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Managing groundwater resources in the limestone in the French – Belgian transboundary aquifer using a jointly developed model

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ABSTRACT

Study region: The French-Belgian Carboniferous limestone Transboundary Aquifer covers 1420 km^2 across France, Flanders (North Belgium), and Wallonia (South Belgium). Heavily exploited since the 19th century for drinking water, agriculture, industry, and quarry dewatering, abstractions peaked at 100 million m^3 /year in 1990, causing water level declines of up to 90 m.
Study focus: This study developed a regional 3D groundwater model collaboratively using the MARTHE finite volume code, integrating officially exchanged data. Calibrated over 1900–2019, it serves as a predictive tool and a scientific basis for decision-makers to coordinate sustainable management under increasing anthropogenic pressures and climate change. This paper examines the sensitivity of specific stresses, including recharge, quarry dewatering, and well pumping.
New hydrological insights for the region: Results indicate that groundwater head in the confined area is significantly influenced by recharge fluctuations as well as abstraction wells. Effective management requires balancing abstraction needs with expected recharge rates over the mid and long-term, particularly in the context of future climate change. The results also highlight the sensitivity of groundwater levels in the confined area to abstraction rates, making the impacts of management actions quickly apparent. This shared decision-support tool is essential to manage the transboundary aquifer and has contributed to progress toward an agreement among involved entities to regulate pumping rates – a critical and rarely achieved step toward coordinated groundwater governance.

1. Introduction and objectives

Groundwater is a freshwater source for more than 50 % of the world's population and 40 % of this freshwater is stored in transboundary aquifers (IGRAC, 2021). Those aquifers are defined by the United Nation International Law Commission as groundwater bodies intersected by an international boundary (United Nations, 2022; Yamada, 2003). Long overshadowed by transboundary surface water bodies, due to their hidden nature (Jarvis et al., 2005), transboundary aquifers have come into the spotlight thanks to various initiative, including the development of the Internationally Shared (transboundary) Aquifer Resource Management (ISARM) initiative led by the UNESCO's International Hydrological Program and the International Association of Hydrogeologists (Puri and Aureli, 2005).

In 2021, 468 aquifers were formally identified as transboundary aquifers by IGRAC (IGRAC, 2021), with various hydrogeological

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and groundwater exploitation contexts. Similarly to all aquifers, those transboundary groundwater bodies and dependent ecosystems are vulnerable to different stresses, according to their specific context, and including quantity and quality issues. Their vulnerability may however be exacerbated because they are potentially exploited by different entities with different interests and administrative contexts, paving the way to non-regulated conflicts (Gorelick and Zheng, 2015). Wada and Heinrich (2013) reveal that 8 % of transboundary aquifers are stressed due to overexploitation.

Possible difficulties or conflicts may be related to different policies about the intensity of exploitation or about the standards to protect the common resource from quantitative and qualitative perspectives. They may originate from different factors including the local demand, the level of pressure placed on the resource, the intensity of hydraulic interactions within the aquifer, on both sides of the administrative boundary, or the uneven distribution of groundwater resources between countries sharing groundwater bodies. This latter factor often comes from differences in topography, burial conditions, surface water distribution and climatic conditions (Yu et al., 2020).

In case of conflict, there is a crucial need for data exchange and scientific characterization, which are at the basis of common agreements. Rivera et al. (2023) place this characterization stage as the base of a three-pillar framework for effective transboundary aquifer management, which includes (1) Assessment, (2) Cooperation and collaboration and (3) Shared management. Assessment includes physical knowledge but also non-physical variables (ex. social, economic, political, cultural). For Fraser et al. (2018), the first step in transboundary aquifers governance is their recognition as such by all parties. They recommend that every country should assess their borders for transboundary aquifers. Velis et al. (2022) suggest that the most significant contributors to efficacy in transboundary aquifer governance are the institutional structure and mandate, objectives and baselines, data monitoring and adaptive capacity such as managed aquifer recharge or sustainable land uses practices. According to Talchabhadel et al. (2021), the integration of social, juridical, political disciplines is important. Data sharing agreements should be made to promote the development of data driven numerical models, as decision support tools for managing the transboundary aquifer.

The elaboration of international agreements on transboundary groundwater aquifer exploitation is however complex, and official agreements between administrative entities remain scarce. According to Burchi (2018), only 6 transboundary aquifers had dedicated formal agreements in 2018 for their management. Only two of them include specific restrictions on groundwater abstraction: the Genevese aquifer between Switzerland and France, and the Disi/Saq-Ram aquifer between Jordan and Saudi Arabia (see also Penny et al., 2021). The other agreements rather rely on general principles and recommendations to support cooperation. Formal agreements do not always exist, such as for the Santa Cruz aquifer across USA and Mexico, where a binational consultation process is used to establish priority assessment activities for the transboundary aquifer (Scott et al., 2012).

Ahead of possible agreements, scientific investigations are thus crucial and were performed in some identified transboundary aquifers, to characterize and understand their functioning and sensitivity to stress. The level of investigation is however variable depending on the considered aquifer, the encountered difficulties regarding the resource preservation and exploitation, and the will of local stakeholders. Different studies are reported in the scientific literature. Some emblematic case studies are listed here below, with no intention to be exhaustive.

The Genevese aquifer extends over about 19 km long and between 1 and 3.5 km wide, across the France – Switzerland border. It is composed of silty-sandy gravels. Since the 1960s over-pumping, up to 14 million m^3 /year led to a depletion of the groundwater storage. A bilateral commission was created to ensure the administration and the implementation of joint scientific studies and actions such as managed aquifer recharge, pollution control and agreements about groundwater abstraction, to ensure the water resource sustainability and establish a joint water management (de los Cobos, 2018, 2015, 2013; Penny et al., 2021).

The large Nubian Sandstone Aquifer System (about 2 500 000 km^2) extends over Libya, Egypt, Sudan and Tchad, under confined and unconfined conditions in the south and in the north, respectively. The aquifer is located in an arid to semi-arid environment and most of the groundwater is fossil water. Large groundwater abstractions are carried out in this aquifer, mainly for irrigation and public water supply, causing depletion (Frappart, 2020; Nijsten et al., 2018a; Vogt et al., 2024; Voss and Soliman, 2014). Agreements between parties aim to support cooperation, monitoring and sharing of collected data (Nijsten et al., 2018b).

The Disi/Saq-Ram aquifer over Jordan and Saudi Arabia is subject to overexploitation due to fast demographic grows, irrigation and decreasing rainfall on both sides of the border (Fallatah et al., 2017). To alleviate the drop in groundwater levels, a 10 km-wide no-pumping zone has been set up on both side of the Jordan-Saudi border. A joint technical committee has been established to monitor the aquifer and share the data (Agreement Al-Sag/Al-Disi Layer, 2015).

The Guarani aquifer system extends over Argentina, Brazil, Paraguay, and Uruguay. It covers an area of 1 087 879 km^2 and produces over 1 km^3 /year of freshwater (Foster et al., 2009). The Guarani Aquifer Agreement signed in 2010 is an example of transboundary aquifer agreements without groundwater related conflicts (Villar and Ribeiro, 2011). It underlines the sovereignty of each country over their respective portions of the aquifer, the equitable and reasonable utilization of the resource, the obligation of not causing harm to other parties, cooperation, exchange of technical information and data to extend scientific knowledge.

The Carboniferous Limestone aquifer, which extends across Northern France and two administrative regions of Belgium (Flanders and Wallonia), is another example of a successful transboundary cooperation and groundwater management. This case is singular because it consists in an historically overexploited aquifer, with high abstracted volumes in a densely populated area, and not located under arid or semi-arid conditions. The cooperation between entities exists for years, at different levels and intensities, and has led to agreements involving scientific research, executive data sharing, but also official restrictions on groundwater abstraction for Flanders and Wallonia.

2. Historical background and objectives of the study

The aquifer has been exploited since the beginning of the 20th century from both sides of the border to supply water in a densely populated and industrial area (Lille – Roubaix – Tourcoing in France; Kortrijk – Tournai in Belgium) (Fig. 1), where it rapidly became a strategic aquifer. Historically, relatively huge volumes of groundwater, up to 100×10^6 m^3/year in the 1980's and 1990's, were abstracted, in particular to meet the demand from the industry, leading to overexploitation. Consequently, an important piezometric level decrease, up to 85 m in 2000 (Caous, 2000; Pinson and Seguin, 2007),was observed in some parts of the aquifer, inducing aquifer depletion, sinkhole collapses and building damages due to the karstic nature of the aquifer (Kaufmann and Quinif, 2002), and hydrochemical imbalances (Fig. 2).

Considering this context, the urbanistic and industrial developments in the area and the management by several political and administrative entities, it was needed to take action. In particular, a better understanding of the aquifer and a long-term management model, involving all concerned countries and administrative regions, were crucial. Those actions were progressively developed across the last decades, but become more effective recently.

In the 1970's and 1980's, considering the extent of the regional drawdown, first versions of numerical models were developed. The aim was to determine the maximum groundwater volumes to be pumped to stabilize the piezometric levels. Models were first developed as single-layer steady-state simulations (ex. Mania, 1974; Youssof, 1972), further upgraded to transient versions, integrating the multilayer nature of the hydrosystem and covering a larger part of the aquifer (Besbes and Talbot, 1983; Combes, 1994, 1991; Mania, 1976). The development of those models was however greatly limited by the lack of knowledge regarding the aquifer functioning, at a regional and transboundary scale. Facing this situation, a transboundary belgo-french scientific cooperation, initiated at the beginning of the 2000's, allowed the acquisition of new sets of geological and hydrogeological data: updated transboundary geological log, new boreholes and observation wells, a common piezometric map, reconstructed piezometric and long-term abstraction time series, chemical and isotopic analyses (Cardin and Dufrenoy, 2010; Crastes de Paulet, 2013, 2012; Crastes de Paulet and Dufrenoy, 2012; Crastes de Paulet and Joublin, 2013; Dufrenoy et al., 2011; Gourcy and Crastes de Paulet, 2014, 2012; Picot and Dufrenoy, 2012), for a better characterization of the hydraulic properties, groundwater flow directions, and the relations between the recharge and confined areas. This characterization allowed the development of a 3D numerical groundwater flow model of the aquifer (Crastes de Paulet and Picot, 2014; Picot et al., 2014; Picot-Colbeaux et al., 2022, 2020), aiming to simulate a bunch of scenarios including the possible evolutions of groundwater abstraction as a function of the demographic, economic and climatic changes in the region, while avoiding overexploitation. The model is used by the different partners to test scenarios and support coordinated actions for a long-term and stable good state of the aquifer.

In the meantime, different agreements were progressively implemented. Since 1997, an agreement between the Flemish and Walloon regions limits groundwater withdrawals in Belgian part of the aquifer. Groundwater abstraction was also specifically regulated in the French area (Caous, 2000). In parallel, major investments were performed to valorize dewatering water from the Walloon open pit quarries, as drinking water distributed in the Flemish and Walloon regions of Belgium, through the 'Transhennuyère' adduction and production facilities. Upgrade of some production facilities in Flanders were also carried out to reduce dependence on the transboundary Carboniferous limestone aquifer and to keep it as a strategic water source when insufficient supply from other freshwater sources arises. In 2017, French and Belgian (Wallonia and Flanders) authorities decided to officially formalize data sharing

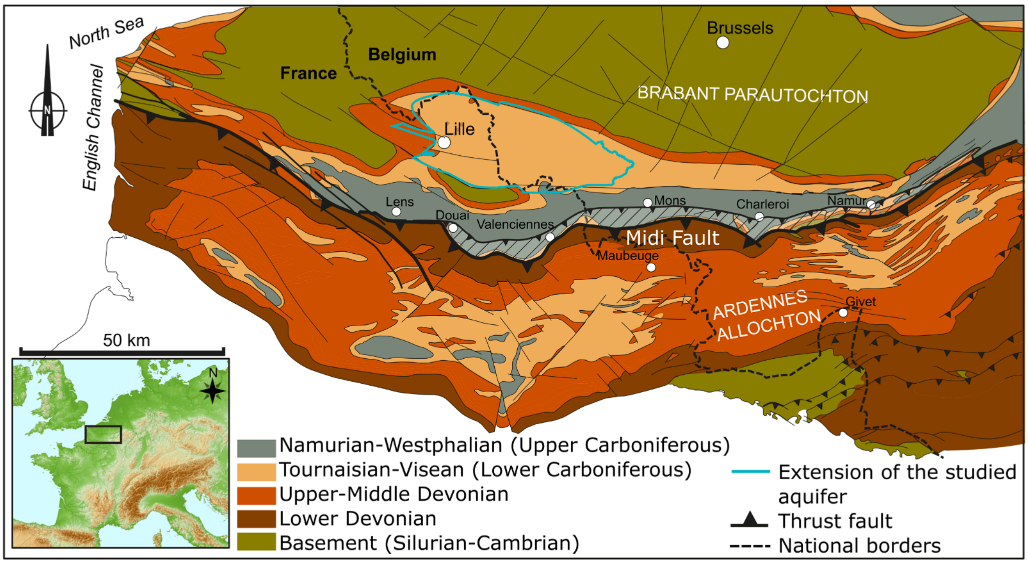

Fig. 1. Map of Paleozoic geological units in the North of France and the South of Belgium (modified and translated from Laurent, 2021). The extension of the studied and modelled Carboniferous limestone aquifer is displayed in blue. Those limits are based on smaller scale geological maps, explaining the slight differences between the displayed geological and aquifer limits.

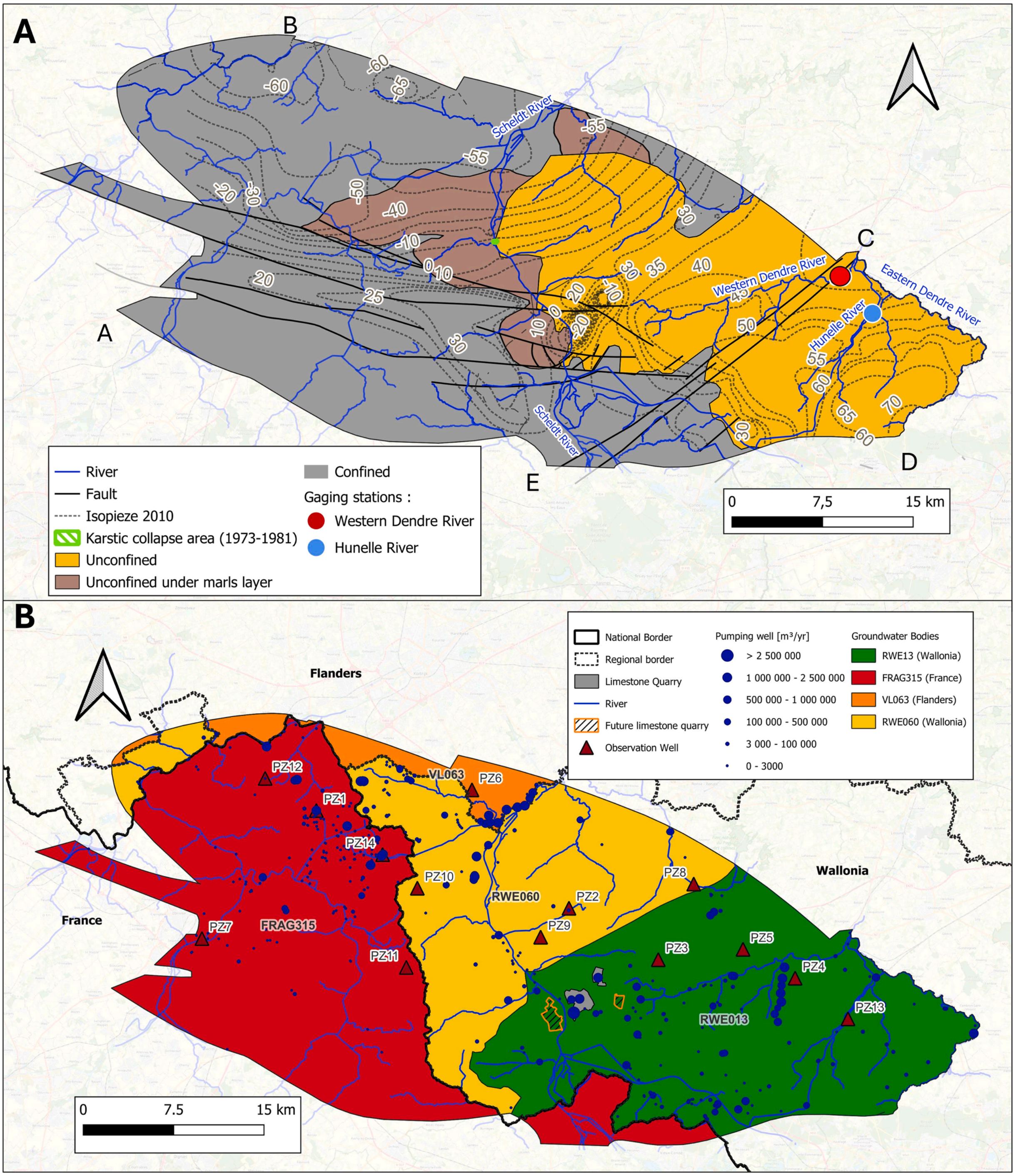

Fig. 2. A. Piezometric contours corresponding to observations made in 2011 and extension of the confined/unconfined areas within the Carboniferous limestone aquifer. The letters displayed along the external boundary are used in Section 4. B. Extension of the administrative groundwater bodies over France, Wallonia (Southern Belgium) et Flanders (Northern Belgium), pumping rates and annual abstracted volumes, location of selected piezometers whose data are shown in this article (see next sections and figures).

regarding the aquifer state and exploitation, through the signature of consortium agreement by Flanders, Wallonia, and France. Crucial data, including annual abstracted volumes, groundwater heads and chemical data are exchanged annually and used for managing groundwater and updating the model.

In this context, the objectives of this paper are to: (1) describe the hydrogeological context and knowledge acquired for years about the transboundary Carboniferous limestone aquifer; (2) describe the regional-scale numerical groundwater flow model to be used as a decision support tool; (3) simulate scenarios predicting the evolution of groundwater levels in the aquifer, as a function of groundwater exploitation in the different regions; (4) highlights the coordinated actions undertaken to promote management of the resource.

3. The Carboniferous limestone aquifer

3.1. Geographical and geological contexts

The studied Carboniferous limestone aquifer extends over France, Wallonia (Southern Belgium) and Flanders (Northern Belgium). The studied area covers a total of 1420 km^2 (Fig. 1), entirely located in the Scheldt hydrographical basin. It extends over four administrative groundwater bodies: one located in France, two in Wallonia (Belgium), and one in Flanders (Belgium) (Fig. 2).

The aquifer is mainly composed of Tournaisian and Visean limestone units belonging to the Missippian series of Early Carboniferous. Those rocks are fractured and permeable. In the eastern part of the studied area, limestone units are outcropping or are covered by relatively thin Cenozoic clay and sand deposits. Those overlying deposits globally remain thin and generally permeable, so that direct recharge is generally observed over this area, where the aquifer is considered as unconfined (Fig. 2). The presence of karstic alteration features is common in this area as described by Kaufmann and Quinif (2002). Close to the eastern limit of the study area, the top of the aquifer is above 50 m asl. Westwards, limestone units are getting deeper and are progressively covered by a thick unit series composed of Cretaceous marls (Cenomanian), Cretaceous chalk (Cenomanian to Maastrichian) and Cenozoic sands and clays, from bottom to the top. In this area, the aquifer is generally considered as confined under the marl layers (Fig. 2A). Close to the western limit of the study area, the top of the aquifer is below −100 m asl. Limestone units also present a west-east syncline-shape general structure.

In the unconfined area, groundwater level time series exhibit a seasonal behaviour (Fig. 2A) controlled by recharge rates. To the west, where the aquifer is confined, a low-intensity recharge only occurs through very slow vertical fluxes through the marl units, from upper aquifers. Due to groundwater abstraction in the aquifer, piezometric levels are severely depleted in the area mainly corresponding to the western confined area (Fig. 2 and Fig. 3). This difference in piezometric levels between the western and eastern parts, induces horizontal water transfers from the recharge zone (east) to the confined area (west). Note that the exact limit between the confined and unconfined zones is not well defined depending on the depth, thickness and nature of the marls and the piezometric fluctuations (Fig. 2A).

The aquifer is limited to the west and to the north by the low permeability layers of Devonian shales. In France, the southern limit is defined by the Seclin's fault which brings contact with an aquiclude formation. In Belgium, this limit corresponds to the burial of the carboniferous layers under more recent Namurian-Westphalian low permeability formations. To the east, the studied and modelled zone is delimited by the Dendre River, which consists in a well identified hydraulic limit.

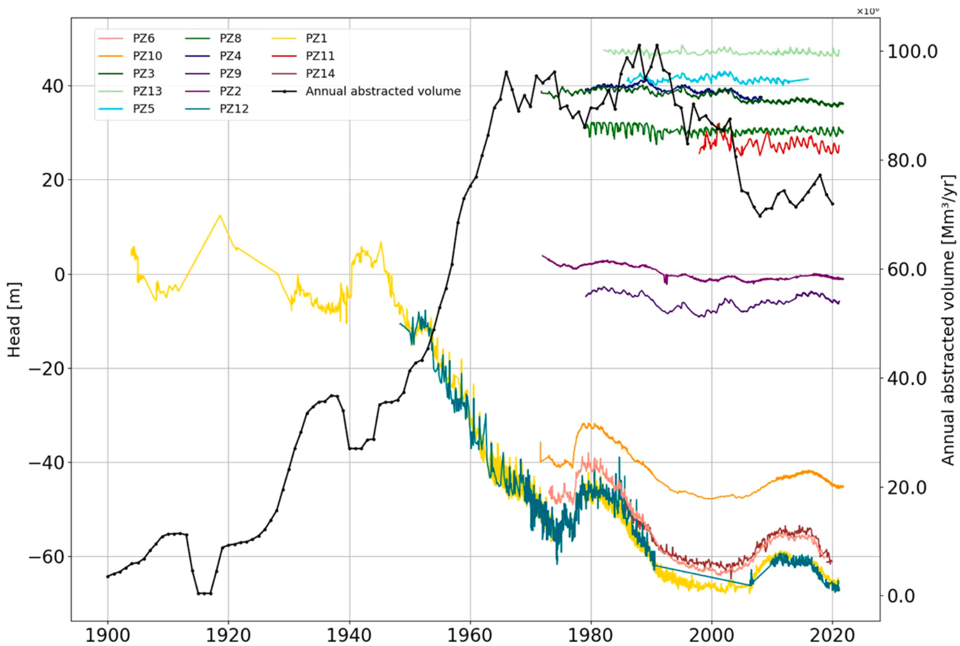

Fig. 3. Piezometric level time evolution in several piezometers located over the aquifer and the total groundwater abstraction volumes over the Carboniferous limestone aquifer. The location of the piezometers and all abstraction wells used in 2018 is shown in Fig. 2.

3.2. Groundwater abstraction context

Groundwater resources of this limestone aquifer are intensively exploited for more than a century. Groundwater is mainly used for drinking water distribution, industry, and agriculture. Important dewatering operations are also performed in large open pit limestone quarries located in Wallonia (Belgium). This dewatered groundwater is partly valorized for drinking water distribution in Belgium, through treatment and adduction facilities. The location of those quarries and the drawdown associated with dewatering is well visible in Fig. 2.

Fig. 3 shows the time evolution of the piezometric level in some of the piezometers located over the aquifer and the total groundwater abstraction volumes over the Carboniferous limestone aquifer (Fig. 2B). The pumping rate time series is a historical reconstitution, also inducing some uncertainties before the 60's. The location of the piezometers and all abstraction wells used in 2018 is shown in Fig. 2B. Abstracted groundwater volumes vary on a pluriannual basis. The total abstracted volume increases from the beginning of the 20th century and reaches a maximum value of about 100 Mm^3 /year between 1965 and 2003. This includes pumping by wells and open pit dewatering, the latter representing about 10 % of the total in 2020. During the same period, a strong decrease of the piezometric levels is observed in the north-west confined area. In a piezometer located close to the Bondues agglomeration (PZ1 in Fig. 2 and Fig. 3), a groundwater head decrease of about 80 m is observed between 1903 and 2000. This regional drawdown is less intense eastwards toward the unconfined part of the aquifer (as illustrated by piezometers PZ3 to PZ5 in Fig. 2 and Fig. 3). Between 1973 and 1981, a karstic collapse in the Scheldt riverbed (as highlighted in Fig. 2), caused by high pumping rates, has led to significant infiltration (estimated to 1–2 m^3/s) from the river into the aquifer. The result is a rise in the piezometric level for several years (De Roubaix et al., 1979). After 2000, national or regional regulation, and agreements between some involved parties led to a decrease of abstracted flow rates. It has allowed a stabilization and partial recovery of the piezometric surface. Since 2017, a new decrease is observed, concomitant with winter and summer drought events and higher annual abstraction volumes. Piezometric levels remain low in the north-west part of the aquifer, still inducing regional groundwater transfers from the unconfined to confined areas.

4. Modelling

4.1. Conceptual and numerical model

The need for groundwater resource management in the Carboniferous limestone aquifer led to the decision to develop a regional-scale model, to be shared and used by all the involved parties, in the scope of the EU Water Framework Directive (European Commission, Directorate-General for Environment, 2014).

The groundwater flow numerical model was developed using the MARTHE computer code developed by BRGM (Thiéry et al., 2018, 2020). MARTHE ("Modélisation d'Aquifères avec un maillage Rectangulaire, Transport et HydrodynamiquE; Modelling Aquifers with Rectangular cells, Transport and Hydrodynamic) code solves the partial differential equations governing the groundwater flow in porous media through the finite volume method. It allows two- or three-dimensional simulations in multilayer aquifers. It allows the simulation of groundwater flow, solute, and energy transport in porous aquifers with surface flow coupled interactions. In the present model, MARTHE is coupled with the module GARDENIA (Thiéry, 2013). GARDENIA (« modèle Global À Réservoirs pour la simulation de DÉbits et de NIveaux Aquifères ») is a hydrological basin model which simulates evapotranspiration, groundwater infiltration and runoff using different successive 'soil' reservoirs. Water transfers between those virtual reservoirs are controlled by several parameters such as storage, time transfers, and overflow thresholds.

The vertical extension of the model includes, from bottom to top, the permeable Carboniferous limestone unit from Middle Tournaisian to Upper Visean, the low permeability layer of Cretaceous marls (Cenomanian), the Cretaceous chalk aquifer and the Cenozoic sands and clays. The top of the model corresponds to the ground surface. The bottom of the model corresponds to the base of the first 50 m of the Carboniferous limestone aquifer, which are commonly considered as the productive horizon of the aquifer.

Horizontally, the model is limited to the west (section A-B in Fig. 2A) and to the north (B-C) by the contact with the low-permeability layers from Upper Devonian (Fig. 1). To the south, along the border section A-E, the model is limited by the Seclin's fault, which brings the Carboniferous limestone in contact with low-permeability Silurian shales and Devonian units. Still to the south, but along the border section E-D, the model is limited by the outcropping interface with the Upper Carboniferous shale and sandstone units. Along this section, the Carboniferous limestone aquifer is dipping southwards below the Upper Carboniferous units. All those limits are considered as no-groundwater-flux boundaries. The eastern boundary (C–D) of the modelled area corresponds to the Eastern Dendre River, clearly identified as a draining river. At this interface, groundwater and surface water levels are similar and exhibit limited temporal variation compared to groundwater heads throughout the modelled domain. Consequently, a prescribed hydraulic head, constant over time and corresponding to the river elevation along this boundary, is applied. Simulated river discharge is calibrated against available observed flow rate timeseries, by adjusting the hydraulic parameters in the aquifer.

A three-dimensional finite difference grid, composed of four layers of uniform 100 × 100 m rectangular prismatic cells, was developed based on the conceptual model described previously (Picot-Colbeaux et al., 2014a). The geological modelling was achieved by Picot and Dufrenoy, (2012) with the Geological Data Management software and its MultiLayer tool (Bourgine, 2006 and Bourgine, 2008). The grid includes 512 771 active cells. The four layers of cells correspond to the four represented hydrogeological units (from the bottom to the top: The Carboniferous limestone, the marl layers, the chalk aquifer, and the tertiary and quaternary deposits). The Carboniferous limestone layer is continuous all over the modelled domain. Upper layers are represented following the presence or absence of the overlying units (Fig. 4).

In the limestone layer, Neuman no-flow boundaries conditions are implemented along the western (A-B), northern (B-C), and southern (D-E; E-A) external limits, corresponding to the contact with low-permeability Devonian or Silurian shale formations (see Section 3.1 and Fig. 2). Along the eastern external limit, corresponding to the Dendre River, a specified-head boundary condition is prescribed. Those boundary conditions are repeated in the other layers. Each of the four layers may interact with the surface compartment when outcropping (Fig. 4). The topographic surface is implemented as a 'drain' Fourier boundary condition. A head-dependent flux exfiltrates when the simulated groundwater level is higher than the ground surface elevation. At each time step, this flux is transferred to the closest river section. Flux transfers between each layer, according to their existence, are also possible through head-dependent flux Fourier boundary conditions (Fig. 4). Groundwater heads in the layer corresponding to the chalk aquifer are imposed at constant values in time over the whole modelled period. This prescribed piezometric field corresponds to the high-water period in 2001. It is directly taken from the existing French regional chalk model (Buscarlet et al., 2011) which partly extends over the Carboniferous limestone aquifer. This choice, implemented over the specific chalk compartment of the model, interacting with the Carboniferous limestone layer, offers the advantage to rely on another well calibrated and validated model. Simulated transfer fluxes between the chalk and limestone layers nevertheless remain small at any time, compared to groundwater abstraction and recharge in the limestone aquifer. Fig. 4 illustrates the various modelled water transfers between the different subsurface and surface compartments. The orders of magnitude of these transfers are discussed in more detail later in the article (see for example Fig. 6).

Groundwater flow is simulated over a 100-year period using variable timesteps, ranging from 5 years at the beginning of the simulation, to monthly timesteps after 1990. This choice is directly related to the resolution of available data and to limit the numerical burden of the simulations. Recharge flux, runoff and evapotranspiration are calculated internally by the module GARDENIA using spatially distributed potential evapotranspiration and precipitation time series, and spatially distributed soil related parameters. Recharge fluxes are prescribed at the top of all outcropping cells of the groundwater model. Groundwater abstraction points are implemented as Neuman specified flux boundary conditions, with abstracted volumes corresponding to historical or projected data. Dewatering operated in stone quarries are also implemented using specified flux boundary conditions, with corresponding dewatered volumes distributed along the walls of each open pit, where most of the groundwater outflows are observed.

4.2. Model calibration

The model is calibrated in two interconnected steps. First, soil parameters involved in the recharge and runoff computation with GARDENIA are calibrated to piezometric levels and river flow rates at the scale of hydrological catchments. Second, the hydrogeological parameters are calibrated to piezometric levels and surface flow rates for the period 1900–2019. It involves 6 adjustable parameters distributed in several zones, including hydraulic conductivity, anisotropy, storage coefficients, conductance to river, hydraulic conductivity near faults. Observed data are very scarce at the beginning of the simulation, but their availability increases with time. Overall, the calibration stage includes measured data in 9 piezometers for the 1900–1989 period, 34 piezometers for the 1989–2010 period and 11 river gauging stations with heterogenous data availability between 1966 and 2010. The important Scheldt River accidental infiltrations, well observed and identified between 1973 and 1981, with subsequent important piezometric level increases in the confined area (see Fig. 3 and Section 3.2), are specifically used to calibrate the model (Quinif, 1991; Quinif and Rorive, 1990; Van Rentergem et al., 1993) in particular regarding the storage parameters. The model calibration was performed by trial-and-error and was improved successively across projects and model developments by involved teams (Bastien and Rorive, 2016; Picot-Colbeaux et al., 2014a, 2020). The model used in this study is described in Bastien and Rorive, (2016); Picot-Colbeaux et al., (2014b) and (2020b). Special attention, but not exclusive, has been given to the correct representation of (1) piezometric gradients as provided by the 2010 measurement campaign, and (2) the dynamics of piezometric levels in the confined area, as influenced by the

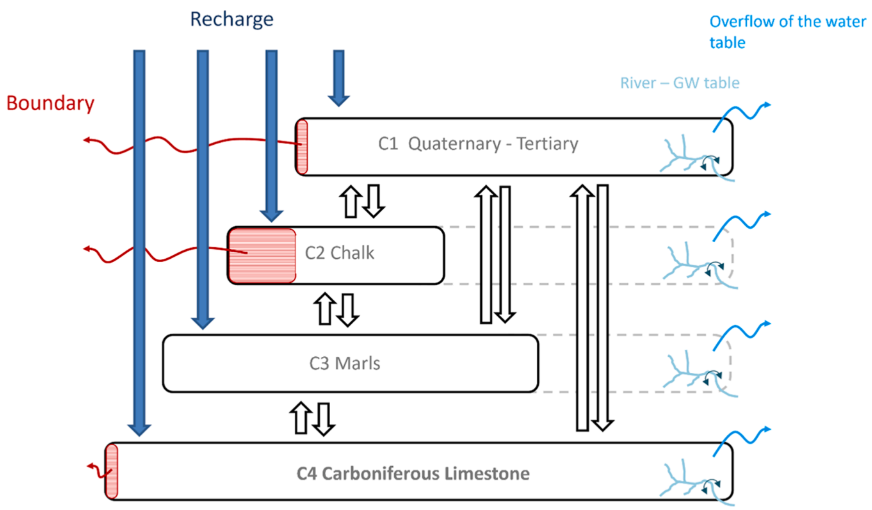

Fig. 4. Conceptual view of the hydrogeological units discretized in the numerical model, with possible interactions between layers and with the surface compartment. Red shaded areas represent prescribed head boundary conditions (Dendre River and prescribed field in the chalk aquifer).

pumping fields present in this zone. This includes the centennial piezometric drawdown (before 2000) and the more recent variations induced by intense groundwater abstraction operations (after 2000).

Selected relevant examples are presented in Fig. 5. These include observed and simulated piezometric levels at 6 locations (Fig. 2), covering both confined and unconfined areas. Also shown are observed and simulated river flow rates at two gauging stations on the Hunelle and Western Dendre, which are two rivers connected to the aquifer in the unconfined area. (Fig. 2). The model is generally able to reproduce seasonal and multi-annual piezometric variations. Differences are observed but the overall calibration corresponds to a trade-off at the scale of the aquifer, in terms of water balance, piezometric level mean values and fluctuations. In particular, the quantity of water flowing to the aquifer and exfiltrating to the surface compartment according to time is well reproduced. The piezometric drawdown and time evolution in the piezometer of Bondues (PZ1 in Fig. 5), where an observed time series is available for more than 100 years, is also well fitted at this time scale, although the groundwater head recovery observed from 2005 to 2015 is overestimated. Groundwater head in the transition zone between the unconfined and the depressed confined areas (Fig. 2) is more difficult to calibrate, although reproducing trends over years were prioritised and looks realistic. The model also reproduces well the seasonal variations in mean water discharge in the rivers (Western Dendre River and Hunelle River in Fig. 6) and the related exchanges with the aquifer.

Fig. 6 shows the water balance terms simulated in the Carboniferous limestone layer, at the scale of the 4 administrative groundwater bodies, and corresponding to the year 2020. It is illustrated that the total 'recharge' and 'drainage from overlying layers' is much higher in the eastern unconfined part of the aquifer, and that transfers are well simulated to the western confined area. According to the simulations, interactions between the three western groundwater bodies are high. Interactions with the groundwater body RWE013 are less intense.

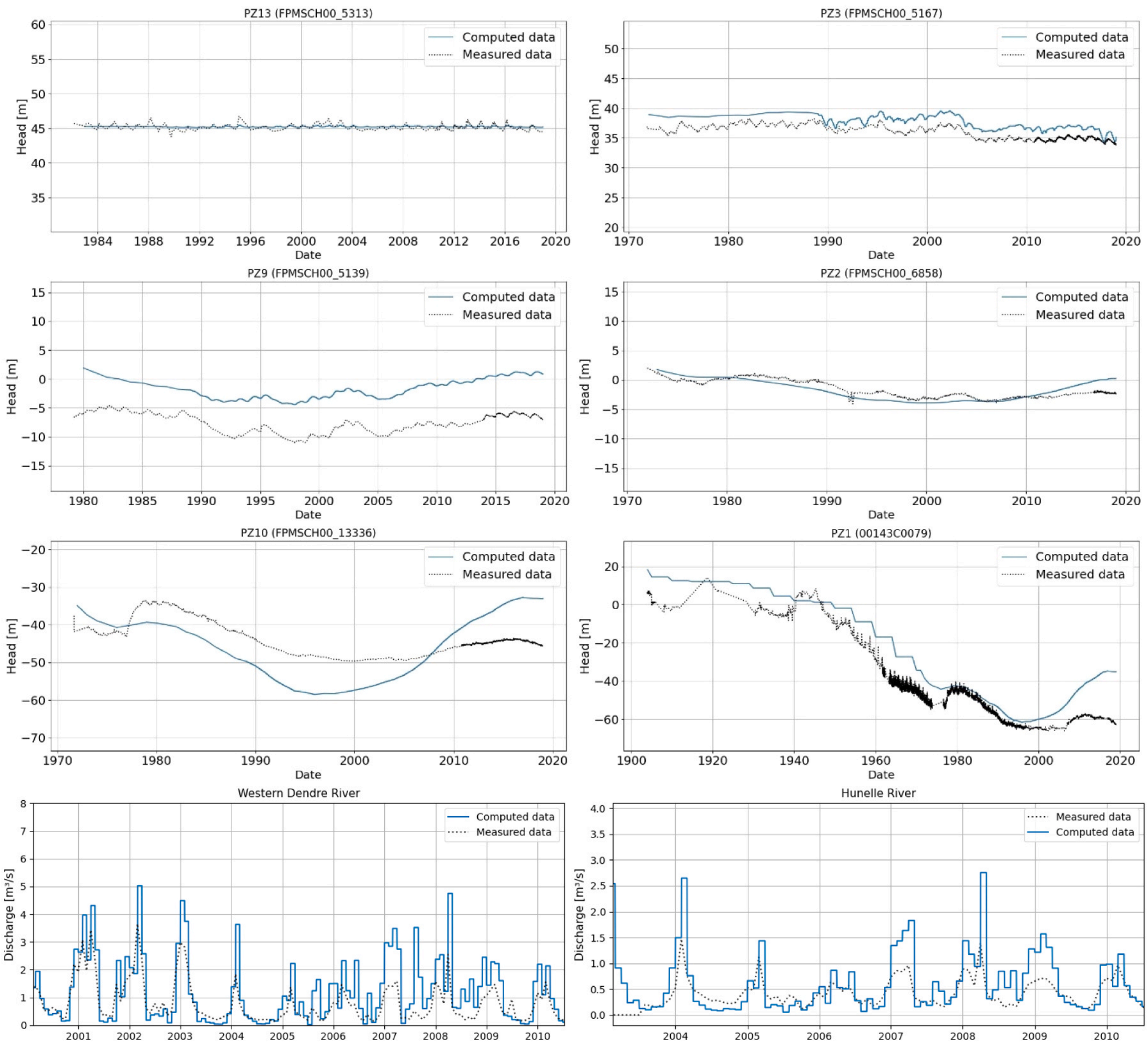

Fig. 5. Observed and simulated piezometric level in 6 selected piezometers and observed and simulated river flow rates at two gauging stations on the Hunelle River and Western Dendre River (Fig. 2). The names in parentheses correspond to commonly used local names. Piezometers are here displayed from east to west.

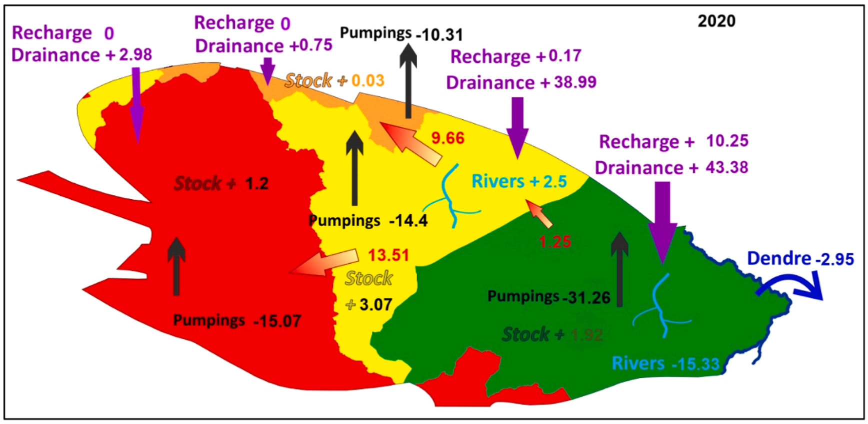

Fig. 6. Simulated water balance terms for the four administrative groundwater bodies at the end of 2020 in Mm^3 /year.

5. Impact evaluation from different sources

The influence of the different stresses is difficult to catch as they vary and control groundwater levels simultaneously over periods where historical data are available. To study the aquifer behaviour and to provide scientific arguments in the management and

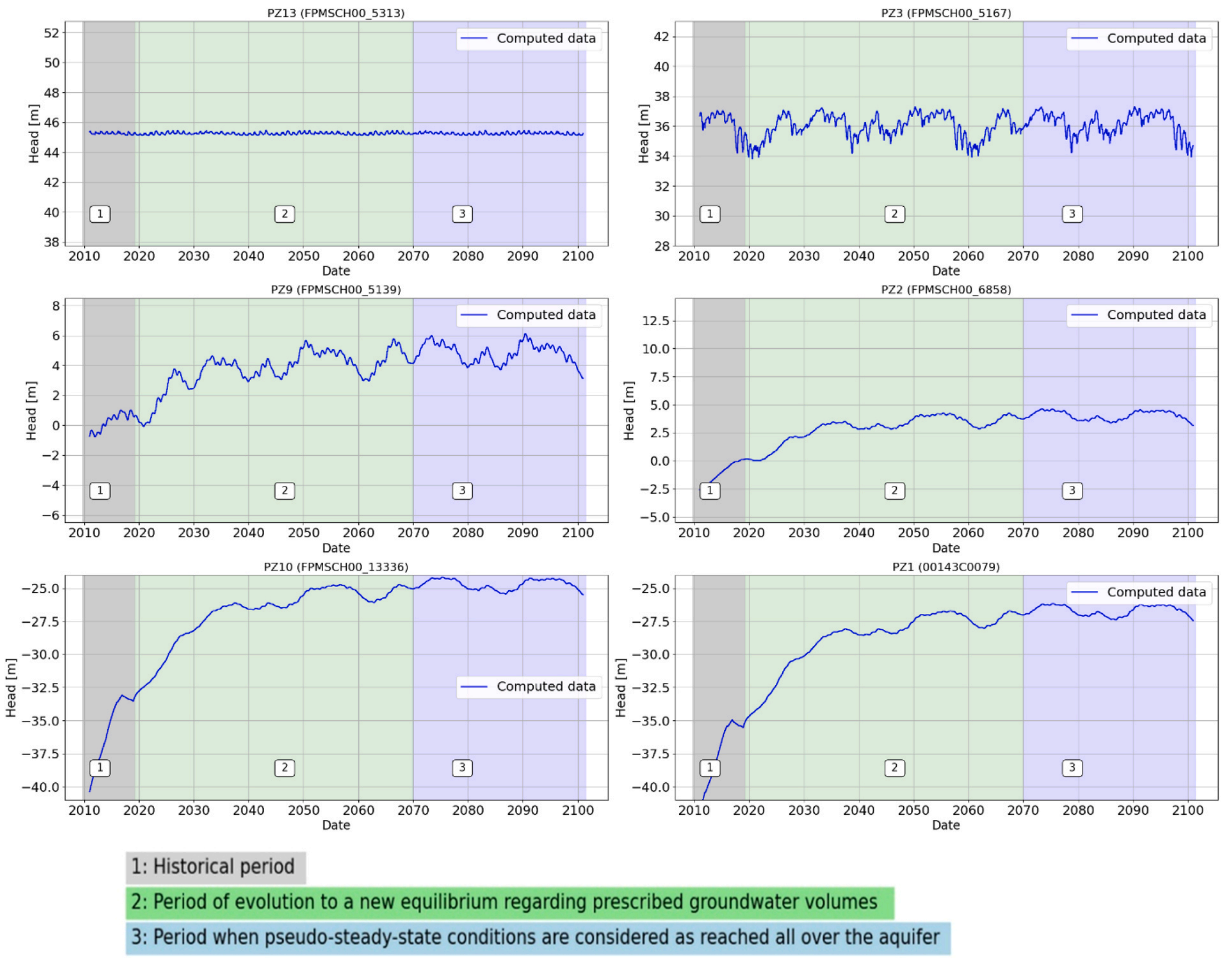

Fig. 7. Simulated groundwater heads at 6 points located throughout the aquifer (see location in Fig. 2) between 2010 and 2100. Groundwater abstraction rates are fixed and kept constant for the whole simulation, from 2020 to 2100. Recharge varies daily and corresponds to the 1990–2020 period, repeated during the whole simulation.

preservation of groundwater resources, different scenarios involving, independently, aquifer recharge, groundwater abstraction rates, and open pit stone quarry dewatering were implemented and applied to the calibrated model. Those simulations allow studying the sensitivity to different stresses and making some predictions, following a long-term time scale. Each simulation is performed over a 90-year period from 2010 to 2100. Initial conditions correspond to the previously simulated groundwater heads, using the calibrated model and corresponding to the beginning of 2010 (see Section 4.2). From 2010–2020, input stresses including precipitation, potential evapotranspiration, groundwater abstraction and quarry dewatering correspond to historical observed data. From 2020–2100, those stresses are applied following different assumptions described in the next subsections.

5.1. *Sensitivity to meteorological events and related groundwater recharge*

To study the influence of recharge on groundwater heads within the aquifer, groundwater abstraction rates are fixed and kept constant for the whole simulation, from 2020 to 2100. The mean abstracted volume of the 2015–2019 interval (74.1 Mm^3/yr) is used for the whole simulation (Fig. 3). The spatial distribution of abstraction points is also preserved (Fig. 2B). Meteorological times series are built using a repetition of historical data. Precipitation and potential evapotranspiration times series are implemented as a succession of the 1990–2020 30-years observed time series. Those input stresses allow simulating predictions representative of the climate observed during the 1990–2020 time slice. No climate change scenario is here considered. The annual precipitation and evapotranspiration rates used in this scenario fluctuate between 700 – 900 mm/yr. The related recharge rate, computed internally using GARDENIA, varies between 150 and 300 mm/yr.

Groundwater heads simulated at 6 selected piezometers throughout the aquifer (see location at Fig. 2) are presented at Fig. 7. In the confined area, groundwater levels are characterized by a long transient behaviour, related to a re-equilibrium corresponding to the prescribed groundwater abstraction flow rates. Abstracted volumes implemented after 2020, are lower than during the historical period, when the aquifer exploitation was more intensive. Simulated groundwater heads thus progressively evolve to a new pseudo-steady-state equilibrium. In the confined area, the time needed to reach this new equilibrium is quite long, up to 50 years approximately (Fig. 7). Eastwards, the time needed to reach pseudo-steady-state conditions decreases and is much lower in the unconfined area. Considering those simulated results, the period 2070–2100 is considered as representative of pseudo-steady-state conditions all over the aquifer, and groundwater head fluctuations are controlled by recharge variations only. This period is used to assess the groundwater head sensitivity to recharge. In accordance with observed data, simulated time series in the unconfined area are clearly characterized by seasonal and multi-annual behaviours. The seasonal signal tends to disappear going westwards in the confined area. Fig. 8 presents a spatially distributed view of the simulated groundwater head variation interval, calculated for the 2070–2100-time interval, and explained by recharge fluctuation only. Groundwater head fluctuations are logically higher in the unconfined area, from 0 m along the draining rivers, up to 10 m. Simulated results also highlight the influence of the recharge in the confined area, up to 1.5 m in the north-west depressed zone. This conclusion is not evident by looking to observed data only, which are strongly controlled by abstraction rates. This is an important insight of this study and further management of the resource in general. In the southern part of the confined area, simulated groundwater head fluctuations are almost zero. This compartment is quite isolated by faulted and horst structures (Fig. 2A). It is also much less exploited and without extensive measured data.

5.2. *Sensitivity to open pit quarry dewatering*

Large volumes of groundwater are abstracted in wide stone open pit quarries for dewatering operations (Fig. 2B and Fig. 3). During

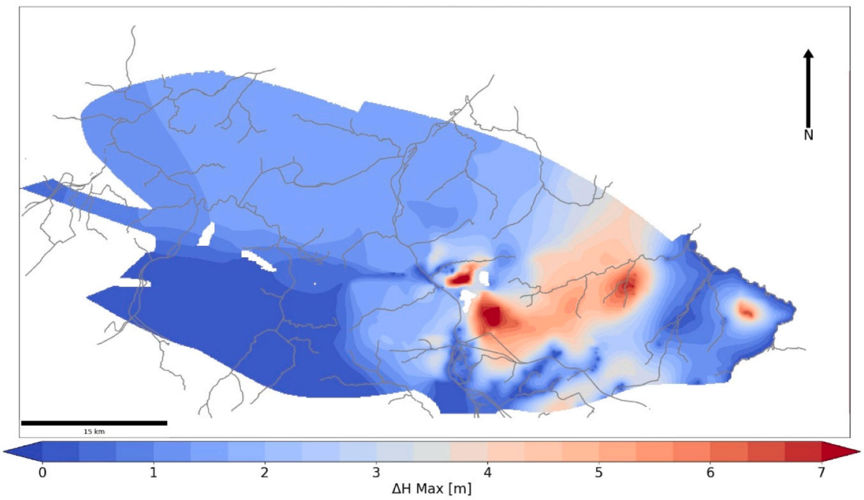

Fig. 8. Spatially distributed simulated groundwater head variation intervals ($\Delta H_{recharge}$) calculated for the 2070–2100 time interval and explained by recharge fluctuation only (see also Fig. 5).

the 2015–2019 interval, mean dewatering volumes represent 7.78 Mm^3 /year or 10.4 % of the total abstracted amount. The impact and the area of influence of those specific abstractions on groundwater resources are assessed by comparing two simulations with and without quarry dewatering, all other stresses remaining equal. Fig. 9A shows the difference of simulated groundwater heads after 120 years of simulation. Fig. 9B shows the change in the simulated water balance terms for the four administrative groundwater bodies, between two scenarios with and without open pit quarry dewatering. In the scenario without open pit dewatering operations, a clear groundwater level increase is logically observed. The difference is equal to several tens of meters at the level of the quarries, approximately corresponding to the depth of the open pits, and decreases moving away. Simulated groundwater levels are impacted (drawdown threshold = 0.1 m) up to 15 kilometres around the quarries, mostly propagating eastwards in the unconfined area. The propagation downstream towards the confined area is limited to about 8 kilometres. Dewatering operations mostly affect river-aquifer interactions in the groundwater body RWE030 rather than the transfers to the adjacent groundwater bodies (Fig. 9B). In the RWE013 groundwater body, removing dewatering flow rate (7.78 Mm^3/year) induces a substantial increase of the groundwater exfiltration to the river network (6.6 Mm^3/year), an increase of the drainage from overlying aquifers, and an increase of groundwater transfers to RWE060 (0.1 M m^3/year), according to the simulations results.

5.3. Sensitivity to groundwater abstraction

The impact of groundwater abstraction is evaluated through 3 different scenarios. Precipitation and potential evapotranspiration

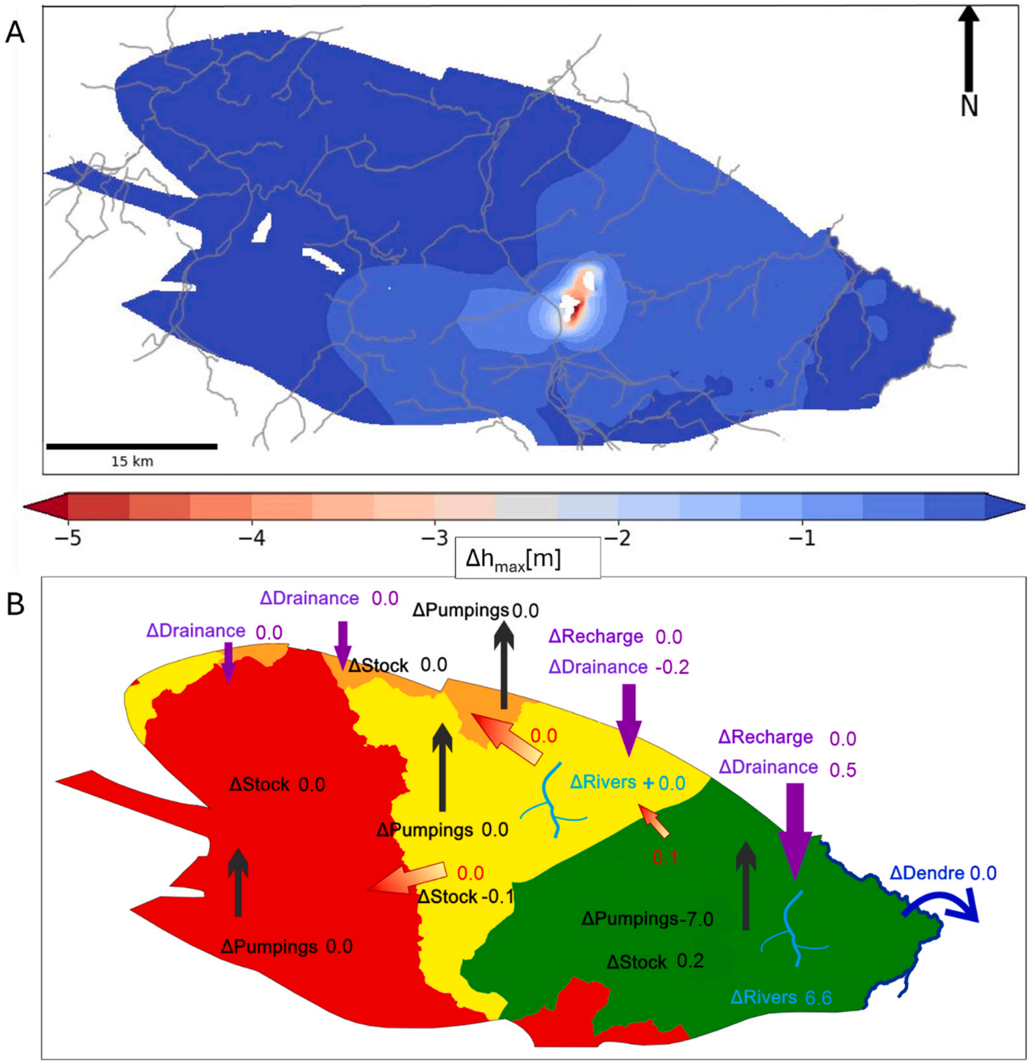

Fig. 9. A. Difference of simulated piezometric levels ($\Delta H_{dewatering}$) between two scenarios with and without open pit quarry dewatering, after 90 years of simulation. Implemented dewatering flow rates are equal to 6.98 Mm^3 /year, representative of the actual context in 2020. B. Simulated water balance difference between a scenario with and without open pit dewatering operations terms for the four administrative groundwater bodies at the end of 2020.

time series are similar to the inputs used in Section 5.1. Simulated groundwater abstraction scenarios include (Table 1):

(1) stop of all pumping operations.

(2) implementation of abstraction points at the maximum legal flow rate, as stipulated in historical and individual production wells permits. This represents an increase of 247 % compared to the current abstraction rates (period 2015–2019) or 165.9 Mm^3 /year.

(3) use of abstraction flow rate values relative to the year 2018 (69.3 Mm^3/year) for the whole simulation. This year correspond to a peak in demand and to the beginning of the groundwater head decrease observed in the confined area between 2016 and 2020.

Those scenarios are compared with the simulation corresponding to groundwater abstraction of the period 2015–2019 (66.9 Mm^3/year) or Scenario 0. Fig. 10 shows the evolution of simulated groundwater heads levels at the level of 6 piezometers (Fig. 2), according to the 4 scenarios. Several lessons can be drawn from those results. Scenarios 1 and 2 illustrate the reactivity of the aquifer when changing the current abstraction rates, either up or down. The highest impact is logically observed in the north-west confined area, which combines high pumping rates and low storage coefficient values. Changes are happening fast. When virtually stopping all pumping operations, groundwater head goes back to natural state in only a few years. It highlights a dynamic system with little inertia, enhancing rapid impacts, but also allowing action with short-term results in terms of resources management. In the unconfined area, changes are observed but at a more local scale. Scenario 3 shows a lower equilibrium or slightly decreasing state compared to the 2020 piezometric situation. This scenario illustrates abstraction rates which are close to the threshold that should surely not be exceeded to maintain the current piezometric situation or allow a recovery.

Maps of Fig. 11 allow comparing the relative impacts of recharge, dewatering and pumping wells on groundwater levels, in the current abstraction context. They show ΔH*, the variations of groundwater levels normalized by the percentage of stress change relatively to mean recharge (Eq. 1) or the variations of groundwater levels given a change in the considered stress, equivalent to 1 % of the mean recharge of the period 1990–2020. Here, the recharge is considered as the recharge calculated by GARDENIA and corresponds to 290.6 Mm^3 /year.

$$\Delta H^{*} = \frac{1}{100} \times \frac{\Delta H}{\Delta Stress / R_{mean}} \tag{1}$$

With:

ΔH^{*} Normalized piezometric level variation [m]

ΔH Piezometric level variation [m] due to a specific change of stress (recharge, dewatering, pumping rates)

$\Delta stress$ Change of stress [m^3 /year] defined as (1) the recharge fluctuation interval over the period 2070–2100, (2) the dewatering flow rate for the specified year, (3) the pumping flow rate difference between 2018 and the mean value of 2015–2019

R_{mean} The mean annual recharge [m^3 /year]

Fig. 11A shows the normalized groundwater variation due to a 1 % increase in recharge. Regionally, recharge variations impact mostly the unconfined part of the aquifer. Parts with draining rivers have low sensitivity towards the recharge changes. Levels are more sensitive to dewatering operations (Fig. 11B), especially near the open pit, extending eastwards and westwards approximately 10 km. The confined part of the aquifer is very sensitive to groundwater abstraction rate changes (Fig. 11C). The unconfined part is also affected around pumping stations with high abstraction rates.

Considering the normalized change in groundwater level, all stresses show an impact which cannot be neglected. Variations however vary in intensity and spatial distribution. The normalized impact of abstraction rates (Fig. 11C) shows the highest intensity compared to the others. Highest values are located in the confined zone which combines low storage coefficients and high abstraction rates. Dewatering operations also show high sensitivity (Fig. 11B), but exclusively located around active open pits. Finally, recharge shows lower but non-negligible sensitivity values (Fig. 11A), mainly in the unconfined zones of the aquifer, but also extending in the confined area.

6. Discussions and model application for resources management

In particular, the model was used to project different scenarios, to support a common official agreement, to be signed by France and Belgian regions, about the maximum groundwater abstraction volumes for the next years. Those scenarios were co-constructed by the involved stakeholders and tested with the model (Picot-Colbeaux et al., 2022). As an illustration, Fig. 12 shows selected results regarding one of those scenarios ("*Scenario 4: "variable abstraction*"), integrating planned or wanted pumping rates and the development of the stone extraction industry and related dewatering operations for the next decades. During this period, operations in some quarries will end, others will be extended and deepened, and new open pits will open. Fig. 12 shows simulated groundwater head in PZ1 and PZ3, and simulated groundwater head at the scale of the studied area by 2050. New extensions and open pits are also

Table 1
Simulated groundwater scenarios used to compute the sensitivity to groundwater abstraction [annual abstracted volumes in pumping wells - m^3 / year].

Scenario	RWE013	RWE060	VL063	FRA315	Total
Scenario 0 (Ref 2015−2019)	24 234 838	15 177 749	10 568 719	16 951 698	66 933 005
Scenario 1 (no pumping)	0	0	0	0	0
Scenario 2 (max pumping)	24 031 499	99 581 560	15 000 000	27 248 300	165 861 359
Scenario (2018 pumping)	23 911 827	15 882 675	11 531 450	17 969 079	69 295 031

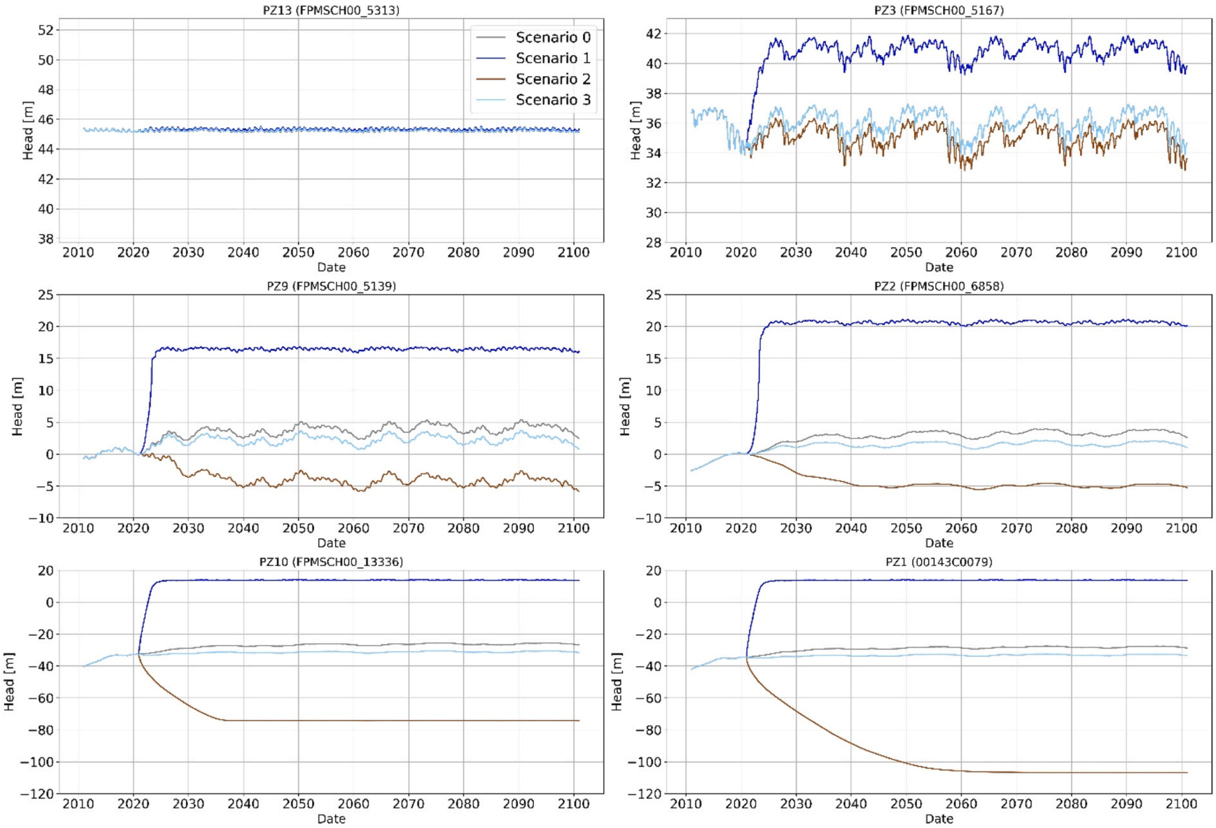

Fig. 10. Evolution of observed and simulated piezometric levels at several piezometers, according to the 3 scenarios related to groundwater abstraction. The locations of the piezometers are shown in Fig. 2.

highlighted in Fig. 2B. They correspond to an increase of the projected dewatering flow rates, from 7.01 × 10^6 m³ /year in 2020–20.6 × 10^6 m³ /year in 2050. Those flowrates were estimated externally, based on the official permits delivered by the public administration.

Results of this scenario show a lateral expansion of the drawdown area around the stone extraction zone, particularly upstream toward the eastern unconfined area. Prescribed pumping rates in wells allow keeping groundwater head in the western confined area stable.

Possible climate change is not considered here. Recharge-induced simulations (Section 5.1) however highlight the possible impact on piezometric level in case of precipitation and recharge decline or increase. Although the hydrogeological context is different and weather slightly differs, Goderniaux et al. (2009),(2015) estimated a significant negative impact on recharge and groundwater levels (up to 20 m) for a chalk aquifer located about 150 km eastwards, using various climate change scenarios up to 2100. For the same aquifer, Goderniaux et al. (2023) also calculated a 43 % annual recharge reduction comparing the 1960–1990 and 1990–2020 periods. Climate change should also impact groundwater resources in the studied Carboniferous limestone aquifer. It must be assessed and considered in the water management plans. Land use planning must also integrate the specific context of the aquifer. In response to dryer and warmer summers projected in climate change scenarios (IPCC, 2023), the use of irrigated agriculture may significantly increase. As groundwater exploitation is already intense in the aquifer, and has caused severe drawdown in the past, available resources could hardly meet this new demand. Further development of agriculture in the region, and selected crop types, must integrate this component. Uncertainty in future recharge projections and the compounding effect of increasing abstractions are important considerations for any joint management strategy (Reinecke et al., 2021; Rusli et al., 2024).

The numerical model is the result of a long process and collaboration among scientists, stakeholders, water companies. Different versions of the model exist. The one which follows the best the temporal trends, particularly in the confined area, is used here. Discrepancies between simulated and observed data may be explained by different sources of uncertainty, beside the challenges related to the model scale and aquifer heterogeneity. The uncertainty related to aquifer stresses (abstraction, weather) increases when going back in time, as the exercise included reconstruction of long-term data time series since 1910. Some uncertainty remains, even for more recent times, as gathering exhaustive and reliable groundwater abstracted volumes remains a difficult exercise. A potential important source of error is also related to river-aquifer interactions and in particular to the Scheldt River (Fig. 2). Due to the important aquifer depletion observed in the north-west part of the area, some Scheldt River sections are disconnected and perched relative to the groundwater table. Some important river losses have been observed in the past (around 1980 – see Section 3.2 and Fig. 3) due to

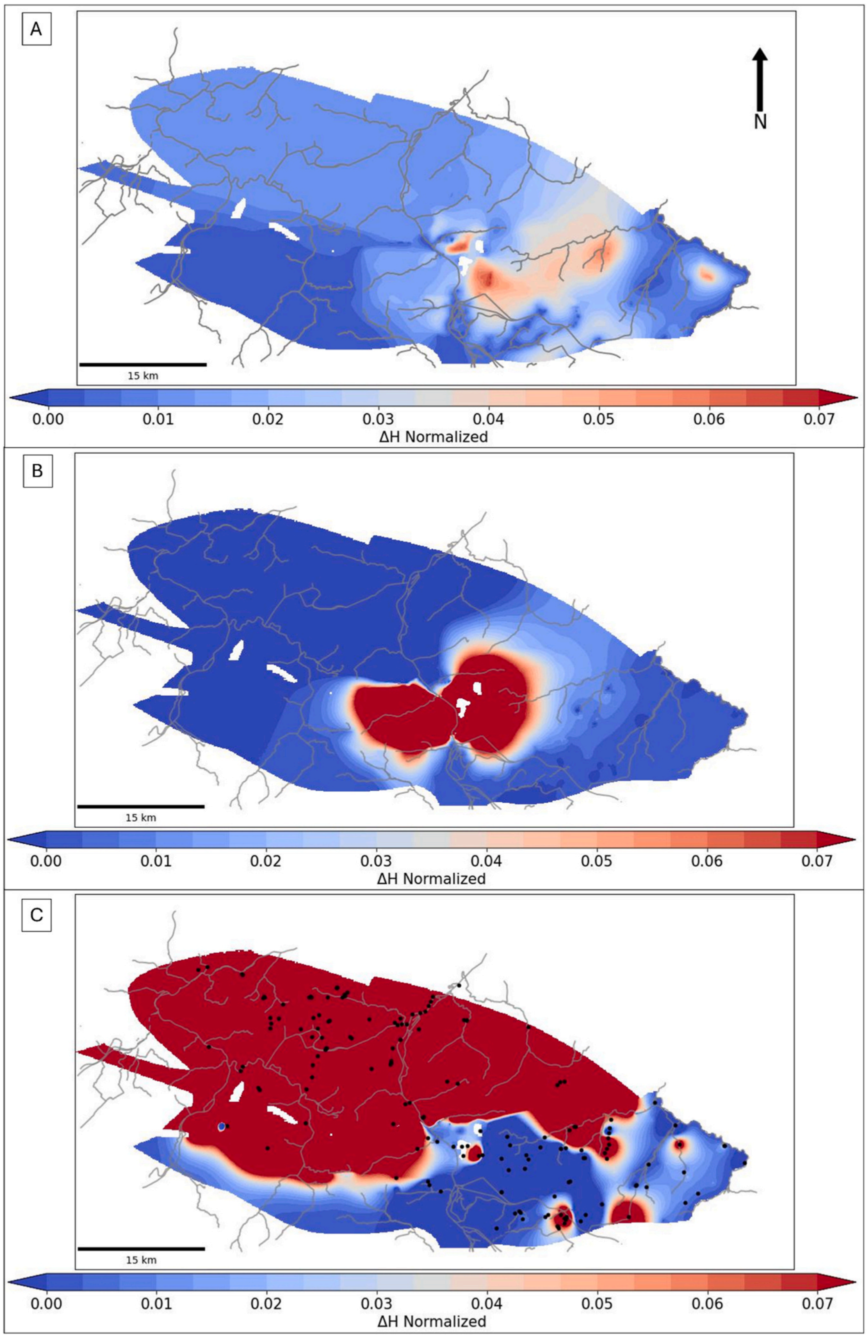

Fig. 11. Comparison of the relative impacts of recharge (A), dewatering (B) and pumping wells (C) on groundwater levels using normalized groundwater levels variation (Eq. 1).

limestone karst collapse within the riverbed. However, the current fluxes between the river and the limestone aquifer are largely unknown, contributing to calibration uncertainty at the entrance of the confined area. Characterizing those fluxes is needed and would strengthen the model regarding the general water balance terms.

Parameter and prediction uncertainty are not quantified, although it would support projections and decisions. Automatic calibration, parameter uncertainty and predictions uncertainty are definitively important aspects of modelling. During this study, considerable time and effort were dedicated to the development of the conceptual model, which was built upon existing data analysis, data collection and interpretation, field investigations, and the delineation of zones with similar characteristics. This foundational work must be carried out collaboratively. It requires the integration of knowledge from both sides of the border, including compromises between different interpretations, even when all are scientifically based. While time-consuming, this step is long but crucial in

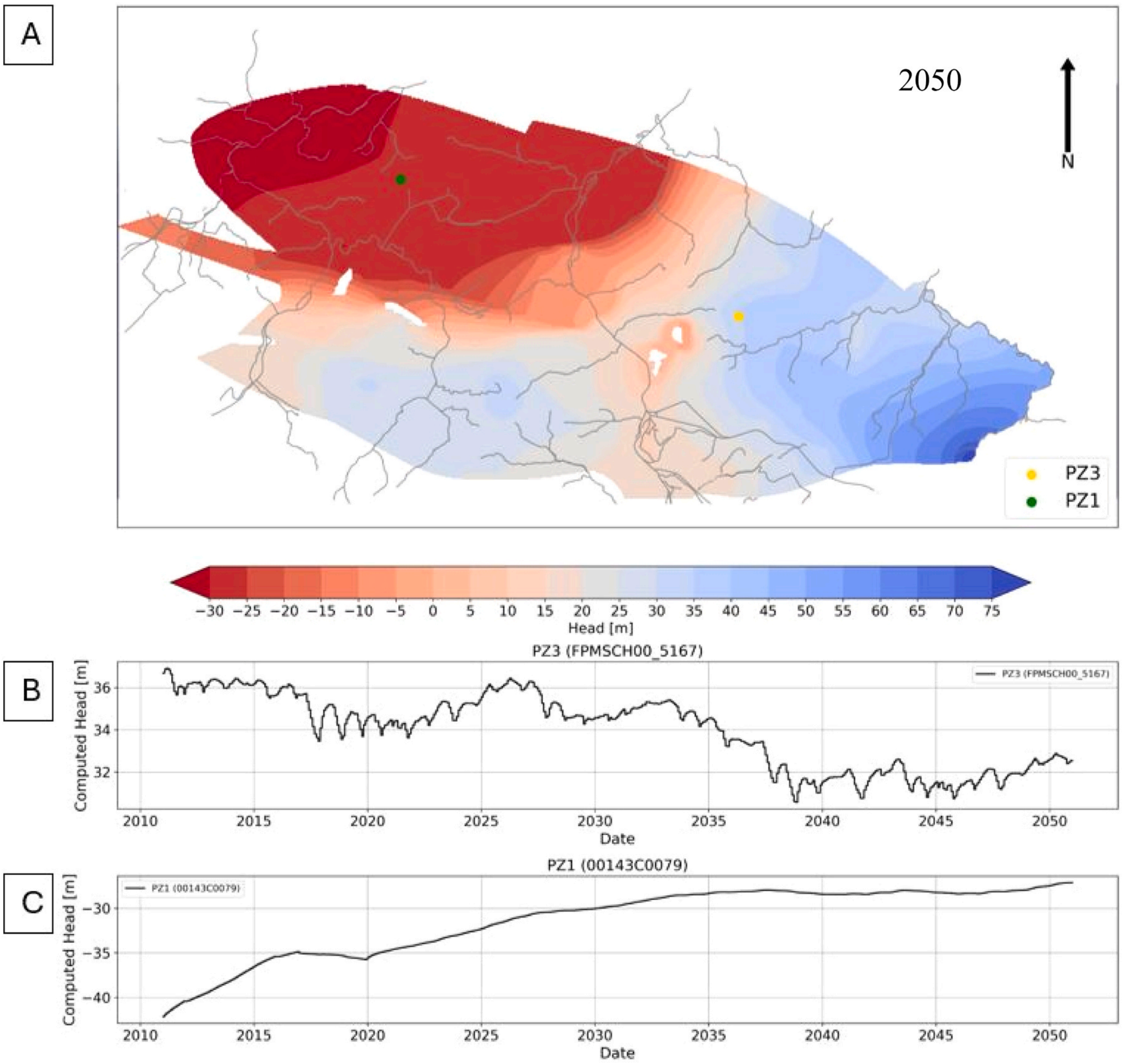

Fig. 12. A. Simulated piezometric levels for 2050 corresponding to projections integrating planned or wanted pumping rates and the development of the stone extraction industry in the next decades. B and C. Simulated groundwater head time series at the level of two piezometers in the studied area.

the joint development of a transboundary aquifer model that aims to be shared and accepted by all parties involved. As a results, throughout the model development process, and in particular during the calibration stage, efforts were made to adhere closely to the initial, jointly developed conceptual model. Calibration was performed using a trial-and-error approach, with minimal adjustments to this framework, acknowledging that it may still be subject to future revision. Improving the calibration through inverse modelling techniques and addressing parameter and prediction uncertainties are actually important aspects, which are part of future research works. Recent developments have enabled and facilitated the integration of inverse modelling algorithms into the Marthe – Gardenia framework. Beyond the technical challenges of applying such methods to large-scale, long-term models (see for example Goderniaux et al., 2015), the transboundary nature of the aquifer also necessitates multilateral coordination and consultation between the involved parties. Nevertheless, applying these approaches to the Carboniferous limestone aquifer model represents a key perspective of this research.

Although imperfect, the developed model constitutes a valuable and unique cross-border decision-support tool available, allowing for guidelines and relative comparison of the impacts of various solutions/management choices. It nevertheless requires regular updates in terms of data, knowledge, calibration, sensitivity analysis, and usage to remain effective. This conclusion aligns with recent syntheses on transboundary aquifers, which emphasize three key pillars for effective management: (i) joint scientific assessment and mapping, (ii) cooperative data exchange and shared monitoring, and (iii) institutional frameworks translating science into adaptive governance (Eckstein, 2024; Rivera et al., 2023). The global mapping and assessment efforts led by IGRAC and UNESCO demonstrate the rapid increase in identified transboundary aquifers and the growing need for coordinated management approaches. These international efforts and recent reviews highlight that collaborative modelling and data sharing, as done here, are necessary precursors to formal agreements and operational rules (Varady et al., 2023).

From an administrative perspective, the management of transboundary aquifers in Europe is currently organized within different groundwater bodies, implemented in the framework of the European Water Directive (European Commission, Directorate-General for Environment, 2014). Those administrative groundwater bodies are managed at the national or regional levels, as all surface or groundwater bodies in Europe. Although official international commissions, such as the 'International Scheldt Commission', invite and promote actors from different entities to discuss and exchange, decisions and official reporting are still performed at those administrative levels. Recent studies highlight that the transition from scientific cooperation to lasting governance arrangements often requires sustained hydro-diplomacy, stakeholder engagement, and institutional clarity (Herbert and Döll, 2019; Rubin et al., 2024). Experiences from other transboundary systems, such as the Guarani Aquifer and several North and South American transboundary aquifers, demonstrate that progressive institutionalization—starting with joint assessment, followed by shared monitoring, and eventually negotiated management rules—offers a realistic pathway toward sustainable groundwater use (Maass-Morales et al., 2024). These lessons strongly support the ongoing discussions between France and Belgian regions and encourage the adoption of (i) harmonized monitoring and data sharing, (ii) management zones defined by hydrogeological rather than administrative boundaries, and (iii) adaptive abstraction quotas tied to observed recharge trends.

7. Conclusion

The case of the Carboniferous limestone is singular and uncommon as it constitutes an example of a transboundary aquifer, affected by a severe exploitation in the past, in a region characterized by a temperate European climate. The aquifer extends over and is currently intensively exploited in three countries or administrative regions (France, Flemish and Walloon regions in Belgium). The current state of groundwater resources is inherited from an historical over exploitation during the second half of the 20th century, leading to an important aquifer depletion.

Beside the analysis of the aquifer system functioning, summarized in Section 3, (see Picot-Colbeaux et al., 2014a for more exhaustive information and data), this paper describes some results mainly coming from modelling works. The developed model is based on a long-term collaboration and detailed characterization performed together by scientific teams of the involved regions and countries. The model allowed simulating numerous scenarios proposed by the different stakeholders, promoting debate about the shared sustainable exploitation and management of the groundwater resource, and supporting decisions. The original groundwater numerical model was developed using the MARTHE simulator, integrating groundwater abstraction, open pit dewatering, and the interactions with the hydrological network and the overlying aquifers. In particular in this paper, we show some of the developed scenarios and highlight the sensitivity of specific stresses (recharge, dewatering in existing open pit quarries, pumping in wells). Among the key results, this study shows that, in the confined area, groundwater head is also significantly influenced by recharge fluctuation and not only by abstraction wells. It indicates that both types of stress must be considered to adequately manage the resource in the confined area, combining abstraction needs and expected recharge rates at mid- and long-term. It is therefore important to take decisions, considering future expected climate change scenarios. Results also highlight the high sensitivity of the groundwater levels in the confined area relatively to abstraction rates at a relatively short-term, making any actions rapidly visible, positively, or negatively.

The case is also remarkable because of the successful official collaboration between the three involved entities and the commitment to have a joint management. Since the end of the 20th century, facing the poor state of resources and the non-perennial on-going exploitation, scientists, stakeholders, and water companies initiated a joint characterization and modelling approach to promote a sustainable exploitation of the resource. The different scientific works have been performed through different projects and conventions funded by public authorities. In parallel, trans- regional and national agreements progressively emerged. Since 1997, an official agreement between the Flemish and Walloon regions limits groundwater withdrawals in the aquifer. Major investments were performed to valorise as much as possible dewatering water open pit quarries, as drinking water. In parallel, abstraction in the French part of the limestone aquifer were also reduced. Another official agreement was signed in 2017 to officially share data including annual abstracted volumes, groundwater heads and chemical data, between France and Belgian regions.

A new possible agreement is currently being discussed by the three entities to rule groundwater abstraction in the transboundary groundwater bodies in the context of intensive exploitation. This agreement would represent a new stage promoted by and in logical continuation to the work undertaken over the last 2 decades. The objective aims to promote sustainable exploitation of the resource, considering the hydrological functioning of the aquifer, the needs in the 3 regions, in a climate change context. The approach intends to keep the resource as a short- and long-term buffer to face repeated and more intense summer drought events expected in the future. During those events, the water demand may be significantly increased for both public supply and agricultural irrigation. In this context, any decreasing trend must be countered. Groundwater head in the aquifer must be kept to a new hydraulic equilibrium, above the lowest levels observed in the past, to avoid any unexperienced and unmanageable disruption in terms of quantity and quality. To reach this goal, the new possible agreement includes official monitoring, share of data, and groundwater abstraction quotas in the three transboundary groundwater bodies.

The scientific and administrative work and collaboration performed about the studied aquifer finally result in a very positive experience. This collaboration is not always easy, but has forced people to talk, share data, understand processes that go beyond administrative boundaries. In this task, the involvement of scientific teams from the different regions, supported by their administration offices was determinant. Collaboration is being continued, including through the support of the authorities for maintaining, using and improving the model with time.

CRediT authorship contribution statement

Picot-Colbeaux Géraldine: Writing – review & editing, Validation, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Vandelois Guillaume:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Goderniaux Pascal:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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