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Restoring morphodynamics downstream from Alpine dams: Development of a geomorphological version of the serial discontinuity concept

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ABSTRACT

There is well-established evidence that dams disconnect upstream to downstream sediment flux in rivers and that this may have negative impact on downstream ecosystems. For this reason, the development of environmental flows now includes sediment supply and transport whether through reconnecting upstream supplied sediment to a river downstream of a dam, eco-morphogenic flows to rework the stream bed, or artificial sediment supply. However, especially in Alpine systems, there may be unregulated tributaries that are able to deliver gravel and coarser sediment naturally to compensate for the effects of dam-related sediment disconnection. To represent these effects we propose a geomorphic form of the serial discontinuity concept and apply it to two hydropower dam-impacted Alpine streams in the Swiss Pennine Alps. Conceptually, the relative position of a dam influences the degree of coarse sediment disconnection as well as the rate of coarse sediment recovery, especially as many Alpine valleys have strong down-valley gradients in tributary sediment delivery. In both case-studies, there was rapid recovery in likely coarse sediment delivery downstream of the dams. By following geomorphic response of the rivers to eco-morphogenic flow trials, proposed as a solution to perceived dam-driven coarse-sediment disconnection, we confirmed that both rivers are likely to have more than sufficient natural coarse sediment supply and unregulated floods. Natural coarse sediment supply is rarely considered in the management of Alpine streams impacted by hydropower but it needs to be evaluated through a geomorphological assessment, considering both the geomorphic context of the river reaches downstream of the dam and the geomorphic attributes of the basin in which the dam is found.

1. Introduction

As dams disrupt downstream fluxes of both water and sediment, they can have a major impact on river morphodynamics downstream, although the exact impacts will depend on: the dam and its operation; where it is built within a river basin; and characteristics of the river itself (Sherrard and Erskine, 1991; Church, 1995; Kondolf et al., 1996; Rollet et al., 2014). Reduced sediment flux to downstream may lead to channel incision if the post dam-closure hydrology can still produce the flood peaks needed to mobilize sediment (e.g. Galay, 1983; Williams and Wolman, 1984; Smith and Mohrig, 2017). The associated incision may lead to disconnection of rivers from their floodplains (Kroes and Hupp, 2010; Renshaw et al., 2014). Changes in channel pattern can occur (Galay, 1983; Kondolf and Swanson, 1993; Draut et al., 2011) often with an evolution to reduced morphological diversity. Coarsening of bed sediment through the winnowing of sand and gravel has also been reported leading to the development of armoring (Andrews, 1986; Erskine et al., 1999). Coarsening, coupled to the reduced magnitude and frequency of sediment transporting flows, leads to more stable stream beds and biogeochemical processes that reinforce the problems of colmation (Zhang et al., 2011; Gartner et al., 2012; Wharton et al., 2017), the process of fine sediment accumulation in the surface layers of river-bed sediment, and the associated biological and chemical processes that can then follow. It is not surprising, then, that dams have been reported as having a negative impact on downstream ecosystems in a wide variety of river settings (Ligon et al., 1995; Camargo and Voelz, 1998; Ogbeibu and Oribhabor, 2002; Lessard and Hayes, 2003; Wright et al., 2008; Jansen et al., 2020). Dam operations such as periodic flushing of fine sediment accumulated behind the dam, if not carefully designed, may exacerbate these negative impacts (e.g. Brooker and Hemsworth, 1978; Cushman, 1985; Moog, 1993; Lauters et al., 1996; Céréghino and Lavandier, 1998; Smokorowski et al., 2011; Schülting et al., 2016, 2019; Bruno et al., 2019; Gabbud et al., 2019a, 2019b).

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Given the above, reducing the extent and impacts of sediment disconnection caused by dams has been an important component of restoring rivers regulated for hydropower. At the most extreme, this involves dam removal (Bednarek, 2001; Pizzuto, 2002) which is now widespread in some geographical settings (e.g. O'Connor et al., 2015; Bellmore et al., 2017). However, this is not a solution if the dam is still needed for hydropower provision or drinking water supply. One alternative is a flushing flow. Here, there is some confusion of terms in the literature (Loire et al., 2021) between a flushing flow needed to remove sediment accumulated behind a dam and an environmental or artificial flow designed to morphologically-rework the river downstream of the dam, what Loire et al. (2021) call eco-morphogenic releases. Where dams have to be flushed to avoid sediment over-accumulation, notably of fine sediment, flushing may be designed to have beneficial downstream impacts (e.g. Kondolf and Wilcock, 1996; Espa et al., 2019; Grimardias et al., 2017; Doretto et al., 2019; Loire et al., 2019; Lane et al., 2020). The dam infrastructure itself may limit the possibility of flushing, notably of gravel and coarser sediment that commonly moves as bedload, so maintaining downstream coarse sediment deficits. For this reason sediment by-pass tunnels to re-establish coarse sediment connectivity have been suggested (Auel et al., 2017; Martin et al., 2017; Serrana et al., 2018). Their success varies between sites (Serrana et al., 2018) and depends upon the frequency and magnitude of bedload flux induced by the bypass (Auel et al., 2017; Martin et al., 2017). They also require expensive modification of the dam infrastructure itself.

Eco-morphogenic releases, also referred to as channel maintenance (Loire et al., 2021), environmental or artificial floods commonly involve introducing a flow that is capable of producing changes in channel form in rivers that are sufficient to have positive ecosystem consequences. These do not explicitly re-establish sediment connection and deal with downstream coarse sediment deficits. However, if the long-term effects of reduced sediment supply are armoring, colmation and reduced morphological diversity (e.g. single- rather than multi-thread channels), then introduction of a morphologically-forming (i.e. morphogenic) flood may have positive ecosystem consequences (e.g. flushing of fine sediment; removal of excess biofilm-development; opening of secondary channels) and hence ecosystem benefits (e.g. Kondolf et al., 1987; Schälchli, 1992; Kondolf and Wilcock, 1996; Wilcock et al., 1996; Robinson et al., 2004; Newson et al., 2012; Robinson, 2012; Quesada et al., 2014; Rivaes et al., 2015; Robinson et al., 2018). Whilst having a clearly demonstrated potential they may also be limited by dam infrastructure and the ideal timing may be complicated by when a dam has water that can be released.

One alternative to changes in dam infrastructure and operation is the artificial supply of coarse sediment to reaches downstream of dams. Rapid recolonization by benthic fauna has been reported after such supply (e.g. 6 weeks; Merz and Chan, 2005). Improvement in the habitat available for target organisms has been noted (e.g. Chinook salmon spawning, Elkins et al., 2007; and rearing, Sellheim et al., 2016; macroinvertebrates, Stäntzel et al., 2018). However, artificial coarse supply has had mixed results (Wohl et al., 2015). The volume of coarse sediment that can feasibly be introduced is commonly small compared with the volume that is retained behind the dam (Kondolf, 1997). Artificially-supplied coarse sediment may be rapidly washed out (Merz et al., 2006), especially finer gravels (Sklar et al., 2009). This can be particularly the case where a river downstream of a dam is still prone to floods (Arnaud et al., 2017) whether from unregulated tributaries or artificial floods from the dam itself, especially if those floods are themselves sediment-starved due to upstream regulation (Kondolf et al., 1996). The solution is only sustainable with continued coarse sediment supply (Welber et al., 2020). Beneficial effects, notably rates of reworking of coarse sediment, may be spatially-localized (Gaeuman, 2014) or influenced by existing sediment stored within the channel (Gaeuman et al., 2017). These issues aside, artificial coarse sediment supply is being routinely suggested as a solution to the disruption of sediment flux (e.g. the International Hydropower Association, 2019).

In Alpine river basins, such solutions merit reflection because unregulated basins may deliver coarse sediment downstream of dams at a rate that is substantially greater than that possible artificially; we label this natural coarse sediment supply. The importance of natural coarse sediment supply may be increased because, in retaining water for hydropower, the dam also reduces transport capacity downstream (Elliott and Parker, 1997). Natural coarse sediment supply can be interpreted in the framework of the serial discontinuity concept (SDC) proposed by Ward and Stanford (1983). The SDC provides a theoretical description of how dams regulate the downstream hydrology and ecosystems of streams and rivers. It was developed to complement the dominant view at the time that rivers could be described as uninterrupted continua (after Vannote et al., 1980) and to recognize that dams: (1) perturb this continua; but (2) there is then recovery with distance downstream of the dam to the conditions that might have been expected without the dam. Ward and Stanford (1983) note that: (1) not all parameters will be perturbed to the same degree, this degree labelled as the "parameter intensity"; and (2) natural processes should lead to the recovery of parameters over a certain distance that they label the "discontinuity distance". Ward and Stanford (1983) initially developed the concept for a set of physical (e.g. bottom light intensity, diel temperature range, annual temperature range, annual flow range, nutrient availability) and biological parameters (e.g. photosynthesis: respiration ratio, plankton density, biotic diversity) that reflected the focus of Vannote et al. (1980). They include little reference to sediment, noting in only one figure "substrate size", simply conceived as declining continually down from the dam. However, geomorphological research has shown that unregulated tributaries have the capacity to perturb downstream fining (Rice and Church, 1996, 1998; Rice, 1998; Menting et al., 2015) and cause sediment aggradation in the main channel (Rice, 2017). They may impact the forms present on the river bed and lead to local bed aggradation, alluvial fan formation and width constriction (Elliott and Parker, 1997; Yanites et al., 2006; Dean et al., 2016). Tributary effects may be persistent in time depending on river context (Marteau et al., 2020) and be of ecological importance (e.g. Rice et al., 2001; Benda et al., 2004; Rice et al., 2006; Davey and Lapointe, 2007; Lanthier et al., 2015; Tavernini and Richardson, 2020). This importance appears to be magnified in rivers regulated by dams (Elliott and Parker, 1997; Yanites et al., 2006; Dean et al., 2016; White et al., 2018; Milner et al., 2019) not least because dams modify the magnitude-frequency relation for discharge and hence of sediment transporting events. Where tributaries deliver sediment to regulated rivers, the effect of that sediment on river sedimentology and morphology may also depend on its ability to be reworked (Melis et al., 2012). It follows that, if unregulated tributaries can lead to substantial natural coarse sediment delivery, whether and how much artificial sediment delivery, or other infrastructure related interventions (e.g. modified flushing flows, sediment by-pass channels) is needed should be considered. We emphasize that natural coarse sediment volumes in the main stem of a river can never be fully restored by tributary supply as by definition sediment is being stored behind the dam. Thus, rates of tributary supply and the reduced magnitude and frequency of coarse sediment removal in the main stem need to be considered with respect the critical ecosystem services sought downstream of the dam in order to decide if tributary supply is a sufficient compensating measure.

The aim of this paper is to show that in an Alpine context it is vital to take into account natural coarse sediment supply in deciding whether or not interventions are required based on artificial coarse sediment addition or infrastructure modification and operations. We have three objectives. First, we aim to develop a conceptual basis for a geomorphologically-explicit form of the SDC suitable for Alpine streams. Second, we illustrate this geomorphic-form of the SDC using a heuristic basin-scale model of both dam and unregulated tributary impacts on the likelihood of coarse sediment delivery downstream for two hydropower-impacted Alpine streams. The results show that geomorphological context is crucial in determining whether the coarse sediment disconnection caused by dams and other hydropower operations can be mitigated via natural coarse sediment supply. Finally, for the same two case-studies, we show that the responses of these streams to environmental or artificial floods were commensurate with there being significant natural coarse sediment supply to deliver the ecosystem services required given the flow regulation associated with the hydropower schemes themselves.

2. Development of a geomorphologically-informed serial discontinuity concept

The development of a serial discontinuity concept for coarse sediment, defined here as gravel and coarser, must recognize six key points. First, downstream from a dam, initial coarse sediment starvation may be replenished by the delivery of gravel and coarser fractions from unregulated tributaries which join the river downstream. A number of studies have shown that such tributaries can interrupt downstream fining (Rice and Church, 1996, 1998; Rice, 1998; Menting et al., 2015; Rice, 2017). Tributary sediment supply can lead to local biodiversity increases (Rice et al., 2001; Thorp et al., 2006) and modify sediment supply to reaches immediately downstream. Thus, with distance downstream, tributary-supplied coarse sediment may progressively compensate for the coarse sediment that has been stored behind the dam. Eventually, the level of coarse sediment supplied to the stream, downstream of the dam, reaches the level that was supplied to the dam. This occurs at the "discontinuity distance" in the terminology of Ward and Stanford (1983).

Second, the rate at which replenishment occurs will depend upon the extent to which the dam, or other infrastructure, disconnects coarse sediment flux, as not all interventions lead to complete sediment disconnection (Gabbud and Lane, 2016). This effect can be seen as equivalent to Ward and Stanford's (1983) parameter intensity. In fluvial sedimentary systems, this parameter intensity is not only impacted upon by dam-related infrastructure but also the natural processes of coarse sediment storage that would have occurred upstream of the dam. Indeed, most river basins have sediment delivery ratios (defined as the proportion of sediment eroded in a basin that leaves the basin) for all size fractions that decline exponentially with distance downstream and increasing upstream basin area (Ferro and Minacapilli, 1995) because some sediment goes into temporary or long-term storage. Thus, the absolute value of the parameter intensity is not only related to the dam, but where it is located with respect to upstream sources of coarse sediment and the valley-bottom space available for coarse sediment to be stored naturally before it reaches the dam. This same process also has similar effects downstream of a dam as if coarse sediment goes into storage so it will require more coarse sediment delivered from tributaries before the discontinuity distance is reached.

Third, the rate of replenishment will depend on the availability of potential coarse sediment sources in tributary basins downstream of the dam. There are potentially two reinforcing processes. First, especially in Alpine or mountain river basins there may be strong downstream gradients in hillslope erosion potential especially where declining altitude increases the percentage of a basin that is forested and hence more stable. Second, with distance downstream, so the probability of a contributing tributary with a significant surface area grows (this follows from Strahler (1952) area-altitude relationships). Thus, we might expect a size effect in terms of coarse sediment delivery rates, with bigger basins more likely to be able to deliver more sediment (if not necessarily more coarse sediment). However, as basin area increases so sediment delivery ratio declines (Ferro and Minacapilli, 1995) such that very large tributaries may supply very low volumes of coarse sediment. It is only possible to determine the effects of these processes with reference to where the dam is located within a basin, as well as each tributary's own characteristics (altitude, land use, size, etc.). Thus, the rate at which natural coarse sediment supply compensates for sediment flux disconnection by a dam is context specific (Wohl, 2018).

Fourth, potential coarse sediment sources also need to be combined with an assessment of the extent to which they connect with the river. There is a growing appreciation that on-hillslope and within-stream connectivity exert a critical effect on coarse sediment delivery, especially in river basins with a history of glaciation (Cossart, 2008; Cavalli et al., 2013; Messenzehl et al., 2014; Coassart, 2016; Micheletti and Lane, 2016; Guillon et al., 2018; Rainato et al., 2018; Clapuyt et al., 2019; Mishra et al., 2019; Millares and Monino, 2020). As a deglaciating landscape has an evolving connectivity through time (Lane et al., 2017; Mancini and Lane, 2020) and as the time since deglaciation will increase with distance down valley, there may be a progressive change in tributary connectivity with distance downstream from a dam. This connectivity may also itself be influenced substantially by non-natural processes (Scorpio et al., 2020). Checks dams are a common solution adopted in Alpine environments to reduce tributary connectivity to rivers (Piton et al., 2017; Marchi et al., 2019). There is similar evidence of substantial gravel extraction in Alpine streams (e.g. Lane et al., 2019). Infrastructure such as roads may also have important effects on tributary sediment connectivity (Schopper et al., 2019).

Fifth, the rate of replenishment will be impacted upon by controls on coarse sediment flux and so the by hydrology as modified by the dam and the valley geomorphology downstream of the dam (e.g. valley slope, accommodation space). Not only do dams reduce sediment supply from upstream, they also reduce sediment transport capacity. Even when minimum flows are introduced these are not normally sufficient to cause coarse sediment transport. This reduced sediment transport capacity is one of the motivations for morphology-forming floods as insufficient bed reworking can lead to biogeochemical processes that reinforce the effects of colmation (Zhang et al., 2011; Gartner et al., 2012; Wharton et al., 2017) and negative ecosystem consequences (Camargo and Voelz, 1998; Ogbeibu and Oribhabor, 2002; Jansen et al., 2020).

Fig. 1 aims to illustrate how these controls might interact. The black curve in Fig. 1a shows how coarse sediment flux increases due to

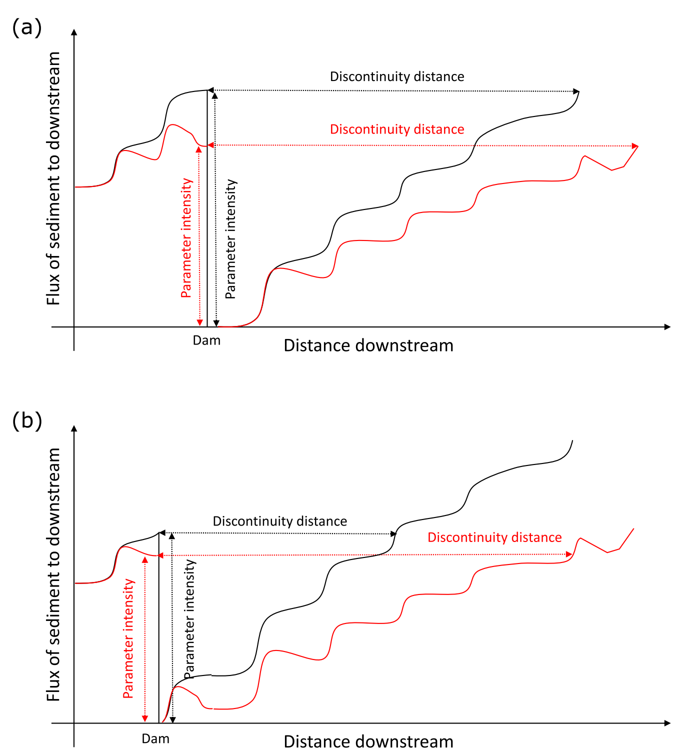

Fig. 1. Illustrations of the conceptual model for a dam without valley storage (black) and with valley storage (red). In Fig. 1b, the dam is moved upstream for both the scenarios shown in Fig. 1a.

tributary sediment delivery with distance downstream until the dam is reached. Here, it is assumed that there is no coarse sediment connection through the dam, and that defines the parameter intensity. Downstream of the dam, coarse sediment flux increases progressively due to tributary supply. In this illustration, coarse sediment supply is conceptualized as declining in importance as it is assumed that whilst tributary connectivity may increase with distance downstream due to the long-term effects of reworking of landforms linked to glacial legacy, a progression to more stable land covers, larger tributaries and the disconnecting effects of infrastructure is dominant.

Eventually, coarse sediment supply is restored in volumetric terms to the total supplied to the dam itself, at the discontinuity distance. The red curve in Fig. 1a shows what happens if some of the sediment delivered to the main trunk of a river is stored within the valley system. This has the effect of reducing the coarse sediment volume that is delivered to the dam, and so reducing the parameter intensity. But, because this effect may continue downstream, despite reducing the parameter intensity, the discontinuity distance is longer. It emphasizes a key point that valley-bottom storage controls both the natural coarse sediment accumulation upstream of a dam and, through sediment storage effects downstream, the discontinuity distance that results. Fig. 1b then moves the dam upstream. The parameter intensities for the no valley storage (black) and valley storage (red) cases are both smaller in magnitude. This results in shorter discontinuity distances. The further upstream a dam, the lower the parameter intensity and, when combined with tributaries that are delivering proportionally more coarse sediment (closer to sources), the shorter the discontinuity distance. A key point that emerges from this conceptual model is that, in Alpine environments with strong down valley gradients in process intensity, the spatial extent of dam impacts on coarse sediment flux depends on where the dam is, rarely considered in policy development in many situations, even though tools to inform this issue exist (Rinaldi et al., 2013).

3. Materials and methods

In this section we apply this conceptual model to two Alpine streams where, under the Swiss Water law, mitigation of dam impacts is required and where eco-morphogenic flows have been tested; the Hérémence and Turtmann streams in south-west Switzerland (Fig. 2). First, the conceptual model is applied through a simplified analysis of potential coarse sediment sources coupled to a hydrological routing treatment that takes into account possible sediment disconnection based upon the method published in Lane et al. (2017) and Mancini and Lane (2020). We validate the model by comparing the estimated importance of tributary coarse sediment delivery with observations of whether or not a tributary appears to be actively supplying coarse sediment to the stream. Second, to test the relevance of this model in practice, we report the flow trials studied in 2018 and 2019 (Hérémence). Those for the Turtmann (studied in 2019) have already been published (Lane et al., 2020) and we also refer to these. Development of bed armoring is a consequence of an excess of sediment transport capacity over sediment supply and the subsequent increased channel stability can lead to accumulation and/or reduced flushing of fine sediment from the bed, the development of colmation, vegetation encroachment, channel narrowing and a tendency to more single-thread rather than multi-thread channels. A lack of bed armoring should lead to lower critical shear stresses required for coarse sediment transport and hence the rapid onset of sediment transport as discharge rises in alluvial reaches downstream of a dam. A river response that is highly sensitive to flow increases would suggest that, notwithstanding dam-related coarse sediment disconnection, there is substantial and sufficient natural coarse sediment supply.

3.1. The Hérémence and the Turtmann river basins

The Hérémence and the Turtmann river basins are both true-left tributaries of the (Swiss) Rhône River in South-West Switzerland.

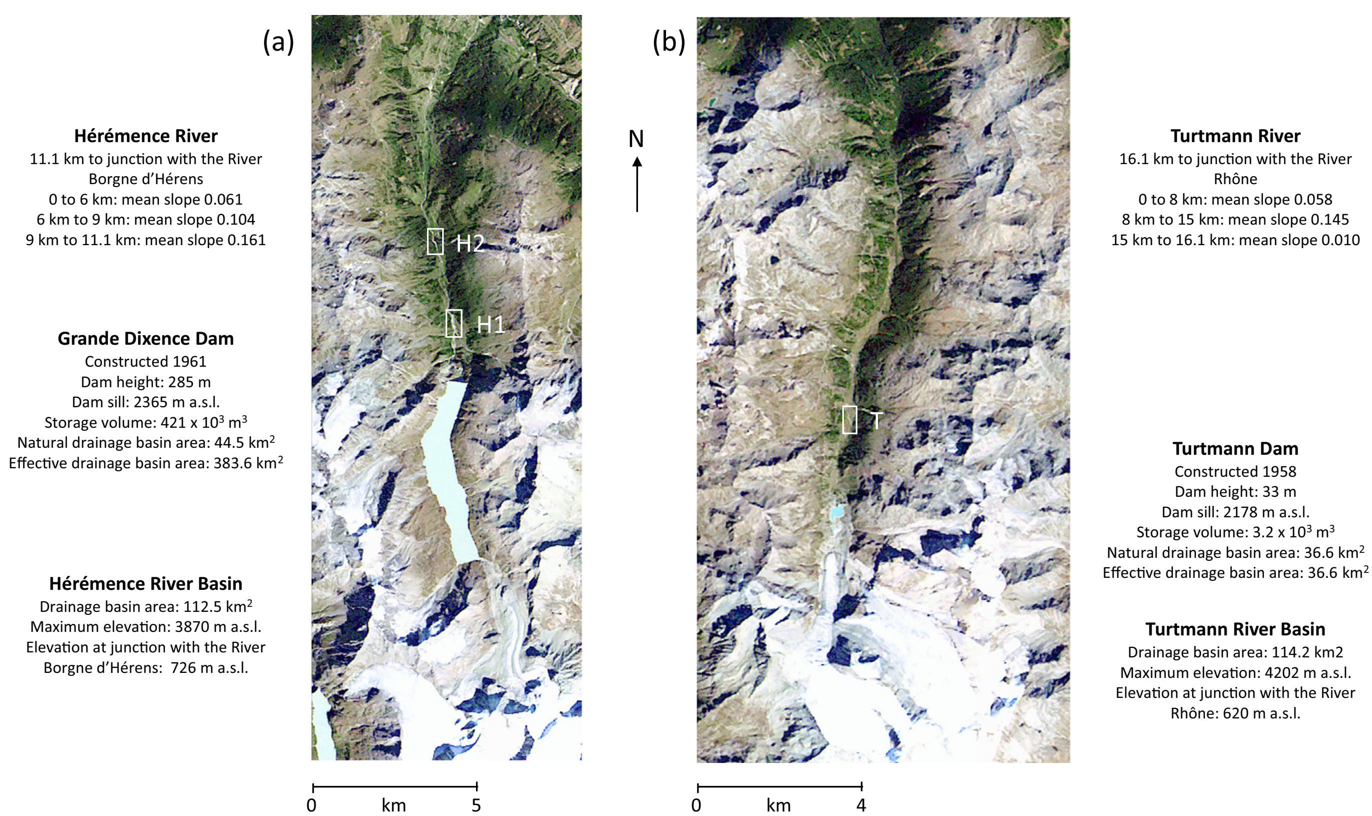

Fig. 2. The basins of the Hérémence (a) and Turtmann (b) rivers showing the two water storage dams, the Grande Dixence Dam (a) and the Turtmann Dam (b).

Fig. 2 shows that they share similar land cover characteristics with a gradient from South to North; the basins are glacial (following Weingartner and Aschwanden, 1992) close to the Alpine divide in the south; by their North they are dominated by forest and Alpine pasture. Downstream of the dams, both rivers are convex downwards (except for the most downstream segment of the Turmann valley where it enters the River Rhône). In the less steep upper reaches (0 to 6 km downstream of the Hérémence dam and 0 to 8 km downstream of the Turtmann dam) there are reaches with sufficient valley bottom width for the rivers to be multi-thread and alluvial (up to 40 m in the Hérémence and 80 m in the Turtmann) and the sediment is dominated by gravels and cobbles. In the steeper lower reaches, the rivers are both single thread and tend to be semi-alluvial.

The two reservoirs differ in their storage volume. Both have similar natural drainage areas (Fig. 2), the Grande Dixence has a markedly greater effective drainage area because it is the recipient of tunneled water originating in the Hérens and Mattertal valley to the West. This is reflected in very different dam storage volumes (Fig. 2) and also dam operations. The Grande Dixence dam was not designed to be flushed annually as most sediment (sand and coarser) is removed before water enters the tunnels in a series of flow intakes (Gabbud and Lane, 2016; Camargo and Voelz, 1998; Ogbeibu and Oribhabor, 2002; Jansen et al., 2020). The Turtmann dam has to be flushed annually, mainly to remove the accumulation of sand and finer-sized sediment. Under Swiss legislation, the hydropower operators are required to implement mitigation plans for both systems to reduce the impacts of water storage and coarse sediment disconnection downstream of each dam.

3.2. Modelling of coarse sediment supply from tributaries

Modelling of coarse sediment supply is based upon: (1) identification of possible coarse sediment sources in each tributary stream; and (2) determination of their possible hydrological connectivity and hence delivery to the main stream. We focused on delivery by streams, and hence hydrological connectivity, as there is negligible direct coarse sediment supply to the streams such as from rock-walls or other mass movements.

Possible sediment sources were mapped using automated classification of 25 m Landsat imagery interpolated onto the 2 m resolution topographic data supplied by the Swiss Federal Topography Office (SwissTopo®). These data were obtained using LiDAR at altitudes below about 2000 m a.s.l. and stereo photogrammetry at altitudes above 2000 m a.s.l. Whilst the LiDAR data have an estimated precision of around ±0.30 m, the photogrammetric data are precise to ±1 to ± 3 m, and the spatial variation in this precision is not known. Here we take the middle of this range as the precision (±2 m).

We made the hypothesis that two types of land cover indicate potential coarse sediment supply; zones suggesting active erosion, as indicated by a visual difference in weathering rates; and permanent snow/ice cover. In both river basins, the latter indicated glaciers which, through high rates of glacial erosion (Herman et al., 2015) and relative ease of partial sediment evacuation (Alley et al., 1997) are likely to be important coarse sediment supply sources. We applied a k-means clustering (Tou and Gonzalez, 1974) to Landsat data for the two river basins to classify potential sediment sources. After initial trials, a target of 6 classes was found to be optimal at distinguishing these sources. Fig. 3a illustrates possible sediment sources for the Hérémence and Fig. 4a for the Turtmann river basins. The classes were then grouped into a binary map corresponding to snow/ice/active sediment (1) and other (0) classes.

The analysis of the likelihood that these sources can be eroded and are able to deliver coarse sediment to the main trunk stream is based upon a distinction between process disconnection and disconnection due to error in topographic data (Lane et al., 2017; Mancini and Lane, 2020). Topography can exert a critical influence in mountain basins on whether or not water and eroded sediment can be delivered to the main stream (Cavalli et al., 2013). We defined process disconnection as arising when a flow path encounters a reverse slope. Whether or not this becomes a real disconnection depends upon the magnitude of the reverse slope and, eventually, the volume of fill needed to eliminate the reverse slope. Whilst many hydrological analyses force flow to travel through to a basin outlet by filling DEM depressions (under the assumption that a depression is caused by DEM noise; Arnold, 2010), we used the DEM precision as a filter to define the level of noise-related disconnection that should be removed before connectivity is calculated (see Lane et al., 2017, for full justification); the disconnection due to topographical error. For the latter we use the DEM precision of ±2 m. We checked the effects of this level of fill via sensitivity analysis.

The calculation of flow accumulation uses the multiple-direction flow routing algorithm of Holmgren (1994) where:

$$FS(i) = \frac{(\tan\beta_i)^x}{\sum_{i=1}^{8} (\tan\beta_i)^x} \tag{1}$$

and β_i = slope in direction i; FS(i) = proportion of flow going in direction (i); x = a parameter that can vary between zero and infinity. For $x = 0$, flow is routed equally between all cells regardless of slope. For $x = 1$, flow is routed evenly in proportion to slope. As x tends from 1 to infinity, FS tends to route all the flow in a single direction, the line of steepest slope. Following tests reported in Lane et al. (2017) for a similar landscape, we set $x = 4$. We assessed the effects of this value via sensitivity analysis.

From FS it is possible to calculate the flow accumulation area of A for each sub-basin within the Hérémence and Turtmann basins (Figs. 3b and 4b). We then used $A^{0.5}S$ as an index for erosional power with units of m (Dalla Fontana and Marchi, 2003; Cavalli et al., 2013) where S is the slope (Figs. 3c and 4c). The maps of power are shown in Figs. 3d and 4d. We modified the sediment source maps (Figs. 3a and 4a) under the constraint that locations with a slope > 1.0 are likely to be unable to retain sediment. Although they may be coarse sediment sources (e.g. rockfall), we assumed that this is at a low rate, and we check the effects of this assumption via sensitivity analysis. Then the sediment source maps are multiplied by the erosional power to identify those locations that are potentially erodible sediment sources (E, Figs. 3e and 4e). These sources are then routed according to [5] again correcting for the effects of topographic error by filling to the precision of the DEM data. We manually identified locations where tributaries entered the main stream or the lake. We used these to identify upstream contributing areas and hence drainage basins to the stream (Figs. 3f and 4f). We then accumulated E to each of these locations to produce a total E for each tributary (E_t). Note that E_t has dimensions of length as it is based upon summing the erosion power index (i.e. $A^{0.5}S$) weighted for possible sediment sources.

We accumulated sediment delivery for each tributary from upstream to downstream along the main stream, by adding E_t to the accumulated sediment delivery wherever a new tributary t entered the stream. As for both Hérémence and Turtmann the dams disconnect coarse sediment flux, we reset the accumulated sediment to zero at the dam, and restarted accumulation. This assumed that there is no valley storage. To explore the effects of storage, we introduced a storage parameter which assumes that a certain percentage of delivered coarse sediment enters storage with distance downstream. There are only few data on this effect in hydropower-impacted streams. Bakker et al. (2018) considered a braided stream in the 1500 m downstream of a flow intake (that, as in both cases considered here, only delivered water downstream during flushing). They found coarse sediment storage at the decadal scale that varied substantially between a few % of the delivered

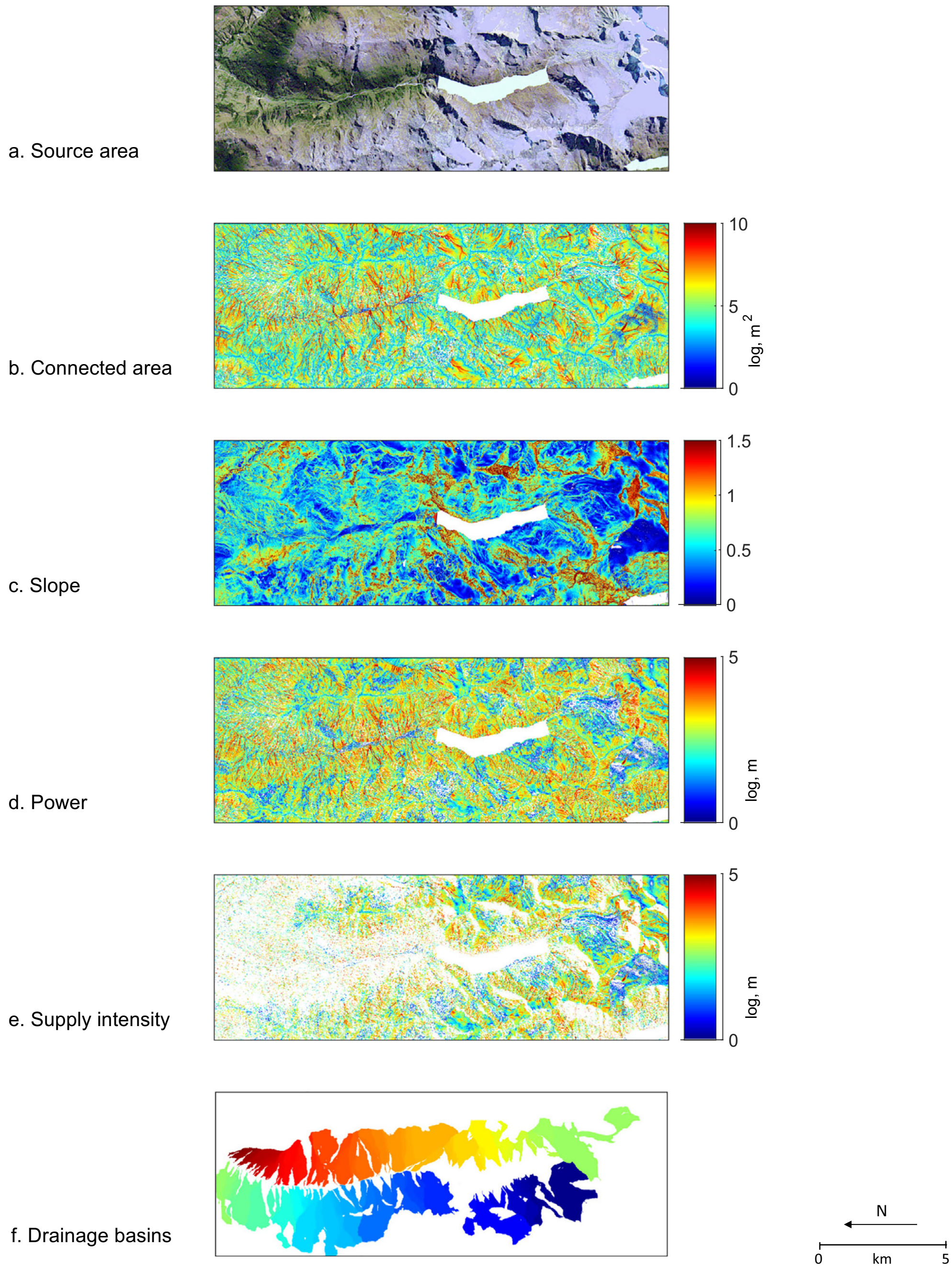

Fig. 3. Illustration of the sediment supply modelling steps for the Hérémence valley.

supply per km to around 40%. Here, we did not attempt to vary this parameter with distance downstream (e.g. as a function of changing valley width). Rather, we assessed the effects of storage as compared with no storage, increasing the storage rate to 10% per km and then 20% per km.

This is a simplified treatment of the likelihood of coarse sediment delivery to the main stream. A fully time-dependent and spatially-explicit treatment might be possible, but this would require a much more complex process treatment and in turn demand data that are not available (e.g. spatial patterns of precipitation at high resolution through time). Such an approach would not be parsimonious. However, our approach has identified parameters that do not necessarily have any a priori means of determination. For this reason we also report on sensitivity analyses for the results, considering: (1) the effects of DEM precision and hence of DEM filling, for which in addition to fill to a default precision of ± 2 m, we also consider no fill, fills of ± 1 m and ± 4 m, and fill of all depressions in the DEM; (2) the effects of the routing parameter in [5], for which in addition to the default of $x = 4$, we consider $x = 1, 2$ and 8; (3) the threshold for sediment accumulation based on slope, for which in addition to the default of $S < 1$ we consider $S < 0.5$ and $S < 1.5$; and (4) the effects of valley storage for which in addition to the default value of 0 we also consider 5% per km and 10% per km (see above). We used one-at-a-time sensitivity with all other parameters held at their default values.

To validate the model we imported the co-ordinates of each basin outlet into the mapping platform (map.admin.geo.ch) of the Swiss Federal Topography Office where it is possible to visualize the 0.25 m resolution SwissImage. We classified each basin outlet on the basis of whether or not there was evidence of active coarse sediment supply to the main stream. We then compared the *Et* values for tributaries with and without active coarse sediment supply.

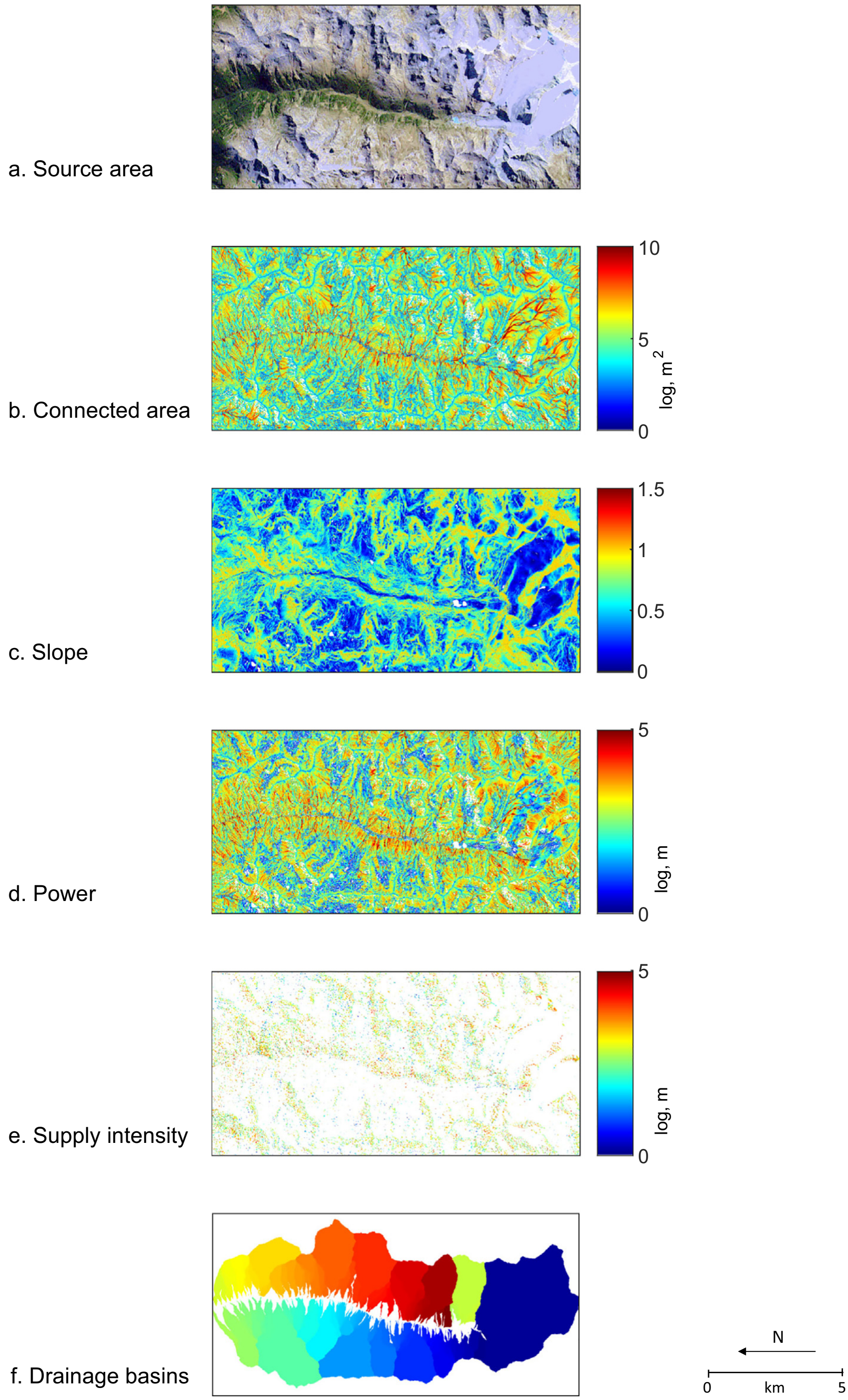

Fig. 4. Illustration of the sediment supply modelling steps for the Turtmann valley.

3.3. Flow trials in the Hérémence and Turtmann rivers

Both the Hérémence and Turtmann rivers were subject to mitigation measures, albeit with slightly different contexts. For the Hérémence River, the measures involved a dedicated eco-morphogenic flood flow. As the Hérémence dam does not allow for flushing, the Hérémence trial was based upon diversion of water; from a tunnel that delivers water to the Grande Dixence storage reservoir on its left bank; and into the first main tributary, the Chennaz stream, that joins the left bank of the Hérémence River downstream of the dam (MFF on Fig. 2a). Initial proposals from a consultancy company had suggested that an artificial flood with a peak magnitude of 15 m^3s^{-1} would be necessary to rework the bed sufficiently. However, such a flood would propose serious coarse sediment transport and flood risks for downstream communities and so a trial was undertaken on the 10th September 2018 with a proposed maximum release of 5 m^3s^{-1} to the Chennaz stream. During the trial, by the time the release had reached 3 m^3s^{-1} there was significant coarse sediment transport and a risk of rates of sediment flux to downstream reaches that could lead to sediment-related damages, directly from coarse sediment aggradation and indirectly from the effects of coarse sediment deposition on water levels during floods. The trial was abandoned at a peak release of 3 m^3s^{-1} (Fig. 5a).

For the Turtmann River, initial proposals for a dedicated morphology-forming flood were not accepted by the local commune due to security concerns. Instead the hydropower operator is trialing modification of the annual flushing flow to have the same effect (Fig. 5b). Lane et al. (2020) provide a detailed description of this trial and provide a presentation and discussion of the lessons for the design of modified flushing flows. This analysis suggested the possibility that there was some natural coarse sediment supply to the river, which is why we include it as a second example in this paper.

3.4. Methodological approach to studying the flow trials

We considered the first reaches in the Hérémence and Turtmann streams where there was likely to have been a positive impact from a morphology-forming flood. The methodology we used to study these trials has been published for the example of the Turtmann River (Fig. 6, Lane et al., 2020), and this is Open Access, so we only include a summary here. The details of its exact application to the Hérémence are available as Supplementary Material; and to the Turtmann in Lane et al. (2020).

We followed the morphological response of the Hérémence river for two sites downstream of the dam (Fig. 2; Fig. 7a, H1; and Fig. 7b, H2) with measurements made at H1 on the 7th and the 11th September

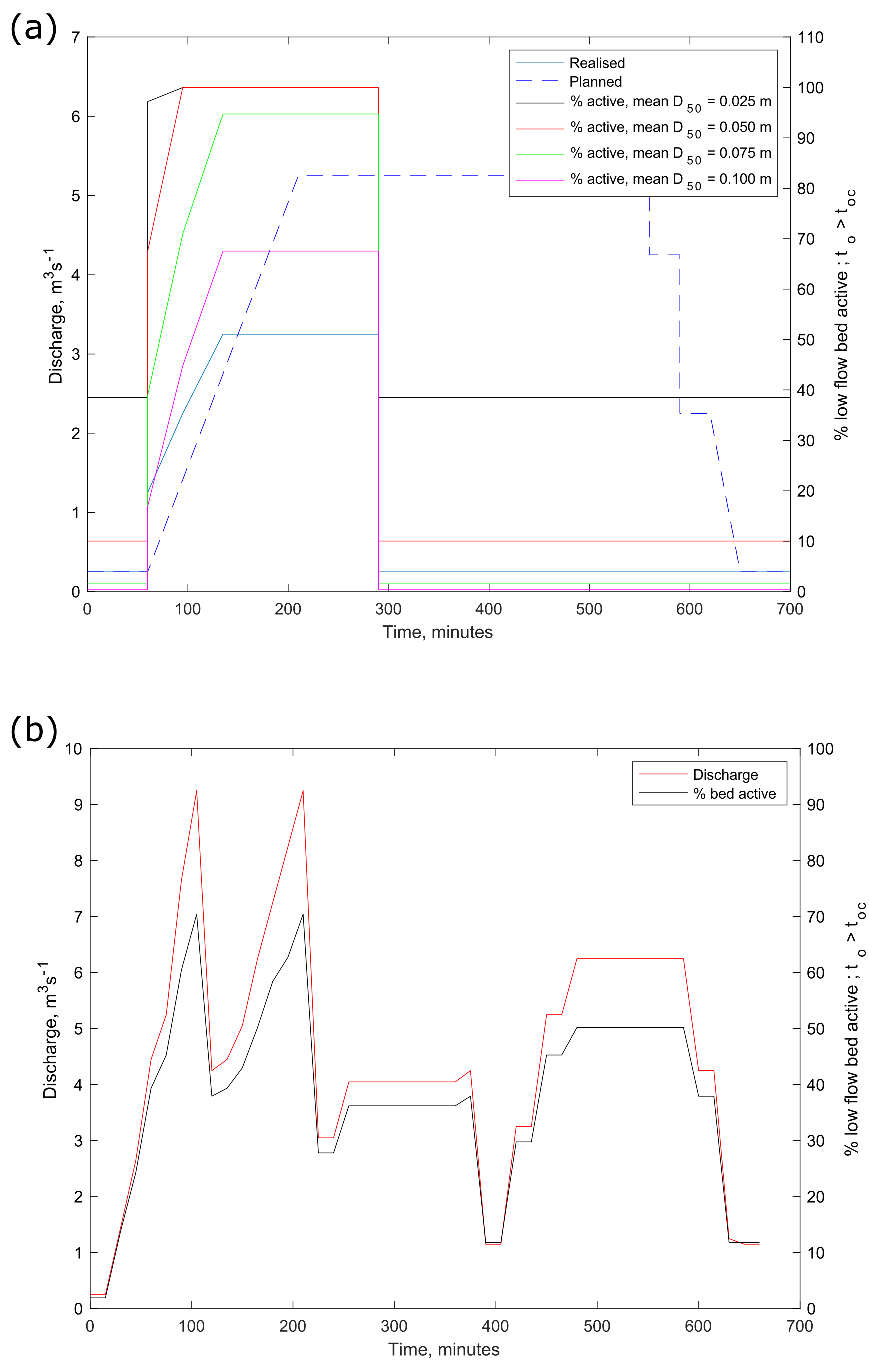

Fig. 5. The Hérémence flow release (Fig. 5a, realized and planned) and the Turtmann modified flushing flow (Fig. 5b). Data provided by Alpiq SA. Also shown are the results of the modelled capacity to transport coarse sediment, for the Hérémence for four uniform grain sizes; and for the Tourtemagne using the spatially-distributed grain-size measured using statistical analysis of drone imagery; see Lane et al., 2020).

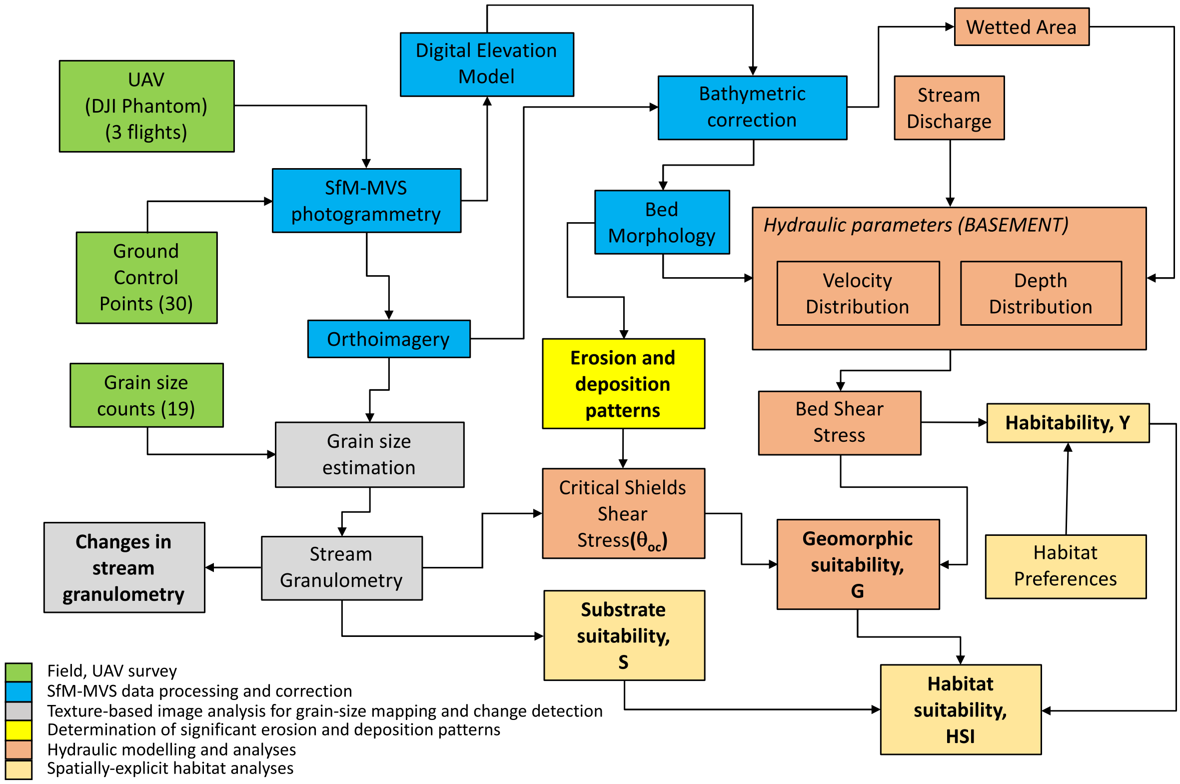

Fig. 6. The integrated monitoring and modelling framework (taken from Lane et al., 2020) used to analyse flow trials for reach H1 in the Hérémence valley and T in the Turtmann valley (see Fig. 7). The granulometric analyses were only undertaken for the Turtmann valley.

2018; and at H2 on the 9th and the 11th September 2018, in both cases either side of the trial on the 10th September. To obtain a longer-term view of the morphological response, we repeated these measurements on the 16th (H1) and 18th (H2) September 2019. There was no trial in 2019. These two sites were chosen both as examples of alluvial (as opposed to semi-alluvial) reaches where there was sufficient accommodation space for the development of multi-thread channels and a theoretically significant level of river bed reworking in response to the flood. Reach H1 (Fig. 7a) is 500 m long and about 1.4 km downstream of the dam. Although there was sufficient accommodation space (up to 35 m wide) for a multi-thread channel to form, the reach is constrained by low level embankments constructed in the mid 1980s for flood management reasons. It has a mean slope of 0.111, approximately twice the average slope of the first 6 km of the Hérémence stream downstream of the dam. The reach has a mixed sand, gravel, cobble and boulder bed with a D_{50} of 0.08 m. Reach H2 (Fig. 7b) is 120 m long and is approximately 1.7 km further downstream from H1. H2 is the first multi-thread reach downstream from H1 with an accommodation space of up to 25 m. This space is limited on the true left by the hillside and on the true right by a road built on a natural river terrace. H2 has a mean slope of 0.025, approximately half the average slope of the first 6 km of the Hérémence stream downstream of the dam. The reach has a mixed sand and gravel bed with a D_{50} of 0.06 m.

The modified flushing flow at the Turtmann was trialed on the 8th October 2019. Data were collected for the first unconfined reach downstream of the dam (T, Fig. 2b), 300 m in length (Fig. 7c) on the 6th and the 14th October 2019. Two important tributaries enter the Turtmann immediately upstream of the reach (the Sanntumbach, left bank and the Brändjibach, right bank) with a total basin area of 7.9 km^2, and which add to the 29.6 km^2 upstream of the dam. Reach T has a mean slope of 0.023, about half of the mean slope for the first 8 km of the Turtmann river downstream of the dam. The reach has a mixed sand, gravel, and cobble bed with a mean D_{50} of 0.019 m.

In this paper we do not present the habitat-related work for either system but focus on the morphodynamic response to the trials and what this means for inferring natural coarse sediment supply. For both the Hérémence and the Turtmann rivers we were able; (1) to calculate net erosion and deposition patterns due to the flow trials for H1, H2 and T, and the erosion and deposition in the year that followed for H1 and H2; (2) to apply the morphological method in one-dimension to estimate the sediment transport required to conserve mass (Antoniazza et al., 2019), which also yields the minimum mass of sediment that must be supplied to the reach from upstream for each time period studied; and (3) to estimate the evolution of sediment transport potential in reaches H1 and T during the flow trial. These methods are explained in the Supplementary Material. It should be noted that as morphological changes may include the release or deposition of sand and finer fractions, the morphological method provides information on all sediment fractions, not just coarse sediment.

4. Results

4.1. Validation and sensitivity analysis for the sediment supply modelling

Fig. 8 shows the distributions of the land-use weighted erosion potential, E_t, for the Hérémence (Fig. 8a) and the Turtmann (Fig. 8b) basins, classed according to whether they were visually supplying coarse sediment or not. In both cases a Mann-Whitney U test confirmed that the modelled values of E_t were significantly higher at $p < 0.001$ for tributaries with observed coarse sediment delivery to the main stem or lake than those with no observed coarse sediment delivery. Higher rates of potential coarse sediment supply were clearer for the Turtmann (Fig. 8b) than for the Hérémence (Fig. 8a). In both cases, it was possibly to find high values of E_t but with no observed coarse sediment delivery to the stream and also some observed coarse sediment supply but with relatively low values of E_t, notably in the case of the Turtmann. Visual inspection provided two explanations. In

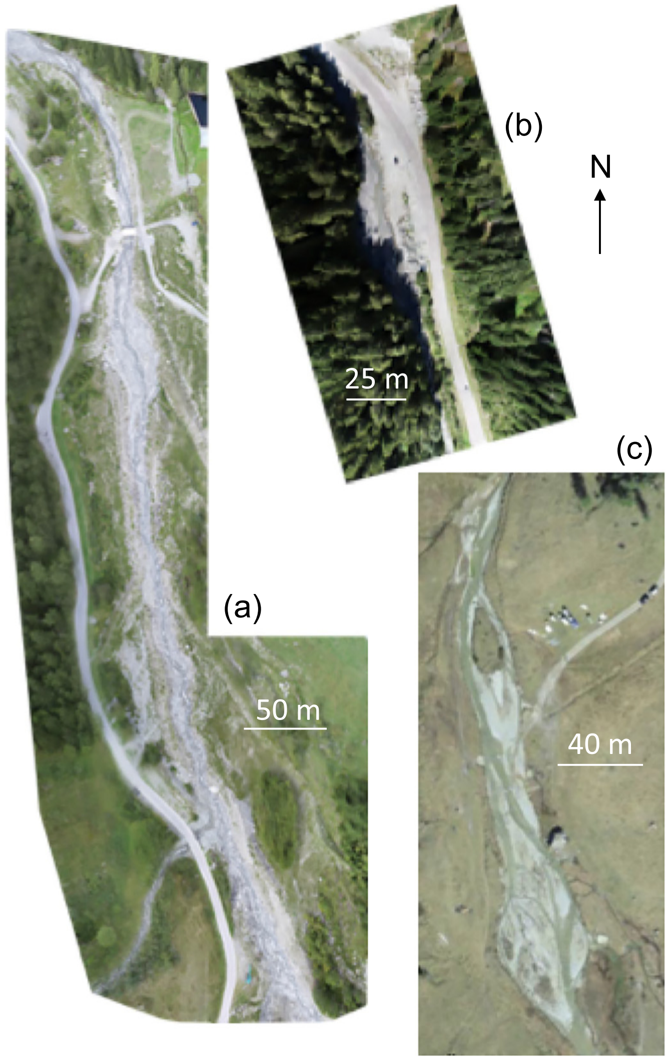

Fig. 7. Orthoimages of the two study reaches H1 (a) and H2 (Fib) in the Hérémence river and the study reach T (c) in the Turtmann River.

some cases, sediment disconnection was caused by infrastructure including artificially created zones of deposition to manage coarse sediment and roads, leading to high modelled coarse sediment supply but no visible active coarse sediment delivery to the stream. In other cases, small (by surface area) basins had intermediate E_t by virtue of their smaller size but these were clearly disconnected from the river by floodplains which are only poorly represented in the model.

Figs. 9 (Hérémence) and 10 (Turtmann) show the results of the sensitivity analyses of primary drivers of model response. The treatment of disconnection (Figs. 9a, 10a) has a very important impact on both the extent of accumulation of E_t upstream of the dam and its recovery downstream of the dam. In both cases, as the forcing of hydrological connection is increased (from no filling through to complete sink removal), the discontinuity distance becomes longer. This is because the level of forced hydrological connection has a very strong impact on parameter intensity as upstream of the dams there are more active sediment sources (Fig. 3a, 4a). The level of diffusion in hydrological routing (x in [5]) has less effect than the degree of forced hydrological connectivity (Figs. 9b, 10b). For both sub-basins, less diffuse routing (i.e. higher values of x) results in higher parameter intensity. The threshold for sediment stability has an important and non-linear impact on accumulated E_t (Figs. 9c, 10c). Reducing this threshold from 1 (45° slopes) to 0.5 (26° slopes) reduces parameter intensity to a much greater degree than increasing it from 1 to 1.5 (56° slopes). Finally, the rate at which delivered sediment enters storage can have an important effect on both the parameter intensity and discontinuity distance. Greater storage rates reduced the parameter intensity for the Hérémence basin (Fig. 9d) but not the Turtmann basin (Fig. 10d) because the latter was closer to sediment sources. However, greater rates of sediment storage have a complex impact on discontinuity distances. In the Hérémence basin, replenishment is almost reached at about 5.5 km downstream (Fig. 9d) but then because E_t values are becoming smaller (see below) transfer to valley storage causes E_t to begin to decline. In the Turtmann (Fig. 10d), even with high rates of storage there remains a balance between loss to storage and replenishment of E_t.

These comparisons also flag an important difference between the Hérémence and Turtmann valleys. The discontinuity distances for the latter are lower than for the former (Figs. 9 and 10) and this is partly because of reduced parameter intensity. However, it is also due to tributary effects. The Turtmann has major tributaries joining in terms of E_t around 2 km and again at around 4.7 km downstream of the dam, and these render the discontinuity distances of the Turtmann much less sensitive to model parameters.

Fig. 11 shows the effects of displacing dam position upstream and downstream. For the Hérémence (Fig. 11a), as the dam moves from 2 km upstream to 2 km downstream, the amount of potential coarse sediment accumulation behind the dam and hence the parameter intensity increases. This has the effect of increasing the discontinuity distance. However, the latter is not only influenced by the parameter intensity but also the position of the dam with respect to potential coarse sediment supplying tributaries. The potential sediment supply increases more slowly from about 5 km downstream for the default simulation (Fig. 11a), but this shifts to closer to the dam for the downstream dam simulation and further from the dam for the upstream dam simulation. Thus, the position of the dam matters not only in terms of the amount of sediment disconnection but the position of the dam with respect to potentially natural sources of coarse sediment. The Turtmann shows a more complex relationship. The parameter intensity is more substantially reduced by moving the dam 1 km upstream than it is increased by moving it 1 km downstream, the latter because of few major sediment supplying tributaries in the 1 km downstream of the actual dam position. However, moving the dam downstream moves the dam closer to a major potential source of coarse sediment supply. The result is that it recovers more rapidly, with a shorter coarse sediment discontinuity distance, than the default dam position.

4.2. Response of the Hérémence and Turtmann rivers to ecomorphogenic flow trials

Fig. 6a showed the percentage of reach H1 that was estimated to be active for different median grain sizes. With the maximum discharge released before the trial was abandoned 100% of the baseflow channel has a shear stress greater than critical if we assume a grain size of 0.05 m or finer (see Supplementary Material for explanation of methods); this falls to 95% with a grain-size of 0.075 m and 67% of 0.100 m. Even for small discharge increases well below the maximum trialed, regardless of grain-size considered, there is a rapid increase in the percentage of the bed likely to be active (Fig. 12a). Levels of activity are lower for reach T in the Turtmann (Fig. 6b, Fig. 12b). Whilst small increases in discharge above baseflow still lead to rapid increases in the percentage of the bed that is active, Reach T is not constrained laterally by embankments (Fig. 7c), unlike reach H1 (Fig. 7a), and increasing discharge can be accommodated by increasing width as well as depth and velocity.

Despite the Hérémence discharge release being abandoned at around 3 m^3s^{-1}, lower than the planned 5 m^3s^{-1} release, both reaches H1 and H2 showed very significant morphological changes due to the flood. Reach H1 was erosion-dominated upstream and deposition-dominated downstream (Fig. 13a) although it is clear that most sections

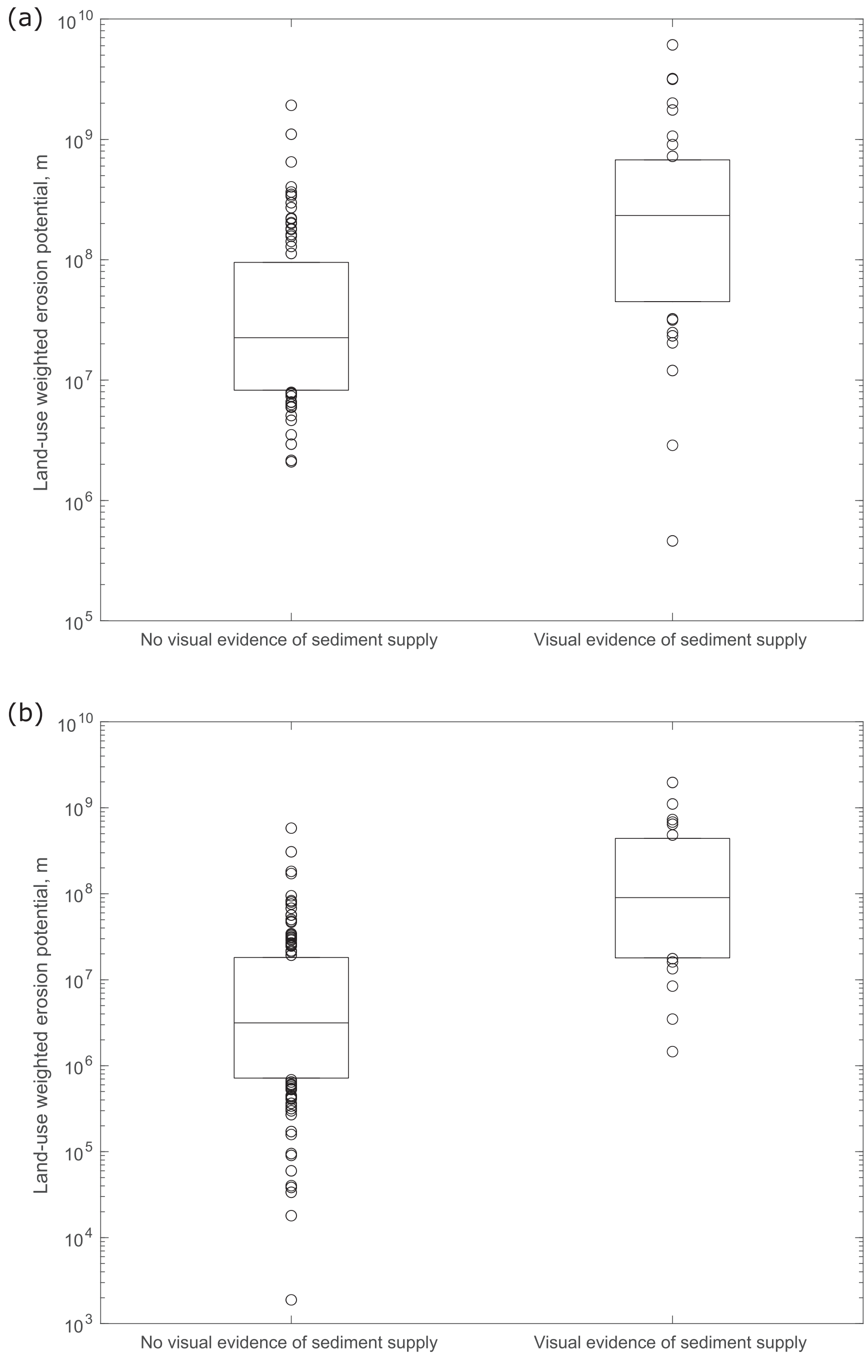

Fig. 8. Validation of the sediment supply modelling showing the modelled land-use weighted erosion potential, E_t, for tributaries observed visually as actively supplying coarse sediment to the stream and not, for Hérémence (Fig. 8a) and Turtmann (Fig. 8b).

contain both erosion and deposition suggesting channel migration. Downstream deposition was also accompanied by lateral bank erosion. The erosion to deposition switch means that the sediment transport required to conserve mass rises at first and then falls as deposition begins (Fig. 13b). To meet the no negative transport condition, at least c. 240 t of sediment needed to be supplied from upstream (net) erosion. Declining mass transport, from about 200 m downstream is also accompanied by a reduction in bed slope from about 280 m downstream and then channel widening (Fig. 13b). Considering zones of erosion only, mean erosion depths are typically three or more multiples of the reach median grain-size (limits of detection for change are slightly smaller than the median grain-size – see Supplementary Material), except around 300 m and 500 m downstream (Fig. 13c), both zones associated with a narrower channel and the downstream zone with substantial deposition. In the year after the flood, the upstream zone was more stable (Fig. 13f). The no negative sediment transport criterion means that at least 70 t of sediment must have been delivered from upstream after the flood (Fig. 13d). Mass transport rises from about 200 m downstream (Fig. 13d) reflect net erosion initially (Fig. 13f) and then erosion in all parts of the channel for most of the last 100 m of downstream distance (Fig. 13f). These patterns are reflected in rising erosion depths from about 300 m downstream to reach 5 to 7 multiples of median grain size where the erosion is most intensive around 500 m downstream.

For both the flood time-scale (Fig. 14a) and the annual time-scale (Fig. 14f), reach H2 was associated with marked deposition. The flood itself had to deliver at least 1300 t of sediment to conserve mass in this reach (Fig. 14b) and mean deposition depths per section were around

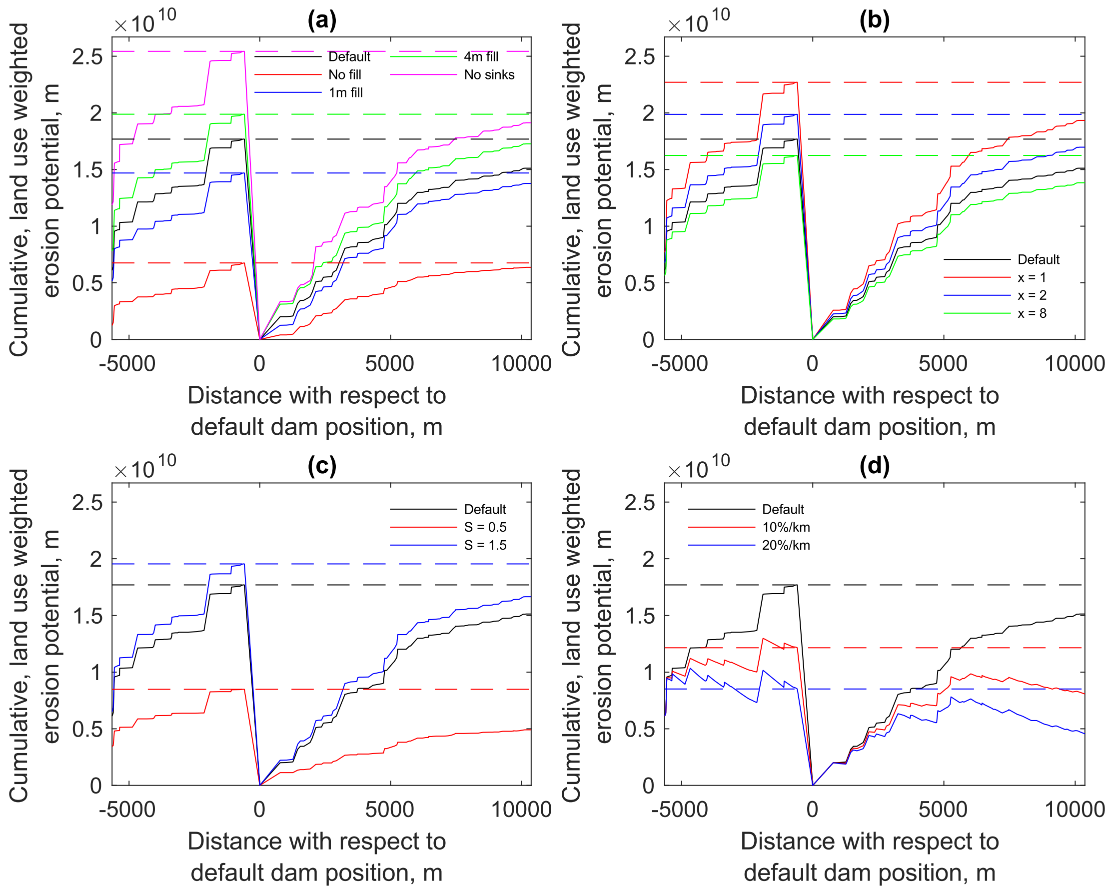

Fig. 9. Sensitivity analysis of predictions of cumulated land use weighted erosion potential (cumulated E_t) for the Hérémence basin for different levels of DEM fill and hence forced hydrological connection (9a), values of the routing parameter (9b), the slope threshold which can lead to sediment accumulation (9c) and rates of valley storage (9d). The default simulation has fill of 2 m, x = 4 in the hydrological routing model [1], $S = 1$ as the maximum slope on which erodible sediment can accumulate and no valley storage.

0.20 m (Fig. 14c). There was more substantial deposition over the annual time-scale, with at least about 3750 t of sediment required to conserve mass (Fig. 14d) and mean deposition depths of 0.30 to 0.40 m (Fig. 14e). Deposition in the main channel also resulted in about 1.5 m of lateral right bank erosion at the annual scale (Fig. 14f).

For the Turtmann reach we have DEMs only at the time-scale of the trial (Fig. 15). The flood resulted in a clear pattern of lateral channel shift (Fig. 15a) but also net deposition of sediment (Fig. 15c). This is reflected in a declining mass transport with distance downstream (Fig. 15b). At least 4000 t of sediment needed to be delivered to the reach in the flood to conserve mass (Fig. 15b). Using grain-size analysis of UAV images, Lane et al. (2020; Fig. 6c) reported that the net mean surface D_{50} increased from 0.0139 ± 0.0078 m to 0.0161 ± 0.0096 m, the coarsening associated primarily with gravelly-fill of the main channel present at the start of the event.

5. Discussion

5.1. Sediment sources, sediment connectivity and the need for geomorphic analysis

In both river basins, the shapes of the cumulative E_t curves (Figs. 9 and 10) illustrate the model outlined in Fig. 1. They also emphasize the key parameters that need to be considered when evaluating whether or not a tributary is capable of contributing to the disconnection in coarse sediment flux in a stream associated with a hydropower dam.

The first of these is the availability of potential sediment sources in basins where glaciers are still present. The classic paraglacial model of sediment delivery following deglaciation (Church and Ryder, 1972; Ballantyne, 2002a, 2002b) recognizes that initial glacier retreat commonly leads to a short period of more intense activity when geomorphic processes are particularly efficient (e.g. Mercier et al., 2009; Cossart and Fort, 2008). This is followed by transition to a more stable period of less intense activity. As a glacier retreats and its margin moves upstream so there should be an up-valley gradient in the intensity of geomorphic activity respect to its paraglacial evolution. This is reflected in the down valley reduction in potential sediment source areas in the Hérémence (Fig. 3a) and Turtmann (Fig. 4a) valleys and also in Figs. 9 and 10 in down-valley reductions in the rate of increase of potential sediment delivery. Thus, the role of natural coarse sediment supply depends on where the hydropower dam is with respect to potential coarse sediment sources.

Second, in general, potential sediment delivery is a non-linear function of tributary area (Fig. 16) and this reflects long-established observations that sediment delivery ratios decline as basin size increases (Ferro and Minacapilli, 1995). It means that further downstream, where tributaries are bigger, coarse sediment supply is less likely to mitigate the effects of dams on coarse sediment flux. Tributary hypsometry also matters as it controls both mean basin slope and how much of the basin is at higher altitudes and so subject to higher glacial et periglacial erosion rates (e.g. for the Hérémence, basin altitude can increase potential coarse sediment supply by up to an order of magnitude, Fig. 16a). As basin altitude declines downstream, the rate of recovery of coarse sediment in the main stem declines (Figs. 9 and 10) emphasising that coarse sediment supply is less likely to be effective for dams at lower altitudes.

The third observation is tributary connectivity matters, especially the case in formerly glaciated landscapes because of the landform legacy of glaciers (Harbor and Warburton, 1993; Orwin and Smart, 2004) On the one hand, tributary streams in formerly glaciated landscapes are likely to be more efficient at transporting sediment than the hillslopes

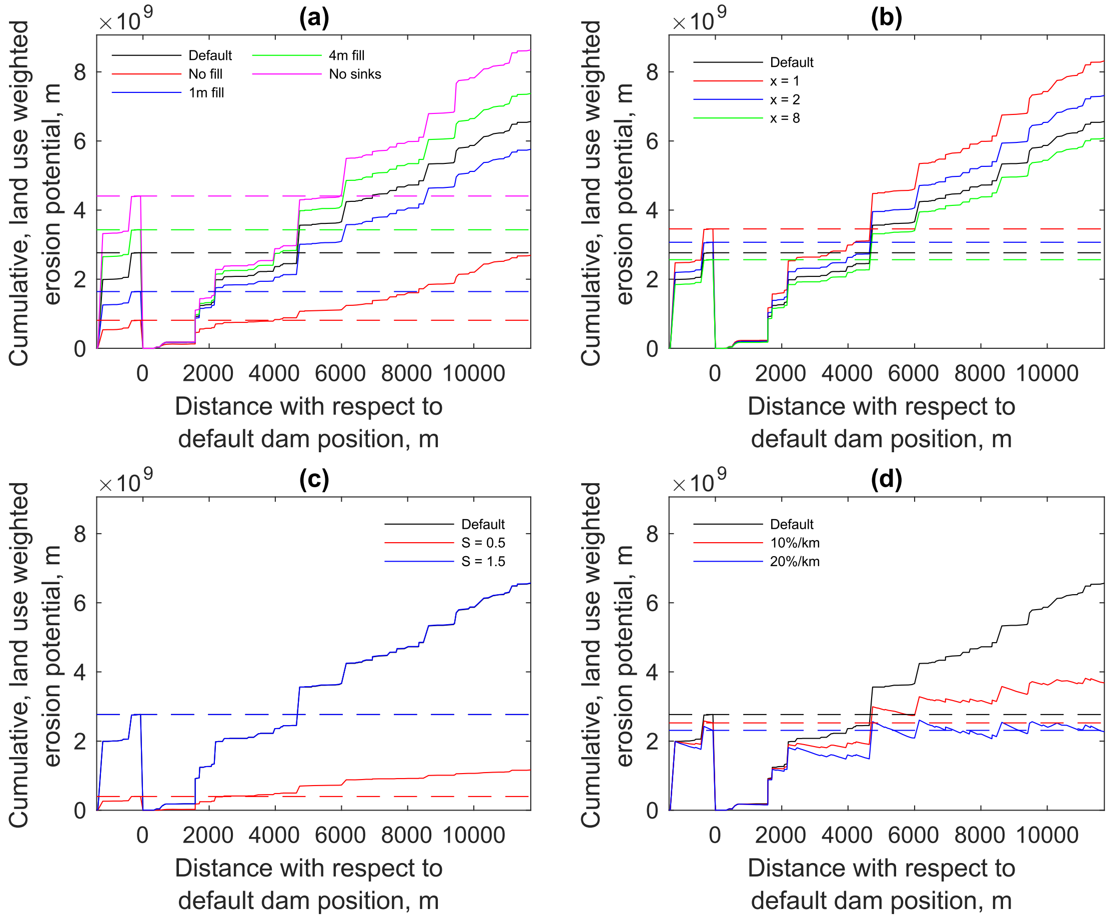

Fig. 10. Sensitivity analysis of predictions of cumulated land use weighted erosion potential (cumulated E_t) for the Turtmann basin for different levels of DEM fill and hence forced hydrological connection (10a), values of the routing parameter (10b), the slope threshold which can lead to sediment accumulation (10c) and rates of valley storage (10d). The default simulation has fill of 2 m, $x = 4$ in the hydrological routing model [1], $S = 1$ as the maximum slope on which erodible sediment can accumulate and no valley storage. Note that cumulated E_t for the slope threshold $S = 1.5$ plots on top of the default value, $S = 1.0$.

that they drain as the latter are commonly till covered with a fine scale surface texture (e.g. Trevisani et al., 2012). If the clay and silt content of the till is low, then it may have high rates of infiltration that impede both runoff and sediment flux. On the other, large-scale features, such as lateral moraines may disconnect tributaries from valley bottoms (Cossart, 2008; Cossart and Fort, 2008; Bosson et al., 2015: Messenzehl et al., 2014; Micheletti et al., 2015; Carrivick and Heckmann, 2017; Lane et al., 2017; Cavalli et al., 2019; Mancini and Lane, 2020). The base level drop that follows glacier recession may lead to headward erosion through moraines so increasing upstream to downstream connectivity (Lane et al., 2017) but the associated increase in coarse sediment flux to the valley bottom may lead to the formation of alluvial fans that act as sediment buffers (Mancini and Lane, 2020), so reducing coarse sediment flux. Thus, individual tributaries need to be evaluated in terms of their degree of connectivity to the main stem.

The validation results (Fig. 8) revealed examples of individual tributaries that appear to have a high sediment supply potential but do not seem to be delivering coarse sediment; and vice versa. Visual inspection of individual tributaries confirmed the observation that in this kind of landscape sediment disconnection could also occur due to sediment management, notably associated with valley-bottom roads and infrastructure (e.g. check-dams) designed to reduce the risks associated with high rates sediment delivery. This emphasizes the need to look specifically at evidence of coarse sediment supply from individual tributaries and not rely only upon the kind of basic modelling illustrated here.

The results also emphasized the importance of valley storage. Sediment storage reduced parameter intensity (Figs. 9d, 10d) which should shorten the discontinuity distance. The role that glacial forefields play in storing glacier and hillslope-sourced sediment is well-established (Maizels, 1993; Carrivick and Heckmann, 2017; Bakker et al., 2018). However, with the uniform storage parameters simulated here, coarse sediment storage also reduces the rate of recovery downstream of the dam, and coarse sediment supply becomes less effective at mitigating for dam effects. Such sediment storage zones are a natural legacy of glacial erosion, with may Alpine valleys associated with alternating steeper, constrained and incised; and shallower, wider and aggraded reaches (Korup, 2006). The origins of these are likely to be multiple and so locally specific (Marrucci et al., 2018). But, as they are associated with systematic variations in slope and potentially hydraulic geometry, they are also likely to cause systematic variations in sediment transport capacity and so storage, especially for smaller floods (Van den Berg and Schlunegger, 2012). Thus, their impact on the flux of tributary supplied coarse sediment to downstream reaches, and hence natural coarse sediment supply, is likely to be context specific. Finally, in some geomorphological contexts, it may be necessary to consider coarse sediment supply by direct hillslope-to-river coupling, such as in canyon systems (e.g. Swanson and Meyer, 2014).

5.2. Responses to eco-morphogenic flows

The morphological responses of the rivers to the eco-morphogenic flows tested (Figs. 13, 14 and 15) were surprising to the responsible authorities as significant morphological change occurred at peak flushing discharges substantially lower than those expected in the initial design. Field observations (and also data collected and reported in Lane et al.,

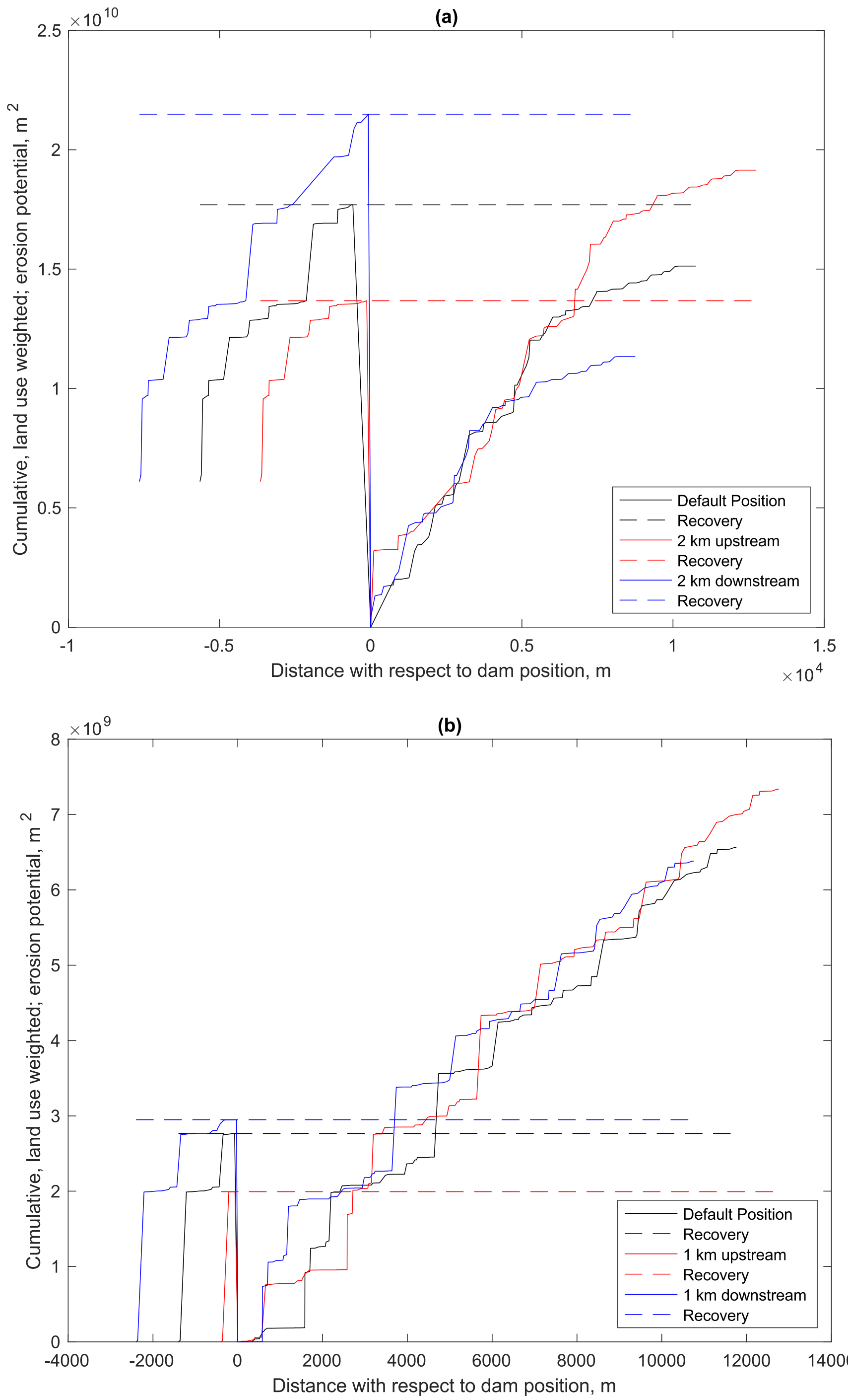

Fig. 11. The effects of moving the dam upstream and downstream by 2 km (Hérémence, 11a) and 1 km (Tourtemagne, 11b). Simulations are for default parameter values, including zero storage.

2020) provided little evidence of the sediment sorting and armoring that would limit the onset of sediment transport and which is commonly invoked as a response of reaches downstream of dams (Andrews, 1986; Erskine et al., 1999). For site H1 in the Hérémence there was clear evidence of coarse sediment supply from unregulated tributaries (Torrent de Merdéré and Torrent Blanc, Fig. 17). The Chennaz tributary (Fig. 17) has an intake that removes water, reducing sediment transport capacity but which has to be emptied regularly, so maintaining sediment connection (Bakker et al., 2018; Gabbud et al., 2019a, 2019b). It was emptied on 10 occasions during 2019 before the eco-morphogenic flow. Intakes similar to the Chennaz release around 40 to 60 t of coarse sediment when they are flushed based on Bezinge et al. (1989). We can compare this with the strategy of bringing gravel in by road which is one solution being advocated in Switzerland (Stähly et al., 2019). If we assume a maximum payload of 24 t per lorry then it is equivalent to around 20 lorry loads. The key point here is that in addition to natural coarse sediment supply from the Merdéré and the Blanc, there was also substantial supply associated with artificial regulation of the Chennaz. Other elements of hydropower management seemed to have been overlooked in planning for an eco-morphogenic flow to mitigate perceived dam impacts.

At H2 (Fig. 14) it was also clear before the flow trial that the river was neither armored nor colmated. This reach also proved very sensitive to the flow trial. It received at least 1300 t of sediment during the

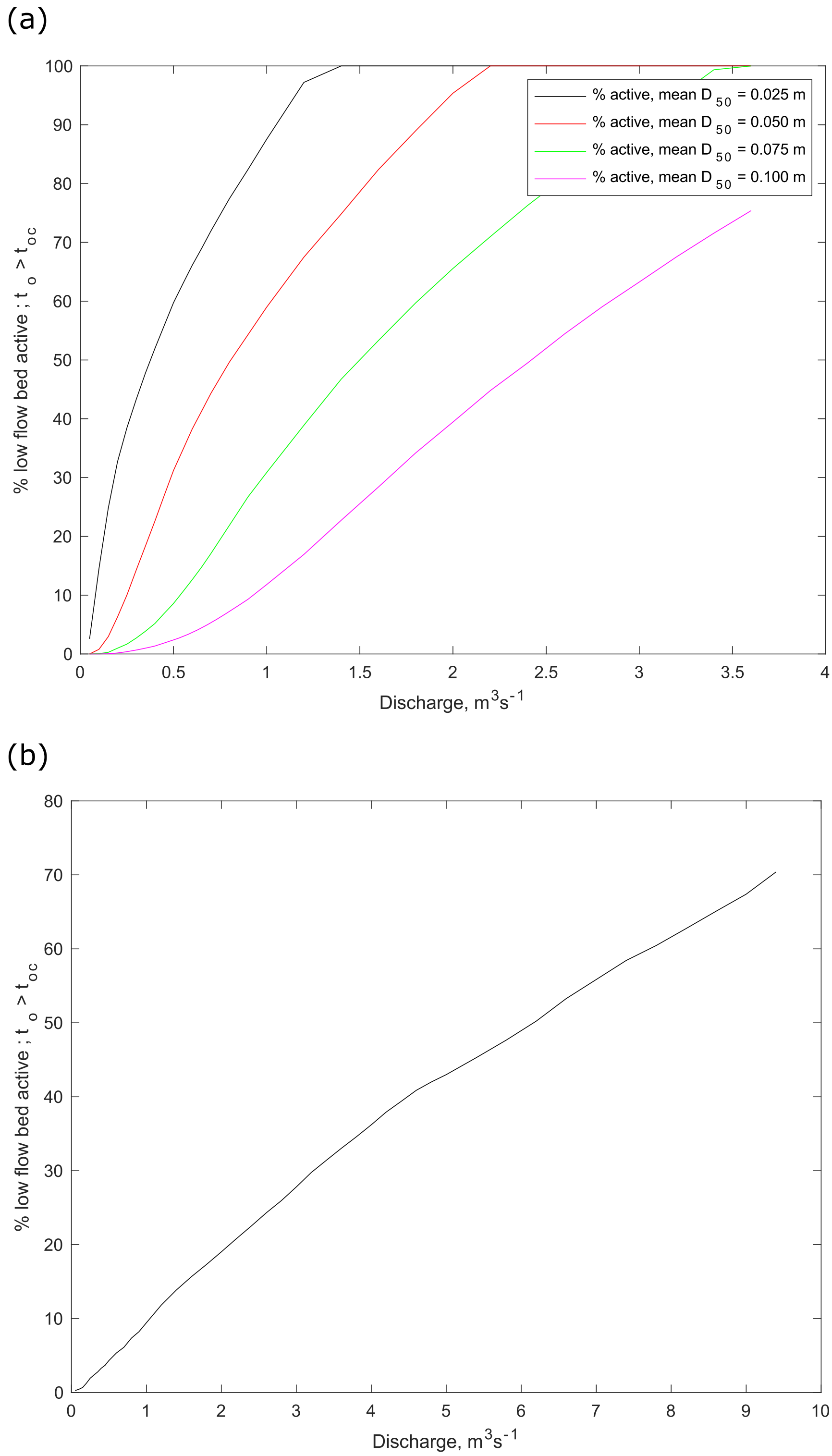

Fig. 12. The percentage of the low flow bed of the Hérémence H1 reach (Fig. 12a) and the Turtmann T reach (Fig. 12b) to discharge changes. H1 shows results for different median grain sizes; T uses estimated grain sizes from spatially-distributed mapping so has only a single curve (Fig. 6).

flood and at least a further 3750 t of sediment in the year after the flood. Sediment sourced from H1 was part of this contribution in the year after the flood (the mass transport rises, Fig. 13d) with about 750 t leaving H1. There is negligible capacity for storage between H1 and H2 and this implies that in the year after the flood there could have been up to 3000 t of sediment delivered via tributaries entering the Hérémence and associated with natural coarse sediment supply. There is a clear increase in the modelled sediment supply for the default simulation between H1 and H2 (Fig. 17). This situation not only emphasizes the importance of natural sediment supply but also that in response to a flow trial the response of one river reach defines the response of the next. The levels of deposition at H2 in the year after the flood were up to 1 m and were forcing right bank erosion (Fig. 14f).

The question that arises from the sediment supply simulation is how much recovery via natural coarse sediment supply is required

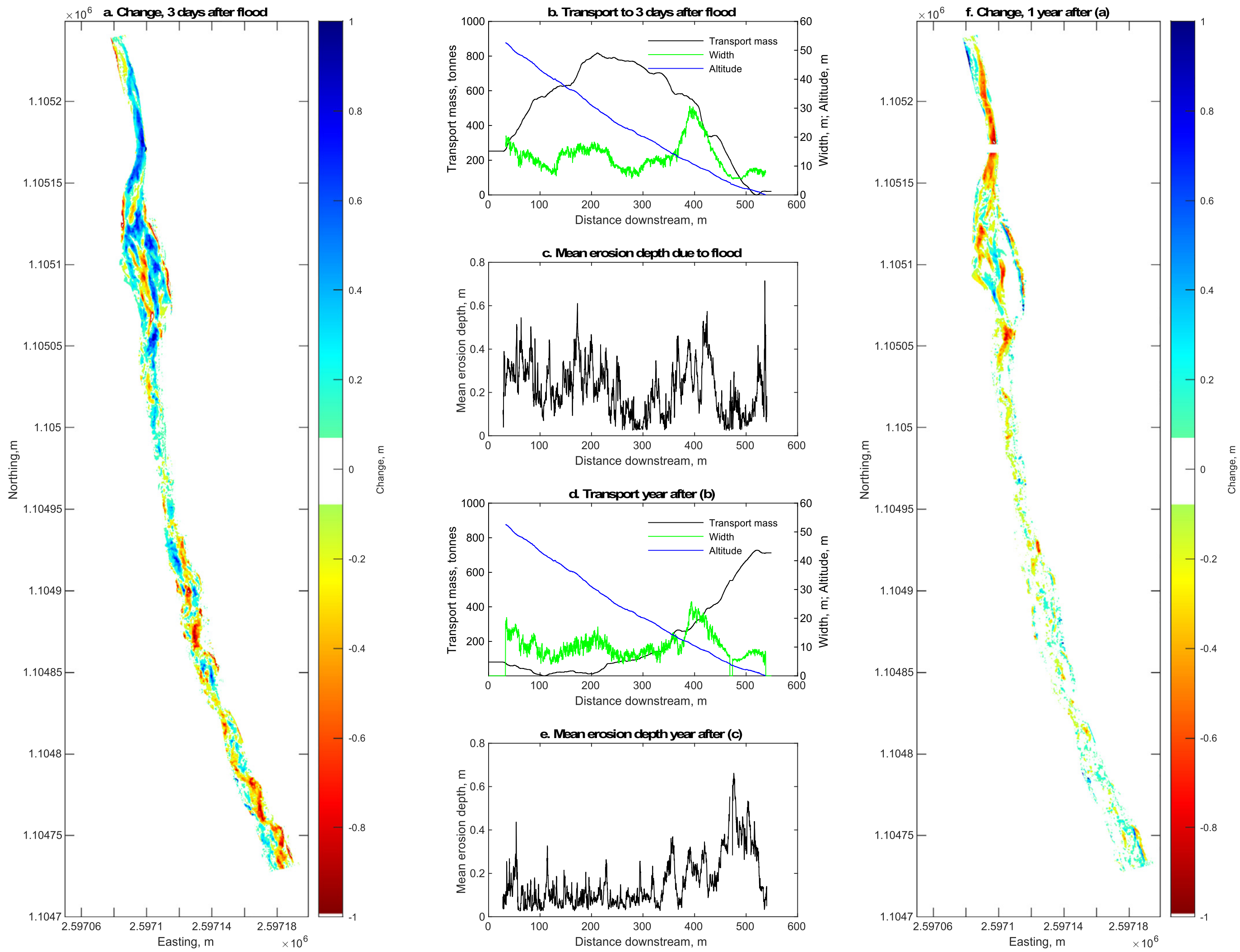

Fig. 13. River channel change due to the Hérémence flow trial at H1, immediately after the flood (Fig. 13a) and one year after the flood (Fig. 13f). River flow is from south to north. Fig. 13b and d show the mass of sediment that needed to be transported for these two timescales estimated using the morphological method. Also plotted is mean altitude of the stream bed and active bed width. Fig. 13c and e show the mean erosion depth against distance downstream.

downstream of a dam for that supply to be sufficient. This is not only a consequence of the rate at which tributaries can replace coarse sediment stored behind the dam. It is also a function of the effects of flow regulation on the magnitude and frequency of sediment transporting events, which will control the rate at which coarse sediment is reworked within the river and then lost to downstream. Flow regulation may cause sediment transport capacity to fall below tributary supply rates leading to aggradation (Brizga, 1998), especially close to tributary junctions with the main stem where there is enhanced alluvial fan formation and width constriction (Elliott and Parker, 1997; Yanites et al., 2006; Dean et al., 2016). A regulated flow may also have reduced capacity to rework tributary supplied coarse sediment such that the benefits of natural coarse sediment supply are not sufficiently distributed down the river corridor. Thus, natural coarse sediment supply should also be considered with reference to the regulated flow regime; some eco-morphogenic floods may still be needed to avoid over-aggradation and to redistribute supplied coarse sediment. Such floods should be timed with respect to tributary sediment delivery but, as the two eco-morphogenic flows studied in this paper, may need to be much smaller than those required to break up a river with an armor layer. The question of sufficient coarse sediment supply is also related to the goals of mitigation and whether or not natural coarse sediment supply delivers those goals in a broader sense; are the ecosystem services required of bedload transport delivered by natural coarse sediment supply downstream of dams? This implies a careful geomorphological and ecological monitoring of rivers downstream from dams before it can be concluded that mitigation measured are needed.

5.3. Relationship to policy and practice

The flow trials that we report in this paper were both motivated by the Swiss Water Law that was modified in 2011 to require that; (1) the bedload regime of a watercourse should not be modified by infrastructure in ways that impact seriously native flora and fauna, their ecosystems and protection against floods (Article 43a, LEaux, 2011); and (2) mitigation measures are adopted where such modification has occurred (Article 83a, LEaux, 2011). Implementing mitigation measures required cantons to identify rivers where the coarse sediment regime has been seriously impacted by hydropower and to propose mitigation measures, the associated findings subject to review and approval by the Federal government. In 2012, the Federal government published a guide (Schälchli and Kirchhofer, 2012) to inform the mitigation of the bedload regime and identified five measures relating to the coarse sediment disconnection caused by dams; (1) a dam bypass tunnel for coarse sediment; (2) modification of the scour valves in the dam to let more coarse sediment pass; (3) regular dam flushing; (4) physically moving

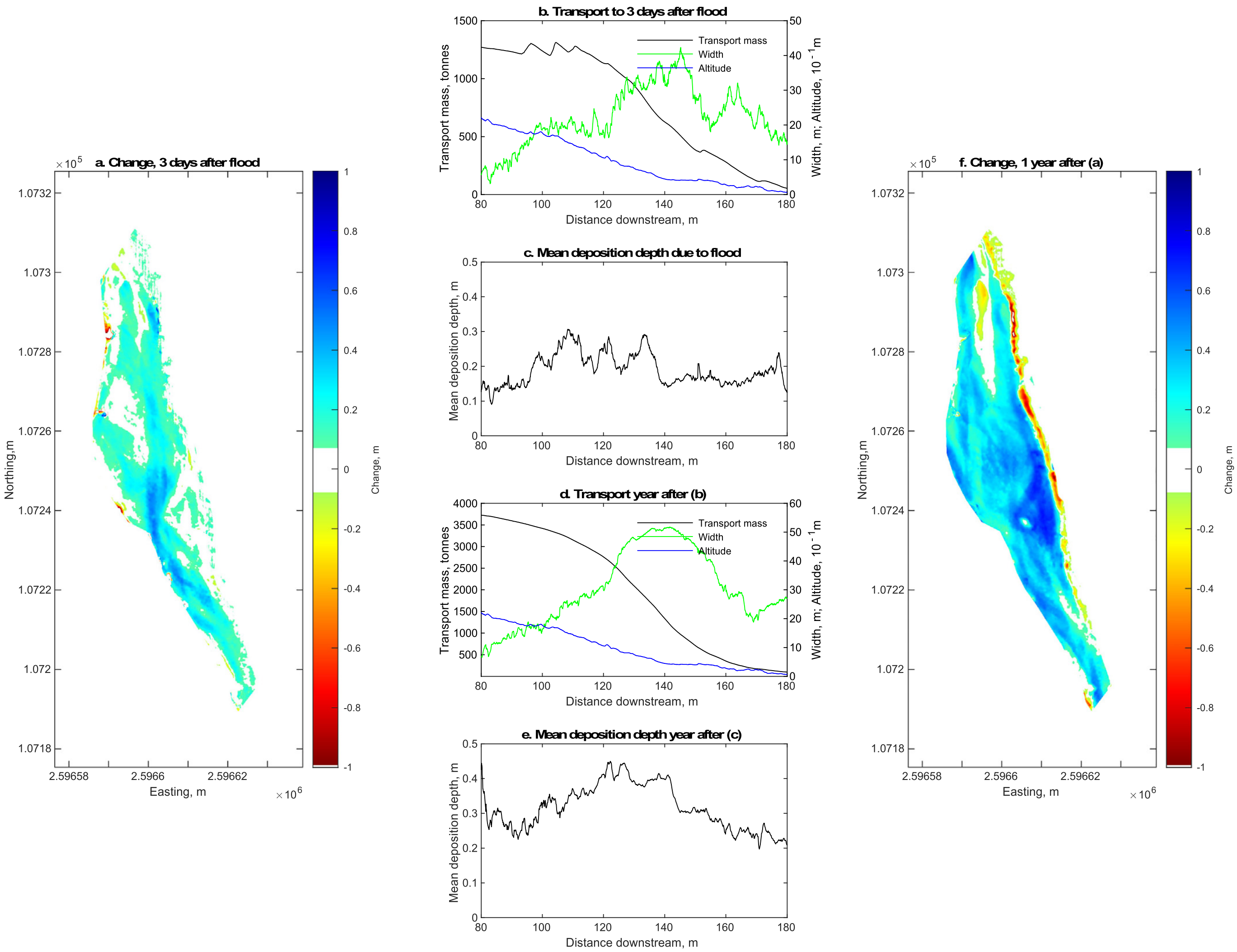

Fig. 14. River channel change due to the Hérémence flow trial at H2, immediately after the flood (Fig. 14a) and one year after the flood (Fig. 14f). River flow is from south to north. Fig. 14b and d show the mass of sediment that needed to be transported for these two timescales estimated using the morphological method. Also plotted is mean altitude of the stream bed and active bed width. Fig. 14c and e show the mean deposition depth against distance downstream; we use deposition rather than erosion here as the signal is almost uniformly depositional.

coarse sediment from upstream of the dam (or elsewhere) to downstream; and (5) artificial floods.

In this case, the Hérémence trial was an example of an artificial flood; the Turtmann trial the modification of a regular dam flushing exercise to have the perceived benefits of an artificial flood; both were designed to be eco-morphogenic (Loire et al., 2021). The Schälchli and Kirchhofer (2012) report recommends that context is factored into the assessment of hydropower impacts on the sediment regime and whether this is negative. It also advocates focus on those reaches that are unconstrained and so able to respond laterally as well as vertically to changes in bedload regime. Such reaches should have gravel bars that are reworked to a depth of at least 30 cm per year. In this sense, the importance of considering reach context (Kondolf et al., 1996) is recognised. However, two points follow. First, the flow trials reported here suggest some gap between the implementation of the Swiss Water Law as recommended by Schälchli and Kirchhofer (2012) and the on-the-ground methods being used to set the required magnitude of eco-morphogenic flows; that is the evaluation of local context. The required flows were over-estimated in both cases, with potentially serious negative consequences, and because of natural coarse sediment supply. Certainly for the Hérémence, it is questionable why there is any need for an eco-morphogenic flood at all, given that in the year following the trial approximately 38% of H1 and 44% of H2 at least were reworked by more than 30 cm; and regular flushing of an upstream hydropower intake on one tributary adds to any natural coarse sediment supply and leads to regular floods. There seems to be a failure to take into account local context in practice, and the reasons for this merit investigation. Article 43a of the Swiss Water Law itself is challenging because it is difficult to see how an unmodified bedload transport flux is possible when the primary vector for the dynamics of that flux, water, remains substantially modified. Interpreted another way, the natural coarse sediment regime is likely to lead to negative impacts on flora and fauna if it is not modified to take into account flow regulation.

Second, the Schälchli and Kirchhofer (2012) report makes no real reference to natural coarse sediment supply: it hints at the importance of tributary sediment delivery (p40, p42) but does not explicitly show how this may counter the sediment-disconnecting influences of dams. A serial discontinuity concept for coarse sediment (Fig. 1) shows how, at least in Alpine systems, it is quite possible to have significant sources of natural coarse sediment supply to a stream, as a function of where the dam is located with respect to those sources. In relation to the Swiss Water Law, despite both of the river basins studied here being required to identify mitigation actions, it is not possible in terms of sediment to conclude that mitigation was necessary. A primary reason for this is floods associated with non-regulated tributaries that in the two contexts studied here, can produce significant amounts of water and sediment.

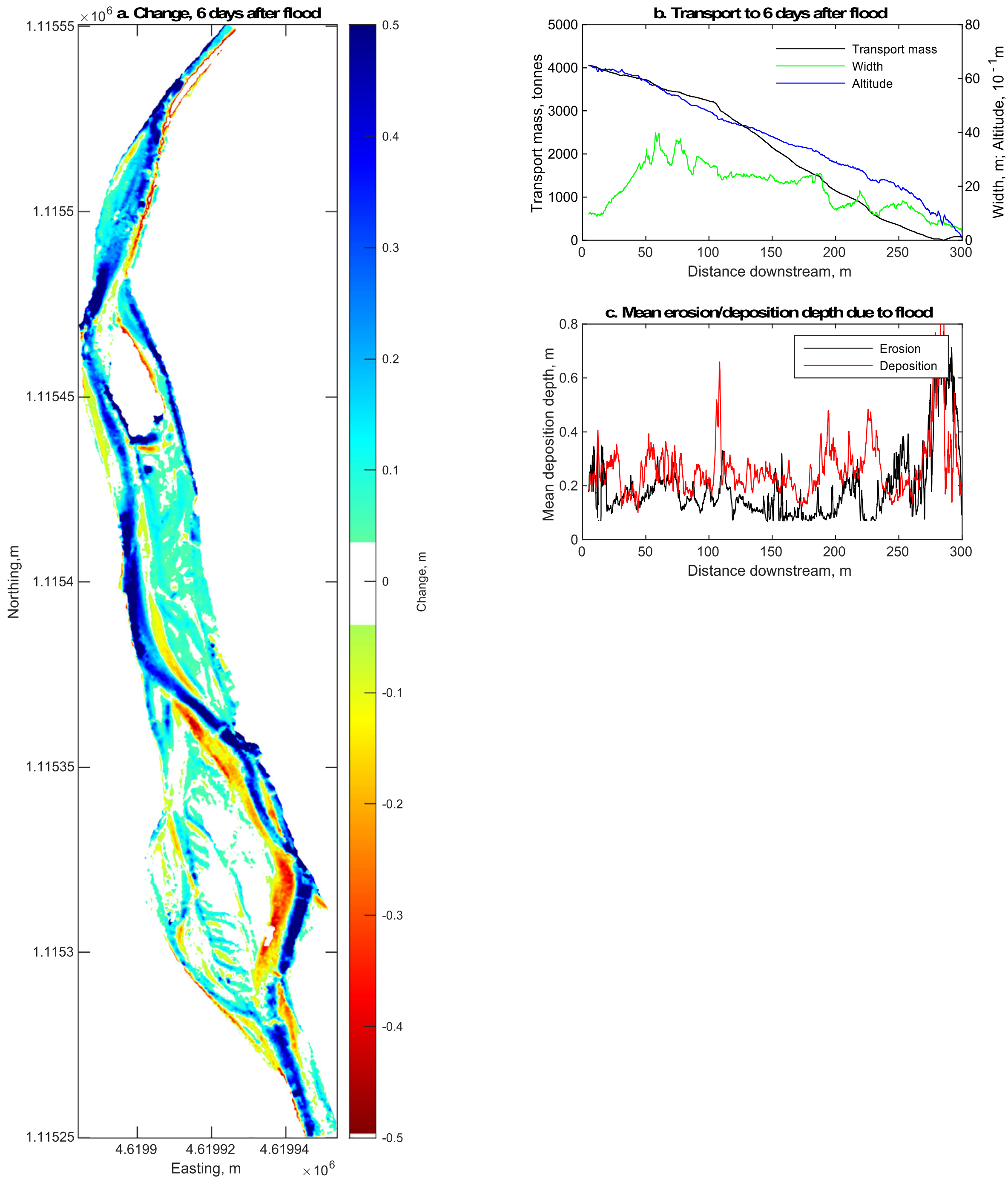

Fig. 15. River channel change due to the Turtmann flow trial, immediately after the flood (Fig. 14a). River flow is from south to north. Fig. 14b shows the mass of sediment that needed to be transported during the flood according to the morphological method. Also plotted is mean altitude of the stream bed and active bed width. Fig. 14c shows the mean erosion and deposition depths against distance downstream.

6. Conclusions

In this paper, we developed and illustrated a geomorphic form of the serial discontinuity concept for Alpine dams. Using a heuristic representation of potential coarse sediment supply to two high altitude Alpine streams impacted by dams, we showed that unregulated tributaries may sufficiently counterbalance the reduction in downstream coarse sediment flux due to dams. Whether or not it does so should consider; (1) how much coarse sediment the dam is likely to be capturing (the parameter intensity effect); as well as (2) the extent to which there are then tributaries downstream that can compensate for this storage; (3) human modifications to sediment connectivity and coarse sediment delivery that may not be clear from the kinds of digital analyses used in this paper; (4) the role played by valley storage in influencing how much coarse sediment the dam captures and changes in longitudinal sediment flux downstream of the dam; (5) whether or not there is evidence of possible over-accumulation (as well as under-accumulation) of coarse sediment downstream from the dam; and (6) whether or not natural coarse sediment supply delivers sufficient coarse sediment to deliver the bedload transport services required in the river. The focus of this paper was a high altitude Alpine catchment with naturally high rates of sediment delivery. With strong downstream gradients in

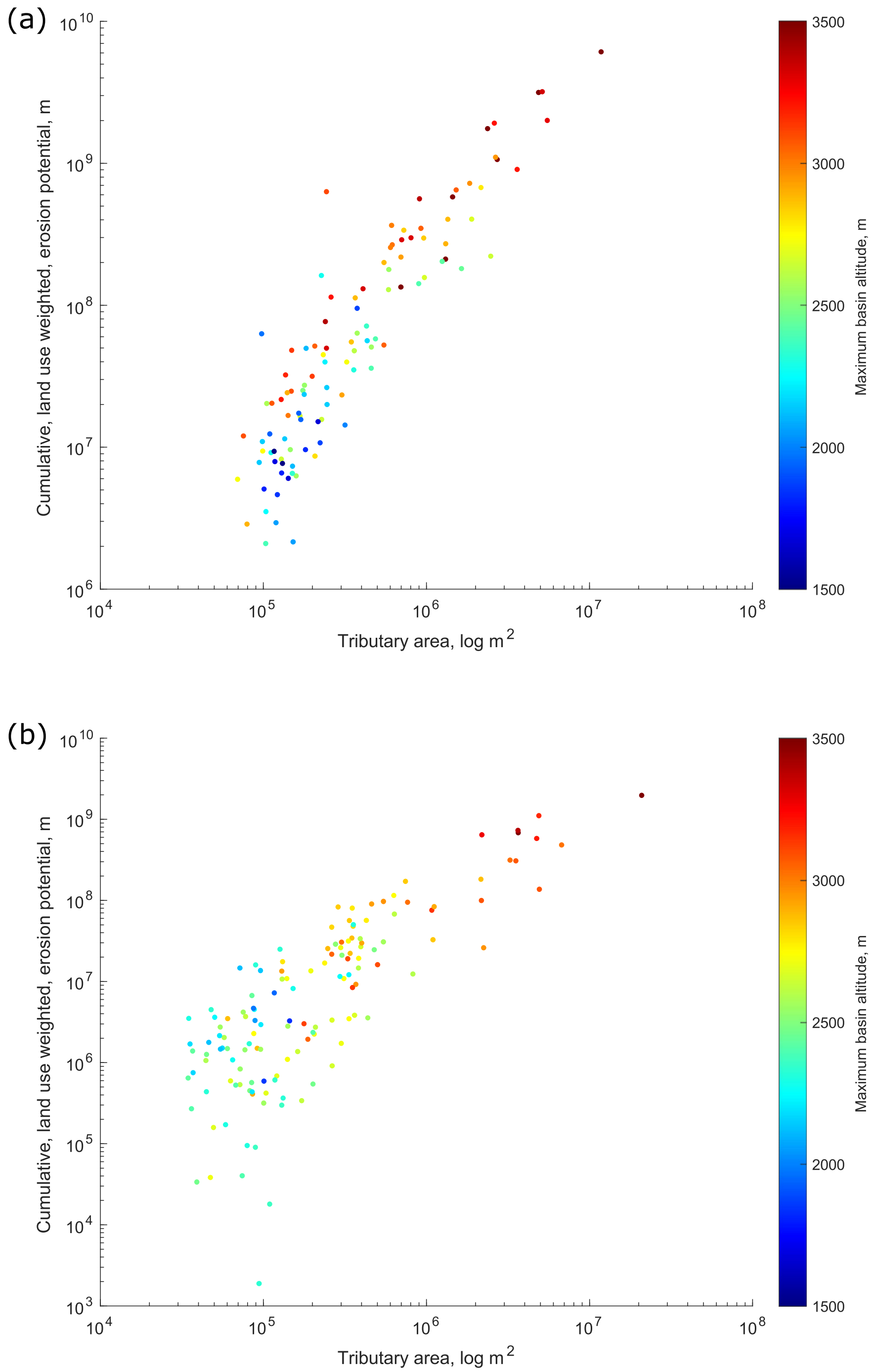

Fig. 16. Cumulative land-use weighted erosion potential, i.e. estimated sediment delivery potential against tributary area for the Hérémence (16a) and Turtmann (16b) valleys. Data points are coloured according to maximum basin altitude.

potential sediment supply likely in Alpine catchments, compounded by increasing storage and decreasing sediment delivery ratio in larger tributaries, it may be assumed that natural coarse sediment supply is most relevant to dams that are closest to river basin headwaters in high altitude settings. Within such systems, where the dam is located with respect to potential, well-connected, sediment sources, impacts both the intensity of a dam's impact (how much sediment is stored) and the rate at which sediment recovers. Given the additional influence of local sediment management practices, both related to hydropower (e.g. the frequency of flushing of hydropower infrastructure) and other activities (e.g. engineering of sediment flux related to road infrastructure; sediment extraction; sediment retention structures), it is crucial to consider the geomorphological context of both the dam and where it is located within a river basin.

The study of two flow trials, designed as eco-morphogenic flows, supported the conclusion that in these cases, despite the studied reaches being downstream of major dams, the rapidity with which the rivers responded to relatively low discharges suggested sufficient natural coarse sediment supply to have prevented development of armoring. The associated legal and policy frameworks required local context to be considered and, if detailed geomorphic and biological investigations had been conducted at the two sites, might have also questioned whether or not the flow trials were necessary. The reasons why such analyses, if they were undertaken, did not question the principle that

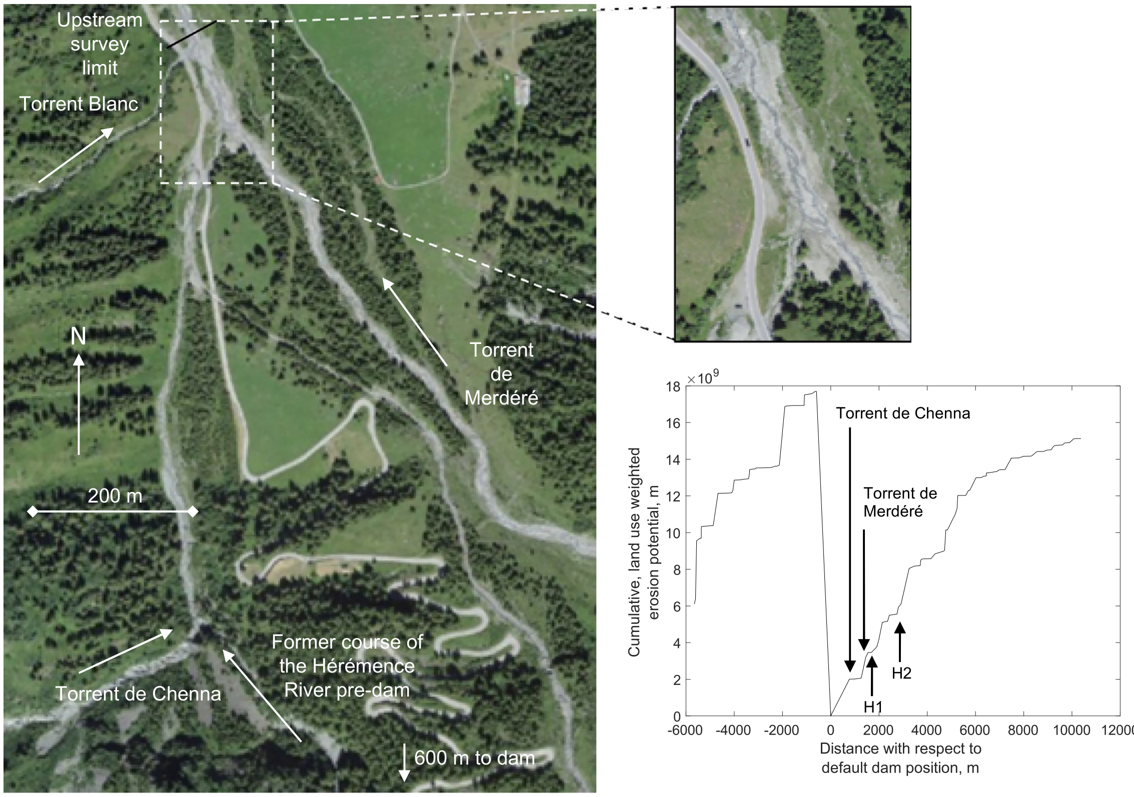

Fig. 17. Aerial imagery (©SwissTopo) of the tributaries feeding the main Hérémence River and showing also the default simulation of sediment delivery.

floods were needed merits investigation. However, more generally, policy and implementation need to evolve to recognize the potential for natural coarse sediment supply in Alpine catchments through a more geomorphologically-informed approach to hydropower management that avoids applying the misperception that the presence of a hydropower dam inevitably means insufficient coarse sediment in the river downstream of the dam.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2022.108131.

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