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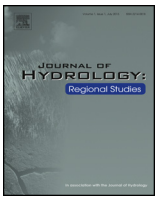

Scenarios of groundwater chemical evolution in a region of the Canadian Shield based on multivariate statistical analysis

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ABSTRACT

Study region: The study of groundwater chemistry of the Charlevoix/Haute-Côte-Nord (CHCN) region in the province of Quebec in Canada is part of a regional hydrogeological characterization project.
Study focus: Groundwater was sampled in 113 wells over the 4500 km^2 study area and analyzed for 39 parameters including major, minor, trace and inorganic constituents, plus stable isotopes 2H and 18O. Two multivariate statistical methods, hierarchical cluster analysis (HCA) and R-mode factor analysis (RFA) were combined with graphic methods to classify the samples according to plausible levels of groundwater evolution in that region.
New hydrological insights for the region: Four sample clusters were identified. Cluster 1 is composed of low-salinity Ca-HCO_3 groundwater corresponding to recently infiltrated water in surface granular aquifers in recharge areas. Cluster 4 Na-(HCO_3-Cl) groundwater is more saline and corresponds to more evolved groundwater probably from confined bedrock aquifers. Cluster 2 and Cluster 3 (Ca-Na)-HCO_3 and Ca-HCO_3 groundwater, respectively, correspond to mixed or intermediate water between Cluster 1 and Cluster 4 from possibly interconnected granular and bedrock aquifers. This study identifies groundwater recharge, water–rock interactions, ion exchange, solute diffusion from marine clay aquitards, saltwater intrusion and also hydraulic connections between the Canadian Shield and the granular deposits, as the main processes affecting the hydrogeochemical evolution of groundwater in the CHCN region.

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1. Introduction

The chemistry of groundwater in the Canadian Shield and its evolution with depth or with distance along a flowpath have been investigated by numerous authors, namely Gascoyne and Kamineni (1994). Recent and shallow groundwater chemistry is controlled by the composition of the local rock, where dissolution reactions dominate, while its isotopic composition reflects the precipitation. In contrast, the chemistry of deeper groundwater is the result of extensive, long-term interactions with the bedrock (Frape et al., 1984). A number of studies (e.g. Melloul and Collin, 1992; Güler and Thyne, 2004; Silva-Filho et al., 2009) have shown that the hydrogeological context, combined with hydrogeochemical and isotopic characterization of an aquifer can help to identify different types of groundwater ($Ca\text{-}HCO_3$, $Na\text{-}HCO_3$ and Na-Cl types) as well as the main factors that influence the chemical composition of groundwater. Other studies (Cloutier et al., 2008; Beaudry, 2013; Montcoudiol et al., 2014) have demonstrated a significant correlation between the hydrogeological context and the groundwater chemistry in regions of the Canadian Shield. Characterizing the hydrogeological context in parallel with the hydrogeochemical and isotopic study of groundwater allows a better characterization of groundwater flow and of the evolution of its chemical composition.

Güler et al. (2002) showed that the combination of graphical and multivariate statistical techniques provides a consistent and objective means of classifying large numbers of samples while still preserving the ease of classic graphical representations. Cloutier et al. (2008), Yidana (2010) and Montcoudiol et al. (2014) used multivariate statistical analysis to supplement graphical representations such as Schoeller, Stiff, Durov and Piper diagrams. Using a statistical approach, they successfully identified major groundwater groups and factors affecting the groundwater chemistry in an aquifer.

The main objective of this research is to characterize groundwater chemistry and to identify the relationships between the hydrogeological context and groundwater chemistry in the Charlevoix/Haute-Côte-Nord (CHCN) region by using a combination of multivariate statistical analysis, graphical representations and maps. "Hierarchical cluster analysis" (HCA) and "R-mode factor analysis" (RFA) are combined with graphical analysis using Durov and Stiff diagrams to develop a better understanding of the groundwater chemistry and its evolution in the CHCN aquifer system located in the Canadian Shield.

2. Study area

In 2008, the Government of Quebec implemented the Programme d'acquisition de connaissances sur les eaux souterraines (PACES; Groundwater Knowledge Acquisition Programme) under the MDDEFP (Ministère du Développement Durable, de l'Environnement, de la Forêt et des Parcs), in order to improve knowledge of this resource (Government of Quebec, 2015a,b). This programme consists of a number of regional hydrogeological characterization projects aiming to acquire knowledge on groundwater resources in the southern, more densely inhabited parts of the Province of Quebec, with the objectives of protecting groundwater and ensuring the sustainability of its supply (Chesnaux et al., 2011).

A regional hydrogeological characterization project, conducted by the *Centre d'études sur les ressources minérales* (CERM) at *Université du Québec à Chicoutimi* (UQAC), started in 2012 in the CHCN region as part of the PACES programme. Even though ongoing industrial and agricultural development presents a risk for groundwater contamination in this region, no regional hydrogeological characterization project had yet been carried out. This situation calls for a proper characterization of the natural geochemical properties of groundwater and a better understanding of the natural geochemical processes that affect the groundwater chemistry during its evolution in the aquifer systems.

The CHCN region is located on the north shore of the Saint-Lawrence River to the northeast of Quebec city (Fig. 1). The study region forms an NE elongated stretch of land extending over 236 km, approximately 20 km wide, for a total area of 4500 km^2. The climate of the region is characterized by long and cold winters, followed by short, warm and humid summers. Precipitation is well distributed throughout the year, mostly in snow from November to April, and totalling around 900 mm per year (Government of Quebec, 2015a,b). The vegetation is mainly composed of deciduous and mixed tree stands. Most of the territory is forested; parts of it are exploited by the forestry industry.