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Determining surface and hyporheic retention in the Yarqon River, Israel

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ABSTRACT: Solute transport in rivers is controlled by surface hydrodynamics and by mass exchanges with distinct retention zones. The downstream propagation of transported substances such as nutrients and contaminants is affected by the transient storage in surface dead zones (e.g., eddies, vegetated pockets) and in the permeable subsurface in the so called hyporheic zones. General residence time models allow to represent surface and hyporheic retention processes via specific modeling closures, yet current stream tracer tests do not allow a clear separation of the different storage components. A conceptual distinction can be given by associating in-channel transient storage to relatively short time scales and hyporheic retention to longer time scales. Based on this conceptual separation, we apply the STIR (Solute Transport In Rivers) model to interpret tracer test data from four different reaches of the Yarqon river, in Israel. In the model we use an exponential residence time distribution (RTD) to represent surface storage processes and we experiment with two distinct modeling closures to simulate hyporheic retention: an exponential RTD and a distribution approximating Elliott and Brooks' (1997) solution for bedform-induced hyporheic exchange which is asymptotically a power law. Both modeling closures lead to acceptable approximations of the observed breakthrough curves, but better fits are obtained using an exponential distribution to represent hyporheic (long timescale) retention. The timescales of both modeling closures appear to be increasing with the length of the study reaches which might indicate a scale-dependent behavior of the model exchange parameters. This suggests that a comparison between different reaches of different streams should take into account of this scale-dependence in order to properly characterize solute retention processes.

Keywords: STIR, Transient Storage, Hyporheic Layer, Dead Zones, Vegetated Zones

1 INTRODUCTION

Water quality assessment and environmental monitoring operations often require predictions of the concentration of solutes in water bodies. The fate of transported substances in streams, such as nutrients and contaminants, is usually controlled by mass exchanges between different compartments. A distinction is typically drawn between a main channel and different retention domains, such as vegetated zones, side pockets of recirculating or stagnant water and the porous medium. The increasing interest in mass exchanges with storage zones, in particular with the hyporheic zone, has led to the formulation of different mathematical models. One of the most commonly used models is the Transient Storage Model (TSM), presented by *Bencala & Walters* (1983), and widely applied to both large and small rivers. In the TSM, the net mass exchange between the main channel and the storage zones is assumed to be proportional to the difference of concentration in the main channel and a storage domain of constant cross-sectional area. The oversimplification of physical processes adopted in the TSM is often cause of uncertainty in the interpretation of the model parameters (*Harvey et al.*, 1996; *Marion et al.*, 2003; *Zaramella et al.*, 2003; *Marion & Zaramella,* 2005a). This weakness of the TSM has led to the development of more complex mathematical formulations for the mass exchanges with the hyporheic zone. *Haggerty et al.* (2000) suggested an advection-dispersion mass transfer equation in which the transient storage is expressed through a convolution integral of the in-stream concentration and a residence time distribution. A similar mathematical formulation was used by *Wörman et al.* (2002) who developed a model (ASP, advective-storage path) based on *Elliot & Brooks'* (1997a,b) theory of bedform-induced hyporheic exchange. Recently the application of a fractional advection-dispersion equation (*Deng et al.* 2006) and of the Continuous Time Random Walk (*Boano et al.*, 2007) has also been suggested. In this paper, the general residence time approach of the STIR (Solute Transport In Rivers) model (*Marion and Zaramella*, 2005b; *Marion et al.*, 2008) is used.

An important distinction often needed when charactering transient storage in rivers is between the exchange with surface dead zones, such as vegetated side pools or zones of recirculating water, and the exchange with the subsurface, with the so called hyporheic zone. Since in-channel and hyporheic storage processes act simultaneously, traditional tracer tests cannot provide a distinction between these two types of storage mechanisms. *Choi et al.* (2000) experimented with a two storage zone model with exponential residence time distributions (RTDs) and showed that, unless the timescales of the two storage processes are sensibly different, a multiple storage zone model is unable to discern between the two retention components. Nevertheless, it should be noted that in the work of *Choi et al.* (2000) the breakthrough curves were analyzed in linear scale, thus neglecting important information related to the tail behavior of the BTCs. *Haggerty and Wondzell* (2002) showed that tracer breakthrough curves of a 2nd order mountain stream showed a power-law tailing over a wide range of times. Subsequent works by *Gooseff et al.* (2005) and *Gooseff et al.* (2007) provided further experimental evidence of power-law behavior, although part of the data presented in these studies were better described by an exponential RTD model rather than power-law.

In this work the STIR model is applied to experimental data from tracer tests carried out in the Yarqon river, in Israel, using two distinct modeling closures to represent transient storage. Both modeling closures assume an exponential RTD to represent exchange with surface dead zones. For hyporheic retention, one of them assumes that transient storage is represented by the residence time distribution derived by *Elliott and Brooks* (1997a,b) for bedform-induced pumping exchange, whereas the other one assumes an exponential RTD. This can be seen as a two-storage zone extension of the TSM in which hyporheic retention is represented by introducing a second storage domain with a physically based RTD.

2 SITE DESCRIPTION

The basin of the Yarqon River spreads out along a wide area of the Israeli territory, from the West Bank down to the plain of Tel Aviv. The total extension of the basin is approximately 1805 km^2. The most important affluent of the Yarqon River is the Ayalon River, which drains all the southern area, including Jerusalem region, and flows into the Yarqon River 2 km upstream of its estuary. A planimetric map of the river is shown in Figure 1. It flows entirely along the coastal strip: the total length is 28 km, the sources altitude is about 50 m above sea level, and its average bed-slope is 1.8‰. These characteristics of the river profile involve the formation of many meanders, which are typical of mild bed-slopes.

The population of the entire river basin counts approximately 750,000 inhabitants. Agricultural and industrial activities are present in this area, as well as trading and urban development, leading to one of the highest population density in Israel. The growth of the population, associated to the industrial and agricultural development since 1948, made water quality of the Yarqon River increasingly polluted. Contamination is mainly due to the drawing of the river sources and the drainage of the industrial effluents into the main river.

3 METHODS

3.1 *Stream Tracer Tests*

Tracer tests were carried out in the Yarqon river in April 2005. The experiments consisted in both instantaneous (slug) and continuous (step) injections of rhodamine-WT (RWT) fluorescent dye. For step injections, a peristaltic pump was used to ensure a constant continuous rate of input throughout the injection period. In each test RWT concentrations were measured at downstream sections with a sampling period of 10 s using portable field fluorometers (Turner Design SCUFA). In addition to tracer concentrations, the fluorometers measured water turbidity, which was then used in the detrend procedure of the tracer BTCs to remove artifact generated by variations of water turbidity.

Flow discharges during the tracer tests were obtained from data provided by local consortia equipped with their own meters. The flow cross-sectional area was inferred from technical cartography of the channel sections and partly from direct measurements along the study reaches. The location of the measurement stations is shown in Figure 1.

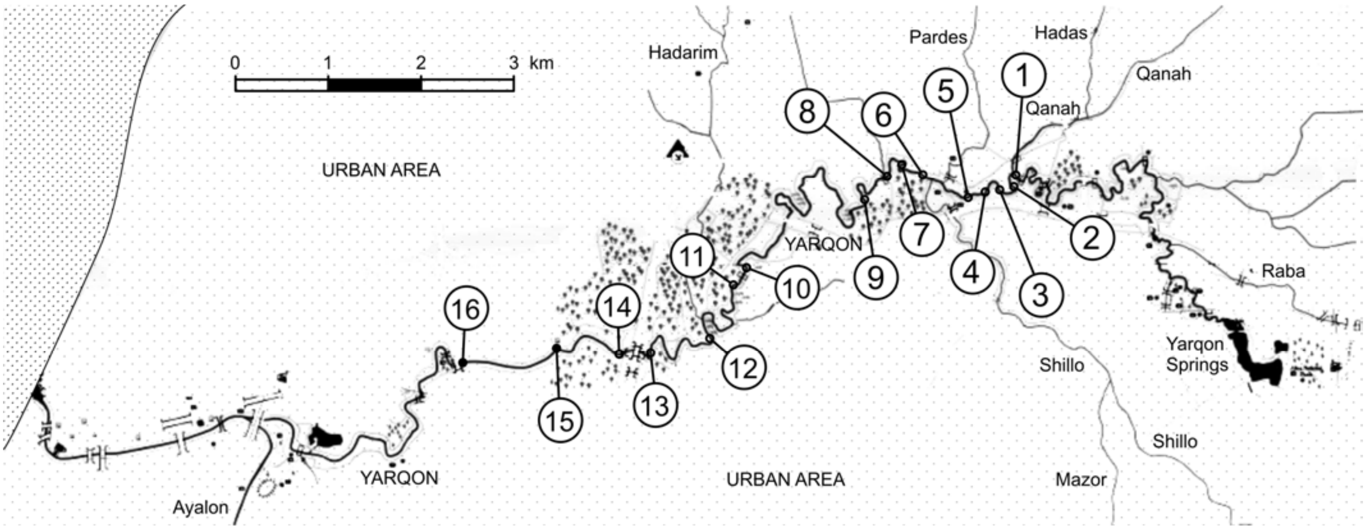

Figure 1. Map of Yarqon River and location of the measurement stations.

Table 1. Summary of experimental conditions.

Test no.	1		2	3
Injection station	1		8	14
Type of injection	slug		slug	plateau + slug*
Injected mass, M_{inj} (g)	21		21	63 + 53
Duration of injection, Δt_{inj} (s)	0		0	3600 + 0
Measurement station	5	7	9	16
Distance from injection (m)	1084	1900	657	1887

*In Test 3 a mass of 63 g of rhodamine-WT was injected with a constant rate of injection for a period of 60 min at the end of which (at time t = 60 min) a concentrated mass of 53 g of RWT was injected instantaneously.

3.2 *STIR Model*

A stream is described here as a one-dimensional system where the x is the longitudinal coordinate, A is the stream cross-sectional area and U is the average flow velocity. In the following derivations, the flow parameters are assumed to be constant along the stream. Nevertheless, the model can still be applied to natural streams by considering a sequence of reaches in which the uniformity condition applies with reasonable approximation.

The transport of a solute in a stream can be modeled by a one-dimensional advection-dispersion equation with an additional source/sink term accounting for the mass exchanges between the main channel and the retention domains. This can be written as:

$$\frac{\partial C(x,t)}{\partial t} + U\frac{\partial C(x,t)}{\partial x} = D_L \frac{\partial^2 C(x,t)}{\partial x^2} - \frac{P}{A}\Phi_S(x,t) \tag{1}$$

where $C(x,t)$ is the average solute concentration over the stream cross-section [M L^{-3}], D_L is the longitudinal dispersion coefficient [L^2 T^{-1}], P is the wetted perimeter [L], and $\Phi_S(x,t)$ is the mass flux at the interface between the main channel and the storage domains [M L^{-2} T^{-1}]. Transient storage processes can be modeled using (1) by incorporating specific modeling closures for the additional fluxes expressed by $\Phi_S(x,t)$. In the following paragraphs a different approach will be used to derive an expression for the solute concentration in the main channel based on the concept of residence time of a solute particle (or molecule), which is considered here as a stochastic variable.

3.2.1 *Residence Times and Solute Concentration*

A particle moving in the main channel follows an irregular path due to turbulence and can be temporarily trapped in different storage zones. The total path travelled by a particle can be considered as a sum of displacements partially in the main stream channel and partially in the retention domains. It is assumed that the distance traveled in the retention domains is negligible compared to the distance traveled in the main channel. This assumption is usually reasonable in practical applications especially for hyporheic exchange produced by bedforms. The total displacements in the hyporheic zones are indeed smaller than the bedform wavelength and are directed both downstream and upstream.

The time spent by a particle in a retention zone is described by a probability density function (PDF) indicated by $r_1(t)$ [T^{-1}]. The residence time of a particle in a storage zone can be assumed to be independent of its previous storage history, so the residence time PDF of a particle entering m times in a storage domain is given by a multiple convolution of the distribution $r_1(t)$:

$$r_m(t) = r_1(t) \underbrace{*...*}_{m \text{ times}} r_1(t) = r_1(t)^{*m} \tag{2}$$

where the symbol ($*$) denotes temporal convolution, i.e. $r(t) * r(t) = \int_0^t r(\tau) r(t-\tau) d\tau$.

The probability of a particle to be stored in a retention domain depends on the time spent in the main channel and so the probability that a particle enters m times the retention domains, denoted by p_m, is conditioned by the residence time in the main channel. Alternatively, this probability can be assumed to be dependent on the distance travelled which, for a stream reach of length x, is linked to the mean residence time in the main channel, $\bar{t}$, by the relation $\bar{t} = x / U$. Although a mathematical derivation considering both spatial and temporal dependence is possible, only the spatial one is here considered. The PDF of the total storage time is given by:

$$r_S(x,t) = \sum_{m=0}^{\infty} p_m(x) r_m(t) \tag{3}$$

It must be noted that $r_S(x,t)$ is a probability distribution only for the time variable. This implies that the time integral of r_S from 0 to ∞ is 1 regardless of the value of the spatial variable x.

If retention processes are absent or negligible, the time needed by a particle to travel a distance x has probability density distribution

$$r_W(x,t) = \frac{U}{2\sqrt{\pi D_L t}} \exp\left[-\frac{(x-Ut)^2}{4 D_L t}\right] \tag{4}$$

Equation (4) can be derived from the advection-dispersion equation in the spatial domain $-\infty < x < +\infty$ with homogeneous boundary conditions $C(x,t) = 0$ for $x \to \pm\infty$ and initial condition $C(x, t=0) = M\delta(x)/A$, and it is valid far from the injection point where the following condition holds:

$$\frac{x}{U} \gg \frac{D}{U^2} \tag{5}$$

The distribution of the total residence time in a stream segment of length x is linked to $r_W(x,t)$ and $r_S(x,t)$ by the relation

$$r(x,t) = \int_0^t r_W(x,\tau)\, r_S(x, t-\tau)\, d\tau \tag{6}$$

Equation (6) can be easily modified to account for exchanges with N types of retention domains, S_i, $i = 1,..,N$:

$$r(x,t) = r_W(x,t) * r_{S_1}(x,t) * ... * r_{S_N}(x,t) \tag{7}$$

It is possible, for example, to distinguish between storage in superficial dead zones and in the sediment bed.

Far from the injection point, where the condition (5) holds, the concentration of solute in the main channel is linked to the overall residence time PDF in the study reach by the following relation:

$$C(x,t) = \frac{M}{A} r(x,t) = \frac{M}{A} r_W(x,t) * \sum_{m=0}^{\infty} p_m(x) r_1(t)^{*m} \tag{8}$$

This expression is based on the assumption of an instantaneous mass injection in $x_0 = 0$ at time $t_0 = 0$. For a time-varying injection characterized by the injection rate $\dot{M}(t)$ [M T^{-1}], the relevant concentration can easily be obtained by time convolution.

3.2.2 *Storage Probability for Uniformly Distributed Retention Zones*

In most practical situations it is reasonable and convenient to assume that the storage zones are uniformly distributed along the study reach. Under this assumption, the probability of a particle to enter a storage zone in a stream reach of length δx can be taken to be proportional to δx. The factor of proportionality, indicated by η, represents the storage probability per unit stream length [L^{-1}], and it is related to the probability per unit time α [T^{-1}] by the expression $\eta = \alpha/U$. The constant α represents a transfer rate in the storage zones. Since the probability of a particle to be stored in a retention domain is independent of its previous history, the probability that a storage event occurs m times in a stream segment of length x is given by a Poisson distribution with parameter ηx:

$$p_m(x) = \frac{(\alpha x / U)^m}{m!} \exp\left(-\frac{\alpha x}{U}\right). \tag{9}$$

3.2.3 *Residence Time Distributions for Superficial Dead Zones and Hyporheic Zones*

Transient storage in superficial dead zones can be expressed by an exponential residence time PDF as implicitly assumed in the TSM (*Hart*, 1995). The residence time distribution in the superficial storage domains for a single storage event is:

$$r_{1D}(t) = \tfrac{1}{T_D} e^{-t/T_D} \tag{10}$$

where T_D is the timescale of the process, proportional to the average residence time. For the mass exchange with the hyporheic layer, the Advective Pumping Model (APM) developed by *Elliott &*

Brooks (1997a,b) can be used. An excellent approximation of that theoretical PDF, given by Elliott and Brooks in implicit form, is the following (*Marion & Zaramella*, 2005b):

$$r_{1\mathrm{B}}(t) = \frac{\pi / \mathrm{T_B}}{\beta \mathrm{T_B}/t + \left(t/\mathrm{T_B} + 2\right)^2} \tag{11}$$

where $\beta = 10.66$ is a numerical constant and T_B is a residence time scale. For $t \to \infty$ the distribution (11) decreases as a power law, $r_{1\mathrm{B}}(t) \sim \pi \mathrm{T_B} t^{-2}$. In this work we also experimented with an exponential RTD to represent hyporheic exchange,

$$r_{1B}(t) = \tfrac{1}{T_B} e^{-t/T_B} \tag{12}$$

This implies that the overall modeling closure for the retention time statistics in the storage zones is given by a weighted average of 2 exponential distributions.

3.3 *Model Parameter Estimation*

The parameters that need to be estimated in order to fully characterize the transport in the study reach are: the average stream cross-sectional area A [L^2], the average flow velocity U [$L\,T^{-1}$], the longitudinal dispersion coefficient D_L [$L^2\,T^{-1}$] and the exchange parameters characterizing the exchange with the retention domains, that is the transfer rate into the surface dead zones α_D [T^{-1}] and in the hyporheic zones α_B [T^{-1}] and the relevant timescales of retention T_D and T_B [T]. Using the average channel width b and flow depth h based on technical cartography and partly on direct in-situ measurements, the average cross-sectional area is calculated as $A = bh$, and the average velocity as $U = Q/A$. The longitudinal dispersion coefficient is calculated using *Fischer*'s (1974) formula:

$$D_L = 0.011 \frac{U^2 b^2}{U^* h} \tag{13}$$

Where $U^* = \sqrt{g R_H S}$ is the shear velocity, related to the hydraulic radius R_H [L] and the average bed slope, S.

Following *Bottacin-Busolin et al.* (2009), model calibration is performed in mixed scale using a linear scale to fit the bulk of the curve and log-scale to fit the tail. In particular, in the optimization procedure the following root mean square error is minimized:

$$\mathrm{RMSE} = \left[\frac{1}{N} \frac{\sum_{i \in I_U} \left(C_{sim,i} - C_{obs,i} \right)^2}{\left(\max_{i \in I} C_{obs,i} - \min_{i \in I} C_{obs,i} \right)^2} + \frac{\sum_{i \in I_L} \left(\log C_{sim,i} - \log C_{obs,i} \right)^2}{\left(\max_{i \in I} (\log C_{obs,i}) - \min_{i \in I} (\log C_{obs,i}) \right)^2} \right]^{1/2} \tag{14}$$

where C_{obs} and C_{sim} are the observed and simulated concentration values, respectively, I_U and I_L are the sets of the observed values higher and lower than a given threshold concentration, respectively, and $I = I_U \cup I_L$ is the total set. The threshold value is set equal to 20% of the peak concentration. The concentration values closer to zero are neglected in calculating $\min(\log C_{obs,i})$, generally by excluding from the computation 5% of the total set corresponding to the lowest values. The optimization is performed using the differential evolution method for global optimization by *Storn and Price* (1997).

4 RESULTS

Results of model calibration are presented in Table 2 and the resulting simulated breakthrough curves are presented in Figure 2. The dispersion coefficients predicted by Fischer's formula increase from upstream to downstream, ranging from 0.24 to 2.8 $m^2 s^{-1}$, consistently with the widening of the channel cross-section. It is noted here that the assumption of geometrical uniformity of the study reach is not well satisfied for the Yarqon river. This means that hydraulic parameters are estimated for each reach as average reference values.

The results show that, for the modeling closure combining the pumping RTD with an exponential RTD, the timescales of retention for the pumping RTD are higher than those found for the exponential one for all the study reaches. In the model with 2 exponential RTDs the timescales of the second retention component are much higher than the first component, with ratios T_B/T_D ranging from about 11 to 15.

In the reach 8-9, examined in Test 2, the exchange rate of hyporheic retention, α_B, returned by the optimization procedure is substantially zero ($\alpha_B \sim 10^{-14}\,\mathrm{s}^{-1}$). This result applies to both modeling closures due to the tail behavior of the breakthrough curve which decreases rapidly relative to the other reaches. Although it is difficult to provide a thorough explanation of this parameter behavior, we argue that it might be due to a rapid

Table 2. Geometric and hydraulic parameters of the study reaches and retention parameters derived from calibration of the STIR model using two distinct modeling closures.

Reach	1–5	5–7	8–9	14–16
Test no.	1	1	2	3
Geometric parameters				
Length (m)	1084	816	657	1887
b (m)	3.13	6.09	6.10	8.14
h (m)	0.34	0.36	0.44	0.26
A (m^2)	1.06	2.18	2.71	2.15
S (‰)	1.1	0.6	0.6	0.5
Hydraulic parameters				
Q (m^3 s^{-1})	0.21	0.21	0.43	0.41
U (m s^{-1})	0.20	0.10	0.16	0.19
U^* (m s^{-1})	0.05	0.04	0.05	0.04
D_L (m^2 s^{-1})	0.24	0.25	0.49	2.80
Exchange parameters of model with exponential plus pumping RTD				
α_D (s^{-1})	7.7×10^{-4}	1.5×10^{-3}	7.3×10^{-4}	9.6×10^{-4}
α_B (s^{-1})	2.9×10^{-5}	1.1×10^{-4}	0	5.8×10^{-5}
T_D (s)	153	63	436	255
T_B (s)	485	297	—	530
RMSE ($\times10^{-2}$)	1.71	5.29	10.29	7.86
Exchange parameters of model with 2 exponential RTDs				
α_D (s^{-1})	7.4×10^{-4}	9.4×10^{-3}	7.3×10^{-4}	7.3×10^{-4}
α_B (s^{-1})	2.5×10^{-5}	9.3×10^{-5}	0	5.4×10^{-5}
T_D (s)	163	109	436	340
T_B (s)	2382	1720	—	3780
RMSE ($\times10^{-2}$)	1.36	4.36	10.29	5.85

decrease of the size of the substrate material limiting hyporheic exchange.

It should be noted that for both modeling closures the timescales of retention appears to be increasing with the length of the study reach, thus indicating a possible scale-dependent behavior. A scale-dependent behavior of the storage parameters for a single exponential RTD closure has also been pointed out by *Haggerty and Wondzell* (2002).

Overall the model with 2 exponential RTDs provide better fits of the observed breakthrough curves for all the study reaches. This modeling closure also allows a direct comparison of the time scale of retention, since the functional form used to represent fast and slow exchange processes is the same, thus providing a useful conceptual separation of the timescales involved.

5 CONCLUSIONS

Transport of solutes in streams is affected by complex interactions between the main channel and different types of storage domains. A distinction is typically drawn between superficial dead zones and the sediment stream bed. Transient storage of solutes produces a superposition of processes acting on a wide range of timescales. In the STIR model the mass exchange with distinct retention domains is taken into account via a specific storage probability and a given residence time distribution. In this work the STIR model has been applied to a case study using two distinct modeling closured for the storage time statistics. Retention in superficial dead zones was assumed to be described by an exponential PDF whereas, for the hyporheic exchange produced by natural irregularities of the river bed, both the pumping theory (APM) and an exponential distribution were used. Since storage in superficial dead zones is characterized by residence time scales smaller than hyporheic exchange, it is reasonable to expect that a separate representation of each retention process would provide more meaningful parameters. Results show that the modeling closure combining two exponential distributions provide a better fit of the observed breakthrough curves. Nevertheless, the timescales of both modeling closures appear to be increasing with the length of the study reaches which might indicate a scale-dependent behavior of the model exchange parameters. This suggests that a comparison between different reaches or different streams should take into account of this scale-dependence in order to properly characterize solute retention in rivers.

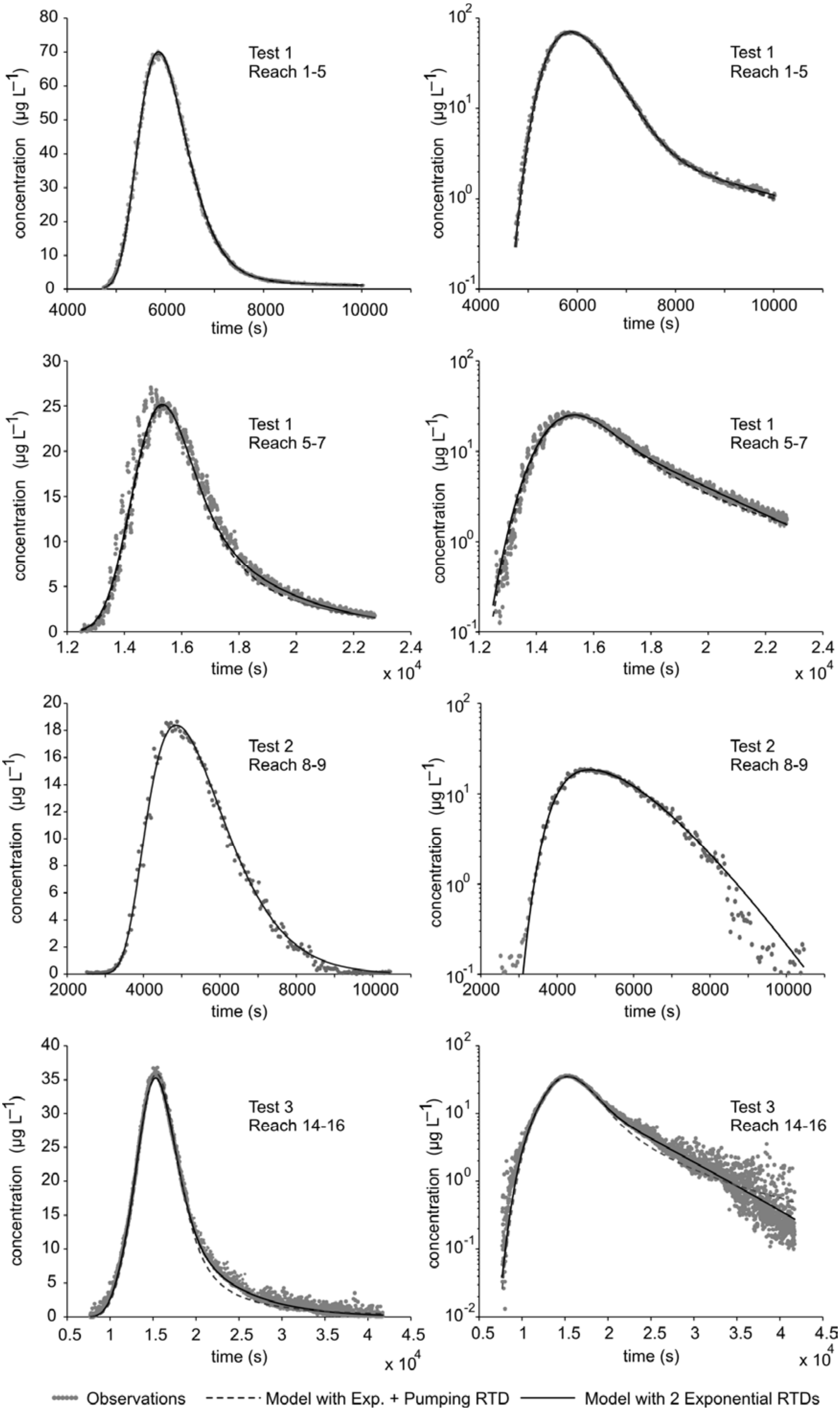

Figure 2. Experimental and simulated breakthrough curves.

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REFERENCES

Bencala, K. E. & Walters, R. A., Simulation of solute transport in a mountain pool-and-riffle stream: a Transient Storage Model, Water Resour. Res., 1983, 19(3), 718–724.

Boano, F., Packman, A. I., Cortis, A., Revelli, R. & Ridolfi, L., A continuous time random walk approach to stream transport of solutes, Water Resour. Res., 2007, 43, W10425.

Bottacin-Busolin, A., Singer, G., Zaramella, M., Battin, T. J., Marion, A., Effects of Streambed Morphology and Biofilm Growth on the Transient Storage of Solutes, Environmental Science & Technology. 2009, 43 (19), 7337-7342.

Choi, J., Harvey, J. W., & Conklin, M. H., Characterizing multiple timescales of stream and storage zone interaction that affect solute fate and transport in streams, Water Resour. Res., 2000, 36(6), 1511–1518.

Deng, Z.-Q., Bengtsson, L. & Singh, V. P., Parameter estimation for fractional dispersion model for rivers, Environ. Fluid. Mech., 2006, 6(5), 451–475.

Elliott, A. H. & Brooks, N. H., Transfer of non-sorbing solutes to streambed with bedforms: Theory, Water Resour. Res., 1997a, 33(1), 123–136.

Elliott, A. H. & Brooks, N. H., Transfer of non-sorbing solutes to streambed with bedforms: Laboratory experiments, Water Resour. Res., 1997b, 33(1), 137–151.

Fischer, H. B., Discussion of "Simple method for predicting dispersion in stream" by R. S. McQuivey & T. N. Keefer, J. Environ. Eng. Div., ASCE, 1975, 101(3), 453–455.

Gooseff, M. N., LaNier, J., Haggerty, R., & K. Kokkeler, Determining in-channel (dead zone) transient storage by comparing solute transport in a bedrock channel-alluvial channel sequence, Oregon, USA, Water Resour. Res., 2005, 41, W06014.

Gooseff, M. N., Hall Jr., R. O., & Tank, J. L. (2007), Relating transient storage to channel complexity in streams of varying land use in Jackson hole, Wyoming, Water Resour. Res., 43, W01,417.

Haggerty, R., and Wondzell, S. M., Power-law residence time distribution in the hyporheic zone of a 2nd-order mountain stream, Geophys. Res. Lett., 2002, 29(13), 1640.

Haggerty, R., McKenna, S. A. & Meigs, L. C., On the late time behavior of tracer test breakthrough curves, Water Resour. Res., 2000, 36(12), 3467–3479.

Harvey, J. W., Wagner, B. J. & Bencala, K. E., Evaluating the reliability of the stream tracer approach to characterize stream-subsurface water exchange, Water Resour. Res., 1996, 32(8), 2441–2451.

Marion, A., Zaramella, M. & Packman, A. I., Parameter estimation of the Transient Storage Model for stream-subsurface exchange, J. Environ. Eng., 2003, 129(5), 456–463.

Marion, A. & Zaramella, M., Diffusive behavior of bed form induced hyporheic exchange in rivers, J. Environ. Eng., 2005a, 131(9), 1260–1266.

Marion, A. & Zaramella, M., A residence time model for stream-subsurface exchange of contaminants, Acta Geophysica Polonica, 2005b, 53(4), 527–538.

Marion, A., Zaramella M., and Bottacin-Busolin, A., Solute transport in rivers with multiple storage zones: The STIR model, Water Resour. Res., 2008, 44, W10406.

Storn, R.; Price, K. Differential evolution - A simple and efficient heuristic for global optimization over continuous spaces. J. Global Optim. 1997, 11, 341–359.

Wörman, A., Packman, A. I., Johansson, H. & Johnson, K., Effect of flow induced exchange in hyporheic zones on longitudinal transport of solutes in streams and rivers, Water Resour. Res., 2002, 38(1), 1001.

Zaramella, M., Packman, A. I. & Marion, A., Application of the Transient Storage Model to analyze advective hyporheic exchange with deep and shallow sediment beds, Water Resour. Res., 2003, 39(7), 1198.

Zaramella, M., Marion, A. & Bottacin¬Busolin, A., Solute transport in rivers with surface and hyporheic storage: The STIR model, in revisione, 2008.