed in the Mechanical and Structural Computation Department of the University of Liège (Charlier, 1987), was employed. This non-linear code has been used successfully in a variety of hydrogeological and geotechnical problems (Schroeder et al., 1988; Dassargues et al., 1988, 1991; Dassargues and Li, 1991).

For the case study described here, 3D brick-like elements with eight nodes and linear interpolation functions were used. A method based on a storage variation law was used to simulate the water-table conditions (Dassargues et al., 1988; Dassargues, 1991, 1993).

Initial and Boundary Conditions

The complete 3D network is composed of 2,356 eight-node brick-like elements and 3,355 nodes. These are arranged in four non-horizontal layers of elements. The 3D discretization was realized on the basis of all available data, and nodes were localized as far as possible at the points where information was available (wells, cone penetration tests, and piezometers). The discretization considers all geometrical data pertaining to changes in bedrock lithology, alluvial lithology, and hillside landforms. Parameters were introduced on the basis of defining distinct "materials." Elements of the same "material" are characterized by the same parameters. The four layers in the model reflect the following geologic materials:

- **Layer 1** (lowest) is composed of elements representing gravel (*material 1*). The detailed distribution of K was determined by either the former or the new correlation of K with geophysical parameters, except in two small northern zones, where chalk and limestone were incorporated into layer 1;
- **Layer 2** is also largely composed of elements representing gravel; K distribution is based on geophysical correlations, except for the following: the incorporation of chalk (as in layer 1); a loam material (*material 2*) near the Lanaye lock; a "water material" (*material 8*) for water bodies like the Meuse River and flooded gravel-pits; and a "fill material" (*material 6*) in some old, filled gravel pits;
- **Layer 3** is largely composed of elements representing the artificial embankments (*material 3*), except for the chalk (*material 5*) (as in layers 1 and 2), the loam (*material 4*) near the Lanaye lock, the filled gravel pits (*material 6*), and the Meuse River or other water bodies (*material 8*);
- **Layer 4** is also largely composed of elements representing the embankments (*material 3*), except for the chalk (*material 5*), colluvium in some places (*material 9*), filled gravel pits (*material 6*), and the Meuse River and water bodies (*material 8*).

Hydraulic-conductivity values that were assigned to the various materials (prior to assignment of detailed K distributions to the gravel) are summarized in *Table 2*. Storativity values were

Table 2. Hydraulic conductivity of various materials used in the model, before application of the correlation between resistivity and hydraulic conductivity for material 1.

Material number	Description	Hydraulic conductivity, K, m/s
1	Gravel	8×10^{-3}
2	Loam	5×10^{-7}
3	Embankment	5×10^{-6}
4	Gravelly loam	1×10^{-5}
5	Chalk	1×10^{-4}
6	Filling of gravel pits	1×10^{-6}
7	Special[1]	--
8	Water	--
9	Colluvium	1×10^{-7}
10	Limestone	1×10^{-5}

[1] Assigned to elements that are inactive in the computations, e.g., old gravel pits above the water.

not included because they have no influence on the computation, as the simulation is for steady-state conditions. The observed potentiometric surface of *Figure 3* was used as the basis for calibration. This map, which corresponds nearly to the lowest water level of the river, was judged by the Ministry of Public Works as suitable for estimation of flow in the alluvial aquifer.

The boundary conditions are shown in *Figure 7* and described as follows:

- *External and lateral boundaries.* Imposed potential conditions that are consistent with the geological and hydrogeological context were chosen for the external lateral boundaries of the model. These prescribe the input or output fluxes allowed at each node of the boundary. For the base of the model, no-flow boundaries were imposed except in particular zones of high-permeability chalk or fractured limestone bedrock. In these areas, imposed potentials were prescribed.
- *Internal boundaries: the banks of the Meuse River.* Where the banks represent natural river levees, imposed potentials were chosen equal to the water level of the Meuse River. In sections where the river is canalized, drains collect groundwater flowing from the alluvial aquifer. In this case, impermeable boundaries represent the river banks, but output flow terms were defined that correspond to the collected flows in the drain, 0.158 m^3/s on the right bank and 0.385 m^3/s on the left. These prescribed flows are spatially distributed among all the nodes representing the drain.
- *Source terms and pumping.* The main source terms are leakage from the bed and the banks of the Albert Canal. The fluxes were previously estimated (Monjoie et al., 1987) and, in the model, as a first approximation, these were distributed among the nodes bounding the canal. Four zones are distinguished: the Hermalle zone, where the flows are from 0.2-0.3 x 10^{-3} $m^3/s/m$ of canal length; the Lixhe zone, 0.45-0.73 x 10^{-3} $m^3/s/m$; the Nivelle zone, 0.08-0.17 x 10^{-3} $m^3/s/m$; and the Lanaye zone, 0.12-0.23 x 10^{-3} $m^3/s/m$. During the calibration procedure, some of these values had to be further modified. Other sources terms taken into account include some border zones of the alluvial plain. In this case, flows entering the alluvium are imposed at the relevant node. All the significant pumping wells (> 0.0004 m^3/s) are taken into consideration by defining abstraction nodes. A uniform seepage of 9.5 x 10^{-9} $m^3/s/m^2$ was introduced in the model, corresponding to 300 mm/yr effective infiltration.

Calibration

The primary calibration was performed using the data set of hydraulic-conductivity values (K_f) corresponding to the former correlation with electrical resistivity. The domain was divided into only 26 "materials" of differing hydraulic conductivity. These values were introduced into the first run. After each successive run, the values and, eventually, their spatial distribution were slightly modified to obtain a fit between the simulated potentiometric surface and the observed surface.

Differences in hydraulic-conductivity values are summarized in *Table 3*. As shown by comparing *Figure 8* and *Figure 3*, at the 23rd run, a mean deviation of about 10-20 cm between observed and simulated heads remained throughout the whole domain, except in the southern part of the zone, where the lack of measured data did not permit a refinement of the calibration.

After this calibration, the data sets obtained by the new parabolic correlation were introduced. The K_{min}, K_{mean}, and K_{max} data sets were successively introduced and comparisons made with the "calibrated" condition. As an example of these comparisons, the simulated potentiometric surface that was obtained by using the K_{mean} data is shown in *Figure 9*, which can

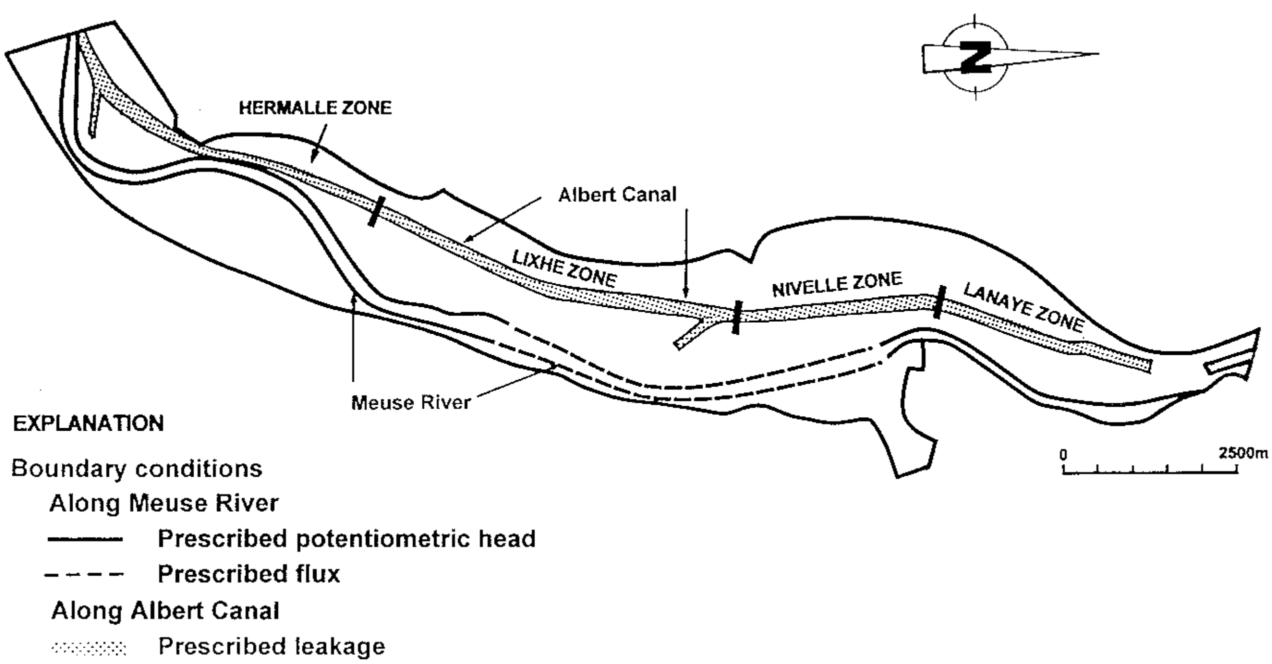


Figure 7. Boundary conditions of the model.

Table 3. Values of hydraulic conductivity used in the model; initial values (Run 01) and calibrated values (Run 23).

Material no.	Description	Hydraulic conductivity, K, m/s	
		Run 01	Run 23
1	Gravel	7.5 x 10^{-3}	1.5 x 10^{-3}
2	Loam	5 x 10^{-7}	5 x 10^{-7}
3	Embankment	1 x 10^{-6}	1 x 10^{-6}
4	Gravelly loam	1 x 10^{-5}	1 x 10^{-5}
5	Chalk	1 x 10^{-4}	1 x 10^{-4}
6	Filling material of old gravel pit	1 x 10^{-6}	1 x 10^{-6}
7	Special	0	0
8	Water	1	1
9	Colluvium	1 x 10^{-7}	1 x 10^{-7}
10	Limestone	1 x 10^{-5}	1 x 10^{-5}
11	Gravel	3 x 10^{-3}	6 x 10^{-3}
12		6 x 10^{-3}	1.2 x 10^{-2}
13		6.5 x 10^{-3}	1.3 x 10^{-2}
14		7 x 10^{-3}	1.4 x 10^{-2}
15		8 x 10^{-3}	2 x 10^{-2}
16		9 x 10^{-3}	4.5 x 10^{-2}
17		1 x 10^{-2}	5 x 10^{-2}
18		1.5 x 10^{-2}	7.5 x 10^{-2}
25	Gravel + colluvium	--	3.5 x 10^{-3}
26	Clean gravel	--	1.0 x 10^{-1}

be compared with the calibrated potentiometric map (*Fig. 8*). Although further calibration refinement could be carried out, the agreement between the initial K_{mean} run and the observed potentiometric surface is very good and approaches the calibration surface shown in *Figure 8*.

Results

Computation of flow was the main objective of this study. Simulated groundwater flow directions and magnitudes that correspond to the 23rd run of the calibration are shown in *Figure 10*. The flow values at the internal and external boundaries of the model are shown in *Figure 11* and summarized in *Table 4*.

Under the calibrated condition, the alluvial aquifer receives about 2.75 m^3/s from lateral hillsides of the alluvial plain, of which only 1.32 m^3/s is derived from the lateral boundaries with the chalk and limestone formations and about the same amount from all the other lateral boundaries. The main input term is leakage from the Albert Canal (2.69 m^3/s). The total output from the alluvial aquifer to the Meuse River is 5.22 m^3/s along the whole studied zone for summer conditions. A larger value is probable during wetter seasons of the year.

On the basis of the model, the additional flow crossing to the Netherlands via the alluvial aquifer and the Meuse River is estimated at 5.4 m^3/s during the summer. This value represents flow not measured by the surface-water gauging system.

For the run using the K_{mean} data set, the flow results at the internal and external boundaries (*Fig. 11*) of the model are summarized in *Table 4*. This run was not spatially calibrated, but the set of hydraulic-conductivity data can be considered as the result of an optimal parabolic correlation with apparent electrical resistivity of the alluvial gravel. The flows derived on the basis of the K_{mean} data set are slightly different from those calculated for the "calibrated" condition (*Table 4*). In the K_{mean} computation,

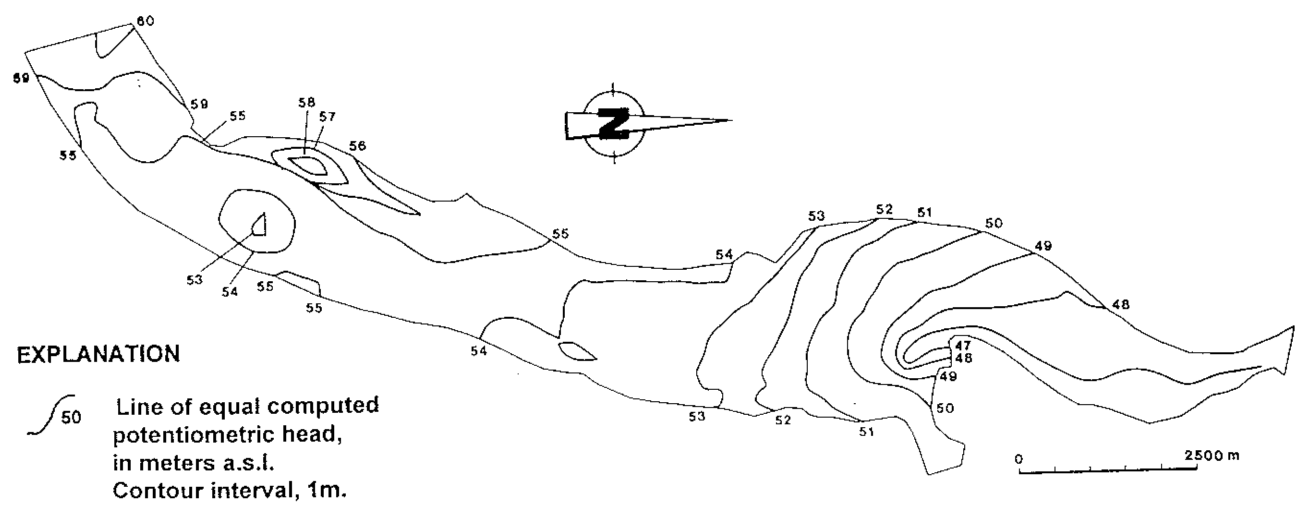


Figure 8. Computed potentiometric surface, 23rd run of the calibration. Values are based on the former correlation between hydraulic conductivity and electrical resistivity.

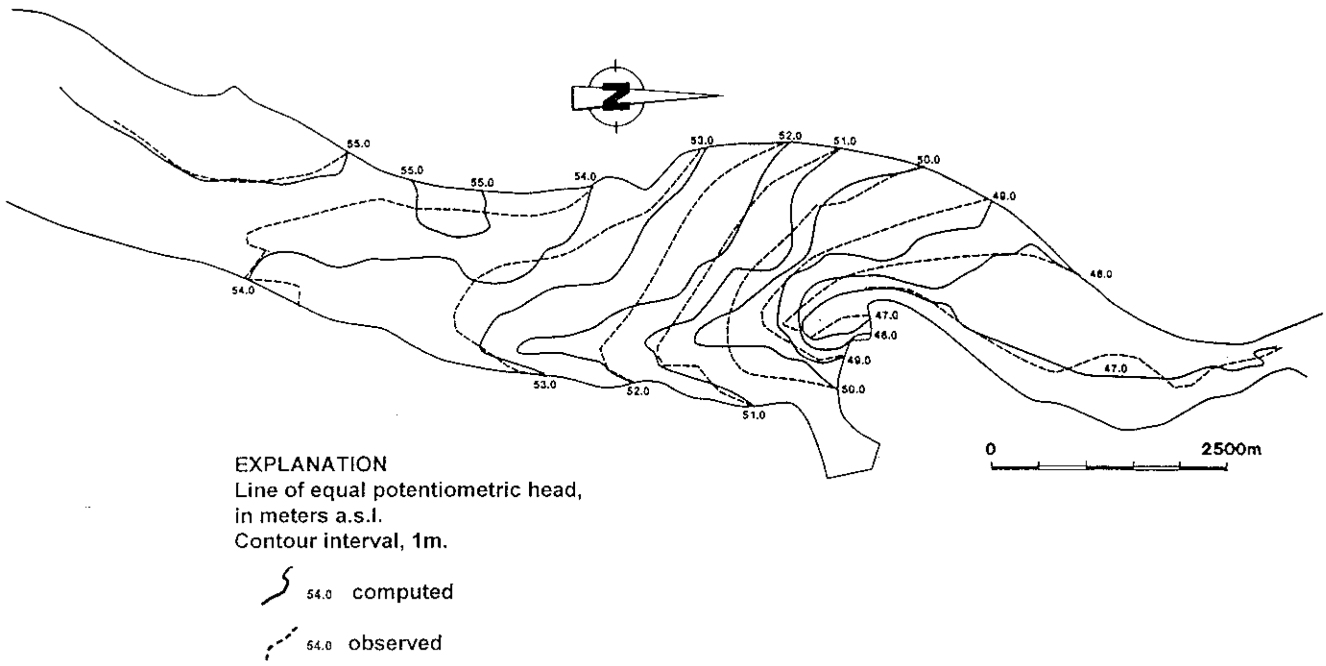


Figure 9. Computed potentiometric surface, based on mean hydraulic conductivity, and reference (observed) potentiometric surface (*Fig. 3*).

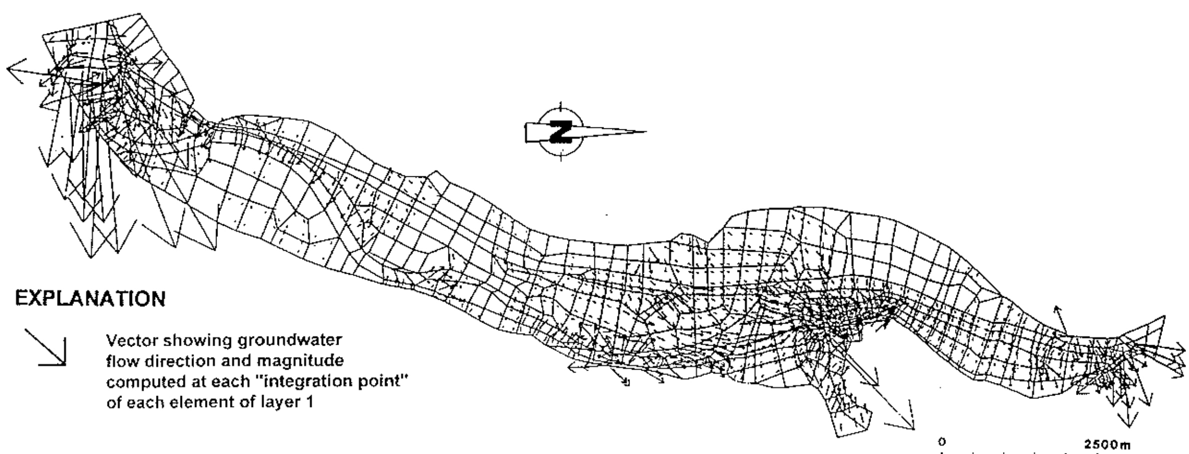


Figure 10. Computed groundwater flow directions and magnitudes, first layer of elements (mainly composed of gravel).

the alluvial aquifer receives about 2.12 m^3/s from lateral boundaries, and the output to the Meuse River is about 4.72 m^3/s.

Simulations were also run on the basis of the K_{min} and K_{max} data sets from the parabolic correlation. The computed potentiometric levels for these data deviate further from the reference potentiometric map than do the results from the K_{mean} data set.

Conclusions

In the case of such a detailed quantitative study of groundwater fluxes, an accurate and detailed groundwater model is undoubtedly a very useful analytical tool. However; it requires the introduction of a geologically consistent spatial distribution of the hydraulic-conductivity values.

The discretization of the model network was developed using all the available geometrical data concerning the subsurface, hillsides, and various alluvial lithologies.

All stresses and influences on the system were taken into account, i.e.:

- Uniform recharge from infiltration;
- Leakage from the canal;
- Local up-flowing infiltration from underlying karstified limestones;
- Impervious banks and drains along the canalized river in some places; and
- Pumping wells.

Using the formerly accepted resistivity-conductivity correlation as the starting point for calibration, a satisfactory match

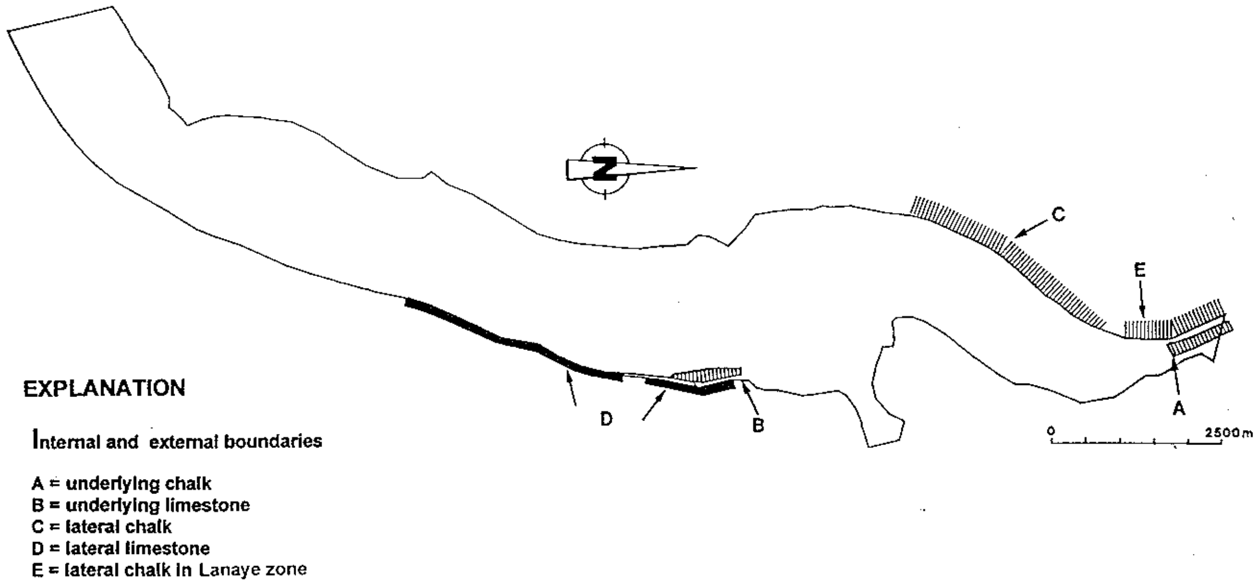


Figure 11. Locations of internal and external boundaries where flows occur.

Table 4. Computed groundwater flow at internal and external boundaries of the model, under calibrated conditions and using mean hydraulic-conductivity dataset.

Boundary		Computed flow, m^3/s					
Symbol	Description	Calibrated model (Run 23)			Using K_{mean} dataset		
		Input (+)	Output (-)	Balance	Input (+)	Output (-)	Balance
A	Underlying chalks	0.334	- 0.094	0.240	0.336	- 0.094	0.242
B	Underlying limestones	0.012	- 0.133	-0.121	0.019	- 0.011	0.008
C	Lateral chalk	0.344	- 0.003	0.341	0.125	- 0.006	0.119
D	Lateral limestones	0.700	- 0.187	0.513	0.522	- 0.105	0.417
E	Lateral chalk in Lanaye	0.565	- 0.104	0.461	0.708	- 0.061	0.647
F	Entering the Meuse River	46.945	- 52.162	- 5.217	45.956	- 50.674	- 4.718
G	All other lateral external boundaries	2.544	- 1.109	1.435	1.841	- 0.904	0.937
H	Source (pumping) term	0.278	- 0.446	- 0.168	0.278	- 0.446	- 0.168
I	Drains along the banks of the Meuse River	-	- 0.732	- 0.732	-	- 0.732	- 0.732
J	Leakage from the Albert Canal	2.692	--	2.692	2.692	--	2.692
K	Uniform infiltration	0.285	--	0.285	0.285	--	0.285
L	Underlying karstified limestones, in connection with an artesian aquifer	0.271	--	0.271	0.271	--	0.271
Sum		54.970	-54.970	0.000	53.033	- 53.033	0.000

was obtained by the 23rd simulation run. The following fluxes were computed from this run: 2.75 m^3/s entering the alluvial aquifer via its lateral boundaries; 2.7 m^3/s to the aquifer from leakage from the Albert Canal, and 5.22 m^3/s from the alluvial aquifer to the Meuse River.

Based on an apparent electrical resistivity map of the alluvial gravel, resistivity-hydraulic conductivity correlations were carried out, enabling the estimation of the most probable hydraulic-conductivity distribution, to be used in the FEM model. Simulations were carried out using these last hydraulic-conductivity data sets. Results of the first run are nearly as good as those obtained after the 23rd run of the previous "trial and error" calibration. This does not automatically imply the success of a similar correlation approach in other studies, but it does illustrate how the use of such a correlation can increase confidence in data to be used in numerical simulations. High data quality generally increases confidence in modeling results.

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