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Bedload transport: Are we doing restoration right in the face of alpine climate change?

Lane, S.N.[1], Antoniazza, G.[1], Dietze, M.[2], Mancini, D.[1]
[1]*Université de Lausanne, Switzerland*
[2]*GFZ, University of Bonn, Germany*

INTRODUCTION

Alpine landscapes are undergoing climate warming at a higher rate than other regions of the world. The current and future impacts of this warming on the cryosphere (snow and ice) and their implications for stream flows are now well known and there exist predictions of how snow, ice and river flows are likely to evolve in Alpine environments over the 21st century (e.g. [1, 2, 3]). There is no doubt that such changes will also impact bedload transport in Alpine streams. Bedload transport in many Alpine streams is, however, also impacted significantly by the direct effects of human activities such as hydropower and gravel extraction (e.g. [4, 5]). These direct effect have dominated the concerns of bedload management or river restoration over the last decade or more. It is therefore a logical question to ask whether or not river restoration and the bedload management policies thought necessary to support them needs to adapt in the face of climate change. The lead in time to many policy solutions for bedload management, especially those involving new infrastructure, is not negligible. Given the current rate of warming in Alpine environments, higher than many non-Alpine regions [6], climate change sensitive bedload management may already be needed. However, the target of river restoration should not be bedload transport itself but rather the societal ecosystem services that are sustained by the *consequences* of bedload transport. This may be in terms of the right level of sediment evacuation to stop bed level rise during a flood that can lead to catastrophic loss of property and even life; or the gravel sized sediment that spawning salmonids need during the late autumn of each year; as examples of a wider set of services that rivers provide. Simply developing a bedload management policy to be climate sensitive is not enough; the focus has to be on the consequences of such policy for erosion, deposition, grain-size, river morphodynamics etc. These need to be evaluated at the scale of a river basin and so also need to recognize the basic challenges posed by sediment continuity; a policy decision to increase or to decrease bedload transport locally will have downstream consequences that may be either positive or negative. Communities and ecosystems downstream, may have already become accustomed to a certain bedload transport regime and this further complicates the problem. In this paper, I seek to answer six broad questions that should be part of a sustainable bedload management policy in Alpine environments in the light of climate change:

I. What must we be capable of predicting?
II. Is there a bedload transport “hockey stick” in Alpine streams?
III. Can we predict bedload transport rates now with sufficient precision and accuracy for them to be usable in predictions of the future?
IV. How might bedload transport capacity change in the future in Alpine basins?
V. How might sediment supply change in the future in Alpine basins?
VI. So, are we doing restoration right in the light of Alpine climate change?

I. WHAT MUST WE BE CAPABLE OF PREDICTING?

Shaping restoration to be climate sensitive in terms of bedload transport has a basic challenge. Climate warming impacts both sides of the sediment transport balance; sediment supply and sediment transport capacity. The response of a river to the Supply-Capacity Ratio (SCR) is substantially different according to whether SCR>1 (aggradation) or SCR<1 (erosion).

Theory that can be traced back until at least the 1950s has taught us that any imbalance in the SCR ratio is likely to be accompanied by an autogenic response. Mackin [7] defined the notion of a graded stream as “… one in which, over a period of years, the slope is delicately adjusted to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin ...”. Lane [8] generalized the notion of grade to recognize that any river faced with a systematic change in discharge of water or sediment should respond by erosion (i.e. where SCR<1) or aggradation (i.e. where SCR>1). Erosion should lead to a systematic reduction in slope and, via size selective entrainment (even if only weakly size selective), a systematic increase in the critical shear stress required for sediment entrainment. Such changes reduce sediment transport capacity, and so this tendency to erosion, until the river profile and its sedimentology is adjusted to the imposed water/sediment discharge, and the SCR=1. Deposition will increase slope and, under the assumption that supplied sediment is less poorly sorted, reduce the critical shear stress, so increasing sediment transport capacity, again until the river profile and its sedimentology is adjusted to the imposed water/sediment discharge.

Three important lessons follow from this discussion. The first is that the autogenic response of rivers to changes in external drivers matters such that systematic evolution in, for example, bed slope, grain-size etc. need to be included in predictive models. Predicting changing bedload transport under climate change needs to include a morpho-dynamic treatment and not just an assessment of how changing climate impacts on bedload transport capacity. The second is that many engineering approaches to river management make the logical assumption that the graded profile should be the target. Lane [8] was actually quite clear that the condition of grade (i.e. SCR=1) should vary rarely exist because rivers are subject to continually changing water and sediment discharge. For most of the time rivers are out of equilibrium and not in equilibrium. We should not talk about a "natural sediment balance", if anything a "*natural sediment imbalance*". Even if such a target can be identified (and a river engineered to support it) now or under future climate change, it is highly unlikely that this will give the expected sediment flux or habitat benefits. Third, the analysis emphasizes that changing sediment supply, and not just changing sediment transport capacity, has to be considered in terms of climate change impacts. In the following section, we illustrate the challenges that follow for predicting bedload transport in Alpine catchments under climate warming.

II. IS THERE A BEDLOAD TRANSPORT "HOCKEY STICK" IN ALPINE STREAMS?

Climatically, Alpine regions, including Switzerland, entered into a period of accelerated warming from the mid 1980s [9]. Thus, if we have data on bedload transport straddling this period and extending to the present, we may be able to test the hypothesis that climate change is impacting bedload transport rates in Alpine environments. Unfortunately, high quality measurement systems do not extend back to the 1960s and 1970s. Even those with longer records are commonly some way downstream such that they contain the signal of both sediment supply to the river and transport capacity within the river system. Rivers are known to rapidly "shred" the signal of exogenic drivers [10]. Given that both supply and capacity may be impacted by climate change, disentangling different climate signals as well as the effects of autogenic response, will be a challenge.

There is one solution provided by long-term records of flushing of hydropower intakes. Designed to allow water to be taken off and transferred to storage, not only are they more frequent than dams but they are; (1) smaller, providing a flushing frequency of hours to days to weeks rather than years or more; and (2) commonly found across a much higher range of altitudes and so river basin types and sizes. Figure 1 shows the reconstructed bedload yield (see Lane et al., 2017 for the methodology) for six river basins in the Val d'Hérens, south-west Switzerland. The characteristics of these basins are provided in [11]. They have varying percentage ice cover (Figure 1).

Figure 1 suggests substantial inter-annual variability in bedload transport rate. For four of the basins (Figure 1a, Douves Blanches; Figure 1b, Bertol Supérieur; Figure 1d, Pièce and Figure 1f, Vuibé) a Mann Kendall trend test suggests a significant positive trend (p<0.05). However, five of the six basins also show correlations with mean annual temperature for a similar altitude and relatively proximate weather station (Table I). The correlations are positive. This suggests that there is a general tendency for climate warming to be increasing bedload transport, but the question is why? Explanations may invoke impacts on both bedload transport capacity and sediment supply.

TABLE I

CORRELATIONS BETWEEN MEAN ANNUAL TEMPERATURE AT GRAND ST BERNARD (C. 28.5 KM TO THE WEST-SOUTHWEST, AT 2'491 M ABOVE SEA LEVEL) AND ANNUAL BEDLOAD TRANSPORT RATE.

Basin	Pearson's correlation, showing significance if p<0.05 (two-tailed)
Douves Blanches	0.469, $p < 0.05$
Bertol Supérieur	0.355, $p < 0.05$
Haut Glacier d'Arolla	0.276, $p < 0.05$
Pièce	0.354, $p < 0.05$
Tsijiore Nouve	0.156
Vuibé	0.407, $p < 0.05$

Lane and Nienow [11] reported systematic increases in the magnitude and intensity of daily discharge variability in five of these basins (all except Douves Blanches) due to climate warming; and this is reflected in systematic increases in annual maximum discharge (Figure 2) for all of the basins except Vuibé (Mann Kendall trend test, $p < 0.05$) which has the highest percentage glacier cover and Douves Blanches (Mann Kendall trend test, $p < 0.05$) which has the lowest glacier cover. Vuibé is also the highest basin (mean glacier altitude in 1973, 3'600 m) and so it is possible that it is only recently, if at all, that it has been affected by temperature rise. The tendency to have more frequent high magnitude flow peaks should increase bedload transport capacity given the non-linear dependence of bedload transport upon discharge (e.g. [12]). However, this effect will only remain significant as long as there is net negative mass balance and an ice-melt subsidy. As glaciers shrink, this subsidy initially rises and then falls giving rise to what is described as peak water (e.g., [13, 14]). Thus, we are likely to see a point at which further temperature rises reduce glacier cover sufficiently that the intensity of diurnal discharge variation and daily flow peak magnitudes fall, with a consequent reduction in bedload transport capacity. Evidence suggests that this has already happened for the basin with the smallest glacier cover (Douves Blanches; [11]).

On the other side of the sediment balance, climate change may be increasing sediment supply. Our knowledge of the geomorphic processes that follow climate warming and glacier retreat is well-developed [15, 16, 17, 18]. Deglaciation implies debuttressing [19] such that previously immobile sediment can be more readily mobilised. The result can be (1) increased rockfalls [20, 21, 22]; (2) moraine evolution through erosion [23, 24, 25, 26]; (3) dead ice melt-out [27]; (4) paraglacial landsliding [28, 29, 30, 19, 31]; (5) debris flow formation [32, 33]; and (6) rock glacier formation/response [34, 35, 36, 37]. These observations are commonly synthesized into the long-established model of paraglacial response of deglaciating basins [38] which argues that during deglaciation, sediment yield rises rapidly at first, before declining as the percentage of a basin that is ice-covered falls further. This decline

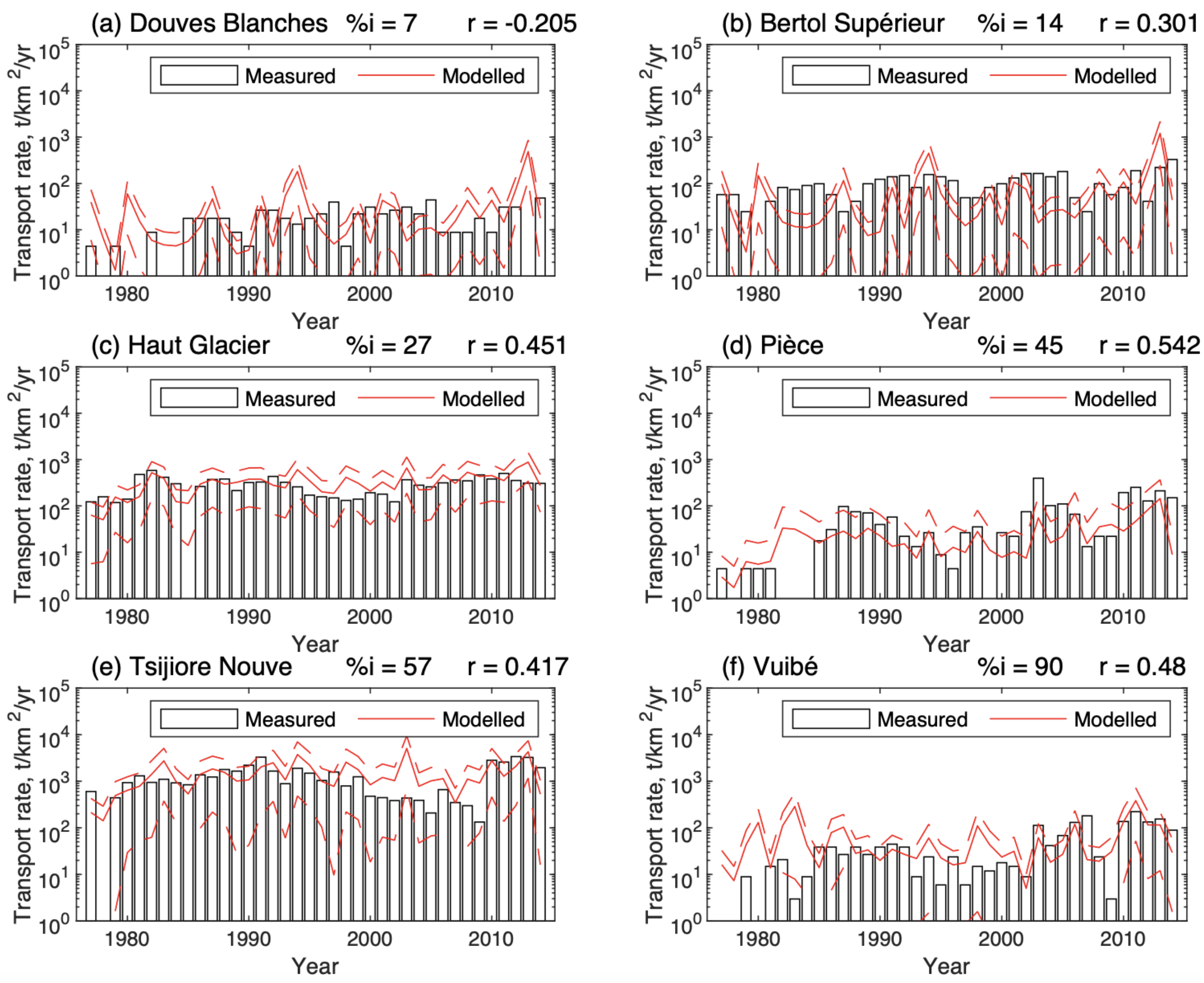

Fig. 1. Measured and modelled annual bedload transport yield, stanadardised by catchment area, for six high altitude discharge monitoring stations in the Val d'Hérens, VS Switzerland. Details of each basin (altitude etc.) are available in [11]). Model predictions show mean and 95% confidence intervals of the estimations. The measurements are based upon rates of bedload transport estimated from emptying of the intakes (see Lane et al., 2017 for the methodology). Note that some years have missing data. Also shown is the percentage of ice cover in each basin in 2009 (%*i*) and the correlation between measuremnts and model predictions (r).

follows from a reduction in glacial erosion rates as glaciers thin, slide more slowly and so erode less [39, 40] but also landscape-scale negative feedbacks including sediment sorting [25], increasing disconnection of sediment supply zones from rivers due to alluvial fan formation [25, 26] and eventual stabilisation by vegetation development following the switch to phototrophic conditions following from glacier retreat [41, 42]. As glaciers retreat, they may develop large forefields, as is the case for the Haut Glacier d'Arolla and Tsijiore Nouve (Figure 1). Such forefields are of crucial importance in bedload transport signals as they may shred [10] the signal of sediment supply from glaciers and valley sides [43, 44]. Indeed, it is interesting that the two glaciers with no linear trend (Haut Glacier d'Arolla, Tsijiore Nouve), including the one with no significant temperature correlation (Tsijiore Nouve), both have extensive proglacial margins with relatively low slopes, and hence lower bedload transport capacities, developing in front of them.

The paraglacial model of Church and Ryder [38] suggests that once ice cover falls beneath a certain level and the landscape has adapted to post-glacial conditions, bedload transport rates should fall. As this happens, bedload transport is likely to become more dependent on extreme rainfall events and less dependent on evacuation of sediment by glacial meltwater. Micheletti and Lane [45] showed that both Douves Blanches and Bertol Supérior, the two basins with the lowest percentage ice cover (Figure 1) has likely already reached this state. We can hypothesise that this trend will generalise progressively to all basins with further glacier retreat. We can also state that it is highly unlikely that Alpine streams will have the kind of "hockey stick" response to greenhouse gas emissions and feedbacks that is commonly shown in and predicted for

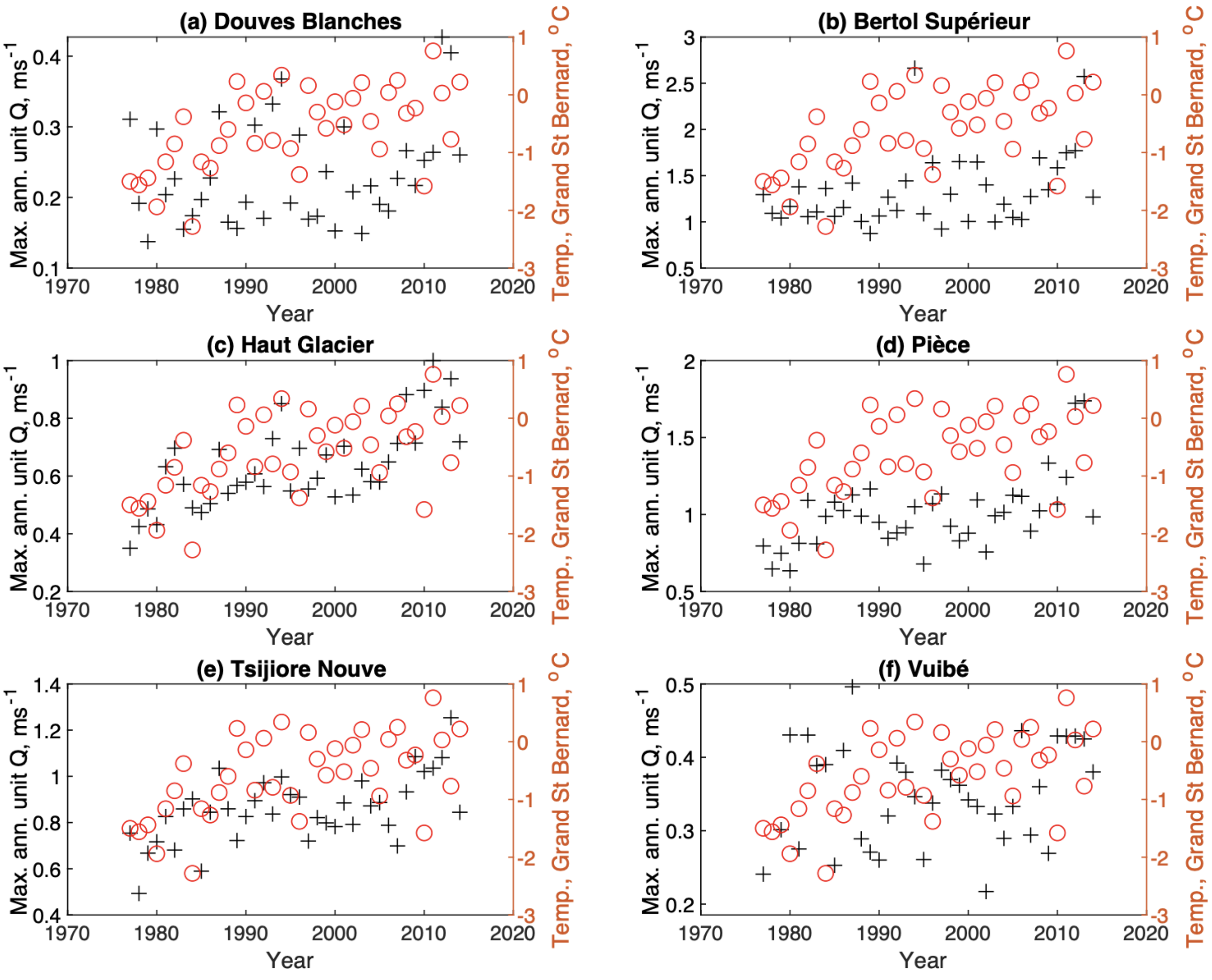

Fig. 2. The evolution of maximum annual unit discharge and mean annual temperature at the long-term Grand St. Bernard monitoring station (c. 28.5 km to the west-southwest, at 2'491 m above sea level). Temperature data were provided by MeteoSuisse©.

atmospheric temperature [46].

III. CAN WE PREDICT BEDLOAD TRANSPORT RATES NOW WITH SUFFICIENT PRECISION AND ACCURACY FOR THEM TO BE USABLE IN PREDICTIONS OF THE FUTURE?

Development of very high quality bedload monitoring systems such as the Swiss Geophone Plate system (e.g. [47, 48, 49, 50]) has substantially aided the development and correction of predictive bedload-discharge relations (e.g. [51, 12]). With these it becomes possible to use measured and predicted changes in river discharge to estimate measured and predicted bedload transport. We hypothesise that a first test of a predictive model of future bedload transport rates must be its ability to reproduce historical variability in bedload transports over some decades. This mirrors the kinds of standards typically applied to climate models. Figure 1 shows such an attempt for six partially glaciated basins in the Val d'Hérens, south-western Switzerland for the period 1977 to 2014. We focus on these basins because, whilst they do not have high quality monitoring systems, they do have records of hydropower intake flushing that can provide a reasonably reliable and multi-decadal records of bedload export from high Alpine environments [25]. The modelled transport rate follows method 6 in [12] and uses discharge data provided by Grande Dixence SA and measured at hydropower intakes. We use Monte Carlo simulation around measured values of slope, median grain-size and width as these are not monitored and are likely to have changed over the decadal time-scale. This practice also mirrors practices in climate modelling where unknown or poorly known parameters are used to train models on past data.

Broadly speaking, the optimized model produced plausible bedload transport rate magnitudes (Figure 1) for plausible values of slope and width immediately upstream of each intake (Table II), the two parameters that we can readily measure from aerial imagery. However, although the measurements suggest a significant ($p<0.05$, Mann-Kendall trend test) rising bedload exports for all basins except Haut Glacier d'Arolla and Tsijiore Nouve the model results predict significant trend for all basins except Vuibé and Tsijiore Nouve. Figure 1 also shows the correlation between the annual modelled and measured bedload export, which is only significant and positive (Pearson's r, $p<0.05$) for four of the basins. The model is unable to reproduce inter-annual variation in bedload transport for the two least-glaciated basins. This is not surprising as this kind of model only represents transport capacity; there is no sediment supply treatment. If there is intra- and inter-annual variation in sediment supply we would also expect evolution in key model parameters (grain-size on the bed, slope etc.). Indeed, a primary weakness of the optimization approach is that if the river bed is not in equilibrium measured bedload transport transport rates will not be at capacity and optimization will fail.

This discussion then poses a challenge for understanding how bedload transport might evolve under climate change. It is perhaps best illustrated by considering systems where we have the very highest quality of bedload transport measurement at a fine (sub-daily) temporal resolution. Figure 3 shows modelled (using the same approach as in Figure 1) versus measured bedload transport for a Swiss Geophone plate system in the Alpine Vallon de Nant catchment, southwest Switzerland. This is a 13.4 km^2 basin with elevations ranging from c. 1'200 and 3'050 m and only 3% glaciated. Figure 3a shows orders of magnitude uncertainty in bedload-hydraulic relations. Some of this uncertainty may be intrinsic to model parameters as was considered in the simulations shown in Figure 1. However, the uncertainty here is also epistemic, arising from within-event (1) autogenic processes such changes in grain size and sorting; changing scales of river bed morphology from roughness to hydraulic radius; and changing river bed slope; and (2) changing sediment supply. The latter depends upon where and when sediment is mobilized in the wider river basin, and the ease with which it is transferred to the river. These sources of uncertainty, in combination reflected in Figure 3a, translate into substantial uncertainty in transport volumes (Figure 3b) much greater than those needed to flip a SCR from erosion (<1) to aggradation (>1) or vice versa.

Two points follow. The first is that it may be tempting at this stage to conclude that bedload transport capacity-based models are not fit-for-purpose. Their substantial uncertainty, as well as their dependence on optimization, produces predictions that in terms of determining the consequences of bedload transport (i.e. the SCR) are insufficiently precise. However, we can learn a lesson from climate modelling here. Numerical predictions of global climate can be traced back to the 1950s [52]. Initially in one-dimension [53] and later in three-dimensions [54]. The latter was remarkably prescient when compared knowledge, predicting a doubling of CO2 concentration would increase global mean temperature by 2.9°C, greater warming in higher latitudes due to snow cover feedbacks and increased intensity of the hydrological cycle (cf. [46]). Most of the qualitative inferences in [54] are being realized even if known atmospheric, terrestrial and marine processes were not included in the model. There may be parallels here with the current state of bedload transport prediction. Whilst there is substantial quantitative uncertainty in current bedload transport rate modelling (Figure 1, Figure 3), it is quite probable that such models do give us a means of understanding how qualitatively bedload transport capacity might evolve in the future.

Second, as capacity is only one side of the SCR balance, it is also crucial to develop a better understanding of how sediment supply is likely to evolve in response to climate warming. Notwithstanding the measured bedload transport rates shown in Figure 1, it remains the case that we have no high resolution long-term records of bedload transport. This will progressively change as the duration of monitoring at stations with Swiss Geophone Plates, and similar, becomes longer. The attribution of such signals to sediment sources is likely to provide some of the first signals of exactly how climate change is impacting bedload transport. However, this also emphasizes that the drivers of such signals are likely to lie outside of rivers, and not in them, and there is an urgent need to understand how rivers couple to sediment sources are responding to changing climate and the ease with which climate-driven changes in sediment sources connect to rivers. This challenges of doing this are shown in Section V.

IV. How Might Bedload Transport Capacity Change In The Future In Alpine Basins?

Despite the argument above that the evolution of SCR in the future needs to consider sediment supply, and notwithstanding uncertainties in the hydraulic relationships between bedload transport and discharge, it is still important to reflect upon how bedload transport capacity might change in the future. This requires a particular focus on the magnitude and frequency of high flows, those capable of entraining bedload sediment. Figure 4 (see Figure caption for full explanation) is reproduced from some of the latest results in this research field [3] and depicts two extremes of possible greenhouse gas concentration pathways (low emissions, RCP2.6 and high emissions, RCP8.5) for two different ways of estimating hydrological extremes (FDC and stochastic) for five parameters (Figure 4a) for the regions shown in Figure 4b. Alpine regions that are dominated by snow- and ice-melt have a darker shading. Changes are shown for 2070-2100 as compared with 1980-2010.

The striking result is that changes in high flow discharge for the Alpine catchments appear to be more dependent upon the method (FDC versus stochastic) used to estimate flow extremes (i.e. maximum discharge) than they are the emissions scenarios. Whilst non-Alpine regions are forecast to have higher maximum flows for both estimation methods; for Alpine catchments, this is only the case for stochastic methods. The FDC method is likely to be more reliable and only weak changes in the maximum discharge during high flows periods are expected (Brunner, pers. comm.). Of course, this remains a highly uncertain field, but there is not yet a clear signal that there will be a marked increase in the magnitude of extreme discharge events in warmer climates.

The focus on flow extremes, however, may hide more subtle changes in bedload transport capacity, especially in Alpine basins influenced by declining ice cover. As noted above, the intensity of ice-melt driven diurnal discharge cycles as

TABLE II
OPTIMISED AND MEASURED VALUES OF KEY MODEL PARAMETERS.

Basin	Optimised Manning's n	Optimised $D_{50,\mathrm{m}}$	Optimised Slope	Measured Slope	Optimised Width, m	Measured Width, m
Douves Blanches	0.114 ± 0.003	0.078 ± 0.002	0.746 ± 0.028	0.74	4.7 ± 0.26	4.4
Bertol Supérieur	0.115 ± 0.003	0.077 ± 0.002	0.741 ± 0.026	0.72	4.8 ± 0.19	4.2
Haut Glacier d'Arolla	0.064 ± 0.003	0.067 ± 0.002	0.075 ± 0.003	0.04	8.1 ± 0.30	7.4
Pièce	0.056 ± 0.002	0.095 ± 0.003	0.260 ± 0.026	0.21	3.4 ± 0.25	3.4
Tsijiore Nouve	0.084 ± 0.003	0.067 ± 0.002	0.310 ± 0.025	0.23	6.6 ± 0.27	6.7
Vuibé	0.079 ± 0.003	0.077 ± 0.002	0.340 ± 0.026	0.36	5.2 ± 0.22	5.1

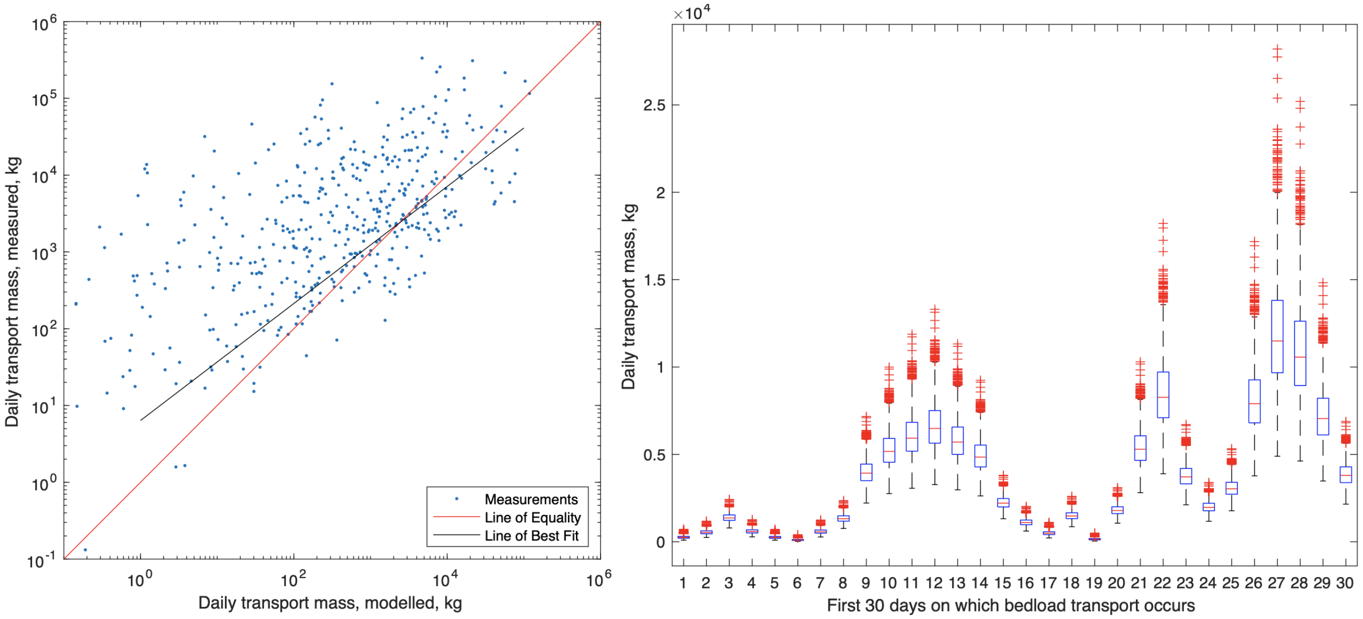

Fig. 3. Modelled daily bedload transport rate versus measured for a Swiss Geophone plate system in the Alpine Vallon de Nant catchment, southwest Switzerland (Figure 1a). Data are taken from [55] (in revision). The modelled transport rate follows method 6 in [12]. Figure 1b is based on each value of the modelled daily transport mass on a day when there is transport. Following [74] it uses Monte Carlo simulation in log-log space to produce a set of 2000 possible measured transport rates for each day given the uncertainty in Figure 1a. The daily distribution of possible transport rates is plotted for the first 30 days in [55] (in revision) dataset when bedload transport is measured as occurring.

increased during the last 30 years due to rising temperatures and their effect, notably upon snow-lines that retreat higher up glacier sooner, lowering glacier albedo substantially [11]. However, as the volume of ice available to melt continues to decline so we would expect a longer term reduction in the intensity of diurnal discharge cycles, something that has already been observed in the basin with the lowest percentage ice cover reported in Figure 1 (Douves Blances). This effect is illustrated by simulating bedload transport with the mean daily discharge rather than the measured discharge that includes diurnal discharge cycles; thus the water yield is held constant, but the variability reduced. For the example of the Haut Glacier d'Arolla this reduces bedload transport over the period 1977 to 2015 by more than one third.

In relation to bedload transport capacity, the key message is that climate change is likely to be seen in two different senses: (1) declining snow and ice cover is likely to reduce the magnitude and frequency of flood events due to "rain-on-melt" processes; but (2) increasing magnitude and frequency of precipitation extremes, although research suggests some geographical variation in the extent to which this is occurring within the Swiss Alpine region [56]. When taken with the long-term loss of ice melt, and hence the capacity for glaciers to evacuate sediment, it is quite probable that even if bedload transport capacity integrated over many years does not change significantly, the shift towards more dependence on extreme rainfall events will increase inter-annual variability. It follows that a major need in terms of bedload transport in Alpine regions is the application of continuous simulations of future runoff in basins with different degrees of ice cover to quantify how bedload transport capacity will evolve under climate change.

V. HOW MIGHT SEDIMENT SUPPLY CHANGE IN THE FUTURE IN ALPINE BASINS?

If future changes in bedload transport capacity in Alpine basins are uncertain, the situation is even more complex for changes in sediment supply. The discussion in Section II has emphasized the complex suite of responses, including feedbacks, associated with sediment supply. Figure 5 attempts to conceptualise these for an Alpine basin that is majority glacier covered and Figure 6 for an Alpine basin that is

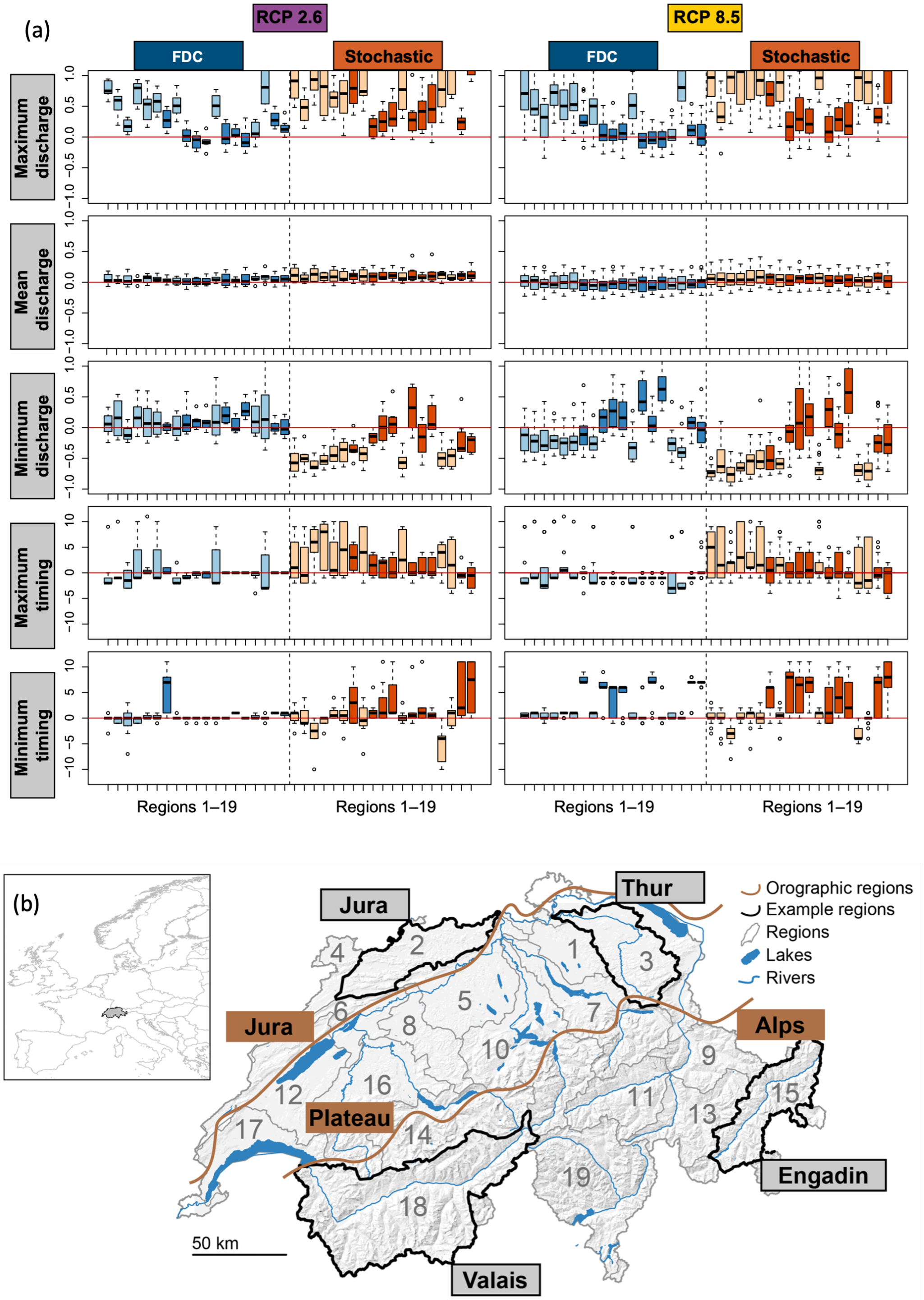

Fig. 4. Predicted hydrological changes (Figure 2a) for the 19 Swiss regions shown in Figure 2b, reproduced from [3] for the high flow seasons. Brunner et al. [3] determined possible changes in 5 parameters, 3 in relative terms (maximum discharge, mean discharge, minimum discharge) and 2 in months (timing of the maximum discharge, timing of the minimum discharge) to the period 2070-2100 as compared with the baseline 1980-2010. They used 39 combinations of Global Climate Models and Regional Climate Models, which included simulations for both concentration pathways RCP2.6 (carbon dioxide emissions start declining by 2020 and go to zero by 2100) and RCP8.5 (carbon dioxide emissions continue to rise throughout the 21st century 2100); the box-whisker plots represent the subset of the 39 combinations that relate to that concentration pathway. The hydrological predictions were undertaken using a conceptual, process-based hydrological model whose simulations were then used to estimate changes in the 100 year flow extremes using two different estimation methods; FDC based on frequency distribution curves; and stochastically). Finally, the darker-shaded regions are those with runoff dominated by snow and ice melt, that is Alpine (regions 7, 9, 10, 11, 12, 14, 15, 18, 19). Figure reproduced with permission from M. Brunner.

majority nival. As yet there are no integrated models that capture the interacting set of processes quantitatively even if the required technologies, notably landscape evolution models could be developed to do this. Thus, this section responds to the question of how might sediment supply change in the future by considering the qualitative implications of these two conceptualisations. It considers Figures 5 and 6 as end members; but it should be noted that for the case of the glacier basins (Figure 5) as the basin area increases, the percentage glacier cover of a basin will decrease and so the overall basin response will shift from Figure 5 to Figure 6. Similarly, as climate warms and glaciers retreat so a basin should shift from Figure 5 to Figure 6.

Figures 5 and 6 represent the complexity of likely bedload transport response to climate change for different kinds of Alpine basins. We can make a series of basic generalisations from the figures. First, bedload transport in Alpine environments, in terms of natural processes, is likely to be undergoing a phase of transience in response to a warming climate [25] because the processes shown in both Figures operate across different timescales. This is nothing new (e.g. [8] was quite clear about this) and it follows from the importance of feedbacks in moderating how climate forcing impacts bedload transport.

Second, glaciers are crucial agents in bedload transport both because they are amongst the most efficient erosion agents known on Earth [70] and because they simultaneously and reliably produce the meltwater that is capable of moving bedload downstream. The effort that has traditionally been put into the management of sediment in relation to Alpine hydropower (e.g. at intakes) reflects this. Given evidence that paraglacial (i.e. non-glacial) zones rapidly stabilize after glacier recession (decadal time-scale), and also that glacier retreat increases the size of proglacial margins that are natural sediment stores, it is quite likely that bedload export from glaciers eventually reaches a point where it declines with further reductions in percentage glacier cover. This may be in space as the size of the river basin that is considered increases, and the percentage glacier cover declines, with distance downstream; or through time in response to glacier retreat.

Third, for all Alpine basins, it is likely that the crucial and as yet poorly known consequences of climate warming will relate to whether or not the magnitude and frequency of extreme rainfall events increases. As basins evolve to be more like Figure 6, this is likely to become a key question.

VI. So, Are We Doing Restoration Right In The Light Of Alpine Climate Change?

In light of the above questions, there are a number of key comments that can be made as to whether or not we are doing bedload restoration right in the light of climate change. The first of these recognizes the challenge that bedload transport under climate change represents for river management. Simply coupling a model of bedload transport capacity to predictions of future river flow is highly unlikely to provide meaningful predictions of how bedload transport will evolve such that a sustainable river management policy can be developed. Not only are levels of uncertainty in hydraulic models of bedload transport extremely high (Figure 4) such models do not take into account how sediment supply will change nor how the evolving balance between changing river flow and changing sediment supply impact river morphodynamics directly and through feedbacks. It is these feedbacks that make river habitat (sediment sorting, bed reworking etc.) yet they are extremely difficult to predict. The importance of changing sediment supply under climate change is likely to be the key challenge for future river management; and as this is so poorly known, it means that sustainable river management policy is highly likely to have to be adaptive.

Second, and more specifically, there are clear areas where we are probably not doing river restoration right in the light of Alpine climate change and this relates to the spatial and temporal sensitivites of bedload management policies. There is some sense in which bedload management policies have failed to be sensitive enough to spatial context, especially in relation to Alpine environments, and this spatial context has a number of dimensions. Take the example of Alpine hydropower infrastructure. There is no doubt that such infrastructure leads to disconnection of upstream sediment supply to downstream zones. However, the S in the SCR ratio is not the only change. The C is also reduced because water may be taken off (at intakes) or stored (at dams) such that the S may actually exceed the C and net deposition results ([69] Figure 7). Early proposals for the management of the Borgne d'Arolla advocated a need for morphology-forming floods even though infrastructure management required repeated flushing of the intake, producing morphology-forming floods sometimes multiple times per day in mid-Summer [71]. The problem was too many floods not too few.

The particularity of different kinds of infrastructure is likely to be dwarfed by the effects of spatial setting on how the S in the SCR ratio is modified by infrastructure. It has been long-recognised that any locationally-specific river-impacting intervention (e.g. a hydropower dam) provokes an initial response after which there is larger-scale recovery with distance downstream. Ward and Stanford [72] called this the "serial discontinuity concept", but they only partially addressed the impact of discontinuities on sediment. Figure 8 shows an example of a sediment version of such a concept for the Hérémence dam in south-west Switzerland based upon modelling of sediment flux from unregulated tributaries to the valley bottom ([73], in revision). It shows how there is sediment accumulation upstream of the dam and the amplitude of the impacts of the dam on flux to downstream. Downstream of the dam, sediment accumulates again. The shape of the accumulation and recovery curve reflects a critical point. The rate of increase of accumulated sediment decreases with distance downstream. This reflects the fact that in Alpine basins there will be strong downstream gradients in sediment supply to a river as tributaries become lower in altitude, more vegetated and stable, and eventually have lower slopes. Thus, where the dam is in the 15 km length of river valley considered here has a direct effect on how much sediment is stored behind the dam (what Ward and Stanford [72] called the "parameter intensity") as well as how rapidly sediment accumulation recovers. In the

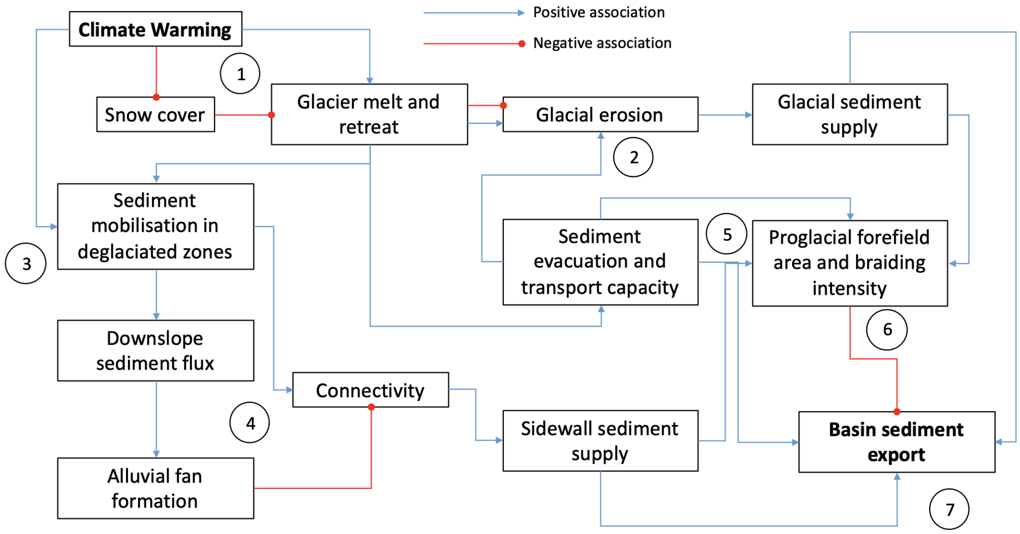

Fig. 5. A conceptual analysis of how glacier covered Alpine basins with glacier retreat will influence bedload sediment export from a river basin under climate change.
1. Climate warming reduces snow cover, reducing glacier accumulation and increasing ablation, and glaciers thin, retreat and have lower sliding velocities [57].
2. Glacier retreat and thinning may reduce (thinner ice = less deformation) or increase (enhanced melt and so enhanced basal sliding) subglacial erosion rates (e.g. [39]) and sediment supply but increases runoff [25] and diurnal hydrograph intensity [58], increasing sediment evacuation rate as long as the basin is sufficiently glaciated [11]; the balance between glacier sediment supply increased sediment evacuation depends on the history of sediment accumulation beneath the glacier.
3. Glacier retreat and thinning exposes valley sides and enables permafrost degradation, also aided by climate warming [36].
4. Sediment mobilisation may involve sediment removal by water, encouraging gullying and headward extension to remove blockages to sediment flux towards the forefield improving connectivity [25, 26]; but increased sediment flux to the forefield may encourage alluvial fan formation at the slope base, reducing sediment delivery, i.e. connectivity [25, 26]; connectivity may increase or decrease; if the net effect is increase, more sediment will be delivered to the forefield.
5. The net sediment export signal is then a product of changing glacial erosion/sediment supply, increased evacuation potential by meltwater and the degree of increased connectivity [25].
6. The growing area of the forefield may extert an important negative feedback to sediment export because it is well established that sediment supply encourages river braiding which may slow sediment flux to the basin outlet [59].
7. There is some support that these processes can be seen at the scale of large river basins (e.g. the Swiss Rhône) in terms of both sediment loading to [9] and sedimentation rates in [4] Lake Geneva.

case of the Hérémence, a tributary arrives in the main river after only a short distance downstream from the dam and this is sufficient to guarantee a significant supply of bedload to the river (Figure 8), that is S. Further, as the dam significantly reduces the capacity to transport bedload (the C), the amount of supply needed to compensate for dam-related disconnection is significantly reduced. It is not surprising, perhaps, that when a morphology forming flood was trialed downstream of the dam, it had to be rapidly abandoned because it was being applied to a stream with extensive deposits of poorly-sorted sediment, bedload transport rapidly increased, and there were serious security issues downstream [73]. So, this is perhaps the first point. The failure to take into account the spatial structure of impacts on bedload transport is already evident; but climate change will impact across the full spatial extent of river basins and it will change both S and C in the SCR. River restoration needs to become much more sensitive to the geomorphological setting and organisation of individual river basin and how climate change will impact these. It is perhaps interesting, if we take the example of Switzerland, that the Swiss Water Law is quite sensitive to this spatial context; it is perhaps the implementation that needs more thought.

Similar arguments apply to temporal dimensions of river restoration and again it is likely that climate change will exacerbate their importance. At least some of the problems associated with the Hérémence trial reported above was that in the summer before the trial there had been a major sediment supply event associated with locally extreme rainfall. Whilst there is debate over whether or not climate change may increase the frequency of such rainfall events in a statistical sense, there is commonly a considerable spatial local variability in the intensity of any one event. Changes in frequency are commonly judged over decades [3]. Thus, it is quite possible that events cluster in time such that even with increased event frequency such that there is no guaranteed sediment supply associated with unregulated tributaries which could provide the bed reworking and/or sediment supply that is needed annually to sustain ecosystem services. Thus, river restoration needs to be much more sensitive to temporal variation; annual morphology-forming floods should be avoided; annual assessments of whether such a flood is needed should be the basis of management.

The discussion to date has not addressed one element of climate change impacts that is now recognized as crucial. Humans are adaptive agents. Figures 5 and 6, for instance, make no reference to the range of human responses that exist to perceived river management problems. It is well-established that at a variety of scales, and faced with rapid

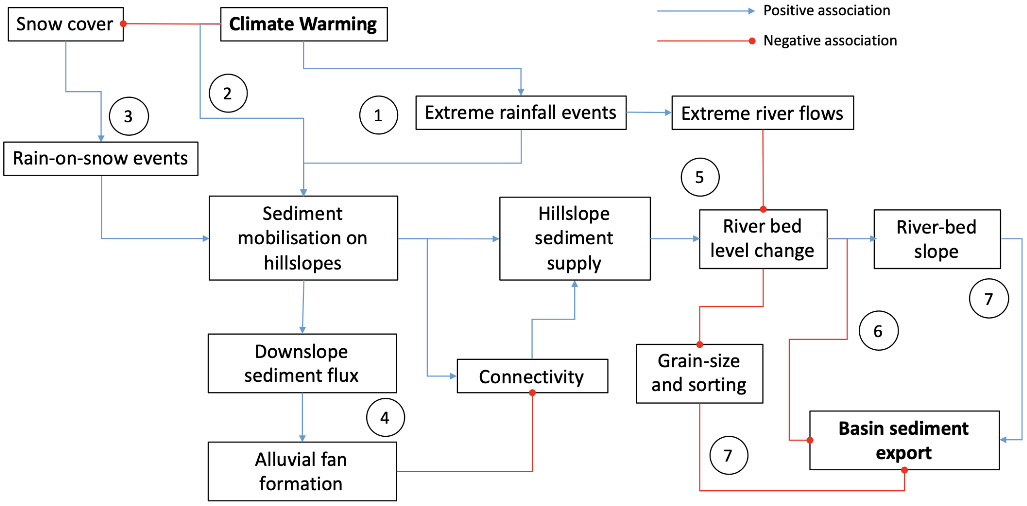

Fig. 6. A conceptual analysis of how non-glacier covered Alpine basins will influence bedload sediment export from a river basin under climate change.
1. An increase in the magnitude and/or frequency of extreme events in Alpine environments is likely to lead to increased mobilisation of sediment on hillslopes, although this is poorly studied.
2. Climate warming may also have a direct impact on sediment availability as a result of permafrost degradation [36, 60], rockfall thawing [61] and the supply of sediment through rock glaciers [62]. Sediment production may shift to higher altitudes due to the effects of warming temperature on the height that is optimal for frost cracking [63, 64].
3. The reduction in snow cover associated with climate warming may reduce the magnitude and frequency if rain-on-snow events, although this is likely to be altitudinally dependent and may actually increase at higher altitudes where there is still snow accumulation in winter but an earlier shift to rain rather than snow in spring [65]; when they occur is also likely to change [66]. The latter can lead to exceptionally high magnitude runoff events [67]. Generally these increase sediment mobilisation and so with reduced snow cover their frequency should fall and so sediment mobilisation is reduced. This may be countered, however, by a loss of erosion protection associated with reduced snow cover. These processes are poorly studied.
4. Delivery of mobilised sediment in Alpine environments is strongly affected by connectivity [68] due to the effect of the legacy of glacial activity on the landscape (e.g. rapid reductions in bed-slope when tributaries enter valley, leading to alluvial fan formation). This connectivity may still be evolving as envisaged in Figure 5, but likely at a much slower rate than in landscapes immediately following deglaciation. 5. The response of the river will depend upon the balance between changing sediment supply and changing erosion. There is clear evidence of river response over decadal scales to this changing balance (e.g. [69]).
6. This is the basic statement of sediment balance; if river bed levels rise, more sediment enters storage and less bedload transport occurs downstream; if river bed levels fall, more bedload transport occurs downstream. This process is scale dependent as it depends upon the timescale of bedload movement and there may be continual cyclicity in erosion and deposition.
7. This represents the classic feedbacks that occur; when river bed slopes steepen and so bedload transport to downstream increases; and when a river erodes and sediment sorting occurs such that the bed material becomes coarser; deposition is assumed to deliver less well sorted material and so make bed material finer and less well sorted.

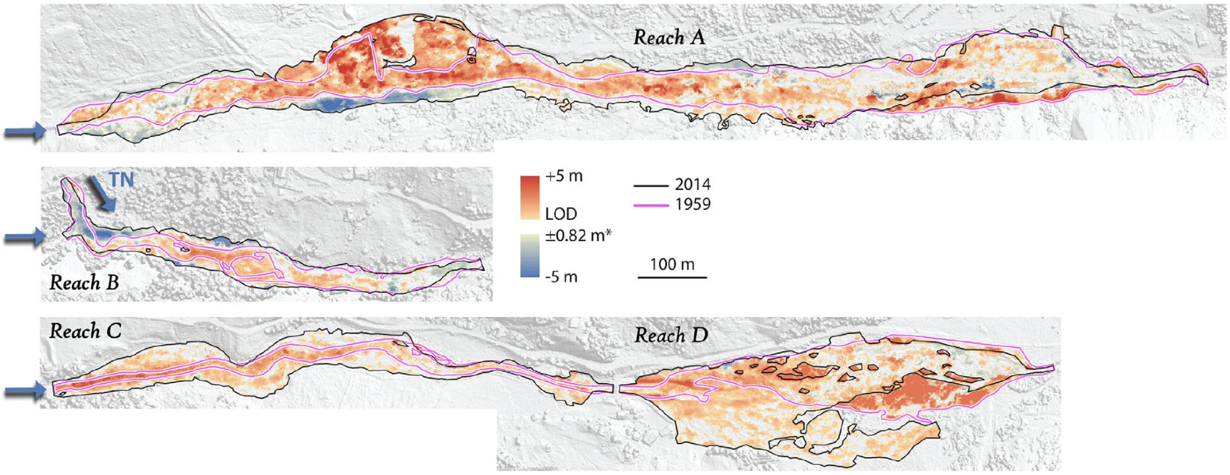

Fig. 7. Long-term bed level rise downstream from Alpine hydropower infrastructure in the Borgne d’Arolla as a result of no change in supply (S) but an decrease in transport capacity (C) (reproduced [69]). Bakker et al. used archival digital photogrammetry to quantify river bed level changes following from closure of the Grande Dixence hydropower scheme. From the mid-1960s, major water intake upstream of Reach A took off all water until a minimum flow was introduced in 2018. Rapid filling of the intake by gravel and sand required it to be flushed, sometimes multiple times per day, and this maintained S in the presence of C. A second major intake system suppled sediment just upstream of Reach B. Reaches C and D were the final reaches where there was enough space and a low enough bed slope for sediment accumulation to occur before the Borgne d’Arolla steepens and joins the Ferpècle stream at the village of Les Haudères.

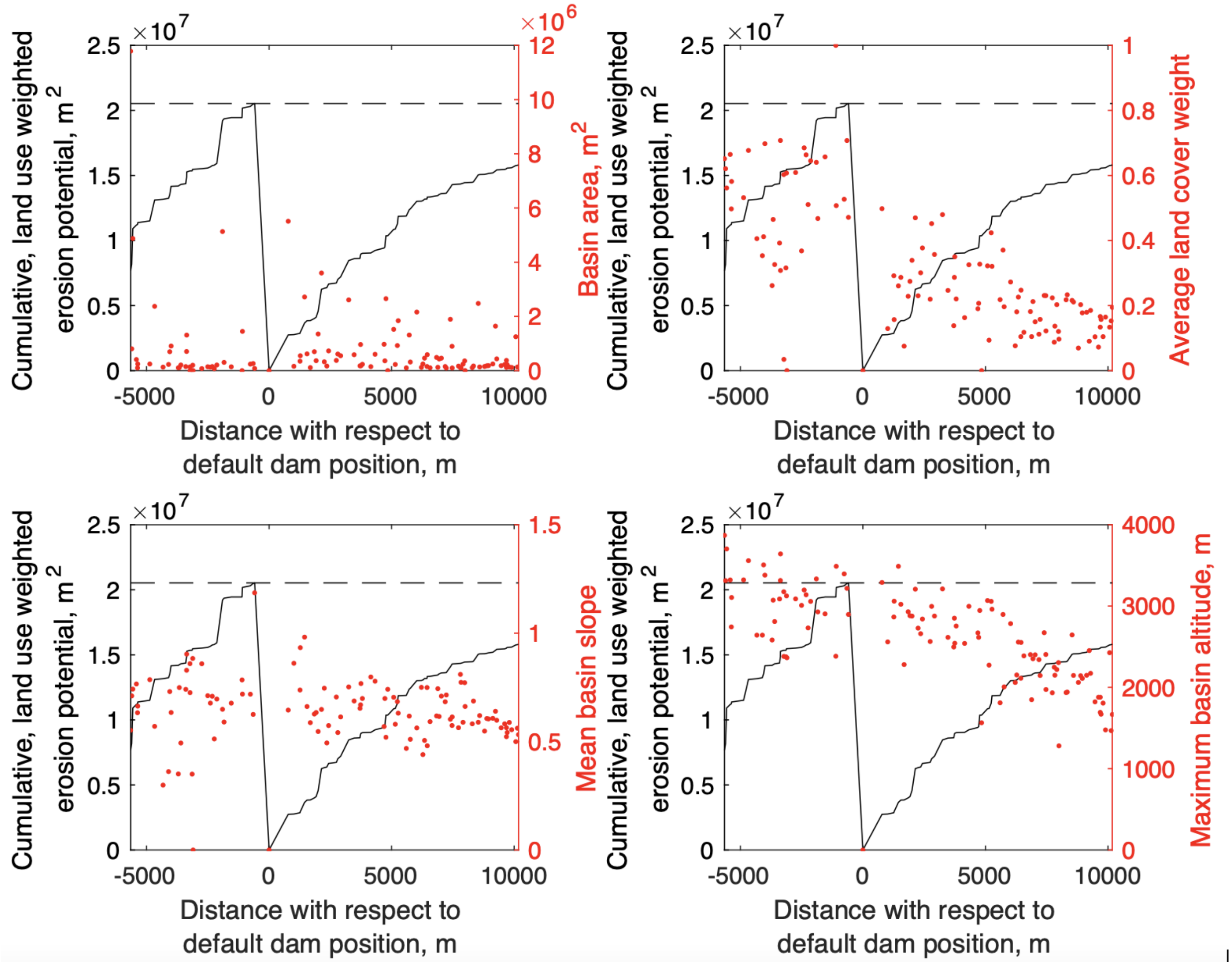

Fig. 8. A model of sediment accumulation to show the effects of a dam on sediment discontinuity for the Hérémence valley in South-west Switzerland. [73] (in review) explains the methodology. Sediment is supplied by individual tributaries to the valley bottom and this is accumulated (black line). The Dixence dam (position 0 m) is assumed to disconnect sediment flux entirely and then sediment accumulates from unregulated tributaries downstream of the dam. Also shown in the figure are parameters that might influence the effectiveness of sediment delivery from unregulated tributaries.

climate change, humans adapt. This adaptation is already a crucial element of Alpine river management. It happens at quite small spatial scales (e.g. communes), is often reactive and rapidly so (in response to an extreme event, for example) and may also imply actors whose remit is far from river restoration (e.g. those responsible for maintaining roads). It may also be linked to quite indirect processes. Lane et al. [4] for example reported a substantial increased in sediment flux to Lake Geneva in the late 2000s due to the effects of reduced sediment extraction following from the financial crisis-induced reduction in building activity. Such adaptive responses can have a significant impact on bedload fluxes in mountain environments and emphasize the need to look more holistically at river restoration; and also to allow it to adapt to a highly uncertain (now and in the future) environment.

Perhaps the final point that merits reflection comes from the rate at which Alpine environments are currently changing. Rapid glacier recession and the shift in winter precipitation to rain at progressively higher altitudes in Alpine environments means that many Alpine rivers are currently in a state of transient and rapid response. This response implies evolution away from the state that they were in prior to the major impacts of human activities before, for example, the widespread expansion of Alpine hydropower in the 1950s and 1960s. Thus, we have a changing "reference state" meaning that we must be very careful about using the term "restoration" and also making calls to restoring bedload transport to its "natural state" in river management. This is a debate held more widely in relation to ecosystem restoration. For instance, we will not be able to restore bedload transport in Alpine streams to pre-hydropower conditions because environmental change means those conditions are no longer achievable. The reference to "nature" found in some legislation becomes problematic because nature is changing so rapidly under climate change that what is "natural" now is not the same as 60 to 70 years ago. Even if we removed all human impacts on both sediment supply and transport capacity in Alpine streams it would not be possible to return to the kinds of river morphodynamics of the middle of the 20th century.

VII. Towards ”Climate Sensitive” Bedload Policy: Key Conslusions

A more “climate sensitive” river restoration and associated bedload management needs to address the six responses to the questions posed in the introduction.

First, we need to emphasize that what matters is not bedload transport itself, but having rivers whose morphodynamic functioning (and ultimately habitat) can sustain life without negatively impacting upon people and property. A focus on bedload transport itself (e.g. guaranteeing that infrastructure allows bedload to pass) will not necessarily deliver better habitat (and may even make things worse) not least if other elements of the system (e.g. transport capacity) remain impacted by humans. It is vital that the effects of bedload management trials are carefully studied in terms of impacts on habitat, ecosystems and people, and they need to become more “goal” or “end-user” oriented. Second, as yet, there is.

Second, there is, as yet, no clear bedload transport “hockey stick” in Alpine streams equivalent to what we see for temperature in the last 100 years of climate change records. There is, however, a shift in the dominant processes that drive bedload transport, notably from glacier-driven to rainfall-driven in basins traditionally with glacier cover. This transition involves an initial increase in bedload delivery to downstream due to increased capacity to evacuate sediment, but evolves towards a reduction in sediment delivery through time as glaciers become smaller, reducing transport capacity, and sediment supply is reduced due to reduced glacial erosion and development of landscape-scale feedbacks that have stabilizing tendencies.

Third, there remains a fundamental limit in our ability to predict bedload transport rates with sufficient precision and accuracy for them to be usable in predictions of the future. There are two broad reasons for this; (a) changes in sediment supply that can lead to substantial scatter in the relationship between bedload transport rate and hydraulic predictions; and (b) changes in discharge or sediment supply both lead to evolution of the morphology and perimeter sedimentology of rivers that are rarely considered in practical studies of bedload transport. Consideration of bedload transport capacity alone is unlikely to predict how climate change will impact river morphodynamics. This is a particular difficulty because what matters for ecosystems, as well as the protection of people and property, is not bedload transport itself but the services (e.g. spawning habitat; sediment evacuation) provided by bedload transport.

Fourth, there is mixed evidence as to how bedload transport capacity will change in the future due to climate change. The effects of the latter are likely to be highly dependent upon the kind of basin being considered, and notably the relative importance of glacier melt and its change through time. Alpine basins are likely to become more similar in one sense; bedload transport capacity will become increasingly dominated by extreme rainfall events and less associated with glacial erosion and sediment transport.

Fifth, to date there have been very few syntheses of how sediment supply might evolve in the future in Alpine basins. The processes are becoming better known, but the analysis presented in this paper shows how sediment supply in Alpine basins will be subject to complex positive and negative feedbacks in response to climate change. However, with reduced glacier cover, sediment supply is likely to become more dependent upon extreme rainfall events in all Alpine basins, and such events are likely to be a primary driver of future bedload transport processes.

Finally, given this evidence, it is likely that river restoration under rapid Alpine climate change will need to be more context-specific, time-specific and adaptive which is going to be a challenge given the long life times of present infrastructure investments. Many of the basic assumptions that we make about sediment transport, notably that there is an equilibrium between rates of sediment delivery and rates of sediment export, are highly unlikely to apply. There is a serious danger in applying much of current bedload transport theory into these systems that are highly out-of-equilibrium with climate. It is also vital that we accept that restoring “natural” bedload transport processes will not be possible as the fundamental template of what drives bedload transport now (and in the future) is very different to that of 100 years ago.

Acknowledgment

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