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Temporal evolution of age data under transient pumping conditions

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SUMMARY

While most age data derived from tracers have been analyzed in steady-state flow conditions, we determine their temporal evolution when starting a pumping. Our study is based on a model made up of a shallowly dipping aquifer overlain by a less permeable aquitard characteristic of the crystalline aquifer of Plœmeur (Brittany, France). Under a pseudo transient flow assumption (instantaneous shift between two steady-state flow fields), we solve the transport equation with a backward particle-tracking method and determine the temporal evolution of the concentrations at the pumping well of CFC-11, CFC-12, CFC-113 and SF_6. Apparent ages evolve because of the modifications of the flow pattern and because of the non-linear evolution of the tracer atmospheric concentrations. To identify the respective role of these two causes, we propose two successive analyses. We first convolute residence time distributions initially arising at different times at the same sampling time. We secondly convolute one residence time distribution at various sampling times. We show that flow pattern modifications control the apparent ages evolution in the first pumping year when the residence time distribution is modified from a piston-like distribution to a much broader distribution. In the first pumping year, the apparent age evolution contains transient information that can be used to better constrain hydrogeological systems and slightly compensate for the small number of tracers. Later, the residence time distribution hardly evolves and apparent ages only evolve because of the tracer atmospheric concentrations. In this phase, apparent age time-series do not reflect any evolution in the flow pattern.

1. Introduction

Groundwater flow is by nature transient, because of the temporal variations of boundary conditions such as the variations of recharge over different time scales (seasons, decades, centuries or more) and because of anthropogenic forcings such as pumping or artificial recharge. Pumping has a significant impact on the flow pattern and on solute transport. They induce more convergent flow pattern and, even in some cases, some extension of recharge areas (Bredehoeft, 2002; Frind et al., 2005). It will as well speed up flows and modify the relative role of structures, hydrodynamic properties and boundary conditions – increasing for instance the effective recharge rate of unconfined aquifers in close connection to the surface (Leray et al., 2012; Sophocleous, 2005).

Environmental tracers have been widely used for water sources identification, estimation of residence time distribution and model calibration amongst others (Castro et al., 1998; Cook et al., 2005; Long and Putnam, 2009; McMahon et al., 2010; Stichler et al., 2008). Because they integrate velocities along flow paths, they reflect flow conditions over various time scales in the past. They are sensitive to transient phenomena affecting the flow field. More precisely, they are sensitive to transient phenomena occurring over time scales comparable to their characteristic time (Zuber et al., 2011).

Yet, the influence of transient flow conditions on environmental tracer concentration has hardly been addressed. Sanford et al. (2004) have reconstructed transient recharge rates using ^{14}C data in the regional alluvial middle Rio Grande Basin. Schwartz et al. (2010) have noticed that the interpretation of ^{14}C age in transient flow models can be ambiguous in terms of flow pattern as data distributed over the aquifer reflect different flow conditions. Long and Putnam (2009) have incorporated CFCs and ^{3}H data from a karstic system in binary mixing model with dilution allowing parameters to vary with time. Fewer studies have analyzed the role of transient flow conditions on residence time distribution. Using numerical simulations, Troldborg et al. (2008) have showed the effect of recharge seasonality on residence time distribution and have noticed distinct behaviors. In the shallowest part of the studied heterogeneous aquifer, residence times tend to be smaller than

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in steady-state flow conditions while they tend to be higher in the deepest part of the aquifer. The effect in a fully-penetrating well is however negligible. Zinn and Konikow (2007) have analyzed the effect of the start of pumping on a synthetic configuration composed of an aquifer overlain by an aquitard. Their study have revealed important changes of the mean residence time at the pumping well and of the residence time distribution over long periods of time. Changes only come from the modification of the flow pattern as they solely focused on the mean residence time and not on the apparent ages obtained from tracers.

In this study, we determine the influence of the transient groundwater flow pattern induced by anthropogenic forcing on environmental tracers concentrations (CFC-11, CFC-12, CFC-113 and SF_6) interpreted in apparent ages. We consider that the transient flow pattern is induced by the instantaneous start of a pumping well. Tracer concentrations are reported at the pumping well. Our study is based on the hydrogeological setting of Plœmeur, which is a well documented aquifer where water has been produced for the last two decades for the water supply of the nearby city (Le Borgne et al., 2004, 2006; Ruelleu et al., 2010; Touchard, 1999). Although based on a specific site, the results of this study can be generalized to shallowly dipping aquifers overlain by a leaking layer. Such condition has been proved to be of importance for groundwater resources in hard-rock aquifers (Leray et al., 2013). While our objective is more methodological than targeted to a specific site, the Plœmeur aquifer still offers a complex and yet realistic hydrodynamic context. We use hydrogeological models previously calibrated in steady-state flow conditions under pumping (Leray et al., 2012) and determine the effect of transient flow conditions on apparent ages. We first aim at determining the causes of the temporal evolution of the apparent ages and specifically when they rather come from the transient modifications of the flow pattern and when they are more linked to the specificities of the tracers, especially their atmospheric concentrations. We second aim at assessing the interest of age data time series for models segregation. After recalling in Section 2 the hydrogeological, flow and transport models, we present the results in Section 3 and discuss them in Section 4.

2. Hydrogeological, flow and transport models

We successively describe the hydrogeological models of the Plœmeur site that will be used as a basis of this study, the flow and the transport models as well as the numerical methods used. We finally comment in details the derivation of the tracer concentrations and the corresponding apparent ages to highlight the possible causes of apparent age temporal variations.

2.1. Hydrogeological model

The study of the effects of transient flow conditions, induced by pumping, on age data is based on the Plœmeur aquifer, a highly heterogeneous hard-rock aquifer located on the south coast of Brittany near the city of Lorient (France). A previous study based on the inversion of gravimetric data has established a geological conceptual model (Ruelleu et al., 2010). This conceptual model is composed of two transmissive structures at large scale, the dipping contact zone and a North 20° normal fault, besides the Plœmeur and Guidel granites and overlying micaschists acting as a typical aquitard. Local heterogeneities are not represented in the model. The supplying area to the pumping well which amounts to a few square kilometers is limited in the North–South direction by these two granites. The pumping rate thus has a strong impact on flow pattern within this heterogeneous aquifer.

Because the shape and the dip of the contact zone are only partially known, the overall thickness of the aquitard–aquifer system remains relatively uncertain. To account for this uncertainty, a few structural models with distinct thickness have been built (Fig. 1 and Table 1). The hydraulic properties of the different rocks have been set either to common values as for the granites which are found almost impervious (10^{-11} m/s), or to measured values as for the micaschists (10^{-7} m/s–5×10^{-6} m/s) and the contact zone (1.9×10^{-3} m^2/s–3×10^{-3} m^2/s). In addition, the potential recharge rate R has been estimated at 200 mm per year (Carn, 1990; Leray et al., 2012; Touchard, 1999). Following these constraints, each model has been calibrated against the mean piezometric level measured at the pumping well (-5.5 masl) in steady-state flow under pumping conditions (Leray et al., 2012) by slightly adjusting the contact zone transmissivity previously estimated from long-term pumping tests (Le Borgne et al., 2006). Uniform porosity has also been calibrated against the CFC-12 age (30 years ± 1 year in 2009). Note that the overall volume of the system is about 1.5×10^9 m^3 and the mean residence time of the model – *i.e.* the first moment of the residence time distribution – is around 13 years in ambient conditions and 50 years in pumping conditions.

Our study has been carried out on about ten representative hydrogeological models differing by their structure, their micaschists permeability and their porosity. The interest of considering different models is to investigate the potential influence of the hydrogeological structure on the apparent ages and their evolution. We discuss further in Section 4 how this sensitivity might be useful as an additional way to characterize the flow pattern. Among this set of models, only two are used here to illustrate the methodology as they all lead to the same conclusions. Table 1 synthesizes the parameters of the two chosen hydrogeological models.

2.2. Flow model

Transient flow conditions are induced by starting a pumping well. The transient pumping rate $Q_w(t)$ is a step function going from zero before the starting date t_{switch}, to a positive value Q_p:

$$Q_w(t) = \begin{cases} 0 & t \leqslant t_{switch} \\ Q_p & t > t_{switch} \end{cases}.$$

In the particular case of the site of Plœmeur, Q_p is set at 3.36×10^{-2} m^3/s. Pumping started in 1991 and the most part of the evolution of the piezometric levels occurred only in a few years after the start of pumping. t_{switch} has thus been set at 1994. We solve the 3D diffusivity equation for the hydraulic head $h(\boldsymbol{x},t)$ with free surface boundary conditions under a pseudo transient flow approximation:

$$\nabla.(K(\boldsymbol{x})\nabla h(\boldsymbol{x},t)) = 0 \tag{2}$$

$$\left.\begin{array}{ll} K(\boldsymbol{x})\nabla h(\boldsymbol{x},t)\cdot\boldsymbol{n} = -R \quad \& \quad h(\boldsymbol{x},t) = z(\boldsymbol{x}) & \text{where} \quad h < z_{\text{ground}} \\ h = z_{\text{ground}} & \text{anywhere else} \end{array}\right\} \quad on\ \Gamma_1 \tag{3}$$

$$\nabla h(\boldsymbol{x})\cdot\boldsymbol{n} = 0 \quad \text{on } \Gamma_{\text{west}} \quad \text{and} \quad \Gamma_{\text{east}} \tag{4}$$

$$h(\boldsymbol{x}) = z_{\text{ground}} - z_0 \quad \text{on } \Gamma_{\text{north}} \quad \text{and} \quad \Gamma_{\text{south}} \tag{5}$$

$$\int_{\Gamma_w} K(\boldsymbol{x})\nabla h(\boldsymbol{x},t)\cdot\boldsymbol{n}_w\, d\Gamma_w = Q_w(t) \quad \text{sink term} \tag{6}$$

where $K(\boldsymbol{x})$ is the hydraulic conductivity; $\boldsymbol{n}$ is the outgoing normal to the saturated domain; R is the potential recharge rate; z_{ground} is the ground surface elevation; Γ_s is the top of the saturated domain; Γ_{west}, Γ_{east}, Γ_{north} and Γ_{south} are respectively the West, East, North and South sides of the domain; z_0 is a reference height; $\boldsymbol{n}_w$ is the