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Infiltration processes in karstic chalk investigated through a spatial analysis of the geochemical properties of the groundwater: The effect of the superficial layer of clay-with-flints

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SUMMARY

In the Paris Basin in Upper Normandy (France), the chalk plateaus are covered with thick deposits of loess and clay-with-flints, from a few meters to approximately 40 m thick locally. A perched groundwater is sometimes observed in the superficial layers in which evapotranspiration processes seem to occur.

This study's objective was to understand the effects of the thick clay-with-flints layers on the infiltration processes. To achieve this, we adopted a spatial approach comparing the maps of the geochemical properties of the Chalk groundwater and the maps of the thickness of clay-with-flints.

The French national groundwater database, ADES (Accès aux Données des Eaux, BRGM), provided the mean geochemical properties in the Chalk aquifer of Upper Normandy. This database was used to prepare maps of the environmental tracers: Ca^{2+}, HCO_3^-, Mg^{2+}, Cl^-, Na^+, NO_3^-, and SO_4^2. The data are spatially well organized.

Using principal component analysis (PCA), these maps were compared with the maps of the thickness of clay-with-flints. A focus on the coastal basins (northern Upper Normandy) shows a very strong spatial correlation between the maps of clay-with-flints thickness and all of the maps of the major ions. The thickness of clay-with-flints is negatively correlated with the autochthonous ions (HCO_3^- and Ca^{2+}) and is positively correlated with the allochthonous ions (Cl^-, Na^+, SO_4^{2-}, and NO_3^-).

These results highlight that the thickness of clay-with-flints controls recharge. Two types of infiltration processes are proposed: (1) Thicker clay-with-flints allows storage in the perched groundwater, which allows evapotranspiration, resulting in high concentrations of allochthonous ions and a decrease in the dissolution potential of water and low concentrations of autochthonous ions. The infiltration of the perched groundwater is thus delayed and concentrated. (2) Thinner clay-with-flints causes the infiltration to be more diffuse, with low evapotranspiration and thus low concentrations of allochthonous ions in the Chalk groundwater; more, there is more dissolution and higher concentrations of autochthonous ions in the Chalk groundwater.

1. Introduction

The Cretaceous Chalk aquifer is the primary groundwater resource in Upper Normandy (France) and has been demonstrated to have karst characteristics (Calba, 1980; Rodet, 1992).

The quality of this Chalk groundwater is generally good; however, its geochemical properties vary spatially and temporally. These temporal variations may be related to climatic impacts, such as rain events, which often result in contamination problems, generally associated with an increase in turbidity in wells and springs (Dussart-Baptista et al., 2003; Mahler et al., 2008; Massei et al., 2003; Valdes et al., 2005, 2006). Chalk aquifer groundwater facies are primarily composed of Ca–HCO_3, but the ions vary spatially throughout the Upper Normandy region. The spatial heterogeneity

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of the groundwater geochemistry is generally related to the heterogeneity of external factors, such as atmospheric inputs (Meybeck, 1983), land use, and domestic sewage (Negrel and Petelet-Giraud, 2005; Sherwood, 1989).

Valdes et al. (2007) have already presented a spatial study of the geochemical properties of the Chalk groundwater in the Paris Basin at a regional scale. They focused on the Eure department in southern Upper Normandy. In this area, the Chalk aquifer is drained by the Seine River, then oriented from south to north perpendicular to the structural settings (anticlines, faults). They showed that, in spite of its karst properties, the large-scale geochemical properties of the Chalk groundwater are strongly spatially organized. Actually, they observed a continuity of the geochemical properties in the Chalk groundwater. To better understand this spatial distribution, they compared these geochemical data to the physical properties of the aquifer, in particular aquifer thickness (representing aquifer geometry) and piezometric level (representing aquifer flow). They observed that (1) the degree of mineralization (principally composed of Ca^{2+} and HCO_3^- ions) increased along the flow direction, corresponding to an increase in the chalk dissolution rate along the flow path, and (2) the steepest mineralization gradients were related to an increase in the Mg/Ca ratio, evidence of longer residence times and corresponding to zones where aquifer flow capacity is limited because of a decrease in the thickness of the flow section (anticlines or faults). These results highlighted the dominant role played by the geometry and structural context in controlling Chalk groundwater geochemistry.

These chalk plateaus are covered with thick deposits of loess and clay-with-flints, from a few meters to approximately 40 m thick locally (Laignel et al., 2002). The flow behaviors of karst aquifers (quality and quantity) are characterized by recharge (diffuse/concentrated), storage (vadose/phreatic), and flow (diffuse/concentrated) (Ford and Williams, 1989; Smart and Friederich, 1986; White, 1988). Many studies have investigated the infiltration and the flow in the unsaturated chalk zone (Brouyère, 2006; Ireson and Butler, 2011; Ireson et al., 2009; Price et al., 2000; Van den Daele et al., 2007), and the infiltration through clay-with-flints is not well understood: in the past, the clay-with-flints layer was considered a homogeneous and relatively impermeable layer. Later, these ideas changed, however. More recently, Klinck et al. (1998) presented heterogeneous measurements of hydraulic conductivity of the clay-with-flints in the UK: 1) in the laboratory the values vary from 10^{-8} m s^{-1} to 10^{-5} m s^{-1} depending on the site measured and the depth; (2) in situ (trial pit infiltration capacity) the values vary from 4×10^{-5} m s^{-1} to 4×10^{-9} m s^{-1}. The effect of the thickness of this layer remains unknown. It can be assumed that infiltration processes differ between zones with a thick layer of clay-with-flints and zones where the chalk almost outcrops. Does this layer concentrate the infiltrated water? Does it protect the aquifer? Can a thick layer be considered an impervious layer?

The objective of this study was to understand the effect of the thickness of the clay-with-flints layers on the infiltration processes. To achieve this, we adopted a spatial approach, which consists of comparing the maps of the geochemical properties of the Chalk aquifer and the maps of the thickness of clay-with-flints using principal component analysis (PCA). We then propose an interpretation of the role played by clay-with-flints in the infiltration processes in the Chalk aquifer.

1.1. Study area

This study focuses on the Chalk aquifer of the Western Paris Basin within the Upper Normandy Region in France (Fig. 1a). There is little urbanization in the area, and land use is primarily agricultural. The climate is temperate and maritime, with average temperatures of 10–12 °C and average annual rainfall varying spatially from 600 to 1000 mm. From a geomorphological point of view, the regional topography is characterized by large plateaus of moderate elevations: <300 m above sea level (asl), deeply incised by narrow valleys draining the Chalk aquifer.

1.1.1. Geological settings

The chalk plateaus are composed of Cretaceous Chalk formations (from Cenomanian to Campanian), with the exception of a zone north of the Seine, which is Jurassic, and a zone in the southern part of the study area, where the Cenomanian has a sand facies (“Perche Sands”) (Fig. 1a). The chalk formations are covered with Cenozoic clay-with-flints, Quaternary loess (Lautridou, 1985) and Tertiary deposits (Fig. 1a and b). The clay-with-flints layer resulted from the weathering of the chalk during different periods of the Cenozoic (Laignel et al., 1998a) and is from 0 to 40 m thick (Fig. 1a). The thickest clay-with-flints is located in the southern and western portions of the study area. The Quaternary loess deposits are eolian in origin and range from 0 to 5 m thick. The Tertiary deposits occur as infill on weathered surfaces (pockets) in some places and provide continuous cover in other places (in the eastern portion of the study area, near the Seine River, Fig. 1a); they are composed of clayey sands and clays with up to 90% smectite content, with the smectite often containing Mg^{2+} and SO_4^{2-} (Laignel, 2003).

1.1.2. Hydrological and hydrogeological settings

Although the clay-with-flints formation is relatively impermeable, the saturated zone in the Chalk aquifer is lower than the base of this overlying formation. The Chalk aquifer is considered to be an unconfined aquifer. The thickness of the saturated aquifer varies from a few meters to more than 300 m (Valdes et al., 2007). The aquifer is karstified to some degree (Massei et al., 2003; Rodet, 1999; Valdes et al., 2006), and the groundwater flow velocities are extremely heterogeneous because fissures and conduits provide underground drainage routes for the highly localized transport of water at velocities from 50 to 300 m/h (Calba et al., 1979). During rain events, concentrated infiltration of surface water may result in a rapid increase in turbidity at springs and wells connected to the surface via karst systems.

The major drainage axis is the Seine River; the hydrologic network is typical of a karst zone, with primarily low-order streams (Hauchard et al., 2002) because most of the flow is subsurface. The Chalk aquifer can be divided into three parts (Fig. 1a): (1) the SEA basins: the coastal basins where the direction of flow is toward the sea (La Manche); (2) the SEINE RIGHT basins, which drain into the right bank of the Seine River; and (3) the SEINE LEFT basins, which drain into the left bank of the Seine River.

Perched groundwater is sometimes observed at some sites, particularly in the clay-with-flints layer a few meters above the soil surface (Jardani et al., 2006).

2. Data and methods

2.1. Data

The French national groundwater database, ADES (Accès aux Données des Eaux Souterraines, BRGM), provided the mean turbidity and the mean geochemical properties for approximately 300 springs and wells in the Upper Normandy Chalk aquifer (Fig. 2a). The geochemical part of the study focuses on the environmental tracers: Ca^{2+}, HCO_3^-, Mg^{2+}, Cl^-, Na^+, NO_3^-, and SO_4^2 (Table 1). Sampling was conducted from 1995 to 2005. For each sampling site, the number of measurements ranged from 2 to 23, with a mean of five measurements per site (the distribution is presented in Fig. 3a). Those few samples with an charge balance error greater than 10% were removed. For each site, the mean concentration