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Summer is in winter: Disturbance-driven shifts in macroinvertebrate communities following hydroelectric power exploitation

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HIGHLIGHTS

- Alpine stream mitigation through e-flows might not work downstream of water intakes.
- Sediment accumulation results in the need to flush intake basins periodically.
- We hypothesis that sediment flushing controls habitat and macrofauna.
- We conclude that flushing inverts the expected summer-winter macroinvertebrate abundance.
- We question e-flow improvements unless accompanied by sediment management.

GRAPHICAL ABSTRACT

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ABSTRACT

In Alpine streams, humans have strongly modified the interactions between hydraulic processes, geomorphology and aquatic life through dams, flow abstraction at water intakes and river channel engineering. To mitigate these impacts, research has addressed both minimum flows and flow variability to sustain aquatic ecosystems. Whilst such environmental flows might work downstream of dams, this may not be the case for water intakes. Intakes, generally much smaller than dams, are designed to abstract water and to leave sediment behind. Sediment accumulation then results in the need to flush intakes periodically, often more frequently than daily in some highly glaciated basins. Sediment delivery downstream is then maintained through short duration floods with very high sediment loads. Here we tested the hypothesis that sediment flushing, and the associated high frequency of bed disturbance, controls in-stream habitat and macroinvertebrate assemblages. We collected macroinvertebrates over a 17-month period from an Alpine stream as well as a set of lateral unperturbed tributaries that served as controls. In contrast to established conceptual models, our results showed that the stream is largely void of life during summer, but that populations recover rapidly as the frequency of intake flushing falls in early autumn, producing richer and larger populations in winter and early spring. The recovery in autumn may be due to the recruitment of individuals from tributaries. We conclude that intake flushing in summer inverts expected summer-winter macroinvertebrate abundances, and questions the extent to which environmental flows

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in intake-impacted Alpine streams will lead to improvements in instream macrofauna unless sediment also is managed.

1. Introduction

The management of Alpine rivers requires the balancing of two competing uses: water supply for hydropower production and sustaining instream flora and fauna. Much attention has been given to securing both the sustainability of reservoir operations and improving aquatic ecosystems (e.g. WFD CIS, 2015) through flow regulation and environmental flows, so-called "e-flows". E-flows recognise the need for regulated streams to have not only minimum flows but also flow variability, including flow magnitude, frequency, duration, timing, and rate of change (Poff et al., 1997). In this context, ecosystem impacts downstream of dams have been widely studied (e.g. Ligon et al., 1995; Petts and Gurnell, 2005; Childs, 2010) to identify the volume of water that should be released downstream, and its variability, as a compromise between exploitation and ecosystem needs (King et al., 2003; Acreman, 2016). In contrast, there has been much less attention given to the ecosystem impacts downstream of water intakes (Gabbud and Lane, 2016). In sediment terms, dams are at one end of a spectrum of sediment disconnection: sediment tends to be retained behind a dam for a long time period, although occasional flushing may be required (a typical frequency of many years). Water intakes are at the other extreme. They are designed to allow the abstraction of water for within- or between-valley transfer by separating out sediment from water. They commonly have a smaller sediment storage capacity and need to be emptied more frequently in "flushing" events. In basins with high erosion rates, such as glaciated basins, flushing frequency may even be subdaily at certain times of the year. Flushes feed the river with solid material as well as the flow needed to evacuate the intake of sediment. However, after flushing, as abstraction recommences, sediment transport capacity is reduced. As waves of sediment move more slowly than waves of water, downstream locations typically receive a short duration flood with an exceptionally high sediment load (Petts and Bickerton, 1994; Lane et al., 2014) followed by deposition of sediment. The following flush may then erode some of this sediment, especially if the water wave becomes separated from the sediment wave within this following event, a probability that increases with distance downstream. This event-scale cycle of deposition-erosion in the short-term leads to net long-term river bed aggradation, notably in catchments with a high proportion of glaciation (Koppes and Montgomery, 2009; Lane et al., 2017; Bakker et al., 2018). The long term effect of flow abstraction coupled with continued sediment delivery leads to the accumulation of "legacy" sediment (James, 2013) and long-term bed level rise (e.g. Bakker et al., 2018). Unlike dams, intakes maintain sediment connectivity from source to sink (Lane et al., 2014, 2017).

Research has found that flushing may have a significant impact on downstream river morphology, habitat conditions (Kondolf et al., 2014; Wohl et al., 2015) and potentially flora and fauna. Both coarse and fine sediments can impact aquatic life (Jones et al., 2012) and both their excess and shortage can have negative impacts (Wood and Armitage, 1997; Milhous, 1998; Jones et al., 2012; Extence et al., 2013). For example, increases in fine sediment concentration in the river flow can trigger a suite of responses such as downstream invertebrate drift (Culp et al., 1986) in order to escape the negative effects of high turbidity (Ciborowski et al., 1977). This may cause a local diminution of invertebrate abundance and alter community composition (Ehrhart et al., 2002; Jones et al., 2012), allowing more resistant species to survive and more rapidly establishing species to quickly return. Whilst some macroinvertebrates have developed adaptations to disturbance (Matthaei et al., 1996), it appears that river morphodynamics that are slightly balanced towards erosion may allow sufficient transport and nutrient mixing to reverse fine sediment accumulation provided that there is not so much erosion that habitat is destroyed (King et al., 2003).

In glacier-fed rivers, macroinvertebrate assemblage composition varies seasonally, according to dominant water source (glacial, snowmelt and groundwater, respectively, kryal, nival and krenal systems (Ward et al., 1999; Füreder et al., 2001; Brown et al., 2003)). The hydrology of these systems leads to snow- and glacier-driven flood pulses (Malard et al., 2006; Cauvy-Fraunié et al., 2014). The origin of water, and these pulses, influence population dynamics (Malard et al., 1999; Brown et al., 2003; Gabbud and Lane, 2016). At high altitudes, macroinvertebrates depend more on channel stability, water source and temperature than on longitudinal trends due to altitude (Maiolini and Lencioni, 2001). Habitat diversity has been defined as maximal when these water sources are mixed (Brown et al., 2015).

Following from these hydrological observations, macroinvertebrate biomass, species richness and abundance tend to be higher in spring and autumn in nival systems (e.g. Burgherr and Ward, 2001; Füreder et al., 2001; Robinson et al., 2001; Schütz et al., 2001). For systems with kryal influence, these seasonal windows may be complicated because glacially-fed rivers commonly have summer water temperatures <10 °C (Milner and Petts, 1994) for some kilometres downstream from the glacier. They also may have a very distinctive sediment regime with particularly elevated suspended sediment concentrations in summer (Gurnell, 1987; Milner and Petts, 1994; Brown et al., 2003), relatively low organic matter supply and nutrient loading, and high rates of morphodynamic disturbance (Gabbud and Lane, 2016). Milner and Petts (1994) proposed a spatially-explicit conceptual model for glacier-fed streams that reflects this pattern, suggesting that the abundance and diversity of species tend to be low close to glaciers and increase with rising water temperature and increasing channel stability downstream. Individual species may differ in their adaptation to colder temperatures (Robinson et al., 2001) and it has been noted that higher macroinvertebrate abundance and diversity can be found at different times of the year, with taxa absent in summer being present during other seasons (Milner et al., 2001; Brown et al., 2015).

Hydroelectric operations associated with flow intakes may complicate this conceptual model for a number of reasons (see Gabbud and Lane, 2016). First, flow abstraction leads to long periods of minimum or no flows, depending on the policy regime in place in the basin (for instance, in Swiss streams, there remain examples where there is still no minimum flow applied). These periods shorten in duration as glacier melt increases, and it is necessary to flush the intakes with growing frequency. Second, flushes lead to short duration flow peaks with very rapid flow rise and fall (typically 15 to 30 min from minimum to maximum), more rapid than that associated with normal diurnal discharge rise and fall in glaciated basins (typically >6 h from minimum to maximum depending on catchment buffering effects). Third, these flow peaks are often accompanied by peaks in suspended load and bedload (Gurnell and Warburton, 1990; Lenzi et al., 2003), with peak sediment concentrations that range from 20 to 100 mg/l in the downstream channel due to water abstraction to concentrations >6500 mg/l directly below the intake during flushing (Gurnell, 1983). Fourth, the increased flow