Abstract

Hyporheic exchange is the main driver of the biogeochemical transformations of nutrients in streambeds. The bed morphology and its interactions with surface flow induce different scales of flow in the hyporheic zone. The aim of this study is to better understand the mixing processes underpinning hyporheic exchange in streams. Improving our ability to quantify the mixing processes in stream sediments is crucial for enhancing the study of biogeochemical processes involving nutrients and other contaminants in streams.

Alternate bars are one of the complex morphologic configurations that can affect the characteristics of the hyporheic zone. The modeling results presented in this thesis show that two main hyporheic zones are formed in sediments with alternate bars: a shallow zone that is highly linked to the streamflow, and a deep one that is more influenced by groundwater flux variations. This distinction between the two zones is reflected in the hyporheic residence times distribution (RTD), that displays a bimodal shape. This bimodality is enhanced by anisotropic sediment conditions, while it is much milder in isotropic ones. The bar submergence has various effects on the hyporheic zone characteristics; higher bar submergence induces less hyporheic flow with longer residence times in the shallow zone. Moreover, the deep zone is significantly affected by the groundwater flux, which decreases exchange flow, hyporheic extent in the sediment, residence times, and the area of exchange. The hyporheic extent is further enhanced by sediment anisotropy.

Considering a different type of streambed morphology, dune-shaped bedforms have been shown to play a paramount role in driving hyporheic exchange. An analytical representation of the RTDs would be important to facilitate the study of hyporheic exchange processes because of the importance of the RTD for biogeochemical reactions in the hyporheic zone (e.g., as quantified by the Damköhler number). The analysis considered different conditions in terms of dimensionless sediment depth d_b^* and groundwater underflow u_b^* and their influence on the shape of the hyporheic RTD was assessed. Empirical RTDs were generated, over a range of combinations of d_b^* and u_b^* values, with numerical particle tracking experiments. The resulting hyporheic RTDs were then compared to different analytical distributions (Exponential (EXP), Gamma (GAM), Lognormal (LN) and Fréchet (FR)) with the Anderson-Darling test. The empirical RTDs were found to be represented by different distributions over the considered range of d_b^* and u_b^*. FR is the best fit for deep beds ($d_b^* > 3.2$) and negligible underflow ($u_b^* < 0.1$). LN is often the best representation for $u_b^* \leq 0.8$, while GAM performs better for larger values of u_b^*. In general, LN provides a good

description of the empirical RTDs in all cases, as it was identified as either the best or the second-best fitting distribution. The parameters of these analytical distributions vary with d_b^* and u_b^*.

The analysis described above relied on the adoption of a physically based model of hyporheic exchange induced by the streambed morphology. A different approach to describe the surface water-groundwater interactions was also considered in this thesis. It employs the diffusion equation to represent the overall transfer at the Sediment Water Interface (SWI), lumping all the physical mixing processes in the so-called effective diffusion. Specifically, a 1-D diffusive model was adopted to describe the vertical exchange at SWI and in the benthic biolayer, the biologically active upper ($\sim 2 - 5$ cm) layer of the streambed. The model was here applied to an extensive set of previously published laboratory experiments with different morphology types**:** flat beds, ripples and dunes, and alternate bars. Although there are different physical processes at the SWI associated with these morphology types, the overall mixing can be very well represented by a parsimonious diffusion based model controlled by only two parameters. These parameters define the exponential diffusivity model, are the effective diffusion coefficient at the SWI and the decay coefficient of the exponential profile. Moreover, a single predictive equation can estimate the effective diffusion coefficient based on stream and sediment properties. However, different equations are required to predict the decay coefficient of the exponential profile for each morphology type.

Finally, the thesis also focused on travel times of solutes on a much larger spatial scale. The travel times of salt tracers were examined in the Occoquan reservoir in northern Virginia (USA) as a case study. Observed time series of solute concentration and solute load, and discharge time series, were analyzed using a geostatistical method to determine the travel times distribution. The Occoquan reservoir is very relevant as it hosts the Fairfax water treatment plant, that is the main water supply for the surrounding region, and it is affected by the increasing salt concentration in recent years. The analysis of the concentration time series revealed that the salt takes $8 - 9$ days to travel through the system, while analysis of time series of the salt load – as well as discharge – indicated a much faster response (from 5 to 14 hours). These results can be useful in the regulation and operation of the Occoquan reservoir.