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The dominant mechanisms of hyporheic exchange

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The mechanisms driving hyporheic exchange are of significant interest facilitating transfer of nutrients, oxygen and energy essential for benthic ecology. The hyporheic zone is the region directly beneath the sediment-water interface (SWI) marking the transition from stream to porous flow. Hyporheic exchange is controlled by a range of variables of the stream, streambed and the geometry of the SWI. The boundary layer of a stream is characterized by a slip velocity across the SWI, facilitating transition from free fluid to Darcian flow. Mass and momentum transfer across the SWI are driven by either (1) advective pumping from variation in dynamic head at the SWI causing potential flow into and out of the streambed, or; (2) turbulent structures in the boundary layer which penetrate into the streambed. Unlike the advective pumping, turbulent structures penetrate well beyond the characteristic mixing length scale and lead to permanent displacement of fluid. The advective pumping model assumes a potential field directly beneath the SWI, despite the slip layer propagating into the bed. Furthermore, turbulent exchange can lead to a permanent displacement of fluid, while advective pumping is multidirectional and periodic. Models derived from flume experiments have been based on one of these mechanisms and have been presented as two alternative approaches for modelling hyporheic exchange. However, the incongruence of these mechanisms leads us to investigate and model each individually.

Our investigation treats coherent turbulent penetration and advective pumping as unique mechanisms which both contribute to rates of hyporheic exchange. Using bedforms as a proxy for advective pumping allowed us to gain insight into the dynamics of exchange mechanisms. Analysis of 93 past flume experiments has shown that bedforms alter the dependence of hyporheic exchange on these exchange mechanisms. Power models developed through a multilinear regression analysis showed that exchange in plane beds due to coherent turbulence primarily scales with the Reynolds number and the shear Peclet number, while exchange with bedforms also depends on bed depth and permeability. This suggests that while turbulence is ubiquitous in exchange across the SWI, enhanced rates of hyporheic exchange observed due to bedforms results from variation of dynamic head at the SWI alone. Our meta-analysis has shown changing dominance of exchange mechanisms. However, the dynamic relationship of the two mechanisms will not be understood until measurements of the turbulent structures and pressure fluctuations in flume experiments are correlated to existing models derived from flume studies. We are undertaking investigations coupling experimental techniques in measuring exchange flows to further understand the dynamic nature of these exchange mechanisms. This work will be essential in quantifying rates of hyporheic exchange relative to specific controls in natural and regulated streams. Ultimately, this will be an important step in predicting the impact of changes to stream and bed conditions on benthic organisms and aquatic ecology more broadly.