Characterization of hydrogeological processes of karst-influenced multi-layered aquifers of basin edge using statistical and geochemical approaches (northern Aquitaine basin, France)

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Abstract

This study aims to characterize the regional hydrodynamic and hydrochemical variability of multi-layer carbonate aquifers of basin edge by considering their karst feature. The study area is the northern edge Aquitaine Basin in Southwest France, which is characterized by two main Upper Cretaceous and Jurassic reservoirs. A dataset of water levels and physico-chemical analyses in 65 springs/shallow wells and 94 boreholes was collected from French public database. A statistical approach was conducted in order to differentiate aquifer compartments in relation with their hydrogeological context. First results show a contrasted physico-chemical signature between Jurassic and Upper Cretaceous aquifers, which is explained by the lithological properties, the aquifer depth and the residence time. Nevertheless, some locations present temperature and hydrochemical anomalies. Likely hypothesis are the karst influence due to localized recharge from fast river losses, as well as the karstification degree in unconfined and confined compartments.

Introduction

The edge zone of sedimentary basins is the site of interactions involving the recharge of multi-layer aquifers, affecting the quality of the water resource. At the regional scale, the karst feature of the reservoirs is rarely taken into account in hydrogeological processes. However, karst aquifers are characterized by complex recharge, exchanges and mixing between reservoirs, and interaction with surface water. Previous studies on Norther AB were conducted to understand the geological and hydrogeological functioning of different aquifers (Cabaret et al., 2017; Husson et al., 2016; Lorette, 2019; Platel et al., 2010; Von Stempel, 1972). Nevertheless, a major question remains about the karstic feature of the carbonate aquifers. This study aims to characterize the regional hydrodynamic and hydrochemical variability of multi-layer carbonate aquifers located in the basin edge by consider-ing their karst feature. The study site is the Northern Aquitaine Basin (AB) in Southwest France, characterized by two main Cretaceous and Jurassic reservoirs. First, we present a spatial analysis of the hydrodynamic variability of the two main reservoirs. Then, we investigate the geothermal gradient over the study zone. Finally, we explore the spatial hydrochemical variability of the compartments in link with geological and hydrogeological characteristics. This study focuses on the relationships between the secondary aquifers, Upper Cretaceous and Jurassic, and the role of the edge zone in the water quality. Thus, our objective with this method is to identify representative hydrogeological parameters of the main aquifers, and to identify the processes that best explain their variability.

Study area

The Aquitaine Basin (AB) is a regional multi-layer aquifer system located in Southwest France (

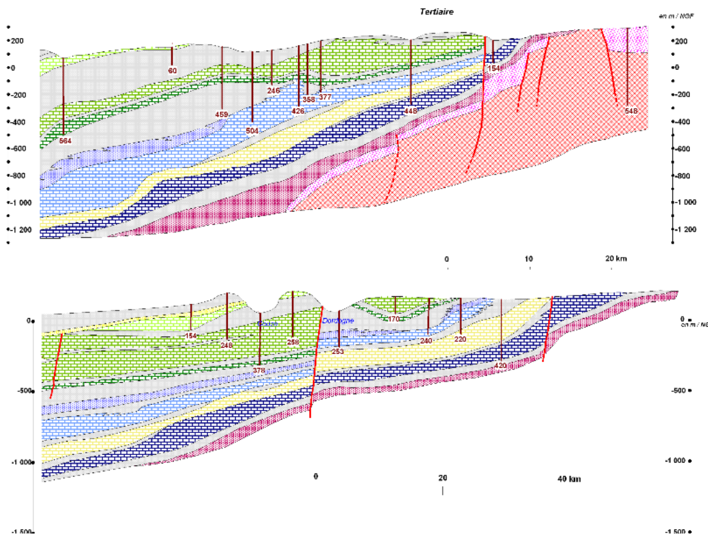
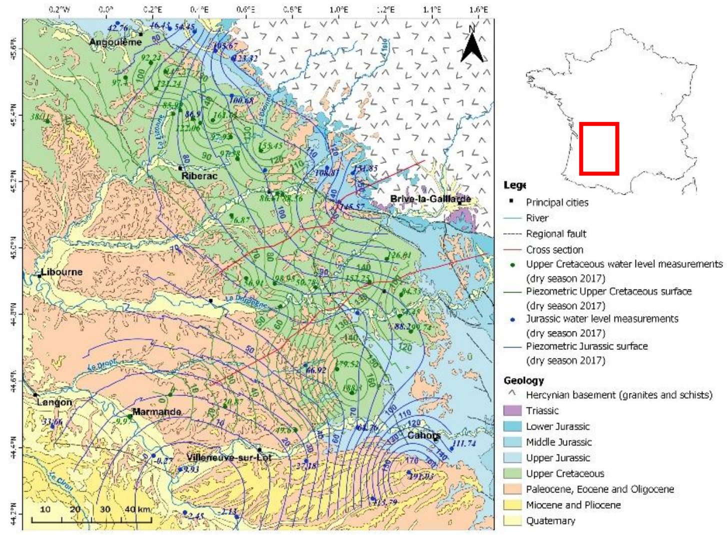


Fig. 1). In the Northern AB, sedimentary terrains from Trias to Upper Cretaceous overly a Hercynian granite and schist basement. Because of the variety of sedimentary deposits, the alternation of aquifers and aquitards create a complex multi-layer aquifer system composed of six majors reservoirs: Jurassic, Upper Creta-

ceous, Eocene, Oligocene, Miocene and Plio-Quaternary, which can themselves be subdivided (Platel et al., 2010).

The Jurassic and Upper Cretaceous (at the East of the Northern AB) outcrops show evidence of two vast marine transgressions during Mesozoic. These predominantly carbonate formations are karstified, both outcrop and undercover. (Platel, 1996). The Upper Cretaceous multi-layer system is mainly composed of fractured limestone and contains four aquifers (from the deeper to the shallower): Cenomanian, Turonian, Coniacian-Santonian and Campanian. The Cenomanian aquifer (50 m thick) is located only in the North of the Northern AB. The Turonian (30-60 m) is a fractured and karstified aquifer, which contains predominantly limestone. The Coniacian-Santonian aquifer geometry follow the one of Turonian, and is the thickest cretaceous aquifer (30-275 m). It results a complex system with lateral and vertical variations of facies, which develops a secondary porosity in granular limestone (fissures and karstic conduits) and in sandstone layers with interstitial porosity, separated by chalky and marls formations. In the Jurassic unit, it is possible to identify five reservoirs, in some places separated by marly or marl-limestone layers. The Lias aquifer (35-100 m thick) made up of sandstone and dolomitic limestone. The limestone and dolomite of the Bajocian aquifer (30-70 m thick). The limestone of the Bathonian - Callovian – Oxfordian aquifer (100-650 m thick), which represent the principal Jurassic aquifer in the region. The limestone of the Kimmeridgian aquifer (50-210 m thick). These three aquifers can be considered as a monotonous and homogeneous series formed of limestone with partial secondary dolomitization, highly karstified. However, some marly levels might be present and can delimit local aquitards. Finally, the dolomitic limestone of the Tithonian aquifer, which is located above the marly levels, representing a local aquifer.

(a)



(b)

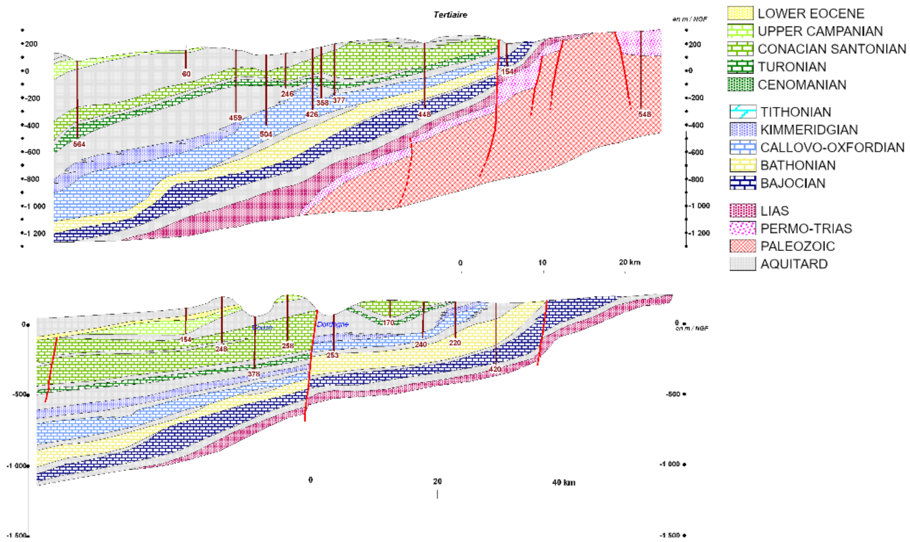


Fig. 1 : (a) Study area in the edge North Aquitaine Basin (southwest France) showing the piezometric map for both Upper Cretaceous and Jurassic aquifers (dry season 2017) and the (b) hydrogeological cross sections.

Materials and methods

Groundwater and hydrological dataset was compiled from several public databases. It comprises (1) hydrochemical data (major elements) and water levels from “ADES,” n.d.) and (2) geological and technical information from springs and wells (“La Banque du sous-sol (BSS) | InfoTerre,” n.d.)

Regarding water levels, 54 boreholes were selected: i) 29 in Upper Cretaceous aquifers (Turonian and/or Coniacian Santonian and/or Cenomanian), ii) and 25 in Jurassic aquifers (Bajocian and/or Bathonian Callovo Oxfordian and/or Kimmeridgian). Therefore, piezometric maps were established using standard krigging interpolation method for both aquifers during the dry and wet seasons of 2017.

Regarding hydrochemical data, 65 springs and shallow wells (maximum 7 m depth), and 94 boreholes (up to 1.2 km in depth, 330 m in average) were selected. To ensure that each borehole capture only one reservoir, the boreholes screened both in the Jurassic and Upper Cretaceous aquifers were not selected. Additionally, a minimum of 5 samples per site over the 2000-2019 period was required to integrate the analysis. An ionic balance was carried out to validate the samples, of which a value greater than 5% was not accepted. Physico-chemical parameters (temperature, pH, and electrical conductivity at 25°C), chemical analyses of major elements and nitrogen parameters were selected. In this study, the median value of the hydrochemical dataset is considered more representative than the mean, since it does not take into account the extreme or aberrant data that can bias the analysis.

To identify patterns in our large dataset, multivariate analyses were conducted using a Principal Component Analysis (PCA) on primary variable descriptors of all hydrochemical and physico-chemical data. Linear regression were also used to assess the correlation between variables. The geothermal gradient was calculated from 81 sites (boreholes) with a screen at least at 25 m deep and with flow logs and/or water strikes information. The screened interval must be less than 100 m. For the determination of the gradient, a simple linear regression was used. Additionally, PCA method was used to identify the main hydrochemical components

Results and discussion

Hydrogeological characteristics

The general pattern of the piezometric map (
Fig. 1) in Upper Cretaceous and Jurassic is similar in both the dry and wet seasons. In the Upper Cretaceous aqui-fers, the seasonal variations are up to 12 m in the unconfined area (outcrops) to a few centimetres in the confined area. The groundwater flow direction is globally from Northeast to Southwest. These maps highlight recharge zones on the Turonian and Coniacian Santonian outcrops but do not show evidence of groundwater recharge by river losses. Nevertheless, rivers such as Dordogne, Lizonne, Dronne and Isle appear to drain the cretaceous aquifer.

In the Jurassic aquifers, the average seasonal water level fluctuation is about 3.1 m, and can locally reaches 15 m. Two main flow direction are observed, the first is East-West in the area of Périgueux, and the second is NE-SW between Sarlat-la-Canéda and Cahors in the Causses du Quercy area. This dividing line seems accentuated by the piezometric depression in the Southeast of Sarlat-la-Canéda, which is probably due to the large amount of water abstracted by pumping in this area. Previous Jurassic piezometric surface (Bichot et al., 1997) from the 95-96 years, shows the same piezometric depression but 10 meters less deeper and with a main East-West flow direction. Which shows the vulnerability of the Jurassic confined aquifers in Villeneuve-sur-Lot.

From the piezometric point of view, it has been shown that stable levels and cyclic seasonal variations, mainly due to aquifer recharge (Platel et al., 2010), characterize the Upper Cretaceous and Jurassic aquifers. Nevertheless, a diminution of the Jurassic groundwater table from the years 95-96 has been shown, especially at the confined areas.

Geothermal gradient

Groundwater temperatures from the 81 selected boreholes vary from 13.5 to 40°C, of which a global regional geothermal gradient of 2.060 °C/100 m (r^2=0.59) was computed (Fig. 2). This model significantly differs from the theoretical geothermal gradient (3°C/100 m). This difference is due to cold-water anomalies at important depths, which can be explained by mixing processes with colder superficial waters transported by karstic features. The calculation of the geothermal gradient accounting for the two main Upper Cretaceous and Jurassic reservoirs does not improve so much the model in both cases (r² of 0.65 and 0.61, respectively). A slightly more efficient model is observed for the Upper Cretaceous aquifers. This could be link to a weaker degree of karstification and an important geological compartmentation of these aquifers, contrarily to the Jurassic aquifers that are strongly karstified.

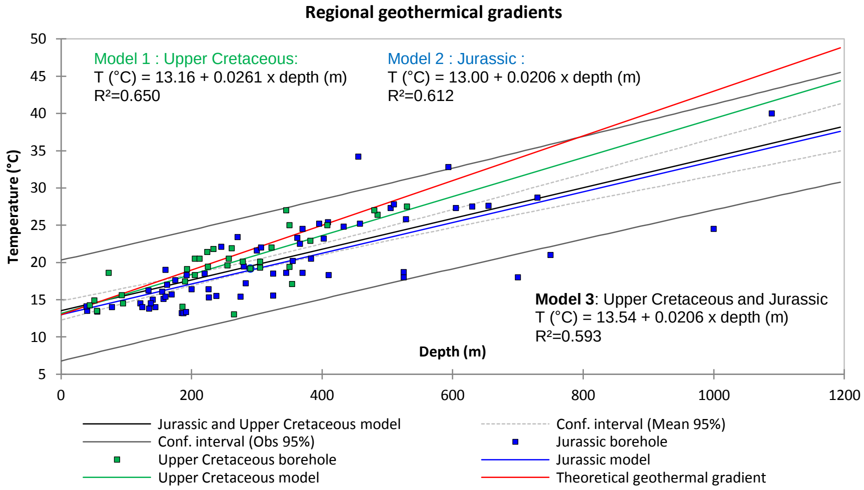


Fig. 2: Regional geothermal gradient models for models. Only the confidence intervals for the model 3 is presented.

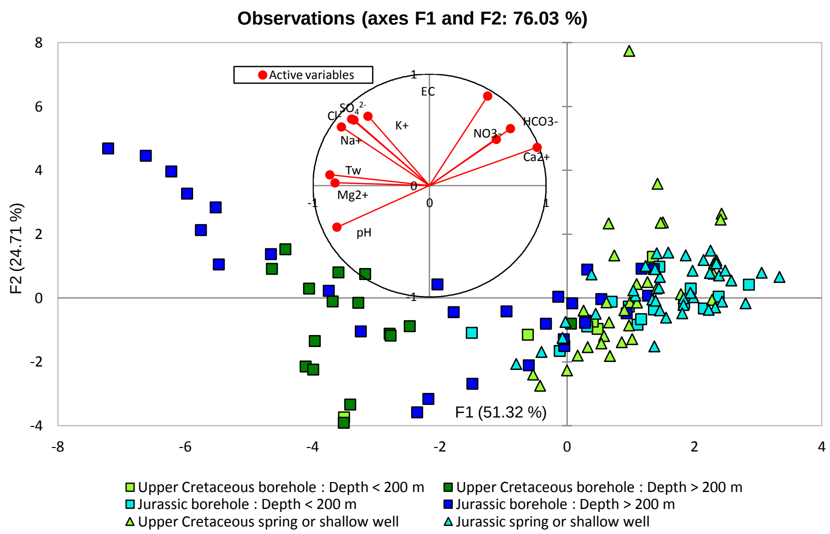
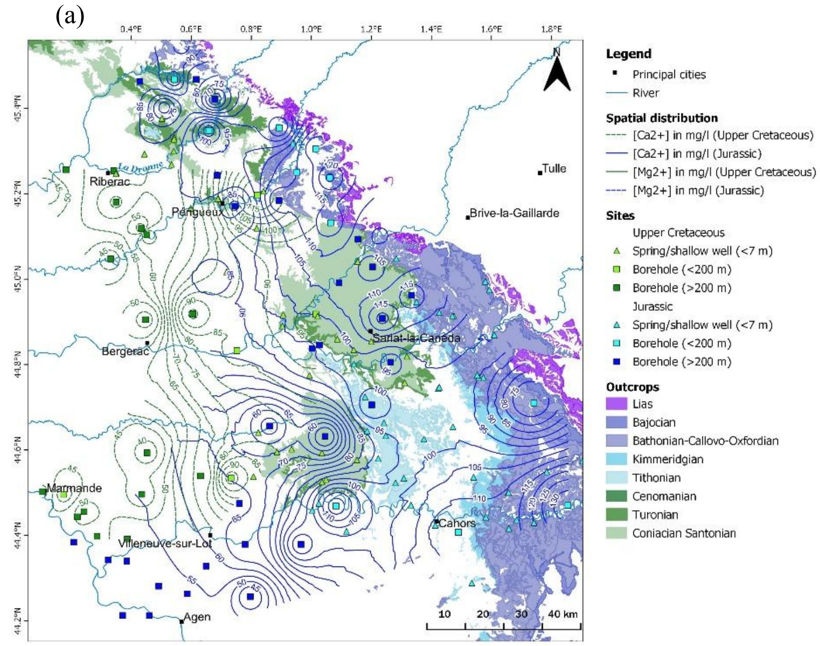


Fig. 3: Plot based on principal components analysis of hydrochemical sampling from springs and boreholes.

(a)



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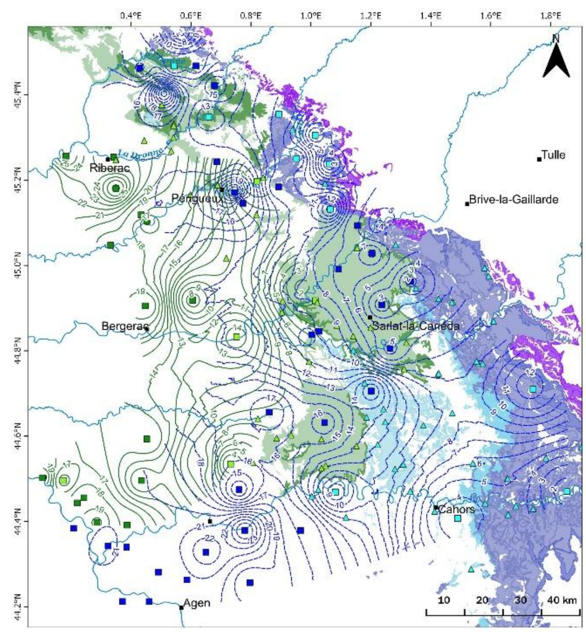

Fig. 4: Spatial variability of Ca (a) and Mg (b) concentrations in both Upper Cretaceous and Jurassic aquifers.

Hydrochemical variability

The results of PCA on hydrochemical data are shown in the

Fig. 3. The two first axes explain 76 % of the total variance, where two majors poles are differentiated.

Regarding variables, Mg^{2+} is well correlated with water temperature (Tw) and is negatively correlated with Ca^{2+}, HCO_3^-, and NO_3^-. These two groups of variables outline the first axis on Factor 1 of water transit time, increasing from NO_3^- (surface pollution) towards Mg^{2+}, which are indicators of fast infiltration and high mineralization (and of dolomite dissolution), respectively. A third group shows that Na^+, Cl^-, K^+ and SO_4^{2-} are well correlated and have a nearly independent pattern compared to tracers determining Factor 1. Na^+ and SO_4^{2-} enrichment in Jurassic waters can be explained by vertical leakage from the Lias aquifer because of its evaporitic component (presence of anhydrite). However, an evaporitic and dolomitic signature can be also seen on the confined Upper Cretaceous waters, even if dolomite and anhydrite are not present in its lithology. Following the natural course of Na^+ and K^+ is difficult because of possible addition from anthropogenic activities .

Regarding observations, a first group is formed mainly by boreholes deeper than 200 meters with a few exceptions. This group represents boreholes with elevated values of temperature, and ions such as Mg^{2+} (7-26 mg/L), Na^+ (5-72 mg/L), SO_4^{2-} (5-64 mg/L), Cl^- (9-24 mg/L), that might indicate a higher mineralization (LeGal LaSalle et al., 1996). The mineralization is observed in the deep confined area of Upper Cretaceous and Jurassic aquifers, towards Villeneuve-sur-Lot, which may suggest an enrichment because of the residence time and a vertical drainage up to the upper Cretaceous layers. On the other hand, a second group is formed by springs, shallow wells and boreholes of shallow depth (<200 m). This group is dominated by high values of calcium (60-140 mg/L) and bicarbonates (220-420 mg/L), which characterize the water-rock interaction in an open carbonate system (Edmunds et al., 1987; Hanshaw and Back, 1979). Moreover, higher concentration of nitrates is found in this group (mean value of 12mg/L and a maximum of 44 mg/L), due to its sensitivity to agricultural practices. However, some deep boreholes are within this group indicating a mixing zone in which the karstic features may play a major role.

The spatial variability of the main major ions (Ca^{2+} and Mg^{2+}) is presented in Fig. 4. High concentrations of Ca^{2+} (around 120 mg/L) are seen in both Upper Cretaceous and Jurassic outcrops, explained by the immediate dissolution of the calcite in an open carbonate system. Rainwater infiltrating the soil overlying the carbonate outcrops quickly becomes saturated with respect to calcite. However, there is a Ca^{2+} decrease from East to West and Southwest, which is consistent with the progressive confinement of Upper Cretaceous and Jurassic formations. A similar phenomenon is shown at the chalk aquifer (Edmunds et al., 1987), where it is likely the a Mg and Ca exchange takes place during progressive recrystallization of microcrystalline calcite or by incongruent dissolution of the carbonate.

On the contrary, there is an Mg^{2+} increase from East to West and Southwest, in both Upper cretaceous and Jurassic aquifers. This pattern is likely explained by the dolomite facies that are only present in Jurassic layers. Additionally, little impurities of magnesium and high residence time in the Cretaceous reservoirs can be the source of the increased concentrations.

Conclusions and perspectives

The aim of this study was to characterize the hydrogeological processes of a karst-influenced multi-layered aquifers of basin edge. From a regional analysis in the Aquitaine Basin (AB) of hydrogeological and hydrochemical data, we showed the role of the edge zone into the recharge of multi-layered aquifers. The Upper Cretaceous and Jurassic aquifers are widely heterogenous. The hydrogeochemistry varies according the lithology facies, the residence time, the depth, and very likely because of the karstic feature. Our results show evidences of mixing zones between the two main Cretaceous and Jurassic reservoirs. This is probably due to the karstic and fractured natures of the carbonate formations that allow a fast infiltration through vertical drainage of water from the surface towards the deep parts of the aquifers. Thus, the groundwater that constitutes the global resource of the AB show a certain vulnerability due to the karstification of the main geological formations. Physical and chemical characteristics of the groundwater data show important variations according to increasing depth, to the progressive confinement from NE-SW and to the geological variations of facies.

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