Catchment-scale patterns of hyporheic exchange

Echanges hyporhéiques à l'échelle du bassin versant

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RÉSUMÉ

Il existe trois types principaux d'échange dans un cours d'eau : les échanges le long du cours d'eau (échanges longitudinaux), les échanges entre le cours et le lit majeur (échanges latéraux) et les échanges entre la masse d'eau et les sédiments du lit (échanges verticaux). Tous ces échanges jouent un rôle important sur les processus écologiques du milieu aquatique à l'échelle du bassin versant et ainsi sur la santé humaine et celle du bétail élevé près du cours d'eau. Dans une étude précédente, les auteurs ont proposé un nouveau modèle de la résistance des échanges interfaciques entre les sédiments et l'eau à une échelle allant de 1 à 10 m, incluant les processus des échanges hyporhéiques. Le modèle exprime ces échanges en termes de résistance du transfert de masse (coefficient R). Une loi scalaire pour le coefficient R a été développée à partir d'une meta-analyse d'expériences publiées précédemment sur les échanges hyporhéiques, effectuées en laboratoire à l'aide de canaux de recirculation. Pour la présente étude, on adapte la loi scalaire pour les cours d'eau naturels du bassin versant du Murray-Darling River, Australie, en utilisant une valeur moyenne à l'échelle du tronçon pour les paramètres hydrauliques clés. Les résultats du modèle mettent en évidence des interactions importantes entre les connexions verticales et horizontales, à la fois hydrologiques et biogéochimiques, à l'échelle du bassin versant. Selon les prédictions de ce modèle, les échanges entre la masse d'eau et le lit sont bien plus fréquents pour la partie amont du cours d'eau, où le lit est plus pentu. Une molécule d'eau transportée sur une longueur de 100 km dans la partie amont du cours d'eau peut passer de la masse d'eau au lit plus de 1000 fois. Au contraire, il est probable que la même molécule ne passe dans le lit qu'une seule fois en parcourant la même distance dans la partie aval du cours d'eau.

ABSTRACT

Hydrological connections in streams occur longitudinally along the stream channel, laterally with the floodplain and vertically with the hyporheic zone. These connections are an important control on freshwater ecosystem processes at the basin-scale and influence human and riparian livestock health. Recent work by the authors has led to the development of new resistance model of sediment-water interfacial flux at the patch scale (ca., 1 to 10 m) including processes of hyporheic exchange. The model parameterizes patch-scale hyporheic exchange in terms of a mass transfer resistance coefficient R, and a scaling law for R has been developed based on a meta-analysis of previously published hyporheic exchange experiments in recirculating laboratory flumes. For this study, we adapt this scaling law to natural stream channels in the Murray-Darling Basin, Australia using reach-averaged values of key hydraulic variables. Model results suggest an important interaction between vertical and longitudinal hydrological and biogeochemical connectivity at the basin-scale. This model predicts much more frequent exchange between the water column and the streambed in steeper upland streams. A molecule of water transported along a 100 km length of upland stream may journey into the streambed more than 1000 times. In contrast, the same molecule might only pass into the streambed once while being transported a similar distance in a lowland river.

KEYWORDS

Ecohydraulics, Environmental flow, Hyporheic exchange, Resistance, River networks, Scale.

1 INTRODUCTION

Hydrological connections in streams occur longitudinally along the stream channel, laterally with the floodplain and vertically with the hyporheic zone. These connections are an important control on freshwater ecosystem processes at the basin-scale including nutrient cycling and retention; movements of organisms to complete life stages; and the provision of refugia during high and low flow periods. They also influence human and farm health by creating pathways for the sequestration and mobilization of microbial communities including human and animal pathogens. Hyporheic exchange is fundamental to vertical connectivity, transporting mass and energy between the sediment and the water column. This exchange produces steep biogeochemical gradients in the hyporheic zone that support a unique community of benthic and interstitial microorganisms, cycle carbon, energy, and nutrients and decontaminate the overlying water column. The hyporheic zone also regulates stream temperature and sediment budgets, and serves as a spawning ground for fish, refuge for benthic organisms, and a rooting zone for aquatic plants.

Methods are available to observe and model lateral and longitudinal hydrological connectivity at the basin-scale but this is not true for vertical connectivity. There is progress in understanding patterns of hyporheic exchange at individual bed particles, across geomorphic units such as riffles and pools and along short river reaches. However, variation in hyporheic exchange at basin-scales is poorly understood and, until recently, there has been no model available to predict hyporheic exchange using data available at the basin-scale. Our objective in this paper is to map patch-scale hyporheic exchange (ca., 1 to 10 m) at the basin scale using recent modeling developments by the authors.

2 METHODOLOGY

Sediment-water exchange can be modeled using the concept of “resistance” (Grant and Marusic, 2011) using

$$J_y = \frac{-\Delta C}{R} \qquad (2)$$

where ΔC is concentration of the solute in the stream water column less the concentration in the hyporheic zone. The mass transfer resistance (R) has units of inverse velocity. Resistance models for mass transfer at the sediment-water interface are subject to a number of assumptions; most notably that mass flux Jy is constant. This imposes the following three conditions within the region, or “control volume”, across which mass is transferred at the sediment-water interface: (1) steady-state; (2) no sources or sinks; and (3) horizontally uniform. Theoretical and empirical studies suggest that mass transfer resistance due to transport through the hydrodynamically controlled portion of the water column or at roughness elements at the sediment-water interface [so-called “streamside-exchange”, Grant and Marusic (2011)] can be calculated simply from the shear velocity and Schmidt number. More recently, the authors have fitted a scaling law for resistivity using results from the same 50 recirculating flume tracer studies included in the meta-analysis of O’Conner and Harvey (2008). This scaling law is provided here as a preliminary result:

$$u_* R = 3.08\left(\frac{u\sqrt{\kappa}}{\nu}\right)^{-1.24}\left(\frac{u}{u_*}\right)^{-0.51} Sc^{0.84} \qquad (3)$$

where, ν is the kinematic viscosity, u is the mean flow velocity in the water column, u* is the bed shear velocity, κ is the sediment permeability, and Sc is the Schmidt number (Sc = ν/Dm where Dm is the molecular diffusion coefficient). Our purpose in this study is to use equation 3 as a basis for mapping regional scale variations in patch-scale hyporheic exchange through the Murray-Darling Basin. There are a number of challenges and assumptions required in upscaling from laboratory flume experiments to an entire river basin described by Stewardson et al. (2011). The results are presented by mapping two expressions of intensity of hyporheic exchange: (*J*’) an effective volumetric flux rate (into the sediment bed) per unit length of channel; and (*L*) mean travel distance between excursions of individual water molecules into the streambed.

3 RESULTS AND DISCUSSION

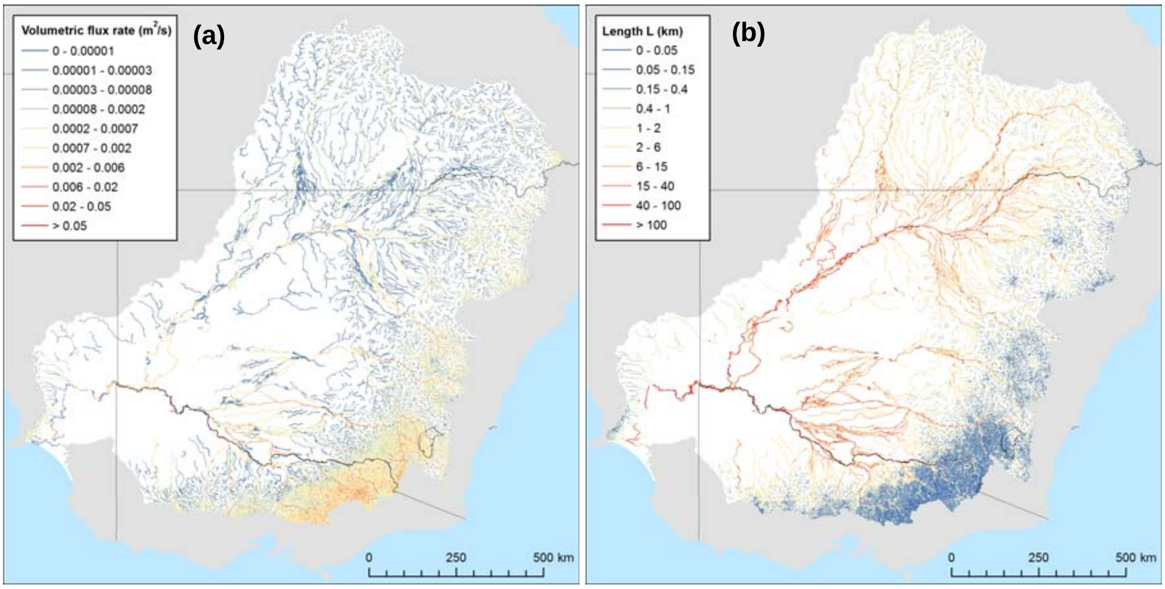

Figure 1 : Distribution of patch-scale hyporheic exchange rates in the Murray-Darling Basin mapped as: (a) volumetric rate of exchange per unit length of channel; and (b) the mean reach length between excursions into the streambed (inset map shows location of the Murray-Darling basin in Australia).

An important limitation of this model is that it only represents patch-scale hyporheic exchange processes. It does not represent hyporheic “pumping” due to steady pressure gradients at pools and riffles, around meander bends or larger scale variations in river gradient. Nor does it represent any groundwater interactions. In this way, the model is a minimum estimate of hyporheic flux and we expect model developments, incorporating these larger-scale processes, to predict greater hyporheic flux rates.

The model of patch-scale hyporheic exchange predicts much more frequent exchange between the water column and the streambed in steeper upland streams (Figure 1b). A molecule of water transported along a 100 km length of upland stream may journey into the streambed more than 1000 times. In contrast, the same molecule might only pass into the streambed once while being transported a similar distance in a lowland river. This suggests that any hyporeheic processes that influence the character of the water column (e.g. through biogeochemical transformations or source-sink dynamics) will have a much stronger effect in steeper gradient rivers. The stronger hydrological connectivity between the water column and hyporehic zone in steeper rivers is likely to promote buffering of solute and suspended contaminants delivered as a pulse from headwater catchments. This suggests an interesting interaction between vertical and longitudinal hydrological and biogeochemical connectivity at the basin-scale. Upland rivers may be characterized by strong vertical and weak longitudinal connectivity whereas the reverse may be true in lowland rivers.

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