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

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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 (NO₃) 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 NO₃ 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 NH₄ concentrations decreased and NO₃ concentrations 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.