Hydrodynamic Modelling of Rising Lower Triassic Sandstone Groundwater in the Lorraine Coal Basin (France)

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Abstract

The cessation of mining operations and associated dewatering, combined with a reduced demand for groundwater from the Lower Triassic sandstone aquifer by local authorities and industries in the Lorraine coalfield (France), has led to a rising water table and a long-term risk of flooding in several urban areas. GEODERIS and BRGM developed a three-dimensional numerical hydrodynamic model to identify flood-prone areas and estimate the time frame within which the water table could eventually reach the surface, both with and without the progressive implementation of a pumping infrastructure. A major update of the model was conducted between 2023 and 2024.

Introduction

The Lorraine coalfield, located in northeastern France along the border with Germany, was the site of intensive coal mining from the late 19th century to the early 21st century. Prior to mining activities, the area was largely covered by wetlands and swamps. Groundwater abstraction for mining operations, industrial use, and municipal supply significantly lowered the water table of the Lower Triassic Sandstone aquifer, leading to the drying up of wetlands. Urban development subsequently took place in these areas without fully considering the long-term unsustainability of this situation with a possible water table replenishment.

The gradual shutdown of water-intensive industries in the 1980s and 1990s, the cessation of coal mining in the 2000s, and increasing water conservation efforts have contributed to the ongoing recovery of the sandstone aquifer. The reestablishment of a new piezometric equilibrium, potentially at or above the topographic surface, must be taken into account.

In this context, GEODERIS was commissioned by the French government, which is fully responsible for post-mining risk management, to conduct various groundwater rise forecasts. In collaboration with BRGM, a three-dimensional (3D) numerical hydrodynamic model has been under development since 2015–2018 to simulate groundwater dynamics across the entire Lorraine coalfield (BRGM 2018, GEODERIS 2018, GEODERIS 2022). Based on the results of this model, areas where groundwater recovery is expected to reach depths of less than 3 meters were delineated. Subsequently, in 2021, pumping strategies were assessed and designed to lower the water table to depths greater than 3 meters within these so-called 'commitment zones.' A major update of the model was conducted between 2023 and 2024 to improve forecasts of both the rising groundwater level in the sandstone aquifer and the required withdrawal volumes (BRGM 2025, GEODERIS 2025). The progressive deployment of the drawdown wellfield will be accompanied by a phased expansion of the piezometric monitoring network to refine predictions through future iterations of the 3D model.

Methods

Structure of the model

The Lower Triassic sandstone groundwater model, which forms the basis of our work, has been developed by BRGM since 1993 using the MARTHE software. MARTHE, developed by BRGM, is a numerical modeling tool for simulating groundwater flow and mass transport (Thiéry 2015). The model covers a large portion of the Lorraine region, primarily corresponding to the confined section of the aquifer. The main model uses a grid of 500-meter square cells for regional-scale representation, while the Lorraine coalfield is represented with a refined grid of 50-meter square cells over an area of approximately 750 km². The model operates in a transient (non-steady-state) regime.

Four geological layers are considered (Fig. 1), listed from the most recent to the oldest (i.e., from top to bottom):

- Alluvial deposits: sandstone facies with occasional impermeable peat horizons.
- Lower Triassic sandstone: predominantly fine to coarse sandstones with clay layers in the upper section, conglomeratic levels in the central part, and clay lenses at the base.
- Permian: clayey sandstones with very low permeability.
- Carboniferous mining works (where present): this formation is considered to have low permeability, with flow occurring only within mining galleries or fractured zones created by mining operations.

Several aquifers are present in these formations: the alluvial domain, the Lower Triassic sandstones and the mining reservoir. The latter was implemented because of the mine induced fracturing of the overlying sandstones, creating infiltration of the water into the mine through so-called “aquifer-mine exchange points”. When the mines closed, pumping stopped, leading to the flooding of mines, which was completed at the end of 2009 in the western sector and in 2012 in the central-eastern sector. Three pumping stations are still in place in the mining reservoir to control its level and maintain it below the Lower Triassic sandstone water level. It allows to avoid the formation of mineralized plumes at the aquifer-mine exchange points.

The Lower Triassic sandstone aquifer is recharged both by outcrops within the basin and by more distant outcrops in surrounding mountain ranges. It is confined where it is overlain by the low-permeability marl formations of the Muschelkalk (considered as impermeable in the modelling). On a regional scale, groundwater flows from the south-southwest to the north-northeast.

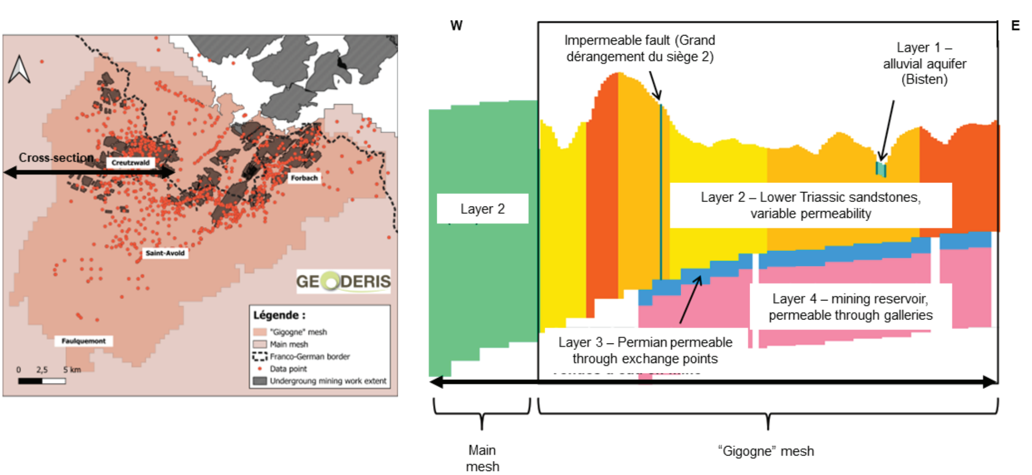

Figure 1 *West-East cross-section of the Lower Triassic sandstone groundwater model through the city of Creutzwald (BRGM, 2015).*

The model explicitly accounts for the hydrogeological role of major faults, including the Hombourg-Longeville, Saint-Nicolas, and Grand Dérangement du Siège 2 faults. Notably, the Longeville-Hombourg fault hydraulically divides the basin into two distinct sectors: the western sector, where the water table is close to the surface, and the eastern sector, where it remains deep (over 40 m).

Interactions between alluvial aquifers (and surface water bodies), the sandstone aquifer, and mining reservoirs via the fractured Permian formations are also modeled. The surface layer is represented using a LIDAR-derived Digital Terrain Model (DTM), the minimum elevation was applied to the center of each 50-meter square cell (safe for the rising groundwater calculations).

Automated history calibration (1976–2022)

In 2023–2024, an update of the 2018 version of the model was carried out (alluvial domain redefinition, change in faults modelling, consideration of climate change). A re-calibration step of the 2018 version of the model was also performed (Fig. 2) based on those major changes and new data acquisition. This process involves adjusting parameters related to the geological formations or the model structure to reproduce observed water level data.

The main parameters used for model calibration include the permeability of the various geological layers and faults, as well as the vertical anisotropy of the alluvial deposits, which represents its capacity to exchange water with the underlying sandstone formation. These parameters were initially assigned uniform values throughout the model. The mean value of vertical anisotropy obtained during the calibration of the latest model version (2018) was retained, while permeability was defined based on the average Lower Triassic sandstone permeability value from the literature in the Lorraine coal basin (1.10^{-5} m·s^{-1}, Noël 1997).

Calibration was conducted using the PEST tool (PEST: Model-Independent Parameter Estimation and Uncertainty Analysis, https://pesthomepage.org/), an algorithm designed to automate incremental adjustments of calibration parameters. The

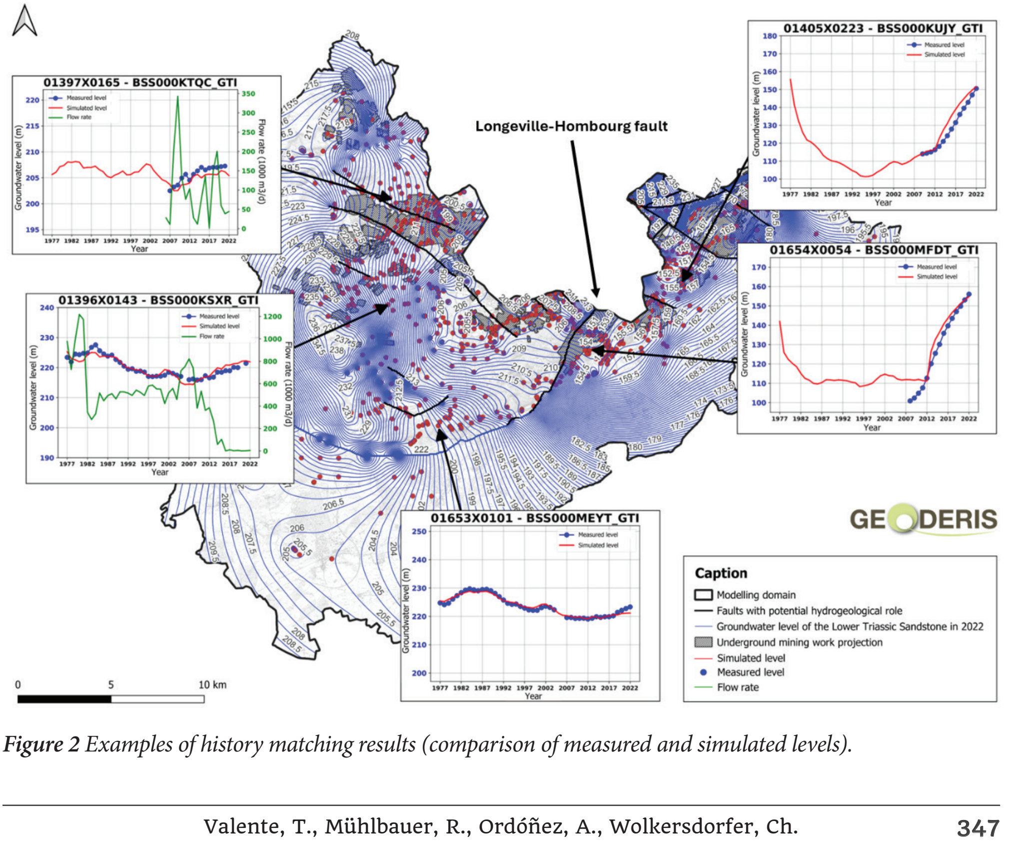

***Figure 2** Examples of history matching results (comparison of measured and simulated levels).*

algorithm iterates multiple times, varying permeability and anisotropy to minimize the difference between model results and observed data. Other parameters, such as stream infiltration and fault permeability, were adjusted manually. The calibration process was considered complete when the parameters stabilized and showed no significant further variation. At the end of this step of calibration, errors vary between 1,68 m and 5,93 m according to the sectors (mean of medians of absolute deviations weighted by number of annual observations, without considering a part of German territory which presents only few piezometric chronicles).

Simulations

The simulation scenarios combine various climate and withdrawal scenarios. The climatic scenario used for forecasting simulations of the effects of changes in withdrawals from the sandstone aquifer and the mining reservoir integrates two distinct climatic periods, each modeled with specific infiltration chronologies based on French IPCC climate projections (DRIAS):

- A so-called "stabilized period", designed to forecast the long-term influence of reduced withdrawals under a fixed average infiltration rate, once the water table has reached equilibrium.
- An "exceptional period", intended to assess the additional influence of recurrent extreme rainfall events by applying a maximum infiltration rate.

The RCP 4.5 (Representative Concentration Pathway) emission scenario from DRIAS was selected. This corresponds to a moderate stabilization scenario in which global efforts are made to limit greenhouse gas emissions.

Regarding the withdrawal scenarios, an initial simulation was conducted using a water demand projection collected by national authorities. This simulation aimed to estimate the evolution of the rising water table in the absence of any active control measures. Based on the results obtained, a second modeling phase was carried out to design a pumping network capable of maintaining the water table at a depth of more than 3 meters in the commitment zones.

Results

The results are presented as calculated isodepth maps for different dates and simulation scenarios, namely: 2023, 2030, 2065, the stabilized period, and the exceptional period.

Fig. 3 and 4 illustrate some key results. Fig. 3 depicts the water table depth in the sandstone aquifer at the end of the stabilized period. The stabilized water level—defined as the point where the rate of water level rise is less than 3 cm per year across the entire basin – is expected to be reached by 2147. Fig. 4 shows the water table depth in the sandstone aquifer under high rainfall conditions, taking into account the progressive deployment of the pumping network. In the model, the pumped water leaves the system whereas in reality it will be discharged into the watercourses.

By 2023, the sandstone water table has stabilized in the Grossbach valley. It is potentially outcropping in the Bisten valley, although impermeable layers within the sandstone or alluvial formations may prevent direct observation of groundwater at the surface. The remainder of the basin was not expected to experience a shallow water table this year.

According to the first simulation scenario – without drawdown measures to control the water table – the eastern sector will be affected by groundwater levels shallower than 3 meters by 2044.

The second type of simulation was used to determine the number of boreholes required to lower the water table to a depth of more than 3 meters below the commitment zones. In the western sector, by 2030, 9 pumping boreholes would be necessary to meet the commitments. Most of these are located in the Bisten valley, with an additional borehole required near the eastern boundary of the Longeville-Hombourg fault. Subsequent modeling indicates that by 2065, 7 more boreholes would be installed in the Bisten valley. By the time the water table stabilizes, a total of 16 pumping wells will be operational in the model. The results also suggest that under a future exceptional rainfall scenario, it may be necessary to install 3 additional pumping wells in the Bisten valley.

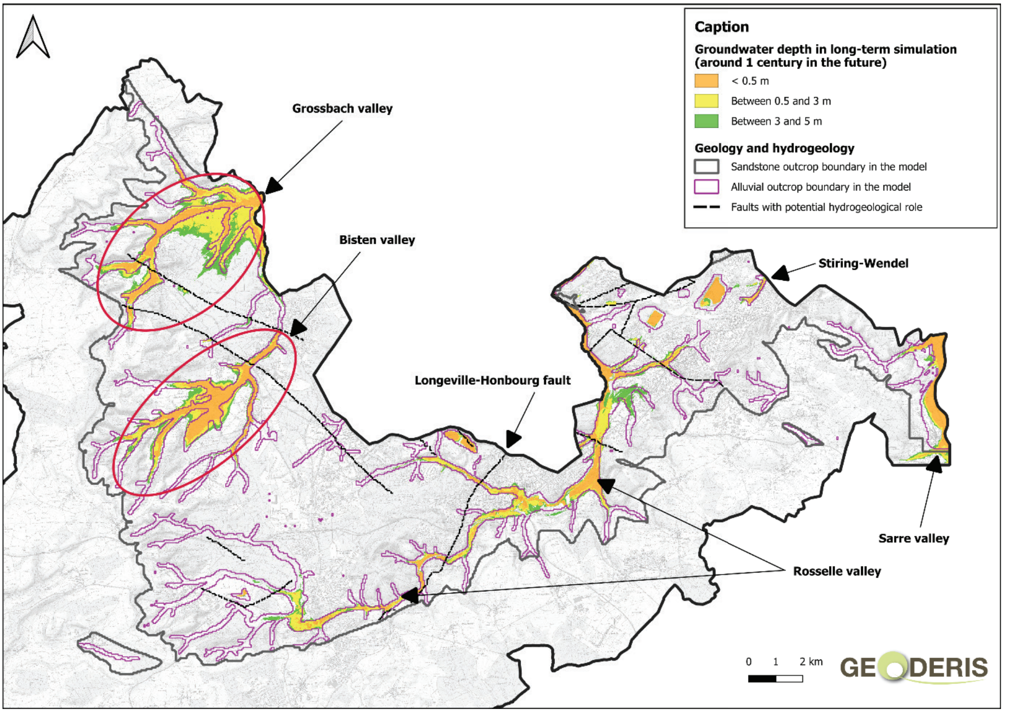

Figure 3 Sandstone groundwater level simulated at the end of the stabilized period (around one century from today).

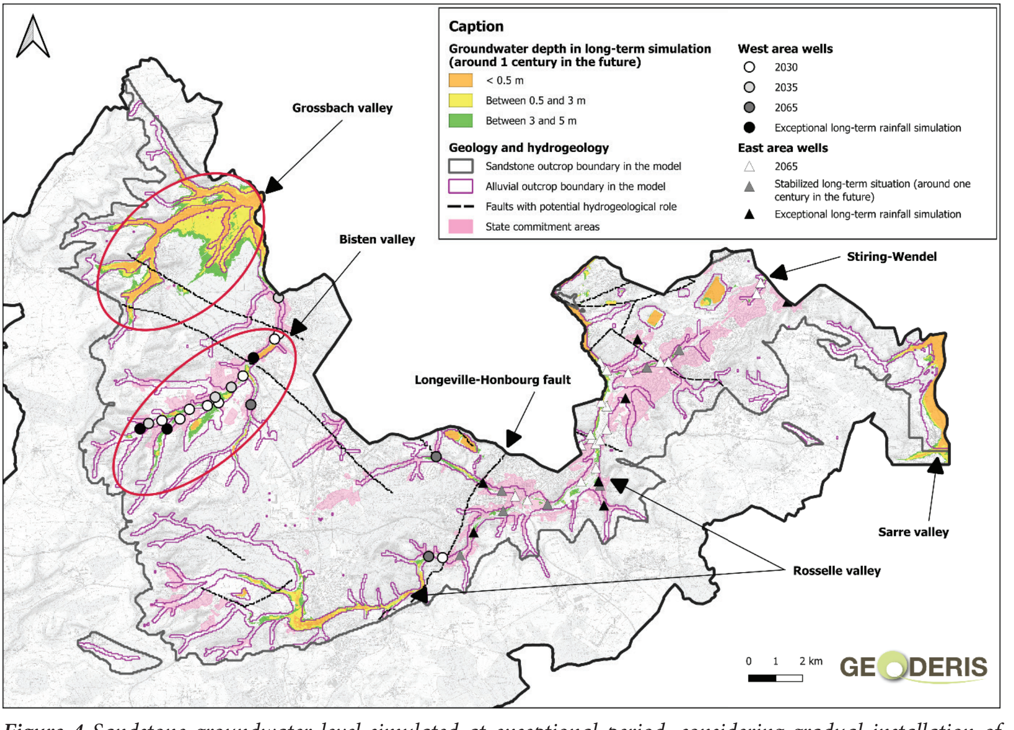

Figure 4 Sandstone groundwater level simulated at exceptional period, considering gradual installation of pumping areas.

In the eastern sector, pumping to maintain the sandstone water table at a depth of more than 3 meters should begin by 2044. By 2065, approximately 20 pumping structures would need to be progressively activated, extending from the Rosselle valley to the Stiring-Wendel township. Under stabilized water conditions, expected to be reached within a century, 5 additional boreholes would need to be activated. In the event of high rainfall conditions, a further 5 boreholes would be required.

Perspectives

In total, approximately 50 drawdown boreholes would be required to maintain the water table at a depth of more than 3 meters below the commitment zones across the Lorraine coalfield. This would correspond to an annual extraction volume of approximately 21 million m^3 under stabilized conditions and up to 40 million m^3 in an exceptional rainfall scenario. These estimates take into account 2 existing boreholes in the Bisten valley, which also tap into the Lower Triassic sandstone aquifer.

To support the progressive deployment of an optimal wellfield, a dense piezometric network will be gradually established, comprising around 200 piezometers throughout the Lorraine coalfield. This expanded monitoring network will allow for precise measurement of rates of water table rise and assessment of the actual effect of drawdown boreholes. Additionally, it will provide valuable data on the geological formations encountered, including peat horizons, improving our understanding of localized confinement of the water table, whether within alluvial deposits or sandstone formations.

Pumping tests and chemical analyses will also be conducted to enhance knowledge of the hydrogeological functioning of different sectors and to determine the origin of the extracted water. Furthermore, chemical analyses will provide critical information on water quality, as compliance with regulatory standards is required before any discharge into surface water bodies.

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