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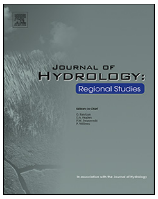

# Development of a conceptual groundwater flow model using a combined hydrogeological, hydrochemical and isotopic approach: A case study from southern Benin

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ABSTRACT

*Study region:* The Turonian-Coniacian aquifer system in the North of the Coastal Sedimentary Basin, southern Benin, West Africa.

*Study focus:* The Turonian-Coniacian aquifer is the major aquifer in southern Benin and is the main source of water supply for the population. The pressure on groundwater resources from the Turonian-Coniacian aquifer is increasing since few artesian wells tapping into this aquifer already show decrease in their yields. Preventing extinction of the artesian outflows requires as a first step a thorough understanding of the groundwater flow system: groundwater recharge areas, downstream areas, and flow directions. In this study, a combined hydrogeological, hydrochemical and isotopic approach was applied to understand the groundwater flow within this aquifer and to develop a coherent conceptual groundwater flow model.

*New hydrological insights for the region:* The piezometric results indicated three main groundwater flow directions. Stable isotopes results confirmed the piezometry as the most depleted and enriched values in Oxygen-18 and deuterium were found respectively in downstream areas (southern region) and in the recharge areas (northern region) indicated by the piezometry. Similarly, higher tritium contents (up to 3.5 Tritium Unit) characterize recharge areas and low tritium contents ( $<$ 0.12 Tritium Unit) were found in downstream areas. The combination of these results with the geologic and topographic data led to a coherent conceptual groundwater flow model shown in this paper.

## 1. Introduction

Groundwater is one of the world's most important natural resources. In several parts of the world, it happens that this vital resource is threatened both quantitatively and qualitatively. The example of the Great Artesian Basin which underlies ~23% of the Australia continent (Powel at al., 2015), where several springs have dried out and several artesian wells have stopped flowing, is an illustration of severe threats that occur to groundwater resources. Several other authors (e.g. Idris, 1996; Powell and Fensham, 2015; Roberts and Mitchell, 1987) have reported similar threats on groundwater resources in different parts of the world.

In Benin, especially in the coastal sedimentary basin, groundwater is the major source of freshwater for the population. The major

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aquifer in this basin (the Turonian-Coniacian aquifer) is artesian in some parts of the basin where artesian wells keep discharging continuously enormous quantity of groundwater to the surface (the artesian wells are free-flowing because they are not pipped and capped, however tapping and capping artesian wells help greatly to reduce water loss and hence aquifer drawdown). It is known from the literature (e.g. Powell and Fensham, 2015) that in some systems, artesian outflows turned out to considerably diminished. Some natural springs have totally dried out and numerous artesian wells have stopped flowing (Powell et al., 2015; Idris, 1996; Powell and Fensham, 2015; Roberts and Mitchell, 1987; Yermani et al., 2003).

Currently in Benin, part of the local population finds the free-artesian outflows beneficial because efforts to manually pump groundwater is not required. However, the other part of the population already express concerns about the sustainability of this groundwater resource (personal communication with the local population) and some artesian wells already show decrease in their yields. So far, no study has investigated the sustainability of this vital resource and therefore groundwater recharge, abstractions rates and free artesian outflow rates required for a sustainable use of this resource, remain completely unclear. To prevent extinction or stoppage of free artesian outflows and drying out of natural springs, it is wise to investigate and identify conditions (recharge and abstractions) that may cause extinction of free artesian outflows and drying out of natural springs. Once the recharge, abstraction rates and free outflow conditions are known, preventive actions could be taken in a short and long term.

Arriving at identifying the conditions that may cause artesian wells outflows to stop and springs to dry out requires as a first step a thorough understanding of the groundwater flow system (groundwater recharge areas, groundwater discharge areas, and flow directions). However, the main problem is that the groundwater head data which is required for the understanding of the groundwater flow and the development of conceptual groundwater flow models (Bredehoeft, 2005; Zheng and Bennett, 1995; Kresic and Mikszewski, 2013) is often quite limited in many hydrological systems (Barthel, 2014; Candela et al., 2013; Carter et al., 1994; Refstegaard et al., 2010). Data related to groundwater systems are limited or absent, as in ungauged basins, due to their inaccessibility and large costs and huge time involved in long-term experimental characterization and monitoring.

In some hydrological systems, boreholes that could allow the measurements of groundwater levels (GWL) do exist, but they were not designed to allow such measurements even though boreholes for drinking supply could well be designed to allow both groundwater extraction and measurements of GWL (Aranyossy, 2007). Only one GWL data, that was recorded during drilling operations is available for those boreholes, and data recorded during drilling operation may not be reliable. For those boreholes that do not allow GWL measurement, the groundwater mineralization as measured through the TDS (Total Dissolved Solids) could still be obtained as long as groundwater abstraction remain possible from those boreholes. But, this raises the following question: “Can the TDS reliably inform about groundwater flow directions and lead to the development of reliable conceptual groundwater flow models?” Groundwater mineralization has been largely investigated (e.g. Verhagen, 1995; Moussa et al., 2009; Fadili et al., 2015; Dieng et al., 2017; Gning et al., 2017) but its validity in helping develop coherent conceptual groundwater flow models is unclear.

To some extents, stable isotopes (Boronina et al., 2005; Dhaoui et al., 2016) and radioactive isotopes (Izbicki et al., 1995; Szabo et al., 1996), though costly, are proved to provide relevant information on groundwater ages, directions of groundwater flow, aquifer recharge and discharge zones. Hence, isotopes, piezometric and also geologic data are often used to construct conceptual groundwater flow models (Dassi and Tarki, 2014; Pétré et al., 2016; Fernandes et al., 2016; Brikic et al., 2016; Bicalho et al., 2017; Madrala et al., 2017; Segadelli et al., 2017).

Based on the knowledge that hydrochemical patterns are influenced by groundwater flow (Stuyfzand, 1999; Hussein, 2004; Novel et al., 2007) and that high and low mineralization of groundwater are usually correlated to long and short resident time respectively (Wilson et al., 1991; Huneau et al., 2007), we focus on accessing the reliability of the TDS in the development of conceptual groundwater flow models.

So, the main aim of this study is to develop a coherent conceptual groundwater flow model for the research area. We use this case study to access whether the groundwater mineralization as measured through the TDS is a relevant element to consider when it comes to developing conceptual flow models in scarce groundwater head data environments, where TDS data could still be obtained. In that sense, we firstly focus on both piezometric and isotopes data to develop a coherent conceptual groundwater flow model using as case study, the Turonian-Coniacian aquifer system in southern Benin. Then, we use data of Tritium and $^{14}$Cfrom the same case study to test the reliability of groundwater mineralization with respect to conceptual flow models development.

## 2. Study area

### 2.1. Location, climate and vegetation

The study area (Fig. 1) is geographically located between latitudes 6°45 N and 7°40′N and longitudes 1°55′E and 2°50′E and covers approximately 4600 km$^2$. It is a part of the northern coastal sedimentary basin of Benin republic (Boukari, 2007; Alassane et al., 2015) and is composed mainly of 3 plateaus (from West to East: Abomey, Zagnanado and Kétou plateaus that are separated respectively by Zou river and Ouémé stream), the Ouémé valley and an East-West belt known regionally as Lama depression (Affaton et al., 1985; Amajor, 1991). The study area is bordered in the North by the crystalline bedrock, in the South by Allada and Sakete plateaus, in the West by Couffo stream and its Eastern border corresponds to the limit between Benin and Nigeria republics (Fig. 1). It is worthwhile noting that the Kétou plateau extends to the south-western Nigeria (Abeokuta township) where similar geological formations as found in Benin are encountered (Affaton et al., 1985). The topography in the study area varies from -1 to about 270 m a.s.l. High altitude values are observed in the Northern plateaus. Low altitude values are found in the Ouémé valley and in the *Lama* depression.

The study area belongs to the sub-equatorial region with a bimodal rainfall distribution (Fig. 2a). It is characterized by two rainy