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Abstract

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The natural flow hydrological characteristics (such as the magnitude, frequency, duration, timing and rate of change of discharge) of Alpine streams, dominated by snowmelt and glacier melt, have been established for many years. More recently, the ecosystems that they sustain have been described and explained. However, natural Alpine flow regimes may be strongly modified by hydroelectric power production, which impacts upon both river discharge and sediment transfer, and hence on downstream flora and fauna. The impacts of barrages or dams have been well studied. In such systems, sediment is commonly retained, except when the associated reservoir is flushed, which is generally a high impact but low frequency event. However, there is a second type of flow regulation, associated with flow abstraction. The abstraction occurs at intakes and the water is transferred laterally, either to another valley for storage, or at altitude within the same valley for eventual release downstream. Like barrages, such intakes also trap sediment, but because they are much smaller, they fill more frequently and so need to be flushed regularly. Downstream, whilst the flow regime is substantially modified, the delivery of sediment (notably coarser fractions) remains, reducing the rate of sediment transport and leading to downstream aggradation. The ecosystem impacts of such systems have been rarely considered. Yet, such consideration is needed because of the threshold-dependent, non-linear nature of sediment transport, which means that simply reintroducing elements of a natural flow regime (e.g. an annual spate flow) is unlikely to maintain the sediment transport rates necessary to prevent significant aggradation and hence reduce ecological impacts. Through reviewing the state of our knowledge of Alpine ecosystems, we outline the key research questions that will need to be addressed in order to modify intake management so as to reduce downstream ecological impacts. Simply redesigning river flows to address sediment management will be ineffective because such redesign cannot restore a natural sediment regime and other approaches are likely to be required if stream ecology in such systems is to be improved.

INTRODUCTION

Glacier- and snowmelt-fed rivers in Alpine regions are a critical resource for hydroelectric power production. There are at least three kinds of water management systems found in such regions: (1) water impoundment behind barrages or dams within a valley; (2) water abstraction from within a valley followed by lateral transfer to a second valley, to increase the production capacity within the second valley; and (3) water abstraction from within a river, followed by down valley transfer at altitude, to create a high hydraulic head, before the water is returned to the same river further downstream. All three systems impact downstream river flows. But they also impact upon sediment transfer, disrupting the natural sediment 'conveyor belt': the source to sink transfer of sediment, as determined by erosion, abrasion, sorting, and deposition[1]. The impacts of such flow and sediment disruption upon downstream river channel morphology and ecology have been extensively studied in relation to the effects of water impoundment behind dams[2,3,4,5]. However, water abstraction and lateral or downstream transfer has been less intensively studied. Abstraction systems differ from dams in one crucial sense: the reservoirs created by dams trap sediments behind them; and sediment is only released when flushing is deemed to be necessary, normally with a return period of some years. The abstraction of water takes place at intakes, which are much smaller than most dams (Figure 1). Thus, their capacity to retain sediment is reduced and they have to be flushed almost completely at a much higher frequency than dams. In Alpine glaciated basins, this frequency may be high for two reasons: (1) natural river flows typically have a diurnal discharge variation linked to solar forcing, such that during summer months there may be many days when sediment transport can occur and sediment can be delivered to intakes; and (2) glacial basins commonly have high rates of erosion[7]. The result is high sediment delivery rates to the point of flow abstraction. Sediment transport is commonly a non-linear function of flow exceedance above a critical threshold. By abstracting flow, there may be a significant reduction in sediment transport capacity, even if periodic flushing maintains sediment delivery. Theoretically, this should lead to a reduction in the rates of sediment transfer downstream of abstraction intakes, and so result in channel aggradation.

It has been shown that the hydrological impacts of flow abstraction on ecosystems can be reduced through a properly designed compensation release[8,9,10,11,12]. Constant minimum flows have been widely shown to be inadequate for triggering and sustaining the range of life cycles and species interactions characteristic of natural, healthy, aquatic ecosystems: the importance of flow variability, including extreme river flows is now recognised[13,6,14,15]. However, in flow abstraction systems, an additional and relatively overlooked issue becomes important: sediment management. Ultimately, sediment erosion, transport and deposition determine the structure and dynamics of river habitat[16]. Theoretically, and in parallel with what we know about the ecosystem impacts of flow abstraction, instream minimum flows are likely to be too low to transport sediment (notably coarse sand and coarser fractions). This suggests that at least some more extreme flows will be needed. However, whilst introducing a single or a small number of extreme flow events may trigger certain desired ecosystem responses[17], total sediment transport will be the integration through time of all flow events that are sufficient in magnitude to transport sediment. Most of these are removed in flow abstraction systems.

At present, the management of sediment is rarely considered in legislation designed to create more environmentally sustainable river flows[16]. This is a particular problem for water intake systems where there are almost no experiments, and hence scientific bases, that might be used to define the kinds of instream flow needs necessary to manage sediment and to secure an improved river ecology. Thus, the aim of this paper is to review the hydrological, geomorphological and ecosystem impacts of Alpine water transfer systems. We do this through a synthesis of what we know about the hydrology, geomorphology and aquatic ecology of natural Alpine streams as a means of identifying possible impacts and the research questions that arise if we are to introduce sediment considerations into intake management.

THE SPATIAL AND TEMPORAL HABITAT TEMPLATE ASSOCIATED WITH NATURAL ALPINE STREAMS

In order to have a baseline against which to assess the impacts of flow abstraction upon stream ecosystems, it is necessary to identify the basic spatial and temporal habitat template, and controls upon this template, associated with Alpine streams. Our review shows that these streams have particular hydrological, water quality and geomorphic characteristics that create a very particular spatial and temporal habitat template.

The flow regime of snowmelt- and glacier-fed Alpine streams

It is well established that the flow regime (its magnitude, frequency, duration, timing and rate of change of hydrologic conditions), exert a critical control upon fluvial ecosystems[18,19,8,14]. The natural hydrological characteristics of Alpine snowmelt- and glacier-fed streams have been established for many years. Generalising these characteristics requires consideration of basin hypsometry (the altitudes over which the basin is distributed), the percentage of the basin that is glaciated, and basin slope and aspect. Such variables may be inter-related: for instance, north-facing basins in the northern hemisphere are likely to be more able to accumulate ice than south facing ones. Weingartner and Aschwanden (1994)[20] provide such a basic hydrological generalisation of Alpine streams (Table 1). The critical element in Table 1 is the mean altitude, which determines when in the meteorological year runoff begins as well as the percentage of the basin that is glaciated. The latter determines the extent to which there is a potential stock of water stored in the basin through the summer months that can sustain river flow. As both the basin altitude and the percentage of the basin that is glaciated decrease, the dominant runoff months shift from mid summer towards spring. With more glacial regimes, there tends to be greater inter-annual variability in the late spring and early summer, which relates to the variability in the timing of the end of snow accumulation and the onset of snowmelt. With more nival regimes, there tends to be higher inter-variability in mid summer, because of inter-annual variability in the extent to which snow remains in the basin and so is available to maintain river flow.

Figure 2 shows two example hydrographs for the extremes of Table 1 (one glacial basin and one nival basin), for the year 1989. The nival basin is dominated by snowmelt which occurs throughout the spring, but which decreases markedly from the end of May. From June, flows are sustained by snowmelt from the very highest parts of the basin plus a small glacier. Throughout the season, it is possible to see very small diurnal fluctuations in river discharge associated with snow and ice melt. By contrast, the glacial system is associated with negligible discharge until late in the month of May, when there is a very small snowmelt peak. From mid June, discharge rises, with very marked diurnal fluctuations, which progressively grow in magnitude. They are maintained until the end of September, and it is noticeable that the baseflow upon which they are superimposed progressively decreases. The latter relates to the particular hydrology of glaciated catchments, both progressive snowline recession which reduces surface albedo and increases the sensitivity of melt to incoming solar radiation, and progressive development of a more efficient subglacial drainage system[21] that reduces the attenuation of surface melt.

Physical and biochemical characteristics of river flow

These hydrological classifications are insufficient to understand the controls upon Alpine stream ecology, but they underpin consideration of the key physical and chemical characteristics of Alpine streams, which in turn impact upon stream ecology. Temperature, sediment load and specific conductance usually constitute the three basic physico-chemical parameters for classifying Alpine streams[22]. Given the particular hydrological characteristics described above, Alpine streams tend to have very particular temperatures, sediment loads and specific conductance, such that they can be considered as a category in themselves, especially if glacially dominated[23]. In addition, they tend to have characteristic morphodynamics, that follow from their altitude (such that they are often close to the limits of vegetation growth), the abundance of sediment due to rates of periglacial and glacial erosion, and the effects of water release from snow and ice stores which creates periodic high flows at both the seasonal and daily time scales (Figure 2).

In ecological terms, temperature is commonly identified as the primary parameter in controlling freshwater ecosystems[24,23,25,26,27,28] as it controls growth rates, timing of life cycles and rates of primary and secondary production[24,29]. Typically, glacier-fed rivers have summer water temperatures lower than 10°C[22] and between -6.5°C and -18°C for the rest of the year[30,31,32]. Generally (although not exclusively) and related to the altitude, the temperature varies as a function of the source of water, that is the relative proportions of glacial meltwater, snowmelt and groundwater, which typify respectively kryal, nival and krenal stream systems[22,25,33,34,35,36]. With distance downstream from a glacier terminus, the relative proportion of the kryal contribution will decrease and the krenal contribution will increase[37]. As Table 1 shows, and according to basin altitude, the nival contribution will complicate this spatial pattern as it will commonly vary as a function of time: in the spring (according to the altitude of the basin), the nival contribution will dominate over both kryal and krenal contributions; but it will decrease through the summer until the autumn when there may be no or only a small amount of nival contribution. The spatial pattern may also be complicated by the supply of water from tributaries that may be kryal, nival or krenal dominated. The net result is a spatial template or gradient of stream temperature, that is dynamic, and which is of major importance for Alpine stream ecosystems (see below). It is this template that may change substantially as a result of flow abstraction. For the time being, there has yet to be a mapping of the hydrological classification shown in Table 1 to include stream temperatures, mainly because Table 1 makes no reference to groundwater contributions. Such a classification is likely to be of value for better defining the expected ecosystems to be found, and so for judging the impacts of flow abstraction.

Studies of Alpine stream ecosystems have also shown that the spatio-temporal variability in temperature needs to be combined with consideration of sediment in order to classify the ecosystem characteristics of Alpine streams[38]. In particular, basins with a glacial or glacial-nival regime may have high turbidity, often in excess of 30 NTU, reflecting the effects of glacial abrasion[39,22]. The characteristic concentration of suspended sediments in glacial streams is between 500 mg/l and 2000 mg/l during the early summer melt period and then decreases to around 20 mg/l from autumn onwards, for the rest of the year[22]. High summer turbidity may significantly reduce light penetration to the stream bed[40] which when taken with high rates of streambed erosion and deposition, may slow organic matter production and accumulation, and so impact upon stream ecology. As with temperature, this temporal variability can also be expressed spatially and Smith et al. (2001)[37] report systematic decreases in maximum and mean suspended sediment concentrations with distance downstream of a Pyrenean glacier.

The typical conductivity of glacial melt water is low, often less than 10 µS/cm, and remains less than 50 µS/cm even if the stream water is ionically enriched[41,22]. However, as with temperature, krenal contributions may cause conductivity increases[42] either spatially, where there are significant groundwater inputs, or temporally when kryal and nival contributions are lower. Similarly, kryal dominated periods commonly may have lower organic matter and nutrient loadings such that it is possible to identify two windows of conditions when krenal conditions become more dominant and which are more suitable for ecological processes[43,44]: an expansion period in the spring (when the percentage of the catchment that is not frozen is increasing); and a contraction period in the autumn (when the percentage of the catchment that is not frozen is decreasing). These periods have been associated with increased macroinvertebrate density and taxon richness[45].

It follows that a classification of streams into kryal, nival and krenal is unlikely to be sufficient for describing the expected habitat template of Alpine streams: it is crucially important to consider their temporal variability following from the evolution of dominant hydrological flow paths within and between seasons. Thus, Brown et al. (2003)[38] divide this three fold classification into nine sub categories, allowing for the relative contributions of each possible source, and emphasising the need to quantify how this variability evolves through time within the melt season, as well as how it changes with distance downstream. This classification provides a more robust means of identifying the expected baseline habitat template for Alpine streams against which flow abstraction can be assessed. However, it needs to be linked to the kinds of classifications in Table 1, such that it is possible to identify which categories and sub-categories could be found and where within Alpine river basins.

Linkage to stream morphodynamics

In addition to the template created by physical and biochemical characteristics of Alpine streams, it is necessary to add the consideration of stream morphodynamics. It is well established in Alpine streams that hydrological variability plus a high sediment load interact with the stream bed and floodplain morphology to determine fluvial ecosystem diversity and complexity over a range of timescales[46,37,38,47]. Crucially, vegetation characteristics, sediment abundance and variable hydrological characteristics tend to make Alpine rivers geomorphically unstable[48,49,50,51]. However, as with the hydrological and biochemical variability, there is commonly a transition in the morphodynamic regime from upstream to downstream[52] with: (i) relatively vegetation free and more braided sections at altitude, close to either major sediment supply sources or a glacier; (ii) a transitional zone; and (iii), at lower altitudes, more stable single or multithread zones with increasing control by riparian vegetation. The river geomorphology that results interacts with hydrological characteristics to determine local spatial diversity and temporal variability in parameters that are key to the physical habitat of the river (e.g. flow velocity, flow depth, grain size, temperature, stability, deposition), which in turn influence physical habitat diversity and possibly ecological richness[53,54,55,56]. Provided they are not heavily engineered, Alpine streams commonly contain a range of velocities, depths and grain sizes such that they are physically diverse. However, they do tend to be unstable, slowing vegetation establishment, and often leading to repeated perturbation of the streambed. This may impact the streambed habitat negatively (burial, scour) but also positively, through reducing colmation or by the winnowing of silt and fine sand. As with hydrological and biochemical processes, there may also be a marked spatial evolution in streambed stability. With distance downstream from a glacial source, for instance, there will be flow attenuation. In the absence of tributary inputs, this will imply a progressive decrease in peak discharge downstream, and so reduced propensity to erosion and sediment transport, and greater stability. However, tributaries will counter this, supplying both water and possible sediment[32], and the river basin has to be considered as a morphodynamic network[57]. In addition, the lateral space available to the river (its ‘accommodation space’) and the longitudinal bed slope will determine the width of the river’s active zone as well as its transport capacity, such that there may be substantial exogenic forcing: of sediment erosion, transport and deposition; and hence of river channel morphological diversity and associated physical habitat. The key point is that there will be a natural, spatio-temporal gradient of morphodynamics onto which flow abstraction will be superimposed, and which needs to be defined before trying to quantify abstraction impacts or to suggest remediation measures.

Biotic interactions

In addition to hydrological, biochemical and morphodynamic variability, biotic interactions, notably in relation to food availability, will regulate ecosystem diversity. In this sense, Alpine streams are no different to other aquatic environments. Competition, producer-consumer and predator-prey interactions have been shown to influence the community diversity and abundance in Alpine streams[38]. Both pollen transported by wind[23,25] and allochthonously-sourced organic matter[58,59] have been identified as major determinants of food availability, although it is now recognised that in Alpine streams food sources are more diverse than were originally imagined[60,61]. Dominant food sources may be epilithic diatoms and filamentous algae[25,62,63,26,64,61]. Reflecting the physico-chemical and morphodynamic gradients described above, and notably a progressive increase in river channel stability and suitability for primary productivity, algal biomass, and in particular bryophytes, commonly increase with distance downstream from a glacier[65]. Algae have the capacity to fix fine particles of organic matter[66,67], and this varies seasonally[68] with higher biomass during less perturbed periods[43,40,64].

The resulting aquatic ecosystems in Alpine streams

Following the hydrological, biochemical, morphodynamic and biotic elements described above, it is possible to outline the key elements of aquatic ecosystems in Alpine streams. At the outset, it is important to note that these are highly dynamic in time. The expansion and contraction periods described above, coupled to lower sediment loads and less morphodynamic disturbance means that biomass development tends to be higher in the spring and the autumn, so leading to a greater species richness and abundance[45,36,40,64]. However, as we review below, certain species are more adapted than others to summer conditions and may thrive throughout the melt season.

In terms of macroinvertebrates, some key generalisations can be made. For instance, in European glacially-fed river systems, *Plecoptera*, *Chironomidae*, *Ephemeroptera*, *Simuliidae*, and *Diptera* are the main taxa found in spring as they are better adapted to cold conditions[24,23,69,70,42]. Their abundance increases through the summer with a particular density augmentation of *Diptera*, *Plecoptera* and *Chironomidae* as they have life history strategies that allow them react to unstable stream conditions or are able to escape these conditions by prolonging their larval development during the more stable periods before and during the winter[64,42]. *Chironomidae* stay dominant also during autumn and winter[72,40].

The glacial signature influences mainly the upstream part of the river, closer to the source. Thus, diversity and abundance tends to be low close to glaciers[71] and the living conditions improve downstream[72]. Milner and Petts (1994)[22] proposed a typical species scheme for glacier-fed Rivers (Figure 3) that reflects the ideas presented in Gurnell et al. (1999)[52] that such streams become more stable with distance downstream, with a progressive increase in water temperature and with both a progressive shift in the dominant macrofauna, the number zoobenthic taxa and the total zoobenthic biomass. However, Robinson et al. (2001)[40] showed that cold-adapted macroinvertebrates were also found close to the glacial source.

Fish are the second ecological group commonly used as ecological indicators because of their specific needs and because they are commonly at the top or close to the top of the instream food chain. Given Alpine stream temperatures, there is a particular need to focus on cold water species[73], such as salmonids, which are often taken as signature species in Alpine streams[74]. In relation to temperature, most fish species have a limited range of tolerance. For instance, *Salmo trutta* cease growing at temperatures less than 2.9 to 3.6°C[75]. As with macroinvertebrates, the distribution of temperature in space, notably is downstream increase, and its variability in time will determine suitable habitat. The high turbidity of such streams may present a natural limit upon salmonid presence but this is complicated by the fact that both suspended sediment concentration and exposure have to be considered[76]. However, in glacier-fed systems, characteristic concentrations may be greater than 500 mg/l for many days[77], leading to long-term exposure to concentrations that may reduce growth rates substantially[76]. Acute toxicity levels for *Salmo trutta* are thought to be 1,700 mg/l at 96 hour exposure and some glacial streams can approach these values[77]. However, suspended sediment concentrations may undergo rapid downstream attenuation, notably with kryal and krenal contributions from tributaries and/or groundwater, and so as with temperature, suspended sediment concentrations may rapidly decrease to acceptable levels. Nonetheless, it has been observed that salmonids are more common in unglaciated tributary streams or in floodplain ponds[78] where turbidity is lower. The final parameter that may be important is morphodynamics, both erosion and deposition. For salmonids, erosion can lead to destruction of redds and loss of eggs[79] although this process is poorly quantified in Alpine streams[76]. Deposition, notably associated with high suspended sediment concentrations, may negatively impact upon spawning habitat (see Scheurer et al., 2009[76] for a more detailed review). These observations aside, compared with macroinvertebrates there has been less research into the distribution of fish populations that might be expected in glacier-fed Alpine streams. In Alpine streams that are more dominated by snowmelt, valuable reviews do exist[76], but research is needed in a wider range of systems not least given possible sensitivity of Alpine streams to climate warming, which may mean that higher altitude streams become more suitable for cold water fish species[80].

Implications of this review

On the basis of this review, Table 2 provides key baseline references for further reading in relation to the key characteristics of natural Alpine stream aquatic ecosystems. The main implication that arises from the review is the notion that in any stream, there will be a spatio-temporal variability in stream flow and biochemistry, morphodynamics and biotic interactions. We would expect there to be a downstream evolution or spatial gradient in stream temperature, fine sediment load, dominant water sources including nutrient supply and channel stability. Superimposed upon this spatial gradient will be a temporal variability such that ecological processes may be markedly more active at certain times of the year than others (e.g. spring and autumn). The result will be a natural spatio-temporal variability in the resultant ecosystems in any Alpine stream system unimpacted directly by human activity.

Two key implications arise. First, designing research programmes to quantify abstraction impacts must be sensitive to what might be expected, ecologically, where and when. At one scale, it probably requires development of stream classification tools for more than just the kind of hydrological characterization shown in Table 1, to include groundwater assessment and to capture temporal variability[38,83]. Such large-scale classification may need to be accompanied by more local scale and detailed analysis of the characteristics of a particular basin, including downstream changes in: the proportions of kryal, nival and krenal sources; flow attenuation and tributary impacts; sediment supply and sediment transport; and channel morphodynamics, including accommodation space and valley slope. It may be aided by some of the classic studies of the biochemical and physical template of natural Alpine stream systems, such as the long term Val Roseg study in Switzerland[43], which may in turn define natural templates; or by conceptual models of downstream evolution of Alpine stream ecosystems[26,28]. Abstraction impacts then need to be described with respect to how this natural template has changed, perhaps aided by longitudinal analyses of historical datasets[72], or by combining more readily available historical data (e.g. on river flow before and after abstraction, historical channel morphology, Lane et al., 2014[84]) with habitat modelling.

Second, the description and explanation of Alpine stream ecology above places a primary emphasis upon the flow regime of the system. Initially, this would suggest that managing the impacts of flow abstraction would need to address basic instream flow needs, as is widely established for streams in general. However, in the next section, we show that a primary impact of flow abstraction is upon the sediment regime that, as the discussion above implies, is also an integral driver of Alpine stream ecological processes. At present, for flow abstraction systems, we do not have the guidelines necessary to identify the flow regimes that would deliver a more natural sediment regime, nor studies that can demonstrate the impacts of introducing a more natural sediment regime upon instream ecology. Thus, the next section sketches out key research questions that follow for reducing the ecological impacts of Alpine flow abstraction.

IMPACTS OF FLOW ABSTRACTION THROUGH INTAKES

The aim of this section is to consider how flow abstraction through intakes may impact upon Alpine stream ecology. We do this in two steps. First, we review the likely changes in physical habitat that might arise from flow abstraction and what this could mean for instream ecology. We do this by drawing upon the evidence contained in studies of low flows, impoundments, etc. which provide some analogue for intake impacts. Second, we consider the impacts of intake management, notably sediment flushing, which is on the one hand a type of spate flow and so potentially beneficial, but on the other hand may lead to high sediment loading to the river reaches downstream of intakes. This leads into a final discussion of the research questions that need to be addressed if we are, as Wohl et al. (2015)[16] recently advocate, to reintroduce effective sediment management into the design of more ecologically sensitive flow abstraction. We emphasise that we focus here on intakes that are primarily associated with hydroelectric power generation because they are the dominant intakes found in Alpine environments. They have a particular characteristic: because the volume of flow abstracted defines directly the hydroelectric power generation potential, there is an incentive to abstract as much flow as possible, leaving either no flow, or a statutorily-required residual flow.

Impacts of flow abstraction on physical habitat

We showed above that the flow regime of Alpine streams is a key driver of their physical habitat[85,86,87]. Alteration of the flow regime will induce physical habitat change and possibly degradation, and this is often claimed as the most serious and continuing threat to fluvial ecosystems[88,89,86,82,90,91]. The primary physical impact of water abstraction is a change in the flow regime due to a reduction in the water availability. Channels that may have been previously permanently or occasionally inundated become generally dry except where there is input from unregulated snowmelt, rainfall and groundwater[92], or compensation releases. Decreased discharge causes decreases in water velocity, depth and wetted perimeter[89,94,95,96,97,98].

A series of other impacts on physical dimensions of habitat should then follow. Few of these have been based upon direct study of intakes, but rather they follow from studies either of drought related low flows, or flow impoundments. First, it is likely that temperatures will increase[99,100,101,102]. It follows from the above that this increase is likely to be relatively greater close to the intake where there will have been the smallest opportunity for recharge by tributaries or groundwater.

Second, if there is reduced dependence upon glacial flows and greater recharge from nival or krenal flows, then suspended sediment concentrations may reduce[103,104]. We show below, however, that this may be countered by short term but rapid increases in suspended sediment concentrations associated with intake flushing. Third, and in contrast, there may be a substantial reduction in sediment transport capacity downstream of the intake with a shift towards bed sedimentation if sediment delivery is maintained[105,106].

Fourth, an increase in the proportion of groundwater flow may also: induce lower or higher nutrient levels, depending on the geology[103]; increase electrical conductivity depending on the solute-richness[102]; and/or increase pH[107].

Ecosystem response that might follow from flow abstraction

Such changes in flow conditions can significantly influence habitat, which in turn impacts ecosystems. First, riparian vegetation may be affected as the relative proportion of groundwater contributions are increased. Conditions may become more suitable for algae[44,108]. Macrophyte patches tend to be more prevalent where disturbance frequency and intensity are lower[109,110,,82]. Vegetation colonization of the riverbed and banks may stabilize morphology.

These functional changes may then impact upon elements of instream ecology such as macroinvertebrates and fish, in theory at any life stage as well as at all spatial scales[111,89,82]. Because of their high sensitivity to changes, their narrow range of tolerance and their low regeneration capacities, aquatic species have to develop adaptation strategies rapidly to survive these substantial stream flow alterations (see Bunn and Arthington, 2002[82] for a review). However, the rapidity of habitat changes may be problematic as they commonly occur at rates greater than those of adaptation.

Whilst several researchers have suggested that the more frequent the disturbances, the greater the species diversity[112,113,13], the vulnerability of macroinvertebrates to rapid changes has also been demonstrated[114,115]. Most authors agree that there is a decrease in macroinvertebrate density in response to flow decreases[116,101,117,96,118]. However, density increases have been detected in some cases[119,108] but they seem to occur when the flow is reduced to a lesser degree[98]. As an example, Rader and Belish (1999)[102] observed that the mean species density augmented by 57 % downstream of a minor diversion but declined by around 50 % downstream a more severe flow reduction. Taxonomic richness should also diminish with water abstraction (e.g. see the review in Dewson et al., 2007[98]). Changes in diversity are likely because changes in the physical habitat may be more tolerable for some species[120] or more preferable for others, e.g. those that prefer in slower water velocity[121].

But the impacts are likely to be quite complex because of the range of changes in other parameters that might also follow (e.g. in nutrient availability and organic matter) and also because of changes in biological processes. These might include competitive interaction[122]. Equally, whilst flow abstraction may make some locations less suitable for a given species, others may become more suitable: that is the spatial organisation of stream may change; patches of lower velocity may be created and cause a part of the lotic habitat to be transformed into a more lentic habitat[123]. Similarly, connectivity between habitats, essential for drift, migration, exchanges or recolonization[124,125,82,126,127] is often interrupted. Thus, the impacts of flow abstraction are likely to be much more complex than those that are suggested by direct changes in habitat (e.g. velocity, flow depth, stream temperature). It remains a key challenge to be able to quantify the relative importance of flow intake impacts upon wider ecosystem processes, going further than the more readily quantified impacts of flow abstraction upon physical habitat. The latter are more readily quantified using habitat modelling methods; the former remain a fundamental research challenge.

The problem with these observations of ecosystem responses, unfortunately, is that either: (1) they are based upon analogy with non-Alpine systems and so do not necessarily represent the specificity of Alpine streams described in the first part of this paper; or (2) they have focused upon impoundments rather than flow abstraction systems, even if the latter are proportionately more prevalent in Alpine environments. Thus, although there may be some analogies to be made with the impacts of hydropeaking[128,129,130] and reservoir overspills[131,132] on Alpine stream ecosystems, there have been very few studies of intakes associated with hydropower schemes. The main exception in an Alpine setting is Petts and Bickerton (1994)[72] who showed that the sensitivity to flow abstraction was conditioned by recharge from unregulated tributaries. They identified that the impacts of flow regulation were countered by the critical influence of macroinvertebrate ‘recharge’ by tributaries: almost 60 % of the communities found along the Borgne d’Arolla were associated with lateral inputs. This high source of tributary-driven main-channel colonization confirmed the critical role played by unregulated tributaries in countering the direct impacts of flow abstraction.

In the next two sections, one concerned with the short term and one with the longer term, we argue: that sediment impacts upon ecosystems may be significant over both the short term and the long term, notably in catchments with a high proportion of glaciation; that this has rarely been considered in any research projects looking at Alpine flow abstraction impacts; and that identifying a suitable sediment management regime must become an integral part of designing ecologically sustainable flows in abstraction systems.

Impacts of sediment releases: short term

Alpine river basins commonly have high erosion rates or have substantial accumulations of sediment due to historical periglacial and glacial activity. Sediment mobilisation is aided by high relative relief and relatively under-developed vegetation that reduces root cohesion[113]. Thus, sediment delivery rates to Alpine streams are commonly high. In order to abstract flow efficiently, flow intakes commonly span the river width. To aid flow transfer, sediment needs to be retained, and this accumulates in the intake. As the intakes commonly have a relatively small sediment storage capacity, they have to be emptied periodically. Figure 4 shows the discharge: (1) delivered to the intake for the Haut Glacier d’Arolla (Valais, Switzerland) in 1989, as an example; and (2) downstream of the intake. Comparison of (1) and (2) shows that most of the flow is being abstracted but that flushing leads to a periodic release that for a very short duration almost mimics the natural flow regime, both in terms of magnitude and rate of change. In Figure 4, flushing is rare in the spring, and then increases in frequency notably during July and most markedly during August, except for a period of low flows in early August. In more general terms, these patterns reflect: (1) a progressive increase in discharge peak magnitude, coupled to the fact that sediment transport, and hence sediment delivery, is commonly a non-linear function of flow; (2) the development of a more efficient subglacial drainage system better able to evacuate sediment from the bed; (3) the effects of short periods of colder and/or wetter weather, which can substantially reduce flushing frequency.

Crucially, this system already has what might be called ‘spate’ flows and shows that introducing more spate flows should not really be an objective of designing a more sustainable environmental flow. Rather, as the graph shows, there may be a case for some kind of minimum flow.

However, such a conclusion is not necessarily correct because it fails to consider sediment. Between spates or purges, suspended sediment concentrations downstream tend to be reduced. Petts and Bickerton (1994)[72] showed that downstream of the lower Bertol intake, in Switzerland, peak sediment concentrations passed from 2000 mg/l to 20-100 mg/l downstream after water abstraction. However, the purges or spates can generate extreme sediment pulses, of more than 6500 mg/l immediately below the intake[92]. The pulses include both coarse and fine material.

Close to the intake, this should lead to temporarily high sediment loads and possibly substantial channel activity. But, the duration of a pulse is relatively short. Thus, the flow, sediment and channel change impacts should attenuate with distance from the water intake, either as a result of kinematic effects (flow and sediment attenuation, plus the lower speed of translation of sediment waves as compared with flood waves) or because of accrual of flow from unregulated tributaries[72,58,133,134]. Attenuation means that the duration of transport during a spate is reduced with distance downstream and so sediment will be deposited[135,84].

The sediment releases are a form of perturbation and research in other systems has shown that perturbations can have a positive effect on aquatic ecosystems. Within year changes in flow or sediment regime may trigger certain life stages[14] or transport organic matter to resource some habitat[136,137,138]. Fish also depend on flow regime modifications for most life stages[139,89]. The question that arises is whether or not these conclusions can also be transferred to the perturbations in flow abstraction systems, given the very high sediment loading associated with them. On the one hand, high sedimentation rates reduce habitat availability[140,141,142,143]. On the other hand, high erosion can destroy the stream bed[144,145,146]. A little more erosion than deposition may allow sufficient transport: (i) to flush suspended sediments which tend to cause problems of vision or choking for fish; (ii) to sweep silt and fine sand from the stream bed, so improving spawning; (iii) to sweep gravel that fills refugia; (iv) to distribute organic matter and finally (v) to scour channels so forming pool habitat[147,148,149,150,151]. However, given the sediment loads associated with releases, these conditions are unlikely to be realised. Research in other systems has shown that in the short term, high turbidity flow events are likely to cause low species diversity and abundance whether in terms of riparian vegetation[152] or aquatic invertebrates[114,115,71]. Critical here are the associated increases in suspended sediment concentrations which reduce light penetration, whilst bed instability and fine sediment deposition destroy available habitat[22,65].

Impacts of sediment releases: long term

Because the number of spates is always less than the number of peak daily flows (Figure 4) and because sediment delivery downstream of the intake is maintained, there will be a net reduction in sediment transport capacity[6,84] and in typical daily sediment transport distances[153] downstream of the intake. The deposition will start to fill the channels vertically and there should be lateral expansion of the zone of deposition until saturation of the available accommodation space[154,155,134,153]. Subsequent purges may remobilise this material[156] but the duration of remobilisation will be commonly much shorter than the duration of mobilisation under natural flows. Hence, the aggrading zone will migrate downstream. This migration will not occur uniformly, but is likely to be lagged in time and space as a propagating sediment wave[157]. Downstream attenuation of sediment waves has been noted by Pickup et al. (1983)[158] and Hey (1979)[159], and attributed to selective particle transport, although this has not been clear in all surveys[157].

In terms of the morphological response, after the start of intake operations, upstream reaches close to the intake may be unstable, with substantial aggradation, but sediment delivery rates to downstream reaches decrease. In a study of one such system, Gurnell (1983)[92] describes that 20 years after the onset of flow abstraction, the river reach 2 to 6 km downstream of the intakes had witnessed marked vegetation encroachment as a result of bed stabilisation. However, it is now clear that this was caused not by the permanent storage of sediment upstream, but by a progressive reduction in the rates of delivery of sediment to these reaches. By the late 1980s and the late 1990s, sediment was being delivered again and these reaches had become subject to marked sediment aggradation, and associated vegetation die back[84]. Thus, in terms of channel response, there may be substantial downstream lags in channel morphological response to the sediment transfer process.

The key point from this discussion is that unlike the case with most dams, abstraction of water at intakes does not eliminate sediment connectivity, rather it reduces its intensity, having profound hydrogeomorphic impacts. In turn, the extreme rates of sediment deposition that result[84] should have major ecosystem consequences: as the sediment wave arrives, the system which has become relatively stable since abstraction has begun, possibly with vegetation encroachment, will become dynamic, with a continuous morphological response of channels, modifying refugia, spatial structure and habitats constantly, and impacting upon ecosystem productivity and diversity. Thus, improving understanding of the long term effects of sediment waves in Alpine streams associated with flow abstraction is going to be crucial to inform strategies designed to reduce the ecosystem impacts of flow abstraction.

THE CHALLENGE OF INTRODUCING A MORE NATURAL SEDIMENT REGIME

The above discussion emphasises a key issue for the management of Alpine flow abstraction systems that are associated with periodic flushing: it is vital to factor the impacts of abstraction and intake management upon the sediment regime that results. To date, the research base needed to do this is extremely poorly developed. Earlier in this review, we identified the need: (1) to develop conceptual models of those ecosystems that might be expected on the basis of river basin characteristics, including their spatial variability and temporal dynamics; and (2) to develop guidelines that might assist in restoring a more natural sediment regime. This section addresses this second challenge.

It is commonplace for regulated rivers to have proscribed flow regimes that can deliver a more natural flow, including at least some temporal variability. It is very rare for there to be any kind of proscription of a sediment regime[16]. With flow intakes, the critical problem is that the capacity-supply ratio (CSR), the ratio of the time-integrated sediment transport capacity to the time-integrated supply[160], becomes very low, leading to substantial sediment accumulation. The introduction of a residual or minimum flow, such as the 0.95 discharge excedance probability (or 5 % flow), will not change this CSR much, if at all, because sediment transport is commonly a non-linear function of the excess of flow (e.g. discharge) over a critical value (e.g. the critical discharge). Figure 5 shows modelled values of critical discharge calculated for different grain sizes and bed slopes. Also superimposed are flow exceedance probabilities, calculated for 1 May to 30 September 1989 for the natural flow regime and that after abstraction shown in Figure 4. First, calculation on the May to September period only emphasises that Alpine streams will need special regulations for minimum flows, as the 5 % flow calculated on the whole year may be negligible, because of near zero winter flows. Second, even if calculated on May to September, Figure 5 shows that the critical discharges, even with steep slopes and relatively small median grain sizes (0.04 m) are substantially greater than the 5 % flow (0.95 exceedance probability). Reinstating a minimum discharge based upon criteria used as standard in other rivers will not impact sediment transport. Even reintroducing a 50 % flow will not impact upon sediment transport for median grain sizes greater than 0.10 m for any of the slopes considered here. Third, there is a very strong grain size and slope effect such that reinstating a flow to achieve sediment transport will need to consider the downstream attenuation of that flow in relation to bed grain size and slope.

In summary, introducing a more natural sediment regime is going to require more attention to be given to higher flow percentiles, and not simply some combination of low flows plus occasional spate flows, something that it likely to impact the economic viability of many hydropower schemes. It may also lead to severe and substantial downstream impacts because the long term effects of low CSR values will be substantial in-channel sediment accumulation downstream of intakes[84] what James (2013)[162] calls 'legacy sediment'. The system is unlikely to become limited by supply whatever the capacity increase might be, leading to short term rates of sediment transport downstream that are greater than those that could occur under natural flows without any history of flow regulation.

Given the above, it is probable that reintroducing a more natural sediment regime through flow management is likely to be implausible in these kinds of systems. Thus, it may be more appropriate to think of a series of other objectives for improving the system that are based upon working with the history of sediment deposition, the legacy sediment, and identifying the flow regimes that might deliver other kinds of improvements. Notably, the flushing associated with these systems already is 'channel-forming' in that it leads to substantial deposition and erosion. But, this is largely because of the sediment delivery associated with the flushing. Thus, one possibility is to introduce more extreme flows *without* sediment flushing, notably with the aim of optimising the benefits of high flows for removing fine sediment[163,164], winnowing finer material and reducing bed cementation. However, the frequency with which these intakes have to be emptied, sometimes multiple times per day, is such that any winnowed fine material may be rapidly replaced by newly deposited sediment. A second objective could be to manage sediment through the use of artificial sediment sinks, which limit sediment impacts to more defined points of the landscape, notably upstream of intakes, such that intakes need to be flushed less regularly. This may be of particular interest if, according to the conceptual ecological model of the system, such ecosystems are more marginal in ecological terms (e.g. due to lower stream temperature or higher suspended sediment concentrations). Of course, the long term sustainability of such sinks will depend upon the volume of storage available which itself needs to be related to the long term evolution of glaciated basins in the face of changing climate. In the short term, it should lead to a reduction in the frequency with which intakes are flushed and sediment is delivered, and so a reduction in the rate of river-bed disturbance, something that may be a critical limit to Alpine stream ecosystems impacted by intakes. A third objective might be to find ways in which legacy sediment may be more readily and permanently accumulated into floodplain systems. Such efforts may be constrained by the space available for the river-floodplain system. It is also likely to require a reduction in the frequency of instream disturbance, and hence other solutions, if it is really to improve stream ecology.

These kinds of objectives need to be sustained by research projects that can quantify the ecosystem impacts of existing management regimes; and test operationally-feasible flows that are capable also of delivering a better sediment transport regime.

CONCLUSION: THE MANAGEMENT CHALLENGE FOR ALPINE FLOW TRANSFER SYSTEMS

It is now recognised that the flow requirements downstream of impoundment or abstraction need to be addressed: the required environmental flow releases or e-flows, the volume of water that should be released in river to guarantee both human and ecosystem needs[165]. Such releases are commonly set in terms of instream flow needs. These needs are unlikely to be met through the use of a constant flow release and it is important to try to reproduce the natural flow regime[18] as far as the constrains of hydroelectric production allow. The restoration of a natural flow regime translates into the reintroduction of flow variability, normally set in terms of five key components (magnitude, frequency, duration, timing and rate of change) of the streamflow[14] and its value has been shown in a number of research publications[166,8,167,168,169,170,171]. Our review does not seek to challenge these conclusions.

However, much less attention has been given to the design of flow releases where sediment is also an issue. In the flow abstraction systems of Alpine environments, where sediment delivery rates can be high and where sediment connection is maintained, albeit at a lower intensity, sediment related problems are likely to be significant. Part of the challenge here is the natural regime of Alpine streams, especially those that are glacial or glacial-nival (Table 1). As we review above, these systems are likely to be unstable and associated with naturally high rates of sediment delivery and sediment transfer. Even before abstraction effects are considered, research has shown that they have a natural ecosystem form and function that is very different to systems less impacted by snow and ice[22,33,58,45,36,65,63,26,40,126,133,38,28]. Differences include very strong downstream gradients in species richness and composition[22] that reflect the co-evolution of water temperature and river stability, as well as the particular nature of controls upon possible food sources[38]. Such streams are also naturally dynamic and have naturally high sediment loads[39,22]. Establishing these downstream gradients, and their temporal variability, on a stream by stream basis is needed such that natural or expected variability and abstraction impacts are not confused. This emphasises the importance of an effective conceptual model of what the natural system should look like without human impacts, which should be the target of any kind of intervention.

However, a more important challenge for managing intakes associated with water transfer systems is how to manage the negative impacts of sediment, notably sedimentation, upon the downstream river corridor. We have argued that sediment impacts upon ecosystems may be significant over both the short term and the long term, notably in catchments with a high proportion of glaciation. High rates of sediment delivery leads to a need to flush flow intakes frequently, as much as daily or many times per day in some cases. This flushing produces short duration floods with exceptionally high sediment loads. These have the capacity to cause substantial erosion and deposition downstream, and hence instability. As sediment delivery is maintained but sediment transport capacity is reduced, the long-term effect on the system will be migrating sediment waves[84]. On the basis of established research in streams more widely, these may have negative impacts upon instream ecology, both flora and fauna although we emphasise that research is needed to distinguish these impacts from the natural spatial and temporal variability in Alpine stream ecosystems.

The question of sediment regime has rarely been considered in any research projects looking at Alpine flow abstraction impacts. Our review shows that whilst identifying a suitable sediment management regime must become an integral part of designing ecologically sustainable flows in abstraction systems, it is not at all clear what that regime might be. Because of the high frequency and duration of sediment transport expected with the natural flow regime of a glaciated basin, delivering a more natural sediment transport capacity through flow manipulation is likely to undermine seriously the ability to abstract flow. Further, the cumulative effects of flow abstraction over many years may have led to substantial problems of 'legacy sediment', whose remobilisation due to flow redesign may be problematic. It is highly likely that restoring ecosystem function in these systems will have to look much more widely than just the redesign of flow releases to include, crucially, options for upstream sediment storage as well as the management of legacy sediment as part of a wider strategy of sustainable floodplain management.

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Figure captions

Figure 1: Example of the Bas Glacier d'Arolla water intake (Valais, Switzerland) and a classic flow intake design (after Bezinge, 1989[6]). The water is caught and diverted to be used for the hydroelectric production; only a residual discharge is released to the river downstream (even sometimes none); the sediments are managed by two traps: the first gravel trap holds the larger sediments by coarse grills whereas the sand trap holds finer sediment with a few water; the respective doors can be manually or automatically opened when the storage traps are full or to let the water flow

Figure 2: Example flow hydrographs for a nival catchment (Vallon de Nant, data for a location at 1350 m a.s.l.) and a glacial catchment (Haut Glacier d'Arolla, data for a location at 2505 m a.s.l.). The Haut Glacier d'Arolla data were provided by Grande Dixence SA (data from 1989 to illustrate and support Table 1)

Figure 3: Characteristic invertebrate taxa distributions in glacial stream according to Brittain and Milner, 2001 (p.1572)

Figure 4: The natural flow hydrograph for a glacial catchment (Haut Glacier d'Arolla, data for a location at 2,505 m a.s.l.) and the flow recorded downstream, produced by events designed to empty the intake of sediment. The data were provided by Grande Dixence SA for 1989 as an example.

Figure 5: Modelled values of the critical discharge for median grain sizes from 0.06 m to 0.16 m, 84th percentiles set always to be 0.04 m greater than the median, and shown for a range of slopes (plotted on the first y axis). Critical discharges are calculated based upon the method of Nitsche et al. (2011)[161] *which corrects for greater energy losses in mountain streams with macroform bed roughness. Superimposed are frequency distributions of discharge for the Haut Glacier d'Arolla (data from Figure 5, plotted here on second y axis) calculated for 1 May to 30 September for the natural flow and the residual flow after abstraction*

Tables

Table 1: Alpine flow regimes, from Weingartner and Aschwanden (1994)[20]*. M = May, Jn = June, J =July, A = August, S = September. The a and b classes are function of the percentage of the surface glaciated. Note that given continued climatic amelioration since 1994 of up to 0.5℃ in the Alps (e.g. http://www.meteosuisse.admin.ch/home/climat/actuel/tendences-climatiques.html), it is possible that the altitudes given in column 2 are now higher for each regime*

Flow regime	Mean altitude (m)	Percentage of surface glaciated (%)	Ranked month of dominant runoff	Coefficient of variation of the monthly discharge for the months of June [%]	Coefficient of variation of the monthly discharge for the months of July [%]
Glacial, a	>2400	>36	J - A - Jn - S	21	11
Glacial, b	>2100	22-36	J - A - Jn - S	21	13
Glacial-nival, a	>2000	12-22	J - Jn - A - M	16	14
Glacial-nival, b	1900-2300	6-12	Jn - J - A - M	17	21
Nival-glacial	1550-1990	3-12	Jn - J - M - A	16	19
Nival	1500-1900	0-2	Jn - M - J - A	20	24

Table 2: Baseline references regarding the nature of natural Alpine stream aquatic ecosystems

Petts and Bickerton, 1994[72]	Reports the influence of water abstraction on macroinvertebrates in a river with a flow abstraction system, Switzerland
Milner and Petts, 1994[22]	Describes the physical habitat and ecology (primary producers, invertebrates, fish) of glacial streams
Richter et al., 1996[8]	Shows hydrological regimes to be a central control upon biotic composition; describes an indicator of hydrologic alteration in an ecological context
Poff et al., 1997[14]	Describes the importance of the natural flow regime for river conservation and restoration; reviews the ecological functions and responses to altered flow
Richter et al., 1997[15]	Asks the challenging question of 'How much water does a river need?'; definition of 'Range of Variability Approach' (RVA)
Giller and Malmqvist, 1998[81]	Provides a solid introduction to the hydrological, physical and chemical concepts of river streams and ecological habitat of rivers
Füreder et al., 2001[36]	Follows Milner and Petts (1994) by adding the importance of spatio-temporal variability
Robinson et al., 2001[40]	Shows the spatio-temporal evolution of macroinvertebrates over an annual cycle
Smith et al., 2001[37]	Describes the relations between hydrogeomorphology and ecology with conceptual models
Bunn and Arthington, 2002[82]	Describes the alteration of flow regimes according to four principles and the influence on aquatic biodiversity
Brown et al., 2003[38]	Through consideration of physical and biochemical variables, develops a more sophisticated classification of glacial streams
Brown et al., 2006[28]	Presents a 7 year timescale study of macroinvertebrate communities for a glacial stream system
Hannah et al., 2007[47]	Addresses hydrological and ecological responses to different water sources in glacier-fed streams