An accurate transient calibration for a detailed 3D model of a highly heterogeneous aquifer

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Summary: The 3D discretization in finite elements and the modelling of a water table aquifer in Cretaceous chalky formations in Belgium is briefly described. Emphasis is given to the very detailed calibration or "history matching" procedure which has lead to solve the complete inverse problem. This calibration has been completed on a period of more than 42 years as historical data since 1951 were available. A "postaudit" study have been also performed comparing the predictions former calibrations of the model to the newest data.
Due to the complexity of the geological conditions, the use of a real 3D finite element mesh is fully justified but it induces heaviness in the calibration. The basic "trial-and-error" approach is used because it seems that no sophisticated optimisation method could respect such a complex and heterogeneous situation, revealed by the numerous field data. About 30 "target-points" for the calibration have been chosen as measurements of the piezometric heads are available monthly in those 30 wells.
Theoretically the calibrated parameters are probably still wrong in many places, but as long as they reproduce the observed behaviour of the system on a "matching period" longer than 42 years, we are confident in the reliability of the predictions on one- or two-years periods.

1 HYDROGEOLOGICAL CONTEXT

A chalky aquifer located near Liège in Belgium (figure 1a) is recharged by infiltration through the overlying loess. Wells and collecting tunnels produce a daily flow of 60000 m³ out of this aquifer when hydrogeological balances have shown that an average yield of 100000 m³/day should be possible.
The studied zone corresponds to an area of 350 km² called 'Hesbaye' and the geological nature of the reservoir is mainly chalk.
The complete collection of data has included informations concerning geology, hydrology, geomorphology and geophysics.
As described by Calembert (1), the geology of this aquifer can be summarised (figure 1b) as Secondary formations essentially composed by Cretaceous layers of 20 to 100 m of thickness with: (1) a layer of hardened calcareous clay (called 'smectite') considered as the bottom of the aquifer, (2) a compact massive white chalk (called 'lower chalk' with main water circulations in the more fractured zones (thickness : 20 - 40 m), (3) a thin (< 1 m) layer of hardened chalk (called 'hardground'), (4) a grey chalk (called 'upper chalk') more exposed to weathering and fissuration phenomena (thickness : 10 - 15 m), (5) a residual conglomerate.
Tertiary and Quaternary formations, composed of sand in some places and most often of loess, are covering the aquifer with a highly variable thickness (2 - 20 m). In the valleys, the loess can be absent but, in some places and especially in the North, near the River Geer (figure 1a), recent alluvial deposits can be found.
Cross-sections and maps have been drawn using all the geological and piezometric data.

The hydrodynamic parameters have been provided by pumping tests in the different lithological units. The following ranges of values are found :

–loess :	$1.10^{-9} \leq K \leq 2.10^{-7}$ m/s
–residual conglomerate:	$1.10^{-5} \leq K \leq 8.10^{-3}$ m/s
	$0.05 \leq S \leq 0.10$
–upper chalk	$2.10^{-4} \leq K \leq 5.10^{-3}$ m/s
	$0.02 \leq S \leq 0.15$
–lower chalk	$1.10^{-5} \leq K \leq 5.10^{-4}$ m/s
	$0.05 \leq S \leq 0.15$

In water tables conditions, the unconfined storage coefficient (S) is approximated by the effective porosity (n_e) of each lithological unit. For this aquifer the measured values of S can sometimes be very high as the chalk is a double porosity medium. The fracture or fissure porosity can influence greatly the total value of the effective porosity (Monjoie (2)).
Since 1951, piezometric levels have been measured with great care. Evolution of the piezometric level in function of the time has been recorded at different 'check points' of the aquifer. Piezometric maps and sections relative to each year have been drawn.
The active hydrographic network is directed to the N-NW as the topographic levels present a slow decrease to this direction. This network is sparse because many 'dry valleys' (mainly due to chalk fracturation and karstification) are working as main drainage axis in the subsoil.
The river flow, the galleries discharges and the rainfall recharge by infiltration are well known time depending date.

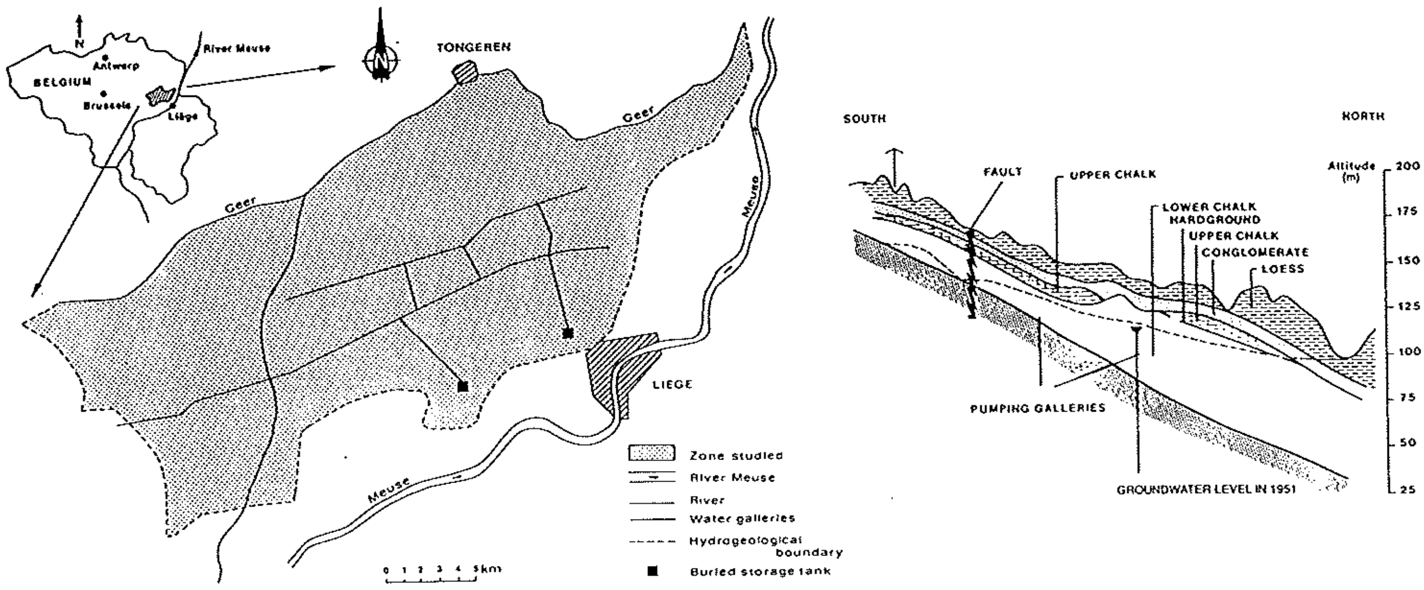

Figure 1: Location map and vertical geological cross section

2 DESCRIPTION OF THE MODEL

A finite element model has been developed to get an integrated analysis of such an aquifer. This analysis becomes more and more essential to get the best development possible avoiding total or partial depletion of the aquifer.
The finite element method seems very well adapted to model such a geometrically complex and heterogeneous problem. Isoparametric finite elements can easily follow the limits of the layers or boundaries. The Representative Elementary Volume (REV) theory (Bear & Verruijt (3)) and conceptual approach assuming the continuity of the porous medium, has been chosen to deduce the parameters to introduce in each finite element of the 3D mesh. Porous medium elements, gallery elements and infiltration elements can be combined.
The finite element code LAGAMINE, developed during the past ten years in the M.S.M. department of the University of Liège, has been used on this application. The 3D discretization and the modelling of the entire aquifer has been realised. The problem requires about 3600 DOF and 2670 8-nodes isoparametric brick finite elements.
The computation in transient conditions and in three dimensions of the water table position is usually one of the most difficult problems to solve. The method which has been used here, is based on a pressure dependent volumic storage law as described previously by Charlier et al (4) and Dassargues (5).
The isoparametric finite elements have been discretized in a classical finite element model :
- plane axisymmetric parabolic elements, 8-node squares and 6-node triangles;
- 3D brick-elements with 1 to 3 nodes on each edge, parabolic anc cubic polynomials can be used;
-3D lines, for one-dimensional flow as in collecting galleries;
-3D thin elements (for faults).

In each element, the volumic integration is performed numerically using the Gaussian scheme. The iteration technique is the well-known Newton-Raphson technique.

The 3D network has to take into account all the geometrical data: location of pumping wells and galleries, main geological faults, limits of geological units or hydrogeological basin. The mesh has been presented in details previously (Dassargues et al. (6)). The collecting galleries are represented by '3D tube elements' with infinite permeability in regard to the neighbouring elements. The initial conditions are the piezometric levels of 1951, from which the simulation is started in transient conditions. Prescribed potential (Dirichlet conditions) are imposed on the northern boundary at the River Geer. The other boundaries are assumed to be impervious (Neuman condition) as it seems that no flow is to be considered through these geological boundaries.
The hydrodynamic parameters affected in each element are the permeability K and the storage coefficient S. Initially different kinds of materials have been defined corresponding, before calibration, essentially to the different distinguished geological units.

3 PREVIOUS CALIBRATION

Before the beginning of the first calibration procedure, the main difficulties encountered were the following :
- the introduction of infiltration recharge by a means numerically compatible with the modelling of the water-table (in fact by surfacic 'flow elements' with normal uniform flow);
- the introduction of very high contrasts in the permeability values in the immediate neighbourhood of the pumping galleries;
- the introduction of the prescribed concentrated pumping flows in these galleries avoiding an important depression cone.

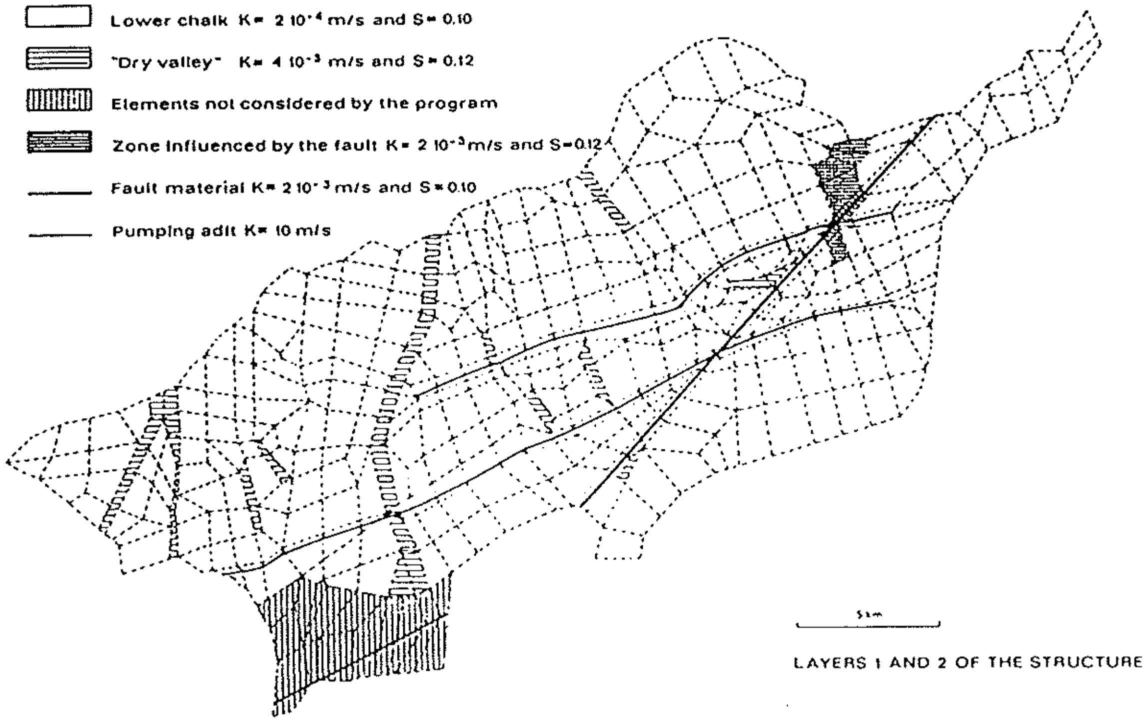

Figure 2: Spatial distribution of the different materials in the layers 1 and 2 of the full 3D structure of the model (end of the previous calibration).

After this, the first calibration procedure has consisted mainly in (Dassargues et al. (6)) :
(1) the fitting of the different hydrodynamic parameters of each material;
(2) some modifications in the spatial distribution of these different materials. These adjustments are made on basis of comparisons between measured and computed values of piezometric levels on the maps and the sections and at some 'check points'.

At this stage corresponding to the end of the calibration procedure completed in 1987, the final values of the different parameters were :

Material 1 :	lower chalk : $K = 2.10^{-4}$ m/s and $S = 0.10$
Material 2:	'dry valley' : $K = 4.10^{-3}$ m/s and $S = 0.12$
Material 3 :	'hard ground' : $K = 8.10^{-5}$ m/s and $S = 0.08$
Material 4 :	upper chalk : $K = 5.10^{-4}$ m/s and $S = 0.12$
Material 5 :	alluvial deposits and residual conglomerate $K = 1.10^{-5}$ m/s and $S = 0.15$
Material 6 :	conglomerate and loess : $K = 1.10^{-6}$ m/s and $S = 0.15$
Material 7 :	'fault material' : $K = 2.10^{-3}$ m/s and $S = 0.10$
Material 8 :	upper chalk in the up-west zone : $K = 2.7\ 10^{-4}$ m/s and $S = 0.12$
Material 9 :	new 'dry valley' in NE area, near the fault : $K = 2.10^{-3}$ m/s and $S = 0.12$

The spatial distributions of these materials in the 3D model, at the end of this previous calibration are shown for layers 1 and 2 at the figure 2.

4 NEW CALIBRATIONS

The previous calibration was completed in 1987 and since this time, new piezometers were drilled and provided piezometric measurements. In order to use the model for prediction computations, it became very important, in 1992, to actualise the calibration taking into account the transient values of the effective infiltrations between 1987 and 1992 and the new target points constituted by the new available piezometers.
At the beginning of this second calibration and using the real infiltration data, the computed piezometric levels provided the possibility of a comparison with the new piezometric data measured between 1987 and 1992. This comparison can be qualified as a "postaudit" analysis of the previous calibration (figures 3 and 4).
The zones of the modelled aquifer, where corrections have to be made concerning the spatial distribution of the parameters and their values, are indicated by these comparisons.

Then the new calibration has been completed in 1992. During this second calibration procedure, many new materials have been distinguished especially to introduce much more details and local accuracy in the chalky layers. For example, at the end of this second calibration, the material map of the layer 1 (lower chalk) has become very complicated with more than 20 different materials describing different hydrodynamic behaviours of the 'lower chalk'.

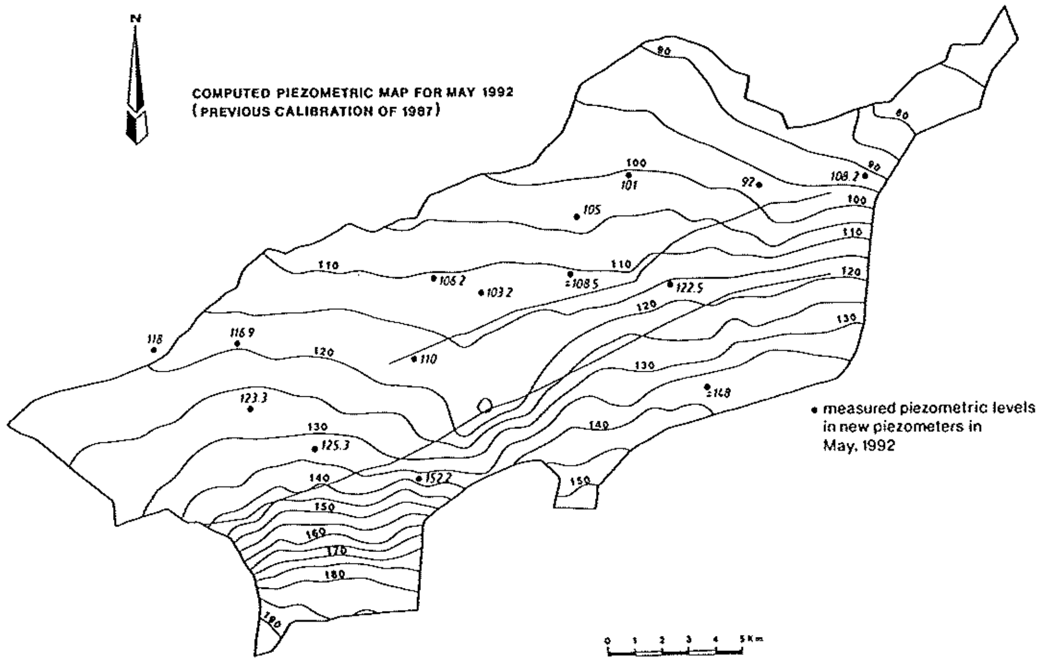

Figure 3 : Postaudit analysis between 1987 and 1992 : Comparison between the map computed by the model calibrated only until 1987, and the 15 new piezometric measurements.

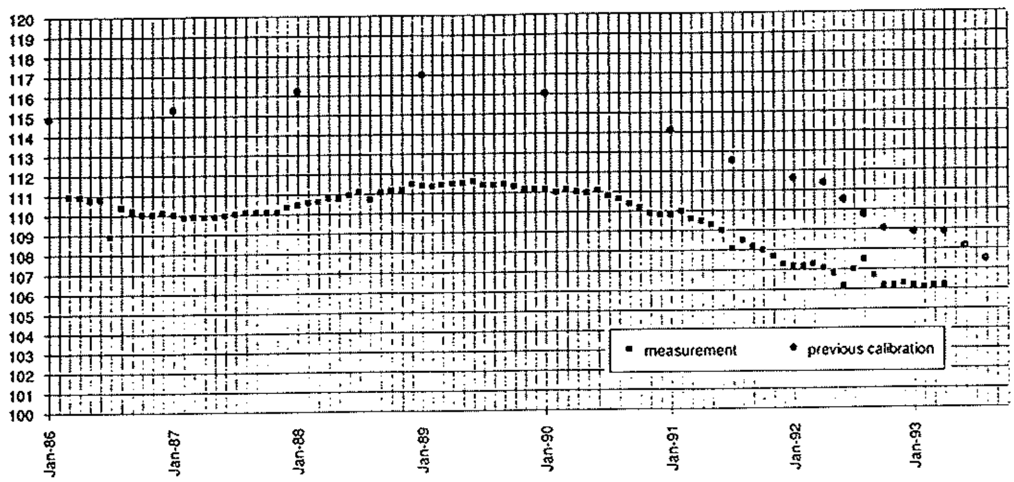

Figure 4 : Postaudit analysis between 1987 and 1992 : Comparison between the evolution of the piezometric level at the piezometer P 10 computed with the model calibrated only until 1986 (previous calibration), and the new measured piezometric levels.

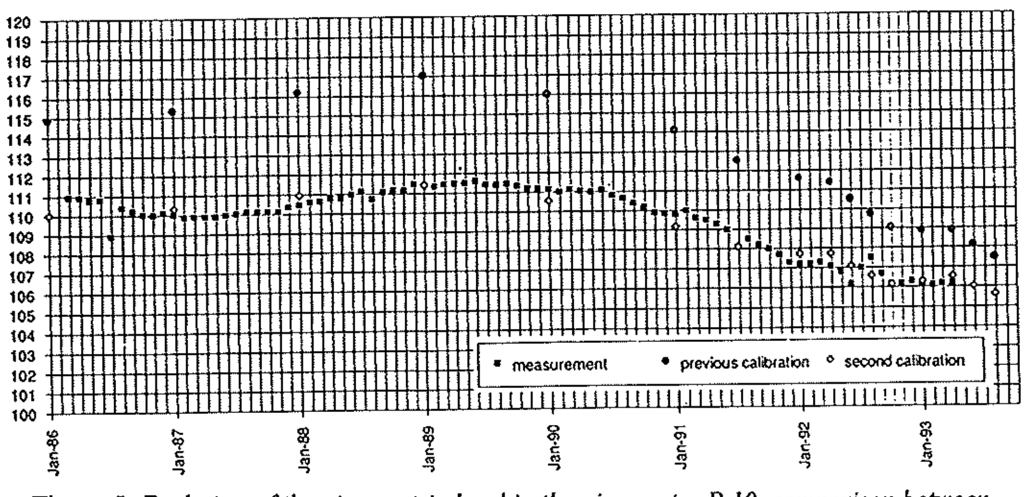

Figure 5 :Evolution of the piezometric level in the piezometer P 10, comparison between measurement and computed result at the end of the second calibration.

As a result, the measured and computed piezometric evolutions are closer than before (figure 5 to be compared with figure 4).

In 1993, 15 additional measurement points of the piezometric levels were provided by the local water company with reliable measurements available since 1986. Consequently the same kind of postaudit analysis has been done comparing the newly available piezometric data between 1986 and 1993 to those computed by the model after the second calibration (figure 6) and before the third calibration. Of course this comparison showed some differences which demonstrated that it was necessary to improve again the calibration and probably to distinguish more different materials (sometimes characterized by slightly different parameters).

So the third calibration has been completed. At the end of this last calibration, 54 materials were used in the model; about 35 materials are used to describe the hydrodynamic properties of the 'lower chalk' (figure 7), and 15 materials for the 'upper chalk'.

The results in terms of computed piezometric maps and piezometric evolutions at the different 'target' points are very close to the measurements (figures 8 and 9). With regard to

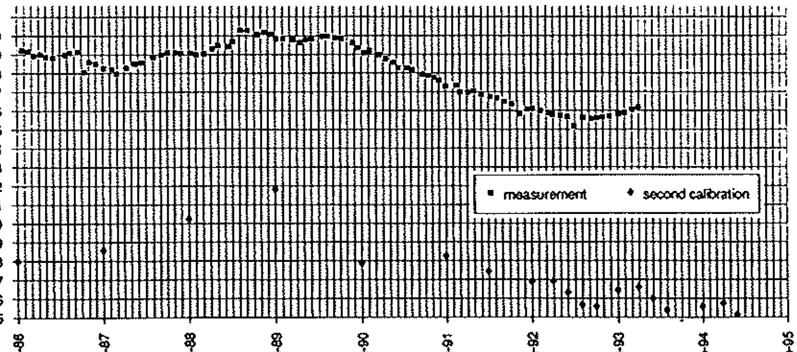

Figure 6 : Second postaudit analysis between 1986 and 1993 : Comparison between the time evolution of the piezometric levels in piezometer PU 2 computed by the model calibrated until 1992, and the new measured piezometric levels.

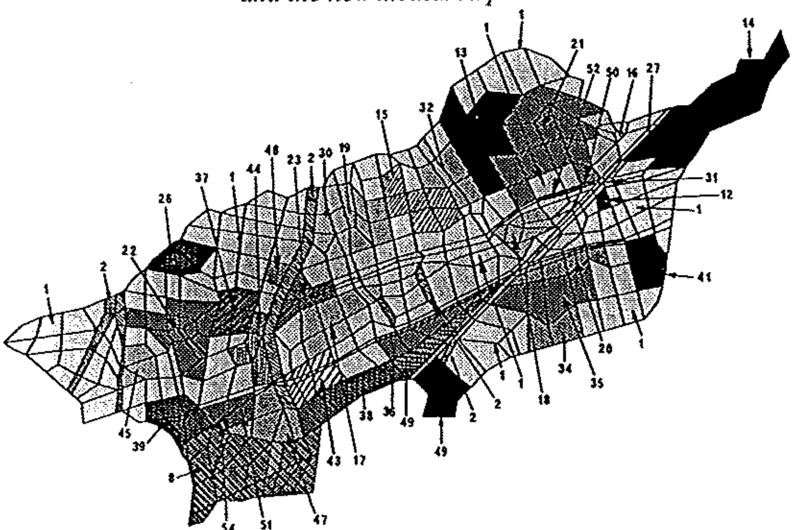

Figure 7 : Map showing the spatial distribution of the different materials in the layers 1 and 2 of 'lower chalk' at the end of the third calibration.

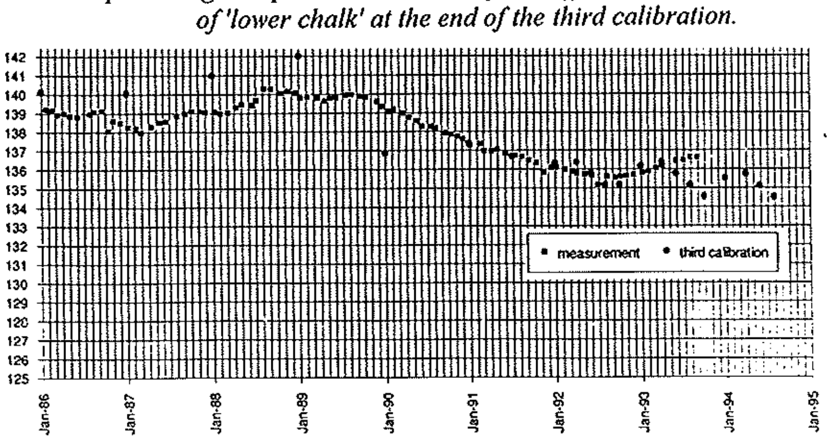

Figure 8 : Evolution of the piezometric level in the piezometer PU 2, comparison between measurement and computed result (end of the third calibration).

the very detailed calibration on a long period (42 years) and taking into account all the transient solicitations of the aquifer, we are able to use this model to make some reasonable predictions for the next years. Given some averaged meteorological conditions (on the last ten years) and some collecting-pumping conditions similar to those of the period September 1992 - September 1993, the computations have provided the piezometric maps for the end of 1994.

5 CONCLUSIONS

The model calibration for the quantitative aspect of the groundwater has been actualised in function of the most recent available data and in function of additional piezometric measurements in new wells. This whole calibration procedure has been realised by 'trial and error' method as we do like to keep and check the geological-hydrogeological significance of each change in the values of the hydrodynamic parameters (or in their spatial distribution), in the context of a highly heterogeneous chalky aquifer.
Of course, as mentioned by de Marsily et al. (1992), the parameters of the model are uncertain and probably still wrong, and the 3D structure of the model can be incorrectly chosen in some places. However, we consider that as it reproduces fairly well the observed behaviour of the system on a long period (42 years), we can be confident of its validity to make predictions.
In this study, we have tried to show an example of successive model improvements raising up from 'postaudit' analysis. Independently of the climate variability, the computed results of a previously calibrated model are compared to the new measurements. From this comparison, conclusions can be drawn out about the validity of the model and, more important, corrections can be brought to improve this validity. Performing these improvements contributes to build the most valid tool to help the decision-makers in their choices. The model can help them to take the best decisions and the better the validation of the model, the better can be the decision.

ACKNOWLEDGEMENTS

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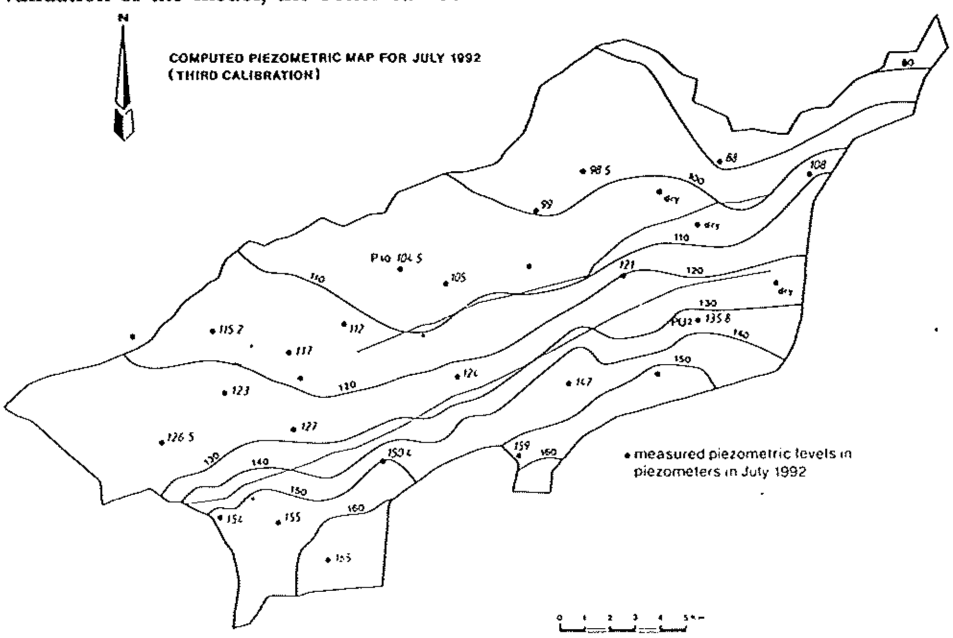

Figure 9 : Computed piezometric map for the end of July 1992, compared to the piezometric levels measured at the 'target points' (end of the third calibration).