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Characterizing solute transport with transient storage across a range of flow rates: The evidence of repeated tracer experiments in Austrian and Italian streams

Bernhard H. Schmid [a,*], Ilaria Innocenti [b], Umberto Sanfilippo [b]

[a] Institute of Hydraulic and Water Resources Engineering, Vienna University of Technology, Austria
[b] Politecnico di Milano, DIIAR, Italy

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ABSTRACT

Solute transport in rivers and streams with hyporheic zone exchange and/or in-stream storage is typically affected by the prevailing flow rate. The research reported here focuses on stream tracer experiments repeated many times along the same Austrian (Mödlingbach) and Italian (Torrente Lura) channel reaches to characterize parameter dependency on flow rate. Both groups of data sets showed an increase of storage zone area and main stream area with discharge. In either case, a strong negative correlation was obtained between storage zone residence time and flow rate. From the Mödlingbach data, no clear relationship with Q emerged for the dispersion coefficient and the dead zone ratio, whereas Torrente Lura showed a clear positive correlation of the dispersion coefficient with the flow rate and a slightly negative Q-dependency for the dead zone ratio. Mödlingbach and Torrente Lura results are presented against the background of other repeat experiments reported in literature.

In practical applications, the computation of peak concentrations frequently rests on the transfer of transport parameters from one flow rate to another. Using the above Austrian and Italian data sets it was shown that the errors in simulated Mödlingbach peak concentrations remain within a 40% margin, if the ratio of flow rates (for calibration and simulation, resp.) does not exceed 2:1. With Torrente Lura, parameter transfer resulted in somewhat lower peak errors.

1. Introduction

Solute transport in rivers and streams with hyporheic zone exchange and/or in-stream storage is affected by a number of factors, among which the flow rate is one of the most important. While this is intuitively clear with regard to the processes of advection (governed by flow velocity) and longitudinal shear flow dispersion (the strength of which is controlled by spatial variation in streamwise velocities), the relationship between the flow rate and transient storage is more complex. Over the past decade, process-based research in this context has made considerable progress, shedding light on important exchange mechanisms and their controls (e.g. Wörman et al. [29], Salehin et al. [21], Boano et al. [2,3], Weitbrecht et al. [28], Cardenas [5], and Marion et al. [14]). While knowledge of individual mechanisms has increased notably (and this also includes a theory of the pumping type hyporheic exchange as a function of flow rate, see Wörman and Wachniew [30]), transient storage in natural rivers and streams is frequently determined by a mixture of intrinsically quite different mechanisms like pumping, turnover, effect of meanders, exchange with pockets along the banks etc. Promising diagnostic tools to distinguish at least roughly between different kinds of transient storage have been developed (Briggs et al. [4], Stofleth et al. [26]), but further progress will be needed before the lumped response of a stream reach can be split reliably and robustly into individual processes on a physical basis. Prior to that, a conclusive and comprehensive physical theory of how solute exchange processes depend on flow rate in a given stream will not be readily available for practical, real world applications. For this reason, the approach followed here is an experimental one which uses stream tracer experiments repeatedly performed on the same stream reach at different flow rates (ceteris paribus). To take a step towards more generality of results, experiments from different streams and stream reaches, respectively, are analyzed to identify common properties and differences in the observed solute transport and storage characteristics.

Previous work typically reported positive correlation of cross-sectional area and dispersion coefficients with flow rate (see Payne Creek results and a brief literary review — not repeated here for conciseness by Jin and Ward [12]). In contrast, varying forms of the relationship (mostly either uncorrelated or inverse) between flow rate Q and relative storage size or 'dead zone ratio' A_s/A were described, (e.g. Legrande-Marcq and Laudelout [13]; D'Angelo et al. [6]; Hart et al. [8]; Jin and Ward [12]). The exchange parameter α in turn, was largely found to be either uncorrelated (Hall et al. [7], Jin and Ward [12]; Osuch et al. [16], Scordo and Moore [25]) or positively

* Corresponding author. Tel./fax: +43 1 3688623.
E-mail address: schmid@hydro.tuwien.ac.at (B.H. Schmid).

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correlated with Q (e.g. Paoletti et al. [17]; Innocenti [10]; Innocenti et al. [11]; Zarnetske et al. [31]).

In the following sections of this paper, short descriptions of the study sites and stream tracer experiments will be given for Mödlingbach and Torrente Lura. Subsequently, analyses of the data sets obtained and the relationships of the estimated parameters with the flow rate will be presented, compared and discussed before the background of directly 'comparable' previous work. In this context, 'comparable' work means that the focus is on repeat experiments (in contrast to inter-site studies), study reaches have a relative storage zone area (dead zone ratio) above one percent and there are no known 'special' mechanisms of importance present in addition to the variation in flow rate (such as the effect of leaf litter, permafrost or the removal of wooden debris).

Finally, the errors associated with parameter transfer from one flow rate to a different one (along the same stream reach) will be computed and plotted against the respective Q-ratios. This part of the study may gain some importance in practical applications with a strongly restricted number of tracer experiments (as is often the case due to financial and time restrictions). From the results given, a maximum advisable step in Q between transient storage model calibration and simulation can be inferred.

2. Study sites and stream tracer experiments

From 2000 to 2007 a series of tracer experiments was carried out on the Mödlingbach, a small stream close to the Austrian Capital Vienna. At the study site (Fig. 1) the Mödlingbach catchment comprises some 60 km^2 and has a mean flow of approximately 0.24 m^3/s. Land use in the catchment varies, with large portions of the area being taken up by forests and fields. There are also some residential areas which may be described as mostly rural to suburban in character. Bed slope is roughly between 0.5 and 1%, and channel width varies between 3 and 5 m mostly. Bed substrate is comparatively coarse and largely consists of sand, gravel and boulders.

Breakthrough curves were measured 200.5 m downstream of the injection site, at time intervals of 30 s or 1 min, respectively. Like in many previous studies (e.g. Hart et al. [8], Hall et al. [7], Schmid [24], Stofleth et al. [26] and Scordo and Moore [25]) sodium chloride was used as a tracer, with no observations pointing to appreciable tracer losses. All experiments, instantaneous injections, were conducted during a steady flow regime, with flow rates below or around mean flow. The steady-state condition was checked by means of a nearby stream gauge read before and after the passage of the tracer 'cloud'. As can be seen from Table 1, all of the experiments remained within the

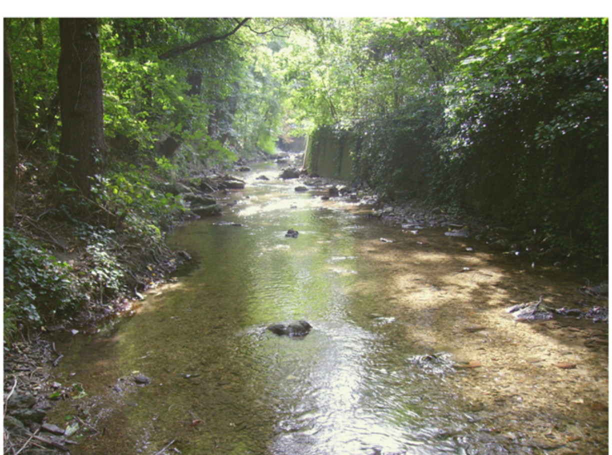

Fig. 1. Mödlingbach study site.

Table 1
Mödlingbach stream tracer experiments: survey of characteristic data and results of parameter estimation.

Injection	Q [m³/s]	M0[g Cl$^-$]	C_{max} [mg/l]	DaI	F_{med}200 [%]	u [m/s]	K [m²/s]	ε [−]	T [s]
M-1	0.0566	7411	198.8	6.51	9.86	0.175	0.350	0.184	208
M-2	0.1153	3377	82.2	7.72	8.40	0.269	0.292	0.152	111
M-3	0.0810	3715	106.8	7.47	9.65	0.237	0.271	0.171	132
M-4	0.2531	3683	38.6	8.43	24.91	0.420	0.239	0.382	78
M-5	0.0706	4833	93.7	5.85	15.34	0.187	0.370	0.274	234
M-6	0.0662	3649	70.4	7.01	17.56	0.174	0.317	0.286	212
M-7	0.0675	4868	87.3	6.21	10.78	0.155	0.470	0.201	250
M-8	0.0787	3659	89.1	9.59	18.44	0.238	0.243	0.269	111
M-9	0.1519	3674	61.9	6.09	14.86	0.310	0.284	0.262	134
M-10	0.1124	3663	80.7	6.88	10.18	0.256	0.286	0.184	135
M-11	0.1512	3669	73.0	7.21	10.72	0.328	0.342	0.187	101
M-12	0.1245	3664	72.0	11.23	16.99	0.272	0.222	0.238	81

favorable 'window of experimentation' to avoid non-uniqueness problems (Schmid [23]):

$$0.6 < DaI = \frac{L\cdot(1+\varepsilon)}{u\cdot T} < 60 \qquad (1)$$

with DaI the Damköhler Index, L the reach length, u the cross-sectionally averaged flow velocity, ε the dead zone ratio (dead zone area A_s divided by cross-sectional area A) and T the dead zone residence time.

DaI reflects the ratio of total reach travel time and dead zone residence time, and is, therefore, a measure of the relative importance of downstream tracer transport and storage processes. Very small numbers of this index ($DaI \ll 1$) indicate that the tracer rushes through the study reach and, thus, leaves little imprint on the breakthrough curve, from which, in turn, storage zone properties cannot be inferred reliably. In contrast, too high values of DaI indicate that storage exchange has reached an equilibrium stage, and its effects can hardly be distinguished from those of other mixing processes (like shear flow dispersion) caused by velocity variations in the stream (Harvey and Wagner [9]). Consequently, a Damköhler index of the order of magnitude of 1 is typically considered desirable (Wagner and Harvey [27]), with the above 'window of experimentation' expressly developed for instantaneous slug releases (Schmid [23]) and therefore applicable to the experiments reported here.

In this paper, reported values of tracer mass and concentrations, respectively, are those of chloride. C_{max} in Table 1 denotes the peak chloride concentrations of the breakthrough curves measured at x = 200.5 m.

As an additional information, Table 1 also lists the metric F_{med}200 computed from Eq. (14) of Runkel [19], which represents the fraction of median travel time due to transient storage at a distance of 200 m from the injection site. Values of this metric range between 8 and 25% and thus indicate a moderate but non-negligible degree of transient storage effects, which is also confirmed by dead zone ratios $\varepsilon = A_s/A$ between 15% and 38%.

The Lura stream is an Italian watercourse north of Milan, in the area where the Expo 2015 will take place; it is well representative of small shallow streams which are receiving bodies of urban drainage systems situated inside their river watershed. Most of the year the flow comes mainly from the outlets of 3 waste water treatment plants (WWTPs) and there is near zero natural inflow during dry periods. On the other hand, sudden flood events (with the associated pollutant loads) are induced by the discharges of several combined sewer overflows (CSOs).

Torrente Lura has a total length of about 40 km. The catchment area amounts to 48.3 km^2 at x = 10.8 km (characteristic for reach D–G) and to 103.5 km^2 at x = 27.8 km (reaches S-I–II), where x is the distance from the source (Fig. 2).