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A fifty-year chronicle of tritium data for characterising the functioning of the Evian and Thonon (France) glacial aquifers

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SUMMARY

Using lumped models and a transfer function model, this paper deals with the interpretation of exceptionally long (up to 50 years (y)) and precise tritium chronicles characterising the rainfall, recharge (efficient rainfall) and outflow from various types of glacial aquifers from the French Alps (Evian–Thonon area). The efficient rainfall tritium chronicle was computed from tritium measurements performed for 11 years (1969–1979) in a lysimeter. The evapotranspiration induces a mean 15% drop of the annual tritium signal. The three superficial glacial aquifers (two fluvio-glacial kame terraces and a lateral till) provide similar results: a best fit with an exponential flow model (EM) (playing the major role) combined in parallel with a piston flow model (PFM), and a rather short mean transit time (T 5-7 y). The deepest mineral aquifer (Evian) can only be fitted with the in a series combination of a highly dispersive model (DM; *T* 68 y; DP = 0.5) and a piston flow model (*T* 2.5 y) or, better, by the in a series combination of an EM (*T* 8 y) modelling the subsurface aquifer and a DM (*T* 60 y; DP = 0.75) and the same piston flow model (*T* 2.5 y) modelling the deep mineral aquifer, this latest combination of models providing the following parameters: *T* 70 y and median transit time 45.5 y. It is also to be noted that a very small part of the recharge; about 1.3%, avoids both the EM and the DM, and directly enters the PFM (at the Northern limit of the Gavot Plateau). These models are very sensitive regarding the *T* (±1 y, 0.25 y for the PFM), less so with DP. These results will prompt hydrologists to (re)work historical data to determine if important hydrologic information is available. The interest and limits of such a modelling, also for other constituents than tritium, along with the future for tritium as a tracer are discussed and it also provides new insights on the structure and functioning of alpine paleo glacial hydrosystems.

1. Introduction – history of isotope measurements in the Evian–Thonon area

To evaluate the potential hydrogeological vulnerability of hydrosystems to anthropic pollution and predict any future changes, the pattern of the transit time of water in the aquifers should be defined. Isotopic measurements are presently used in field investigations and research projects to improve qualitative understanding of hydrosystems and identify the processes involved in water transfer (Turner and Barnes, 1998). Environmental tracers (^{18}O, ^{2}H and tritium) and specific flow models have been used by numerous authors to estimate the transit time of water in hydrological systems (Herrmann et al., 1990; Stewart and McDonnell, 1991; Maloszewski et al., 1983, 1992, 1995,

Abbreviations: Amsl, above mean sea level (elevation); CRG, Centre de Recherches Géodynamiques; DM, dispersion model; DP, dispersion parameter; EM, exponential flow model; BMMEP, in parallel combined piston flow and exponential models; IAEA, International Atomic Energy Agency; LM, linear model; LPM, combined linear flow and piston flow model; NMW, Natural Mineral Water; *T*, mean transit time; PFM, piston flow model; TU, Tritium Unit; y BP, year before present.

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2002; Maloszewski and Zuber, 1982; Holko, 1995; Amin and Campana, 1996; Rodhe et al., 1996; Vitvar and Balderer, 1997; Etcheverry and Perrochet, 2000; Uhlenbrook et al., 2002; Viville et al., 2006; Hagedorn et al., 2011; Morgenstern and Daughney, 2012). One difficulty in estimating the transit time of water is the need of the input function, i.e. the concentration of tritium in the infiltrating water while only tritium in precipitation and precipitation amount are available. McGuire and McDonnell (2006) tried to construct better model to estimate the input function. Moreover, due to the insufficient length of input and output chronicles, hydrosystems with transit times of several decades sometimes cannot be studied.

Tritium (^{3}H) is a natural isotope of hydrogen (half-life 12.32 years; Lucas and Unterweger, 2000), naturally present in the atmosphere at low concentrations (5–10 TU), and at higher concentrations (up to about 6000 TU) due to above ground nuclear weapons testing beginning in the mid 1940s, then dramatically increasing with the development of the hydrogen bomb (first test was in November 1952) until 1963, the year when the atmospheric atomic test was banned (the few small nuclear tests above ground since 1980 have just been too small to make any impact on the tritium burden). However the beginning of tritium recording started in August 1953 (Maloszewski and Zuber, 1994). It has been widely used in hydrology to estimate aquifers' mean transit time (or residence time) since it is a constituent of the water molecule and its concentration in rainfall has varied during the past 60 years, giving a well-known input function for hydrological models. Tritium better captures the longer term components of flow and recharge than other typical approaches (chloride or stable isotopes for instance) (Stewart et al., 2010).

The first tritium measurements of groundwater from the Quaternary deposits of the Geneva Lake basin were taken in the fifties, and have been densified since 1964, shortly after monthly analyses of tritium from rainfall began in June 1963 at the Thonon (France, Fig. 1) Centre de Recherches Géodynamiques (CRG, a branch of the Paris VI University), which was a member of the International Atomic Energy Agency (IAEA) isotopic monitoring network. As early as 1963 this new isotopic tool proved useful in characterising the hydrogeological functioning of the complex glacial aquifers of the area (Blavoux et al., 1964; Fontes et al., 1967). A tritium content of several hundred TU (Tritium Units) was found in 1964 in the Thonon unconfined aquifer while in contrast the water from the Evian confined aquifer located about 10 km eastwards was still only a few TU. Sampling was subsequently performed quarterly in this area to monitor the evolution of the tritium signal until recently, providing probably the longest available detailed temporal record of tritium in groundwater.

In that framework, this paper deals with the interpretation of such an exceptionally long tritium chronicle characterising both the recharge and the outflow from various types of glacial aquifers, using lumped models and a transfer function model. It discusses the interest and limits of such modelling and also provides new insights on the structure and functioning of ancient alpine glacial hydrosystems. Such glacio-fluvial hydrosystems, either quite old, or "fossils" (see for instance Blavoux and Dray, 1971; Dray, 1993; Caballero et al., 2002; Nicoud et al., 1993; Henriot et al., in preparation; in prep. Bayer et al., 2011) or subactual (see for instance McClymont et al., 2011; Rodhe and Seibert, 2011; Clow et al., 2003) are of high interest for their water resources in the many regions of the world that were glaciated, mostly during the Quaternary era, or are still at the margins of glaciated areas: the northern part of Eurasia, North and South America, alpine regions, etc. (see for example Roy and Hayashi, 2009; Beckers and Frind, 2000, 2001).

2. Geological and hydrogeological setting of the Evian–Thonon area

The studied area is about 20 km long by 10 km wide along the southern shore of Lake Geneva (Figs. 1 and 2). As in most of the Lemanic basin (Fiore et al., 2011), the land surface is almost exclusively covered by thick (up to 400 m or more in Evian; Triganon et al., 2005) Quaternary glacial sediments deposited over a major glacial erosion surface truncating the cemented, folded and thrusted Alpine rocks. The lake was dug during Quaternary glaciations by ice originating from the upstream Rhône valley catchment basin. The deep valley of the Dranse River (Fig. 1), the bottom of which exposes much older pre-Quaternary geological formations, divides the study area into two independent zones both from a geological and a hydrological viewpoint.

East of the Dranse River, the *Evian area* Quaternary geological formations are composed of glacial sediments deposited along the Rhône glacier's southern margin (Nicoud et al., 1993), well known from several kilometres of cored boreholes (Blavoux and Dray, 1971; Blavoux, 1988; Triganon et al., 2005) (Figs. 1 and 2a):

- the shape of the pre-Quaternary substratum is the result of erosion from the pre-Wurmian pulsations of the Rhône glacier. This paleotopography is irregular, reaches an elevation less than 100 m amsl at Evian, and progressively rises towards the South, up to a few pre-Quaternary outcrops at the highest points of the Gavot Plateau;
- this depression is filled by about 100 m of thick sands and gravels (older than the last glacial cycle), corresponding to the northern tip of a paleodelta of the Dranse River, covered by a subglacial till up to 200 m thick from the Würmian maximum (65,000 to 35,000 y BP, Triganon et al., 2005), during which the glacier reached an elevation of about 1300 m amsl in the Evian area. This till surely prevents any groundwater flow between the pre-Quaternary substratum and the sediments described here below;
- glacio-lacustrine sediments (small local streams paleodeltas within lacustrine silts) from the "Inferior Complex", older than 30,000 y BP, sedimented during a major retreat phase of the Rhône glacier, overlie this till up to about 390 m amsl;
- the Gavot Plateau glacial margin formation, over 200 m thick, results from the progressive rise of the Rhône glacier during the Würmian "Lemanic stage" (30,000–27,000 y BP, Triganon et al., 2005; Fiore et al., 2011) when the glacier reached the Geneva city area. It is composed of a subglacial till in the Evian area and up to 13 superimposed subglacial and lateral tills with peatbog sediments below the plateau;
- the partial glacier retreat down to an elevation of about 480 m amsl, and then to about 430 m amsl at Evian, was responsible for the deposition of the glacio-lacustrine sediments of the "Terminal Complex" (25,000–21,000 y BP, Triganon et al., 2005) with highly permeable (10^{-3}–10^{-4} m/s) sands and gravels in the fans of the local paleostreams and low hydraulic conductivity silts laterally;
- finally, the last flood of the Rhône glacier, with the western tip of the glacier again reaching Western Lake Geneva – "le Petit-Lac" – (Copet and Nyon readvances, Fiore et al., 2011), covered all these sediments with a final subglacial till (the "terminal till") of 30 to more than 50 m thick up to an elevation of 650 to 750 m amsl in Evian. This till locally comprises kame terraces, mostly deposited at the mouth of local streams during the final deglaciation, and lateral tills.

The Natural Mineral Water (NMW) emerging from the confined aquifer of the "Terminal Complex", particularly at the Evian–