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Defining Protection Works Against Debris-Flow Hazards: Industrial Standard, Tailor-made or Haute-couture?

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Abstract. Despite centuries of forestry and empirical soil conservation works as well as decades of research on debris flow processes, defining protection strategies against debris flows remains complicated. We are far from guidelines resembling an industrial standard to define the type, location and shape of debris flow protection works. We believe that this particular step will likely never be fully standardized because design engineers must have a certain degree of freedom to tailor the protection works to the astonishing varieties of catchments, geologies and geomorphologies, and the associated complex emerging debris flow regimes. Some catchments have such specific features that defining an adapted protection strategy requires innovation: this is not even “tailor-made” but perhaps “haute-couture”. In this paper and the associated keynote lecture, we propose a possible way to approach the problem by firstly focusing on the sediment transport connectivity and the channel malfunctions leading to debris flow deposition; and secondly to select structures that prevent the latter, as well as to adjust the channel capacity to the debris flow supply.

1 Introduction

Debris-flows are ubiquitous in mountainous areas, involving rapid mass movements delivering large amounts of sediment, e.g. mud, gravel, cobbles and boulders, from hillslopes, gullies and steep creeks to valleys [1]. They cause damage and casualties each year [2, 3]. Societies have developed and implemented soil conservation measures and torrent control works to curtail erosion and prevent debris-flows for a very long time. Indeed, these operations have been organized and operated through large-scale plans for more than 150 years [4].

Soil bioengineering and afforestation have been used for centuries to fight diffuse soil erosion and emerging gully processes [5]. Debris-flows often emerge in very active erosion areas sometimes as part of other landslide processes [1]. However; defining mitigation works against these fast, poorly-predictable processes is not simple. Many types of structures have been used over the decades, including hillslope revegetation, drainage systems, check dams, open check dams, bank protections and dikes [6]. Most of these structures have one of three main objectives: (i) preventing sediment supply; (ii) changing some features of the sediment transport process; and (iii) guiding flows [7].

General presentations of these various measures can be found in the literature with many sketches, pictures of existing structures and sometimes basic design criteria [8–13]. A few attempts were made to standardize some topics of the planning, structural design and maintenance of torrent control works [14–16]. However, the functional planning and design, i.e. the selection of the type, location and shape of the

structure to be used, escaped this standardization. Meanwhile, many tests and trials are still performed and structures with strange, huge or surprising shapes are sometime built in particular catchments [see e.g. 6, 17, 18]. In general, this step of functional design of mitigation measures remains difficult. Many questions do not have clear answers, although they seem quite simple. For instance, how can we select the type of protection measures in a given catchment? How to design them? Or, more generally: why can-it be sometimes appropriate to innovate using original structures, while tried-and-tested solutions defined by eventual industrial standards are suitable in other catchments?

If the structures used in torrent control are much more diverse (or weird) than in flood control, it is probably because they mostly seek to influence the processes involved in the sediment cascade which take many forms and cover a wide spectrum of dynamics. One could also speak about controlling or interfering with the sediment connectivity [19]. The study of sediment connectivity and of solid transport processes is making huge progress. The side-effects and consequences of curtailing soil erosion and disrupting sediment transfer to the downstream fluvial networks are thus now much better understood than some decades ago [20]. This enlightened knowledge of the sediment transport process under frequent and extreme events enables us to define structures that are better adjusted to the peculiarities of each catchment. Masterplans and structures are then “tailor-made” to the sites.

In this short paper and the associated keynote lecture, we propose a possible way to guide the selection, location and definition of hazard mitigation

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measures, notably by using results from hazard assessments to adjust the mitigation plans to the elementary processes leading to channel malfunctions, i.e. to debris flow deposition and avulsion. In essence, the idea is to perform a detailed analysis of the connectivity of sediment transport and to identify the processes leading to dis-connectivity. Once this assessment has been performed, defining mitigation measures is mostly a matter of modifying the processes or channels with structures so that the process intensity meets the channel capacity. The approach is described in further detail in a book chapter to be published [21].

2 Channel malfunction analysis

Debris flow hazard assessments seek to identify where debris-flows might deposit, cause avulsion, or impact/bury infrastructure, assets and natural or cultivated areas. Such assessments will necessarily try to identify which channel sections are too narrow and which crossing structures are too small to allow the passage of the flow fronts and the boulders and large wood. The flow capacity of channels is also appraised, as well as the areas of chronic or episodic deposition that include slope breaks and widened areas or confluences.

When sufficiently detailed, such studies can be reanalysed to identify the triggering factors or processes leading to massive deposition, overflowing and avulsion of debris-flows. These triggering factors are hereafter called “channel malfunctions”. The main types of channel malfunctions are identified in Table 1. The associated controlling processes and the driving parameters that could be used to predict whether or not these malfunctions are likely to occur is also provided.

Emphasising which channel malfunctions are likely to emerge and drive debris flow hazards on a given site is an interesting step to perform before defining the mitigation strategy. Doing it after a given debris flow-related disaster is sometimes not straightforward, but we believe that in most cases, it is possible to identify which of them are the best candidates. Several malfunctions can emerge in cases where the channel is strongly ill-designed or overly-constrained e.g. by urbanisation.

Table 1. Main types of channel malfunctions.

Type	Process	Driving parameters
Type-B : Boulder jam	Jamming of a bridge, culvert or dam by clusters of boulders	Boulder diameter / opening size (width or height)
Type-W : Large wood jam	Jamming of bridge, culvert or dam by woody debris	Large wood length / opening width
Type-Q: Discharge excess	Overflowing by mere excess of peak discharge	Peak discharge / channel capacity
Type-S: Deposition at slope break	Deposition related to insufficient transport capacity	Channel slopes
Type-V: Volume excess	Headward deposition due to an excess of sediment volume	Volume supplied / channel buffering capacity

3 Tailoring the strategy to prevent channel malfunctions

3.1 General approach

Once the main channel “weak points” are identified, the general approach consists of adding structures to mitigate malfunctions in three main ways. (i) By decreasing the event magnitude using measures that diminish the catchment sediment supply. (ii) By changing the processes (the presence of boulder and trunks, discharge, volume), making some undesirable functions less likely, and thus also the associated cascading hazards. Some targeted changes can be achieved by using specific open check dams. (iii) By increasing the channel capacity using guiding structures that direct flows in natural areas.

Table 2 provides a qualitative synthesis of the main functions and also lists the structures that can be used to achieve these three main objectives. Figure 1 provides a synthetic diagram showing conceptually how the various functions change the magnitude of the processes, using frequency curves and/or the associated peak discharge and flow depths. The effects of the various types of measures are highlighted and compared to a given reference event of volume V_0 of return period T_0 , having a peak discharge Q_0 and overflowing the channel of depth h_{banks} . The figure is conceptual and thus strongly simplifies reality. In a way, it adjusts the approach of [22] to debris flows and is inspired by [7].

3.2 Prevention of sediment supply

Measures preventing the supply of sediment to the channel have cumulative effects that can be considered as merely reducing the frequency of events of the volume V_0 so that its return period become less frequent ($T_1 > T_0$). The main structures used to do so are soil conservation measures, check dams stabilizing channels or consolidating hillslopes, along with drainage systems and diversion work that bypass sediment sources.

3.3 Changing the processes with open check dams

Knowledge on the functioning of open check dams has improved sufficiently to define the type and shape of structures that are able to achieve clearly defined functions [23–25].

Debris flow breakers and large wood trapping structures are useful to prevent obstructions due to large boulders and large wood (type-B and type-W malfunctions, see Table 1), thus preventing overflowing for discharge $Q_0' < Q_0$ for smaller volumes $V_0' < V_0$ that happened more frequently $T_0' < T_0$ (Figure 1b).

Barriers with large slits or slots enable a debris buffering function, i.e. to reduce the peak discharge of a given volume. If overflow occurs for a given peak discharge Q_0 , it occurs for a larger event supply $V_2 > V_0$ which is also less frequent $T_2 > T_0$.

Structures merely trapping a given volume of sediment, i.e. having a debris deposition function, reduce the event volume by the amount that is trapped. Such structures should have a bottom outlet to allow frequent events to pass through [24]. The case of water retention, not included in Figure 1, is covered by [22].

Table 2. Main types of structure functions.

General objective	Function	Effect on the processes	Typical structures used to achieve the function
Prevent sediment supply	Soil conservation	Prevent erosion on hillslopes using vegetation protective capacity	Afforestation, fascine, terrasses, soil bioengineering
	Channel stabilization	Prevent long term incision and extended channel erosion events	Check dams, channel lining
	Hillslope consolidation	Decrease sediment supply by decreasing landslide and rock avalanche movements	Drainage systems, high or series of check dams
Change certain features of debris-flows (type, size, discharge, volume)	Diversion	Divert water from erosion-prone areas	Tunnels, by-pass channels
	Transformation	Break debris flow fronts by trapping boulders	Debris flow breakers
	Wood filtration	Trap large wood pieces	Racks, Austrian-dams
	Debris buffering	Transiently store debris to reduce solid peak discharge	Open check dams with large slots
	Debris deposition	Trap a certain volume of sediment	Open check dams with small slots or with grills, flexible barriers, large check dams
Guide debris flows	Water retention	Transiently store water to reduce water peak discharge	Flood retention large dams
	Conveyance	Convey flows along a chosen path	Dikes, bank protections, groynes
	Deflection	Deflect flows toward less vulnerable areas	Diversion berms

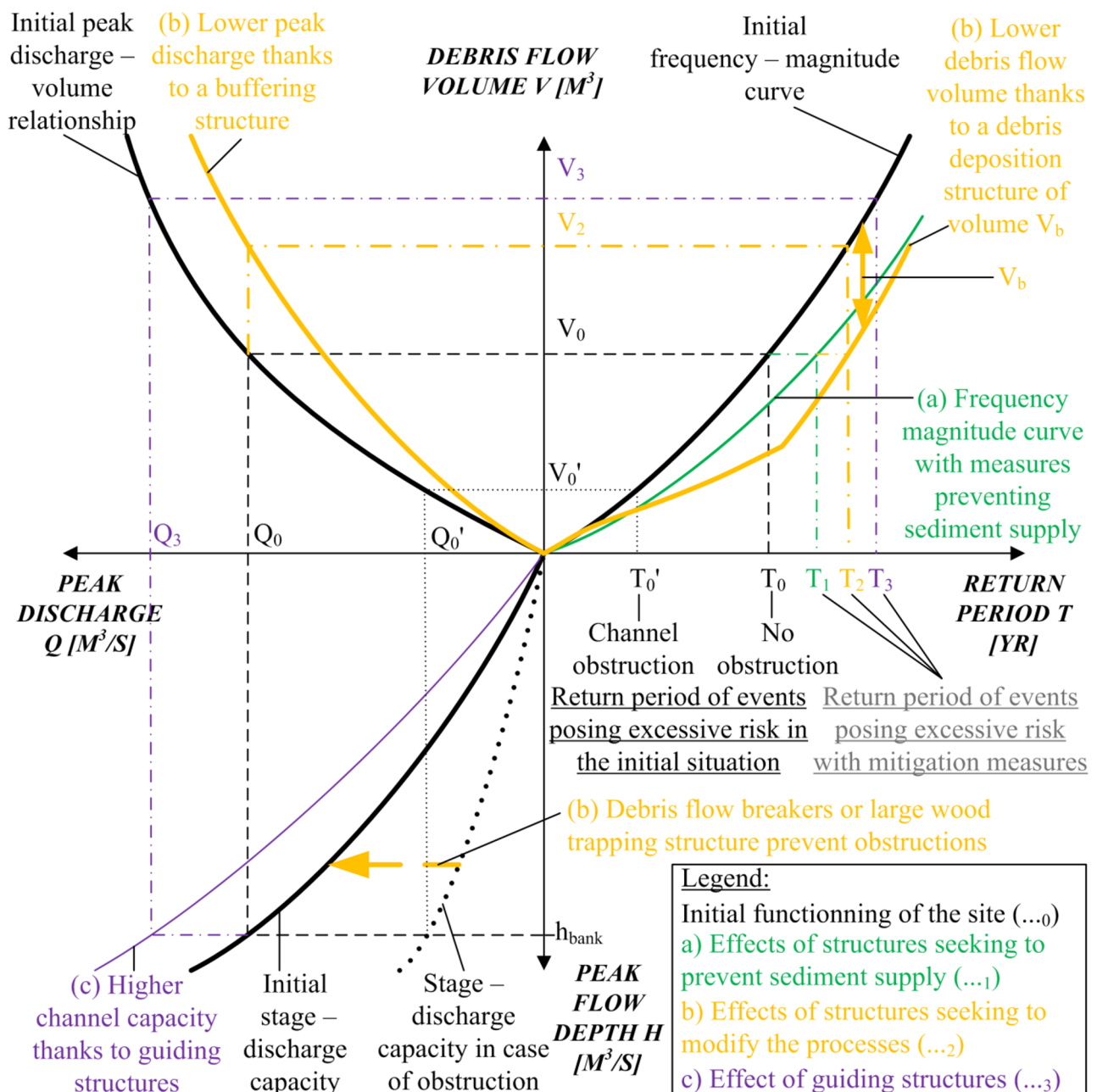


Figure 1. Conceptual multi-panel diagram representing the initial channel functioning in black and changes of processes in colors

3.4 Guiding flows in selected areas

For a given flow depth, guiding structures, i.e. dikes and bank protection directing flow along a chosen path, or deflection berms sending flows to low vulnerability areas, enable the discharge capacity to be increased to $Q_3 > Q_0$. The associated volume that can be handled without damage is then increased to $V_3 > V_0$, thus also reducing the frequency of overflowing to $T_3 > T_0$.

4 Concluding remarks

A comprehensive approach adapted to a topic as complex as the definition and design of debris flow mitigation measures cannot be completely presented in four pages. The present extended abstract is thus a quick and simplistic overview of one possible approach. The general idea is that design engineers should not only have a view of the magnitude and frequency of the debris flow supplied by the catchment (within normal limitations), but must also have a detailed understanding of the way that debris-flows pass, deposit, overflow and cause avulsion along the downstream channel.

Defining mitigation measures is then a matter of selecting the measures that will modify the magnitude of the event, and/or modifying the process or the channel, so that malfunctions emerge more rarely. In the simplest cases, standardized structures will be sufficient. In large catchments where several geomorphological processes interact, a tailor-made strategies should be defined. In some weird sites with specific features and complex emerging processes, this definition requires innovation (the haute-couture case). This extended abstract presents the approach quickly. Tables 1 and 2 are useful for simple classifications of the types of malfunctions and the main functions that structures might achieve. Figure 1 is also a synthetic diagram showing how these types of structures conceptually change the debris flow frequency, volume, peak discharge and peak flow depth. When using several types of structures, such effects will be combined and added. We hope that this short contribution can help to choose an approach to address the complicated challenge of defining mitigation strategies.

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