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Thermal and hydrodynamic variability within a gravel bar of an Alpine stream and its link to hyporheic carbon cycling

Kyle Boodoo (1,2), Jakob Schelker (1,2), Christina Fasching (1), Amber Ulseth (1), Tom Battin (1,2,3)

(1) Department of Limnology and Bio-Oceanography, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria, (2) WasserCluster Lunz GmbH, Dr. Carl Kupelwieser Promenade 5, 3293 Lunz am See, Austria, (3) Ecohydraulics Lab, Ecole Polytechnique Fédérale de Lausanne, CH - 1050 Lausanne, Switzerland

In-stream bodies of fluvial sediment such as gravel bars (GB), form an active interface between streamwater and the adjacent groundwater body. The hydrodynamic exchange, that is, the varying contributions of different water sources to this mixing zone, control the GB physical and biogeochemical conditions, including water temperature, as well as nutrient and carbon availability, likely impacting carbon turnover. We present high frequency data for hydraulic head and water temperature in addition to event based measurements of electric conductivity, nutrients and dissolved organic carbon (DOC) concentration and composition within a GB of an Alpine cold water stream (Oberer Seebach, Austria) for a range of different flow conditions. The highest vertical temperature differences and hydraulic head variability occurred at the head and shoulder - largest raised area perpendicular to surface water flow (downwelling) and tail (upwelling) of the gravel bar. At baseflow, high spatial variability of temperature (up to 4˚C difference among sites within the same horizontal plane) and hydraulic head was observed within the GB. In contrast, floods resulted in markedly lower overall hyporheic zone temperatures (average 2˚C difference among sites within the same horizontal plane) and spatial hydraulic head variability, compared to baseflow conditions. Similarly, the relative difference between surface water and GB nutrient and DOC concentrations and the overall spatial variability within the GB decreased with increasing surface water discharge. For example, at baseflow surface water average DOC and nitrate (NO_3) concentrations were 1.40 $mgL^{-1}$and 810 μgL^{-1}respectively, and 1.97 mgL^{-1} and 779 μgL^{-1} respectively at intermediate flow. Meanwhile, DOC and NO_3 concentrations in the GB ranged from 1.40 - 3.60 mgL^{-1} and 150 – 950 μgL^{-1}respectively during baseflow and 1.48 -2.25 mgL^{-1} and 560 –840 μgL^{-1} respectively during moderate flows. Furthermore, DOC and NH_4 concentrations decreased and NO_3concentrations increased with depth in the GB. These results indicate a combination of shallow surface water downwelling and groundwater upwelling through the heterogeneous porous medium of the GB during lower flows and, increased downwelling of surface water and less groundwater contributions during higher surface water discharges. These flow dependent shifts in water sources are then likely to support high levels of biogeochemical activity and/or dilution of nutrient concentrations by increased downwelling of surface water during and after high flows. Overall our results demonstrate that the main drivers of biogeochemical turnover (flow regime, residence time, water temperature and DOC availability) within GBs vary for different flow conditions, suggesting GB to act as dynamic in-stream hotspots for carbon cycling.