Groundwater Assessment of the Bléone Catchment Karst Aquifer in Southern France

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Abstract. Karst aquifer is an important water resource in southern France. It is the main source for agriculture and for domestic water supply. Hence, it is necessary to assess the quantity and quality of water in the Bléone Catchment. In order to achieve this aim, a groundwater chemistry analysis and regional numerical groundwater flow modelling using MODFLOW were conducted. Groundwater samples from springs and wells analyzed for water quality in the Bléone Catchment demonstrate different water types dominated mostly by fresh water, which is of moderate alkalinity and contains calcium and magnesium as major cations and bicarbonate as a common anion. The saturation indices for calcite and dolomite reveal that dissolution of calcite and dolomite can still take place. In addition, there is a very complex interaction between surface water and groundwater in the catchment.

1. Introduction
Fractured aquifers are recognized as one of the most difficult aquifers to characterize and model. The term fracture generally refers to cracks, fissures, joints and faults over different scales and lithology generated largely by tectonic activities [1]. Depending on the geometric and physical properties of fractures, fractures may serve as pathways or barriers to groundwater movement. Therefore, the connectivity of fractures is a key factor determining flow and transport in the subsurface [2,3]. Fracture connectivity measures the degree of interconnection of fractures and fracture networks. It thus controls the magnitude and distribution of hydraulic conductivity in the network and the larger aquifer system as a whole. In addition, porosity variations in fractures and matrix can result from water-rock interactions as the interactions cause the dissolution of primary minerals and subsequent precipitation of secondary mineral phases like clays and iron oxides and hydroxides. Dissolution and precipitation processes can cause blockage of groundwater flow system or lead to the creation of high permeability preferential flow pathways [4,5].

The principal problem to overcome when dealing with fractured aquifers is data limitation. However, major fracture zones can generally be defined with enough detail and accuracy on maps and cross sections to justify their treatment as deterministic discrete entities in flow and transport models [6]. Effective characterization of fracture bedrock aquifers must therefore rely on the integration of different kinds of data at different scales of study in order to determine the relation between aquifer properties and scale of research through the evaluation of measurements across the spatial scale of interest. Also, integrating
different sets of data at different scale will aid to relate the geophysical and hydraulic properties of the aquifer by correlating geophysical and hydraulic data at borehole locations through empirical or model based relationships [7]. However, measuring and quantifying the fluid flow and solute transport in fracture/karst aquifer is one of the most challenging tasks in groundwater investigation.

The flow in a fractured aquifer is highly heterogeneous over a range of scales and several uncertainties arise from the flow heterogeneity. This has significant implications on the water resource management, from borehole to catchment scale. In addition, a proper understanding of flow heterogeneity in the aquifer is of great importance for groundwater source protection and for our ability to predict the movement and fate of contaminants in Karst aquifer. This paper focuses on the state of water quality and builds the regional numerical groundwater flow modelling under steady-state conditions of Bléone Catchment aquifer in Southern France, where the assessment of the groundwater chemistry is important in order to provide information about the quality of the water for the potential users (agriculture and public water supply).

2. Study Area

The Bléone Catchment (905 km square) constitutes part of the Alpine Catchment in southern France. The study area extending between latitudes 44° 00´ – 44° 20´ north and longitudes 06° 00´ – 06° 40´ east. River Durance is the major river in the catchment consisting of several tributaries such as River Asse and River Bléone [[8]]. This Catchment is composed of Tertiary to Quaternary sedimentary rocks such as limestone, shale, marl, conglomerate and sandstone and alluvium deposit (Figure 1). The watershed aquifer which is largely the Jurassic limestone consist of karst features (springs and caves) which occasionally lead to flood events in the area due to rapid interaction of surface water and groundwater [[9]]. Other exploitable aquifers in the region are the alluvium and conglomerate aquifers. Yearly precipitation in the region from Jan. 1971 to Dec. 2005 was 724 mm and the evapotranspiration was 540 mm.

The Bléone River and its tributaries cut several geologic formations with different time ages. The Mesozoic rocks are represented in the area by a sequence of rocks from the Triassic, Jurassic, Cretaceous ages consisting mainly of limestones, mudstones and shales which are intensively folded. The Cenozoic rocks from the Tertiary period consist mainly of limestone alternated with marls, fluvial conglomerates, molasses and brecias. The Quaternary age formations are represented by alluviums, colluviums and fluvial glacial debris (Figure 2). A calcareous sequence (limestone and shale), which corresponds to the Jurassic and the Cretaceous mainly, constitutes the most important aquifers of the Bléone catchment. This sequence is located at the central and eastern part of the Bléone catchment, in the denominated subalpine field.

The Bléone karst system is binary in nature receiving recharge both from precipitation and river originating from non-karst catchment (Figure 2). Thus surface runoff is captured partly or entirely upstream in to the riverbed which subsequently travel through conduits in the karst aquifer and end up as discharges downstream through springs and caves. More than 15 temporary karst springs have been recorded along the riverbed downstream allowing for direct and fast exchange between surface and groundwater. High water conditions in the region have often leads to flood events in view of the fact that groundwater contributes to surface water along the river bed [9].

3. Groundwater chemistry and dissolution processes

Groundwater samples from springs and wells analysed for water quality in the Bléone Catchment demonstrate different water types dominated mostly by fresh water which is of moderate alkalinity and contains calcium and magnesium as major cations and bicarbonate as anion (Figure 3). The PHREEQC and ChemDiagnostics was also used to analyse the data. The mix water in the south eastern part of the
region is of very low alkalinity and the water composition (Ca, HCO$_3$ and NO$_3$) is an indication of contamination of the fresh groundwater resource through nitrate leaching from nearby agricultural field.

![Simplified map for the Digne Les Bains area showing the Bléone catchment](image1.png)

**Figure 1.** Simplified map for the Digne Les Bains area showing the Bléone catchment
T=Triassic dolomites, gypsum; J3=Jurassic shales, limestones; J2=Jurassic shales; C2=Cretaceous limestones and marls; C1=cretaeous limestons; Miocene conglomerates; P=Pleistocene sandstone, conglomerates; and Q=colluviums, debris. Map source; The French Geological Survey

![Simplified diagram of karst aquifer showing heterogeneity modified after Goldscheider and Drew ([10])](image2.png)

**Figure 2.** Simplified diagram of karst aquifer showing heterogeneity modified after Goldscheider and Drew ([10])
Figure 4 displays calcite and dolomite dissolution in the system. Figure 4a & b show high concentration of calcium relative to bicarbonate and magnesium due to dissolution of both calcite and dolomite in the system. The negative saturation index points to under saturation of both calcite and dolomite in the system (Figure 4c & d). This implies dissolution of calcite and dolomite can still take place, which will thus result to further permeability increase in the area. The dissolution processes occurring in the Bléone karst aquifer system, probably resulted to dual or triple porosity and permeability, which can render the system susceptible to pollution. This is because pollutant may rapidly spread over long distances within the aquifer due to fast and turbulent flow as well as limited or absence of natural attenuation processes. Thus, in the karst aquifer both water quality and discharge volumes may vary rapidly over short time periods, [7].

4. Modelling flow in the Catchment
Data for wells and springs in the alluvium and conglomerate aquifer obtained from the French Geological Survey was used for the construction of a conceptual model which was simulated with 2 layer; the first layer consisting alluvial with conglomerate, and the second layer consist of conglomerate considering hydraulic connection between the two layers. Figure 5 shows the boundaries of a steady state model domain simulated with MODFLOW tool package with PMWIN5 interface in an effort to estimate the
water balance of the catchment. MODFLOW [11] is open source program. In the last decades, MODFLOW has been applied in groundwater resource field in MODFLOW simulates both confined [12,13] and unconfined flow [14,15] in three-dimensional heterogeneous aquifer systems [16,17].

![Figure 4. Dissolution of calcite (a&c) and dolomite (b&d)](image)

The cell size of the model is 1000 x 1000 m and the coordinate system considered as NTF93 zone 32 (6-12E). The model domain is 37 km by 42 km and rivers (River la Durance to the west and River Asse to the South) were assigned under the river package. Easter part of the modelled domain that is the limit of Mesozoic limestone was assigned no-flow boundary condition and the North lower Miocene unit limit was also assigned no-flow boundary condition.

The water balance of the region is displayed in Table 1. It shows higher output river leakage compared to input river leakage.

| Flow Term       | IN [m³/day] | OUT [m³/day] |
|-----------------|-------------|--------------|
| Wells           | 6400        | 23464        |
| Drains          | 0           | 10804        |
| Recharge        | 162271      | 0            |
| River Leakage   | 10000       | 144403       |
| Sum             | 178671      | 178671       |
5. Conclusions/Perspective

Groundwater for agriculture and Public Water supply can be exploited from the main aquifers in the area: Limestone and Alluvium. The areas where demands water for public supply are located close to the villages Javie, Marcoux and the city Dine Les Bains. The areas where demands water for agriculture are Marcoux and the La Cornerie/Mallemoison. Therefore, in order to reduce costs of production the groundwater should be exploited in the vicinities of these areas.

It is pertinent to design a network of multilevel groundwater monitoring wells constructed at specific levels to make use of discrete-zone monitoring for site characterization and long term monitoring of groundwater quality.

This approach hopefully can provide more reliable assessment of biodegradation processes, contaminant transport, peak contaminant concentrations, the geometry and behaviour of the contamination plume for the development and validation of robust conceptual site models for fractured aquifers. Modelling of karst aquifers requires keen consideration of the specific feature of karst system especially with regard to delineating protection zones. Neglecting such features may lead to disease epidemic due to contamination. For the case of the Bléone aquifer, effective monitoring network have to be put in place and modelling in transient state can perhaps give some clues for a better understanding of the system.

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