The Cenomanian Sands aquifer model: an effective groundwater management tool

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ABSTRACT: The Cenomanian sands aquifer represents a strategic groundwater reserve within the Loire-Brittany Basin. It has a surface area of 25,000 km² and spans 10 administrative districts and four regions (Centre, Pays de la Loire, Poitou Charente and Basse Normandie). A regular drop in the water table has been observed for about the past thirty years. This is particularly pronounced in the Tours area. This weakening of the aquifer has resulted in a decrease in borehole productivity and direct contamination from incoming chlorides from the underlying Jurassic aquifer. Faced with the potential overexploitation of the aquifer, a "Committee for the management of the Cenomanian aquifer", involving elected representatives, administrative bodies and water users, has decided to launch a study programme that has resulted in the development of a groundwater management model.

The first stage of this study programme consisted of extensive data collection and analysis work completed with a number of field investigations, to improve knowledge of the aquifer and gain a better understanding of its hydrodynamic behaviour. A large multilayer model was then developed using the FeFlow modelling code. This model was calibrated over the 1994-2008 period. It takes into account the groundwater/river interactions and the lateral changes in the behaviour of the Cenomanian sands aquifer, from confined to unconfined. This model is currently being used to assess groundwater level changes under various stress conditions (decrease/increase in abstraction within some specific areas, decrease in recharge, etc.) and is also being used by the Committee as a decision-aid tool to set water resources use restrictions in some sensitive areas.

POLITICAL DETERMINATION TO STOP THE WEAKENING OF THE AQUIFER

A strategic but weakening groundwater resource

The Cenomanian sands aquifer is considered a strategic groundwater reserve within the Loire-Brittany Basin. It has a surface area of 25,000 km² (cf. figure 1) and extends over 10 administrative districts and four regions (Centre, Pays de la Loire, Poitou Charente and Basse Normandie).

In its water assessment programme the Loire-Brittany Water Authority qualifies the confined part of this aquifer as a resource that must be preserved first and foremost for providing human water supplies.

Over the past 30 years, the increase in groundwater abstraction has led to a regular drop in the groundwater level, particularly in the Tours area, in the centre of the confined part of the aquifer (cf. figure 1). This weakening of the aquifer has led to a decrease in borehole productivity and, locally, to direct contamination from the adjacent aquifers (in particular by chlorides from the underlying Jurassic aquifer). In addition, the threat of the aquifer becoming unconfined in the central area and of a subsequent possible change in groundwater quality has reinforced public concern over the need for concerted groundwater management.

With the objective of introducing concerted groundwater management, the Prefect of the Centre Region has set up a committee to manage the Cenomanian aquifer. This committee involves all the stakeholders: elected representatives, local authorities as well as water users from each administrative district.
A major study programme initiated by the “Committee for the management of the Cenomanian aquifer”

Faced with the potential overexploitation of the aquifer, which could further weaken the aquifer and lead to conflicts between the various water users, the Committee decided to launch a study programme. This programme involved implementing a groundwater management model and was aimed at setting up groundwater management regulation based on a sound assessment of the aquifer’s sensitivity to abstraction. The Loire-Brittany Water Authority was in charge of supervising this programme, which was carried out by Sogreah under supervision by a steering committee.

The steering committee was closely associated throughout the development of the study programme: it provided valuable information on the local hydrogeological characteristics, and it discussed and validated the main steps of the project (especially the choice of scenarios to be run in order to test the impact of different abstraction schemes on the groundwater table).

This close association from the very beginning of the study programme now facilitates the implementation of groundwater management regulation.

MODELLING A LARGE AQUIFER SYSTEM FOR GROUNDWATER MANAGEMENT

An important data acquisition phase to produce valuable inputs for the model

Prior to the building of the hydrodynamic model, a thorough field investigation campaign was undertaken to improve knowledge of aquifer system behaviour. This 12-month data acquisition phase included the collection and analysis of groundwater abstraction data, groundwater level measurements, the building of a multilayer geological model, pumping tests, the collection of aquifer hydrodynamic characteristics, and the assessment of recharge and groundwater/river exchanges.

One of the difficulties was obtaining a good assessment of groundwater abstraction. The well data comprised, on the one hand, well location and characteristics data surveyed by the French Geological Survey (BRGM), and, on the other hand, abstraction data related to water users, with the invoicing address being the only location data stored by the Loire-Brittany water Authority. Therefore, a methodology was established to correlate the abstraction data to the location of the wells from which groundwater is abstracted. A database including all the pumping wells tapping the Cenomanian aquifer was then created.

While this data acquisition phase was expected to produce valuable inputs for the model, it has also produced direct useful results for aquifer groundwater management. In particular, the detailed assessment of geological layer elevations and the updated piezometric levels made it possible to determine the extent of the confined area of the Cenomanian sands aquifer, which was a prerequisite to the zoning of the “groundwater distribution areas”.

In spite of these investigations, some uncertainties remain (such as the easternmost extent of the marl formation separating the Cenomanian sands aquifer from the overlying Seno-Turonian aquifer). The steering committee suggested that the modelling approach should take these uncertainties into account, making it possible to envisage any kind of conceptual model at any stage of the modelling process.
The modelling approach was consequently adapted in such a way that it would be easy to make significant modifications to the initial conceptual model, taking advantage of finite-element spatial discretization and of associated features such as the use of supermesh objects and constraint lines within the FeFlow code.

The various modelling steps and the approach developed to deal with the complex characteristics of this large aquifer are explained below.

**Geological and hydrogeological characteristics**

The Cenomanian aquifer is located in the basin to the south-west of Paris, one of the major geological regions of France. The hydrogeological characteristics of the aquifer differ in its central, confined, part, and in its northern, southern and western borders, where it outcrops. The aquifer is bounded to the east by a lithological change, from sandstones to poorly productive chalk.

In the confined part, Cenomanian sandstones are overlaid by the unconfined Seno-Turonian limestone aquifer. The two aquifers are separated by a Lower Turonian Ostracaceae-containing marlstone aquitard of variable thickness that locally disappears, thus allowing significant water exchanges between the two formations.

The main flow components and geological formations of the Cenomanian sands aquifer system are presented below.

![Figure 2: Schematic overview of the spatial distribution of the main geological formations (f.) and of the flow components of the Cenomanian sands aquifer system](image)

**Conceptual model**

Within the framework of large sedimentary basins, the aquifer under consideration is often part of a multilayer system with alternating aquifers and aquitards. The question is then to determine the most relevant set of geological formations for the model domain.

A first approach is to include the whole multilayer system up to the topographic level. In this case, the upper boundary condition can be defined as recharge from rainfall. However, all the geological formations overlying the target aquifer (Cenomanian sands) must then be described with respect to their hydrodynamic characteristics and to abstraction stress and groundwater/river interaction. This may be difficult or inaccurate due to lack of information.

Another approach is to reduce the domain to the formations surrounding the target aquifer so as to avoid characterizing the upper geological formations and the associated flow components. This can be envisaged if sufficiently reliable boundary conditions can be determined and if these conditions do not bias the results of the predictive scenario simulations.

This latter approach has been selected to model the Cenomanian aquifer system. The geological formations delimiting the model are Cenomanian sands, Ostracaceae-containing marl, and Seno-Turonian limestone, with a prescribed head boundary condition for the third formation (see figure hereafter).
Managing the upper Seno-Turonian aquifer boundary condition

The conceptual approach presented above was possible because a detailed Seno-Turonian water table map was drawn up at the beginning of the study on the basis of the initial phase investigations (groundwater level measurements) and a piezometric network run by the regional industry and environment authority (DIREN).

From a technical point of view, the difficulties associated with this conceptual model are, firstly, building time-dependent Seno-Turonian piezometric maps over the simulation period and, secondly, including in the model prescribed heads that vary in time and space.

A set of Seno-Turonian piezometric maps covering the whole simulation period was built using a methodology based on the following steps:

1) The building-up of a reference piezometric map on the basis of an extensive field campaign in October/November 2003 (186 points);
2) The building-up of a set of relative groundwater level variation maps with a 3-month time-step, based on the DIREN network monitoring data;
3) The building-up of a set of piezometric maps with a 3-month time-step, resulting from superimposing the reference piezometric map on the groundwater level variation maps.

The 3-month time-step between two consecutive piezometric maps was selected after having analysed the groundwater level variations and their potential impact on the Seno-Turonian/Cenomanian groundwater flows.

The hypotheses underlying this method are that the main pattern of groundwater flow directions does not vary much in large aquifer systems (when the abstraction distribution pattern remains fairly similar over time), and that the variations could be estimated from a relatively loose network.
Groundwater simulation codes usually take into account either spatially distributed but not time-dependent prescribed head conditions, or time-dependent but not spatially distributed prescribed head conditions.

Therefore, this method of taking into account the groundwater flow exchange with the Seno-Turonian aquifer involved dividing the simulation period into 3-month periods and running successive 3-month simulations with the corresponding Seno-Turonian prescribed heads as upper boundary conditions. The batch mode of FeFlow code was hence used, a specific program having been developed to enable the results of one simulation to be used as initial heads for the following one.

**Space discretization using FeFlow constraint lines and points**

The main reason for using a finite element code such as FeFlow was that it offers the possibility of representing correctly all the contours (e.g. rivers) and wells in a sufficiently precise manner with a limited number of meshes.

![River representation in the model](image1) ![Well representation in the model](image2)

**Figure 5: Representation of referenced geographical objects in the model**

This space discretization (compared with finite difference discretization) also provides a correct representation of the location and surface area of zones where boundary conditions are applied over predefined areas (such as recharge zones).

After having analyzed the rainfall spatial distribution, several homogeneous recharge zones over the Cenomanian sand outcrops were defined (see figure below). The borders of these recharge zones were defined as 'constraint lines', allowing a specific recharge boundary condition to be assigned precisely on these zones. The total recharge flow over the area was thus correctly represented.

![Recharge zones](image3)

**Figure 6: Building-up of a grid consistent with the conceptual model**

**Model calibration**

Once the model construction had been completed, the model was calibrated by adjusting the hydrogeological characteristics of the three layers, the recharge and the river levels.

The difficulties encountered in satisfying the calibration criteria led to a review of various aspects of model construction, such as levelling the geology, since taking the tectonic accidents into account had led to the creation of badly connected meshes. The Seno-Turonian water table was also described in detail, to represent correctly the groundwater flow from the Cenomanian to the Seno-Turonian aquifer in the vicinity of the rivers (the initially smooth Seno-Turonian piezometry resulting from an
interpolation between a small number of referenced points had led to a drastic reduction in river drainage.

The model calibration targets included the 1994 and 2003 piezometric maps and piezometric head time series observed on the DIREN piezometric monitoring network.

Piezometric maps were built up on the basis of a limited number of observation points. Modellers may devote a great deal of time to representing piezometric curves correctly while not justifying them with enough reliable data. The calibration objectives for the piezometric maps were thus to match general flow directions and hydraulic gradients. As regards the piezometric head time series, the calibration objectives were to match seasonal and interannual fluctuations on the some 50 piezometers monitored by the DIREN.

The first approach envisaged was to calibrate the model under steady-state conditions, equivalent to the 1994 conditions, and under transient conditions between 1994 and 2003. However, this approach was rapidly ruled out because the Cenomanian aquifer was not in a steady state in 1994, but in depletion (as shown on the piezometric head history in Tours, figure 2).

The simulation start was thus set at 1992, i.e. two years before the calibration period, in order to take account of transient conditions in 1994 and reduce the impact of inaccuracies resulting from inexact initial conditions (1992).

The model simulated flow direction and hydraulics gradients correctly. Piezometric levels were simulated correctly, particularly in the central zone, except in some locations where specific hydrogeological features were not taken into account (particularly at some phreatic zones close to the model domain boundary). Differences between simulated and observed heads were less than a few metres in the central zone (when maximum head over the studied area is about 270 m and minimum head about 20 m).

A specific steady state simulation was also run without abstraction, in order to simulate the 19th century hydraulic conditions and check that the Cenomanian artesianism observed around the Tours area during that period had been reproduced correctly.

Transient calibration results are presented hereafter for a few piezometric time series.
The model was then used to assess groundwater level changes under different stress conditions.

The first simulations were aimed at quantifying abstraction schemes that should be implemented to restore initial aquifer conditions at a general level. Targets, such as stabilizing the aquifer water table or raising piezometric levels in the central part, were hence defined by the Committee.

The extent to which abstraction could make the aquifer become unconfined in the central zone (i.e. the piezometric head falling below the base of the Ostracacea-containing marl formation) was also assessed. Simulations also took into account the possibility of increasing abstraction in areas thought to be less sensitive.

Some results of these simulations are presented hereafter.

**Figure 8: Examples of time head series for two scenarios:**
- **Scenario 1:** constant abstraction rate from 2008 to 2025
- **Scenario 2:** 20% abstraction rate decrease after 2008 in sensitive areas (black line)

**EFFECTIVE USE OF MODEL RESULTS IN SETTING ABSTRACTION RULES**

The regional water resources management scheme (‘Schéma départemental d’aménagement et de gestion des eaux – SDAGE) is a regulatory instrument that defines the main orientations for water resources management and may limit groundwater use.

SDAGE clause 7C5 sets two objectives for the management of the Cenomanian sands:
- to stop the groundwater level from decreasing in order to attain a good quantitative state in the aquifer in 2015

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1 The numbers on the map indicate the difference between observed and simulated values. The simulated head time series have been shifted on the graphics to enable a better comparison with the observed heads.
- to maintain groundwater levels above the base of the aquitard overlying the aquifer to preserve aquifer confined conditions and groundwater quality.

In view of the model results, the management of abstraction within the Cenomanian sands aquifer will be underpinned by several arrangements proposed by the Committee.

First, the aquifer was divided into 9 zones characterized by their degree of sensitivity to abstraction stress. Observation boreholes were then selected in sensitive areas and a crisis threshold (10 m above the top of the Cenomanian sands aquifer) was defined for each one. Finally, abstraction restrictions were defined:

- zone 1: 20% reduction in abstraction as of now;
- zone 2: 10% reduction in abstraction to be implemented by 2011 (with the possibility of reducing abstraction by a further 10% - to be implemented by 2013 - if groundwater levels do not stabilize before 2012;
- zone 3 to 8: no reduction in abstraction;
- zone 9: limited increase in abstraction possible.

The corresponding overall envisaged groundwater abstraction amounts (for all water uses) were then established.

CONCLUSION

Strong political involvement enabled a major study programme to be launched. The model of the Cenomanian sands aquifer developed within this study made it possible to assess groundwater trends depending on various stress (abstraction, recharge) conditions in spite of some uncertainties regarding model build-up. The model results were then used effectively to improve groundwater management in order to preserve groundwater quality and achieve the EU Water Framework Directive objectives.

REFERENCES


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