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Groundwater modelling to predict the impact of a tunnel on the behavior of a water table aquifer in urban conditions

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ABSTRACT: In alluvial sediments, big civil engineering works often cause often significant changes in groundwater conditions, inducing possible damage in urban areas. Before construction of a tunnel, the impact of this new and artificial impervious barrier must be studied in detail. For example, an eventual strong rise of the water table must be computed and predicted in order to anticipate the risk of cellar flooding in houses and to take avoidance measures.

In this context, the construction of a tunnel longer than 500 m in the alluvial plain of the River Meuse and River Ourthe, in the city of Liège (Belgium), was considered as a possible factor which could induce water table changes. The alluvial aquifer is crossed transversally by the new tunnel whose the base lies on the less-pervious bed-rock. A finite difference model has been built including all the complex features interacting with groundwater in an urban environment: river-aquifer interactions through embankments, leakage from other surface water bodies, irregular boundary conditions. After calibration of the model on historical data measured in extreme piezometric conditions (floods and lowest water levels), the heterogeneous hydraulic conductivity distribution has been checked against the well-known geological description of the zone. Then, many simulations have been performed for different transient groundwater and surface water conditions (extreme water levels). Drainage 'windows' through the tunnel base have been proposed in order to decrease the 'barrier effect' in the alluvial aquifer. The results of the simulations with and without such a window has provided the information needed about the impact on the water table aquifer behaviour.

1 INTRODUCTION

The geological and hydrogeological data of the studied zone were collected previously so that more emphasis is given here to the modelling approach (Dassargues & Monjoie 1994). In the city of Liège (Figure 1), a new tunnel is planned for the alluvial plain of the River Meuse, near the junction between the Rivers Meuse and Ourthe. This tunnel, whose base is lying on the less-pervious bed-rock, will cross transversally the alluvial aquifer along a distance of 550 m.

Measured piezometric levels of the water table aquifer are given on figures 2 and 3 respectively for situations corresponding to the lowest water levels and to the highest water levels. Due to the geographic layout and the high permeability of the river embankments, these extreme piezometric levels are largely influenced by the water levels in the River Ourthe (north-east zone) and in the River Meuse (south-west zone).

2 MODEL AND DISCRETIZATION

To compute the eventual rise of the water table due to the presence in the alluvial aquifer of this new

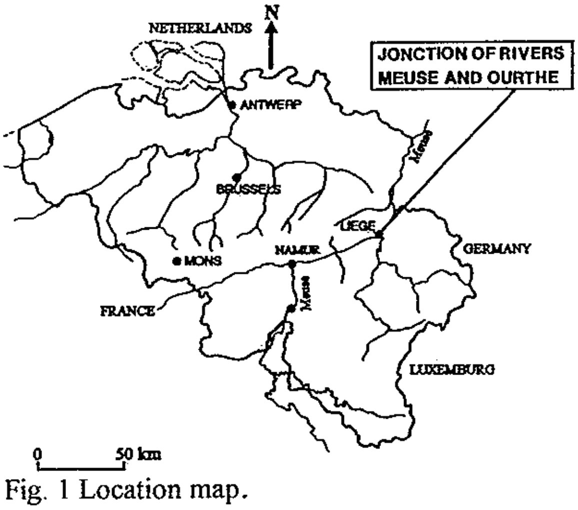

Fig. 1 Location map.

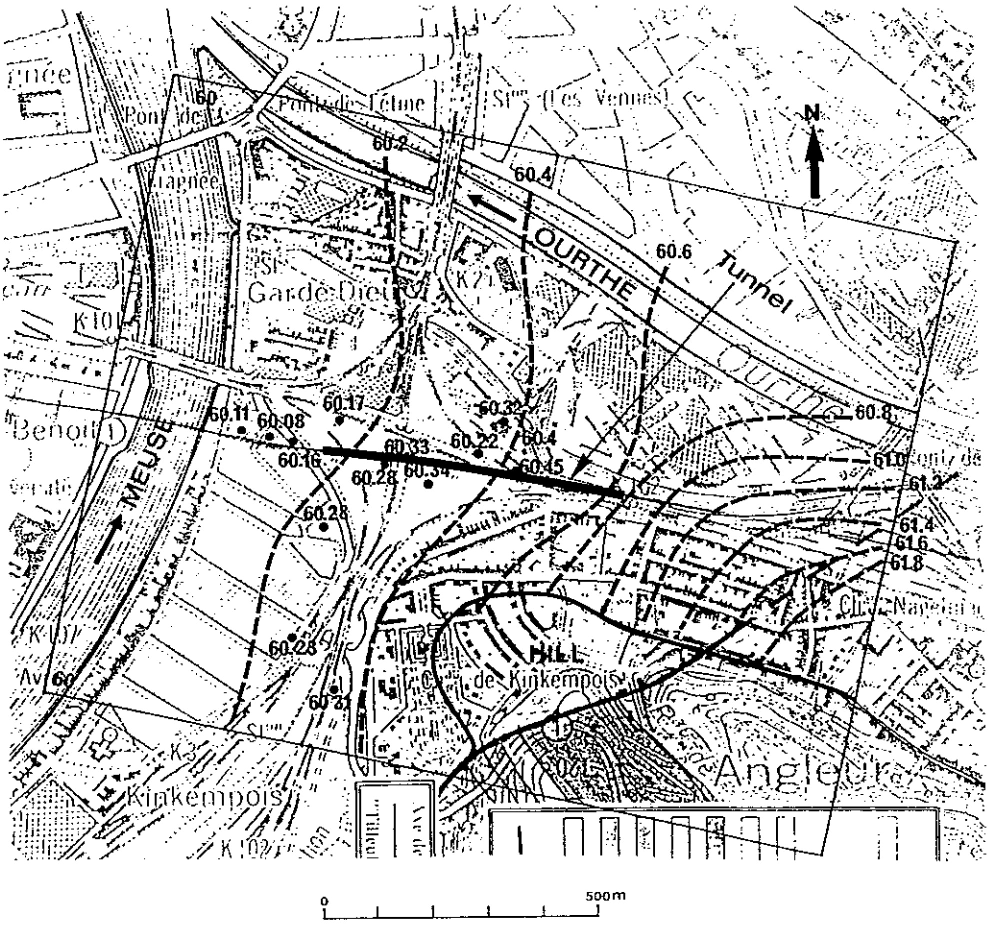

Fig.2 Measured piezometric map in conditions of the lowest water levels (October 1994).

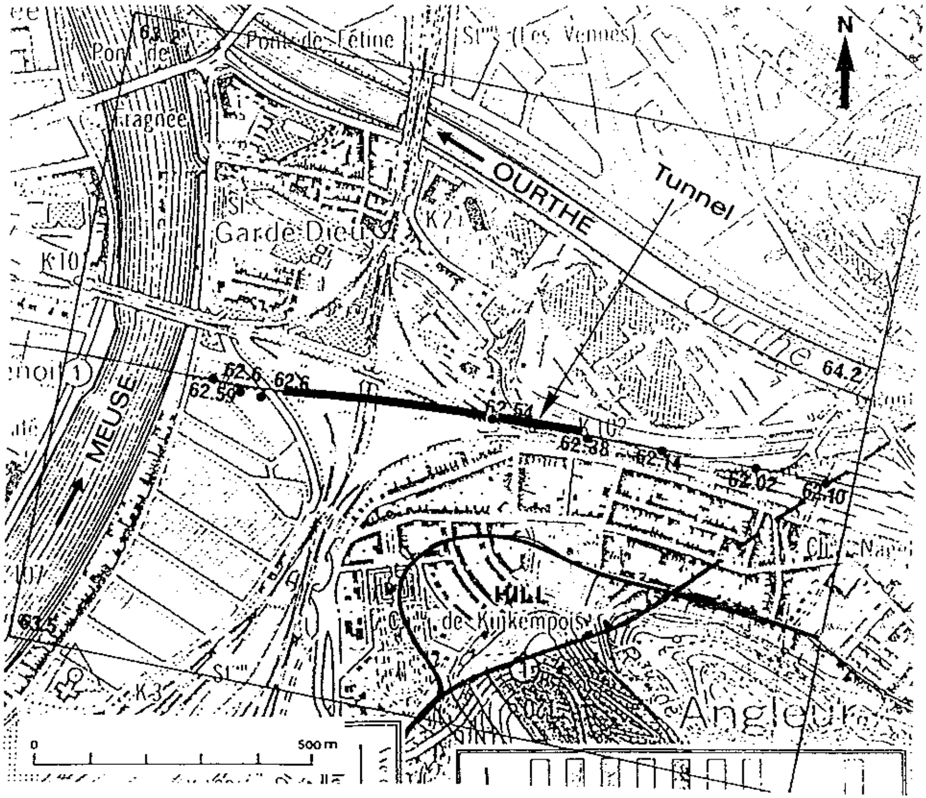

Fig.3 Measured piezometric levels in conditions of the highest water levels in the rivers (27 December 1993).

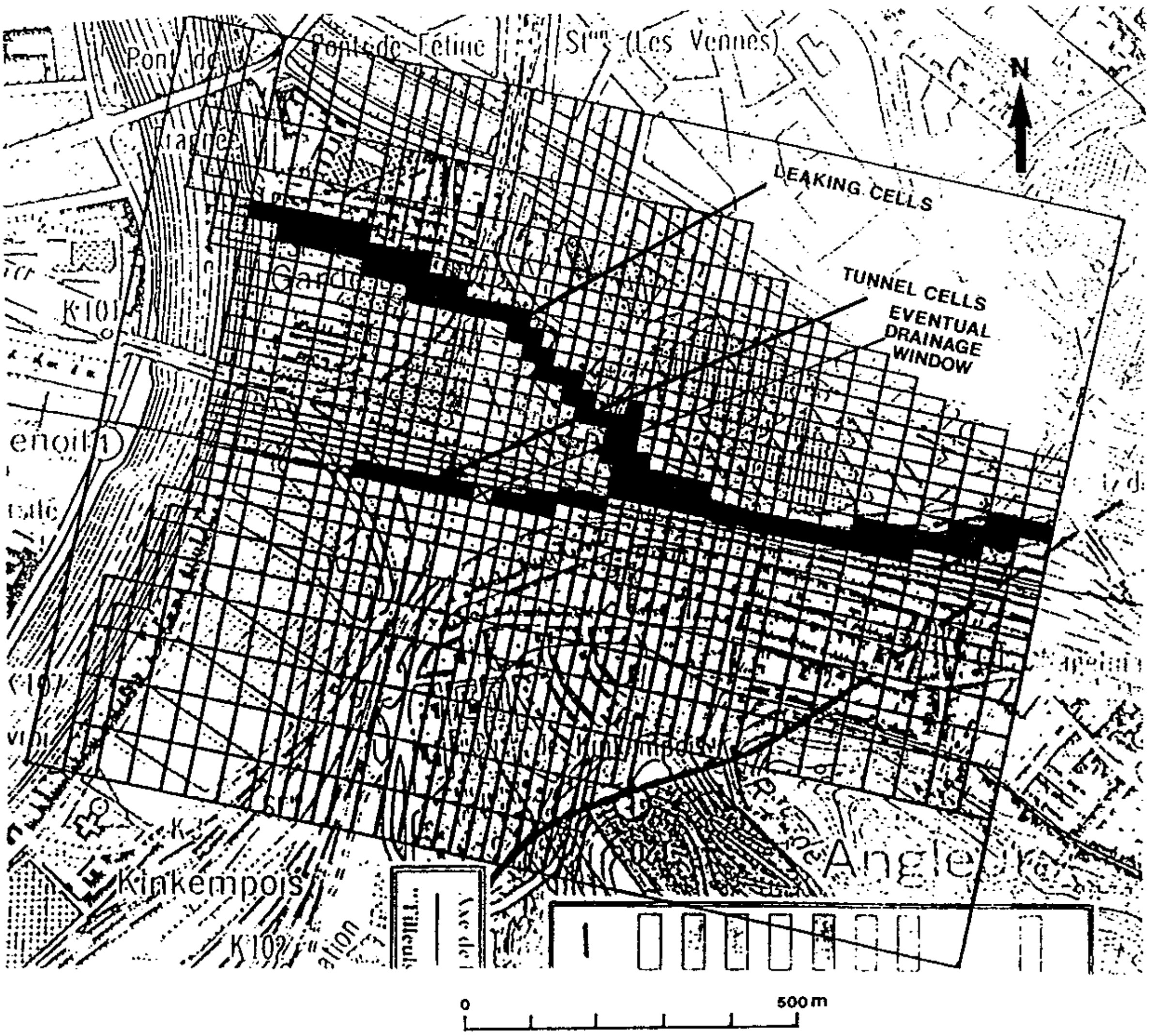

Fig.4 Finite difference grid, 'leaking cells' for infiltration from surface water bodies, and tunnel cells with or without a 'drainage window'.

impervious barrier, quasi steady state conditions are considered for each of these extreme piezometric situations. The finite-difference method was adopted, using a two-layer local network of rectangular cells. MODFLOW (McDonald & Harbaugh 1988), together with the PM3 pre- and postprocessor (Chiang & Kinzelbach 1992) were used.

The spatial discretization of the domain was realized with two layers of 1070 rectangular cells covering an area of 1.7 km^2, the total thickness of the alluvial sediments is about 7 m. The smallest cells have dimensions of 25 m x 25 m.

The chosen boundary conditions can be described as following:

1. on the western boundary, prescribed piezometric heads were taken in equilibrium with the water levels in the River Meuse (60.0 m in the lowest conditions and 63.2 to 63.5 m in the highest conditions),
2. on the northern to north-eastern boundary, prescribed piezometric heads were taken in equilibrium with the water levels in the River Ourthe (60.0 to 60.8 m in the lowest conditions and 63.2 to 64.2 m in the highest conditions),
3. on the southern boundary, prescribed piezometric conditions were deduced from extrapolated measured piezometric heads in the alluvial plain and in the foothill (in both type of conditions),
4. on the eastern boundary, prescribed piezometric heads were deduced from measurements in the alluvial plain of the River Ourthe (in both type of conditions).

At the bottom of the model, an impervious boundary was used to represent the low-pervious bed-rock.

On basis of pumping tests results, the permeability values characterizing the alluvial aquifer range from 1 10^{-3} to 2 10^{-2} m/s. However, it is known that these sediments can be affected locally by lower permeability values in more silty to loamy zones and by higher values in coarse and clean gravels (Dassargues & Lox 1991). A uniform value of storage coefficient of 0.05 was chosen (for computing eventual transient conditions of the highest water levels conditions).

Infiltration due to rainfall can be neglected as the infiltration surface is drastically reduced in urban conditions, but an important infiltration flow (or leakage) is coming from a surface water channel linking the River Ourthe to the River Meuse. The water level of this channel is maintained constant by two locks. Leakage conditions were introduced in the corresponding cells of the upper layer (figure 4). The permeability coefficient and the thickness of the bottom of the channel were taken respectively to 1.10^{-7} m/s and 0.5 m.

After calibration of the model, predictive simulations were performed with the tunnel represented by a line of impervious cells in the two layers of the model. Since the beginning, it was also foreseen to simulate the effect of an eventual (3 m x 30 m) 'drainage window' through the tunnel base (Figure 4). Although the construction of this 'window' would certainly not be easy for civil engineering reasons, it was proposed in order to decrease the barrier effect of the tunnel in the alluvial aquifer.

3 CALIBRATION

The first step of the calibration procedure was made using permeability coefficients that were calculated from pumping-test results. As a second step of the calibration, using a trial-and-error approach, more localized zones of different hydraulic conductivity values were introduced. This optimization process continued until no significant improvement in the calibration on the two extreme measured situations (lowest and highest conditions) was obtained. Figure 5 shows the spatial distribution of the hydraulic conductivity values obtained at the end of this double-calibration procedure of the model on both situations. The corresponding computed piezometric maps are shown for the lowest water levels (Figure 6) and for the highest water levels (Figure 7).

4 PREDICTIVE SIMULATIONS

Predictive simulations were performed, in a first step, with impervious cells representing the tunnel and without any 'drainage window' through it. Then, simulations with the tunnel and the 'drainage window' (as described previously) were also done. These two scenarios were computed in both extreme piezometric conditions (the lowest and highest water levels). Consequently four computed piezometric maps were calculated and differentiation was made from the respective reference calibrated situations of figures 6 and 7.

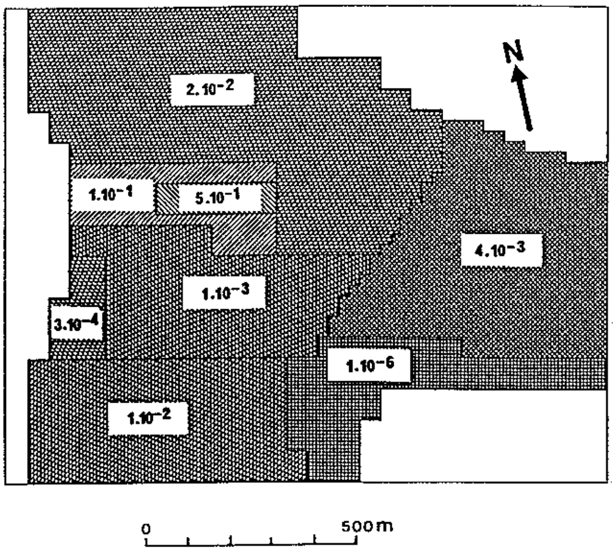

Fig.5 Horizontal hydraulic conductivity in both layers.

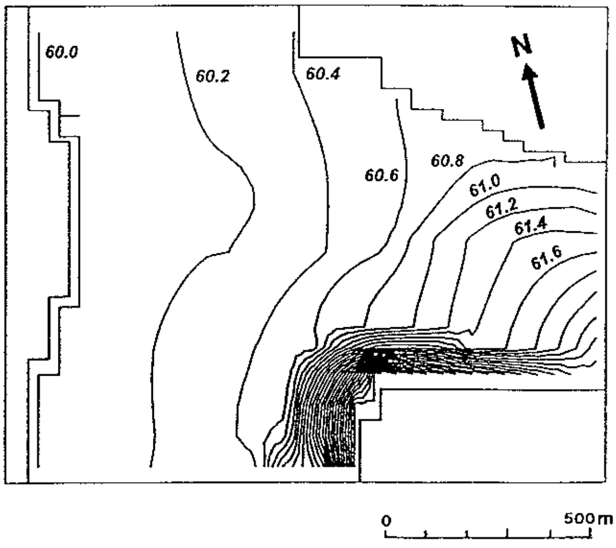

Fig.6 Calibrated simulated piezometric map in conditions of the lowest levels.

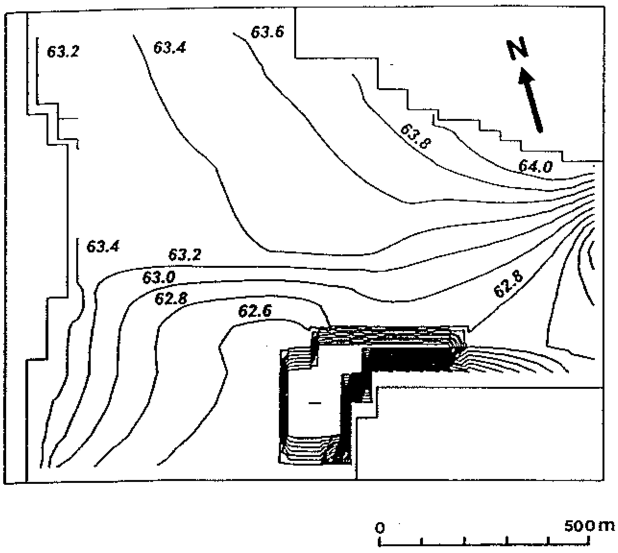

Fig.7 Calibrated simulated piezometric map in conditions of the highest water levels (after 2 days).

In conditions of the lowest water levels, a differential piezometric rise, due to the presence of the tunnel in the alluvial sediments, was computed in the area to the south of the proposed tunnel lineation with a maximum of 0.6 m (Figure 8a). When including the presence of the 'drainage window', nearly no change was found (Figure 8b), the maximum difference reached not more than 0.15.

In conditions of the highest water levels, a piezometric difference of 1.6 m was computed in this area to the south of the proposed tunnel. In fact, in these conditions, the tunnel acts as a protection wall against important and rapid piezometric rises induced mainly by the overwhelming influence of the River Ourthe in such extreme conditions. In such conditions, this area to the south of the proposed tunnel should be better protected against cellar flooding and sewer exfiltration than before. After two days with the highest water levels in both rivers (flood conditions), the comparison between the piezometric situations computed with and without the tunnel, shows clearly that the tunnel is responsible for a slower rising of the piezometric levels in the zone of the alluvial aquifer located just in the south of the tunnel (Figure 9a). Of course, when including the presence of the 'drainage window', this 'protective influence' is partially annihilated (Figure 9b).

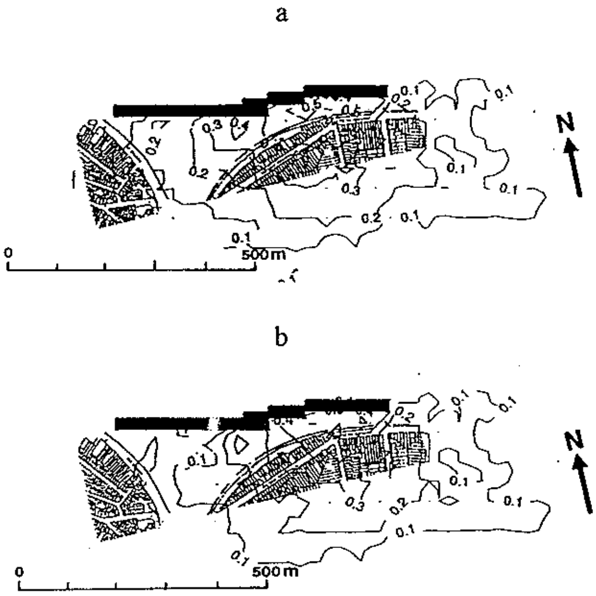

Fig.8 Conditions of the lowest water levels: rise of the piezometric heads due to the tunnel (a) without, and (b) with the 'drainage window'.

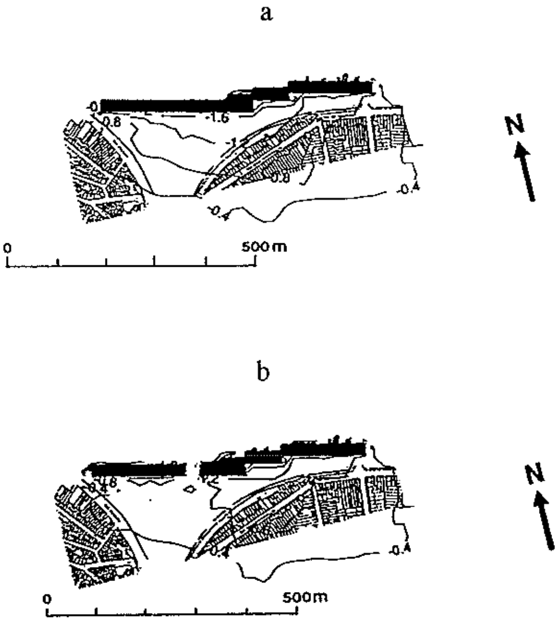

Fig.9 Conditions of the highest water levels (after 2 days): rise of the piezometric heads due to the tunnel (a) without and (b) with the 'drainage window'.

5 CONCLUSIONS

On basis of the computed results, quantitative results were provided to answer the following practical question: what is the expected impact of a tunnel construction on the piezometric levels of an alluvial aquifer in urban conditions. Before that modelling exercise, the impact of this artificial impervious barrier was difficult to assess even if large values of hydraulic conductivity were found by analytical interpretation of pumping tests.

An eventual strong rise of the water table was still to be considered in order to anticipate the risk of cellar flooding in the houses and eventually to take the needed steps to avoid it.

All the important features interacting with groundwater in an urban environment were taken into account : river-aquifer interactions through embankments, leakage from other surface water bodies, irregular geometry of the boundaries, etc. After calibration of the model on historical data measured in two extreme piezometric conditions (the highest and the lowest water levels), the obtained heterogeneous hydraulic conductivity distribution has been checked in relation with the geological description of the zone. Then, using the calibrated model the simulations have provided results showing that:

1. in conditions of the lowest water levels, and in steady conditions, a rise of the piezometric levels can be expected in the zone located in the south of the tunnel with a maximum of about 0.6 m.
2. in flood conditions corresponding to the highest water levels, and after two days of such extreme conditions in the rivers, the strong rise of the piezometric levels in the aquifer is restrained in this same zone in the south of the tunnel. In this case, creating an impervious barrier in the sediments, the tunnel has a protective (but transient) effect on the piezometric levels in this zone.
3. the influence of an eventual ‘drainage window’ through the tunnel is negligible in conditions of the lowest water levels, and is certainly not favourable when the piezometric levels are rising, due to the overwhelming influence of the River Ourthe water levels on the piezometric levels in the studied zone.

The modelling approach has allowed to integrate all the data, parameters, and scenarios in one tool which has provided useful and quantitative answers and which can be easily modified to simulate eventual other scenarios.

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