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Solute transport in heterogeneous karst systems: Dimensioning and estimation of the transport parameters via multi-sampling tracer-tests modelling using the OTIS (One-dimensional Transport with Inflow and Storage) program

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SUMMARY

This paper presents the modelling results of several tracer-tests performed in the cave system of Han-sur-Lesse (South Belgium). In Han-sur-Lesse, solute flows along accessible underground river stretches and through flooded areas that are rather unknown in terms of geometry. This paper focus on the impact of those flooded areas on solute transport and their dimensioning. The program used (One-dimensional Transport with Inflow and Storage: OTIS) is based on the two-region non equilibrium model that supposes the existence of an immobile water zone along the main flow zone in which solute can be caught. The simulations aim to replicate experimental breakthrough curves (BTCs) by adapting the main transport and geometric parameters that govern solute transport in karst conduits. Furthermore, OTIS allows a discretization of the investigated system, which is particularly interesting in systems presenting heterogeneous geometries. Simulation results show that transient storage is a major process in flooded areas and that the crossing of these has a major effect on the BTCs shape. This influence is however rather complex and very dependent of the flooded areas geometry and transport parameters. Sensibility tests performed in this paper aim to validate the model and show the impact of the parametrization on the BTCs shape. Those tests demonstrate that transient storage is not necessarily transformed in retardation. Indeed, significant tailing effect is only observed in specific conditions (depending on the system geometry and/or the flow) that allow residence time in the storage area to be longer than restitution time. This study ends with a comparison of solute transport in river stretches and in flooded areas.

1. Introduction

Tracer tests can be a powerful tool when they are used in a quantitative approach in order to characterize solute transport in karst conduits. They provide direct information about groundwater trajectories and hydraulic connections inside a complex karstic network and give breakthrough curves (BTCs) from which some major transport parameters can be easily assessed (first arrival, travel time, tracer velocity, tracer recovery,...).

Modelling of solute transport in karst conduits consists in fitting a modelled BTC with the one obtained in field experiment. Modelling of BTCs allows to define transport parameters, notably the advection and dispersion effects, to evaluate the active conduit geometry and to predict the behavior of a karstic system in different flow conditions.

The karstic site of Han-sur-Lesse is a major system in Belgium that offers interesting features in a modelling purpose. Indeed, the system corresponds to an entire stream sinking into a hole that can swallow up to 25 m^3/s and flooding a large heterogeneous karstic network made of flooded areas that are interconnected by conduit stretches. Flooded areas are saturated zones of unknown geometry, probably intensely karstified but with limited physical access. The assumption is that the transport dynamic is different in those flooded areas and in the river stretches. Therefore the objectives of this study are firstly to observe and to characterize the solute transport in both the flooded zones and the river stretches; secondly to dimension the active system.

In this aim, the OTIS program (One-dimensional Transport with Inflow and Storage), developed by Runkel (1998), was chosen partly because it offers the possibility to build a discrete system and therefore to test the effect of geometry on solute transport.

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Furthermore the Han-sur-Lesse BTCs show an asymmetry, a tailing that is commonly observed in field BTCs in general. This persistent skewness is often associated to retardation in the literature. The process recognized as the main cause of retardation is the existence of immobile flow regions along the tracer path (Hubbard et al., 1982; Martin and McCutcheon, 1998). As OTIS allows the simulation of discrete immobile water zones, this study will also test the effect of transient storage on the BTCs. Finally, sensibility tests will show the efficiency of OTIS as a modelling program for solute transport parametrization and karst conduits dimensioning.

2. The OTIS program: theoretical background

Ground-water flow and solute transport in karst conduits are characterized by turbulent flow in a non-constant permeability media. Classical advection–dispersion Eq. (1) can explain solute transport in karst conduits only in the case of equilibrium model, i.e. in dynamic processes. In equilibrium model, evolution of the solute concentration (C) with time (t) is only dependent on the longitudinal flow velocity (v_L) and their longitudinal dispersion (D_L). Eq. (1) supposes a decay coefficient (μ) that can affect the restitution rate and a retardation factor (R_f) that is here only linked to solute sorption on solid particles.

$$R_f \frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} - v_L \frac{\partial C}{\partial x} - \mu C \quad (1)$$

Eq. (1) is however not sufficient to explain transport in karstic systems. Indeed, it can't explain the asymmetry generally observed in field BTCs. This persistent skewness and tailing has been widely discussed and considered as the results of complementary processes as adsorption–diffusion, molecular diffusion, dilution effects, multiple conduits effects, but the main process responsible for BTCs skewness is the interaction with immobile water (Hubbard et al., 1982; De Marsily, 1986; Maloszewski and Zuber, 1989; Rossier and Kiraly, 1992; Maloszewski et al., 1992; Werner et al., 1997). Therefore, transient storage has to be taken into account in Eq. (1). It exists in regular or irregular conduits due to the velocity gradient between the main flow zone and the conduits walls that causes turbulent flow (Martin and McCutcheon, 1998; Hauns and Jeannin, 1998; Hauns et al., 2001). Field and Pinsky (2000) proposed the "two-region non-equilibrium model" that supposes the existence of immobile water zones along the solute transport path. An exchange exists between mobile and immobile zones but transport is only effective in the mobile, dynamic zone. Runkel (1998) developed a program called OTIS (One-dimensional Transport with Inflow and Storage) based on the two-region non-equilibrium approach. OTIS was initially created to solve solute transport problematic in surface streams implying concentration variation in longitudinal direction only and free elevation of the water level, features that are relevant for karst conduit flows. As shown in Fig. 1, OTIS supposes a main dynamic flow in mobile zone in which solute is transported by advection and affected by dispersion and, possibly, adsorption and decay. Next to the main channel, immobile zones equally distributed along the main flow zone exist. They act as transient storage zones for the solute that can be affected by chemical reactions but where there is no transport by advection and dispersion. To permit storage in stagnant zones, an exchange between mobile and immobile water zones has to take place. Finally, lateral flow can be added and/or retract from the main flow.

In accord with all these features, the OTIS program is guided by the following equations for conservative and non-conservative solutes (terms in square brackets):

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(AD_L \frac{\partial C}{\partial x}\right) + \frac{q_{lin}}{A}(C_{lin} - C) + \alpha(C_s - C) + [\rho\lambda'(C_{sed} - K_d C) - \lambda C] \quad (2)$$

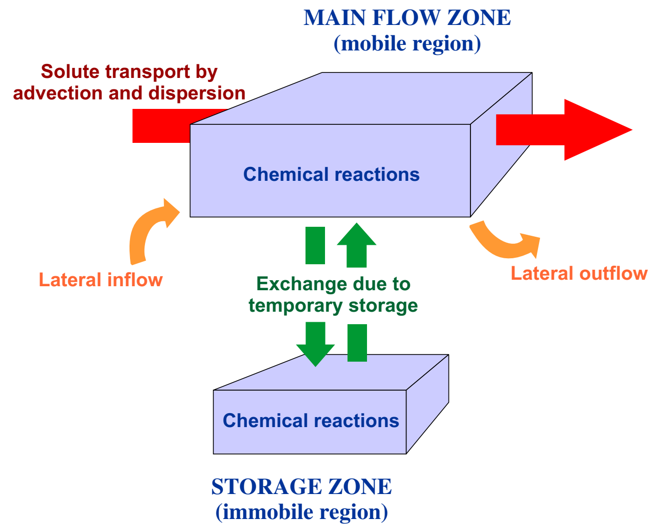

Fig. 1. Main functioning principles in OTIS. Solute transport occurs in the main flow zone while an exchange with a storage zone exists (modified from Runkel, 1998).

and,

$$\frac{\partial C_s}{\partial t} = \alpha \frac{A}{A_s}(C - C_s) + [\lambda'_s(C'_s - C_s) - \lambda_s C_s] \quad (3)$$

where C, C_{lin} and C_s [M/L^3][2] are solute concentrations in, respectively, the main channel, the lateral inflow and the storage zone; A and A_s [L^2] the cross-sectional areas in the main channel and storage zone; Q [L^3/T] the volumetric flow rate; q_{lin} [L^3/T L] the lateral inflow rate; D_L [L^2/T] the longitudinal dispersion coefficient; α [T^{-1}] the storage zone exchange coefficient; t the time [T]; x the distance [L]. Considering non-conservative solute, C_{sed} is the sorbate concentration on sediment; C'_s the background storage zone solute concentration; K_d [L^3/M] the distribution coefficient; λ and λ_s [T^{-1}] the first-order decay in the main channel and the storage zone; λ' and λ'_s [T^{-1}] the sorption rate coefficient in the main channel and the storage zone; ρ [M/L^3] the mass of accessible sediment by volume water.

The major advantage in OTIS is the possibility of discretization of the system which is a very interesting feature in heterogeneous environments. A system needs therefore to be conceptualized in order to be cut in "reaches" that can be modelled separately, and so being characterized by different dimensions and transport parameters. Each reach is subdivided in a number of discrete segments that represent control volumes within which mass is conserved. Eqs. (2) and (3) apply then in each segment and numerical solutions have to be found.

To implement a numerical solution scheme, OTIS uses the implicit Crank-Nicolson method (for details on the solutions, see Runkel, 1998; Runkel and Broshears, 1991). The solution has to be constrained by conditions at the upstream and downstream boundary of the system. The upstream boundary condition (USBC) is the solute concentration injected in the system. This concentration can vary in time regarding to the injection mode (concentration-step, flux-step, concentration-continuous). The downstream boundary condition (DSBC) is not a concentration but a dispersive flux. This flux is defined at the interface between the last segment in the modelled system and an additional fictitious segment. Eventually, to solve the equations that governed the model, it should be precise if the solute is conservative or not (Eqs. (2) and (3) without or with square brackets) and if the transport occurred in steady or unsteady flow.

[2] The fundamental units of Mass [M], Length [L] and Time [T] are used throughout this chapter.