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Mass-Movement Types and Processes: Flow-like mass movements, Debris Flows and Earth Flows

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This chapter is an update of the previous version: Processes, Transport, Deposition, and Landforms: Flow by T. Davies, C. Philipps, and J. Warburton (2013)

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Glossary

Flow Motion of a material with respect to a solid boundary, characterized by internal shear deformation and lack of slip at the boundary.

Fluid A material that moves by flowing.

Debris flows Mass movements on slopes or in channels that behave as intimate mixtures of coarse solids, fine solids and water, and develop well-defined pulses with coarser solids at the front and finer solids as a water slurry to the rear.

Earth flows Large, long-lived slow flows of moist, fine-grained material that may be stationary in dry conditions but accelerate significantly as a result of increased pore-water pressure.

Granular flow A flow comprising many solid grains, individual solids slide or bounce past each other, and the large-scale mode of deformation is internal shear. Interstitial fluid, if present, plays a minor role on the flow features

Mass movement Gravity-driven motion of solids (with or without water) down a slope, in which many solids move together interacting with each other as they do so.

Non-Newtonian flow Flow whose local shear rate is nonlinearly related to the local shear stress.

Sliding Motion of a material with respect to a solid boundary and lack of internal shear deformation.

Unsteady flow Flow whose local characteristics vary with time.

Viscosity The ratio of local shear stress to local shear velocity gradient (shear rate)

Abstract

Mass flows on hillslopes and steep channels are high gradient, subaerial mass movements of highly concentrated grain-in-fluid materials. They are generally initiated by liquefaction or erosion and bulking, and rapidly transform into non-Newtonian unsteady (surging) flows. Deposition or entrainment of material during flow may be very significant. Debris flows, most often observed in channels, consist of large clasts moving in a slurry of fine material in water, with boulders being carried at the front of large surges. Earth flows, most often observed on hillslopes, are generally large fine-grained long-lasting features that move slowly in response to rainfall and increased pore-water pressure. All kinds of mass flows can pose a significant threat to human lives and settlements.

Introduction

This chapter deals with flow-like mass movements (or mass flows) on hillslopes and steep channels. These phenomena are gravity-driven and occur at steep gradients, which provide high potential energy. This topic aligns closely with other processes of material motion on slopes treated in detail in adjacent chapters, and it is important to outline what constitutes a flow for the purpose of the present chapter. Herein, a flow is a mass movement of bulk material with distributed shearing. We typically consider subaerial flows of grain-in-fluid materials with solid

concentration generally > 40 – 50 % in volume, and sometimes much more. The interstitial fluid is most often water, but is sometimes only air, and may present complex interactions with the finest fraction of the solid material. Such flows initiate on steep slopes where loose material is originally present. They are consequently most often observed in mountainous environments.

Although flows on hillslopes are in principle similar to flows in channels, the hillslope environment differs from the channel environment in being (1) generally steeper, (2) less confined, and (3) commonly not formed by previous flows or showing very different features from one event to another. The first two of these do not necessarily cause flow activities that differ from those in channels, but the last does; this is because many slope flows are first-time flows in that even if a flow has previously occurred in the same place, its geomorphic signature may have been eliminated by other slope processes before the next one occurs. As a result, the activity of a slope flow is generally less predictable than that of a channel flow.

Having emphasized the distinctiveness of slope flows, we recognize that a continuum of phenomena exists between the extremes of the granular flow of dry rock debris down a steep slope and the transport of sediment in suspension by a large river. In particular, the mechanics of subaerial (i.e., gravity-driven) flows operate in all situations, irrespective of the gradient or the material involved. Recent works in granular physics (Houssais and Jerolmack, 2017) aim at unifying sediment transport theories (e.g. soil creep, landslides, debris flow, bedload and suspended-load transport), and argue in favor of a continuum of sediment transport processes.

In that context, the real distinctiveness flows we consider here, lies in (1) their extremely discontinuous nature in both time and space; (2) the generally large grain size distribution of their solid material, which induces coarse grain interactions that may be influenced not only by the fluid but also by the fluid-fine fraction interactions (e.g. physicochemical interactions due to clay aggregates); (3) their generally monophasic and laminar aspect, at the macroscopic scale; (4) and their generally non-Newtonian behavior, again the result of very high sediment concentration.

The variety of mass flows considered here can differ from a geomorphic or mechanical point of view, depending on grain-size distribution, fine sediment concentration, nature of the interstitial fluid, shearing rate, triggering conditions, or typical geomorphic signature. This participates to the existing multiplicity of terminologies and not all of them are strictly related to mass flows: for instance, debris flood (Hungri et al., 2014), immature debris flow (Takahashi, 2014), debris flow (Jakob and Hungri, 2005; Takahashi, 2014), granular/muddy debris flow (Coussot and Meunier, 1996; Ancey, 2001, 2007; Bonnet-Staub, 1999), granular/slurry flow (Pierson and Costa, 1987), mudflow (Varnes, 1978), hyperconcentrated flow (Pierson, 2005), earth flow (Keefer and Johnson, 1983), rock avalanche (Hsü, 1975; Bertran, 2003). Each of these flow types was scientifically described independently in a way that it is hardly possible to establish a unified classification. Furthermore, each classification presents its own interest in highlighting the phenomena under a different perspective. Another difficulty to deal with terminology is that the flow type can change in a single event during flow propagation, even along short distances.

Mass flow characteristics make their realistic analysis problematic, and management of the hazards they cause intrinsically difficult. This chapter is accordingly (and necessarily) light on detail and heavy on description. We recognize in a first part, that despite common features, Nature offers a large diversity of phenomena with specific geomorphic characteristics, and we introduce a tentative classification accordingly. In a second part, we present the basic processes, common to most types of mass flows that lead to common features. This notably includes mechanical properties of constitutive materials, initiation processes, and propagation characteristics. In a third part, we illustrate both geomorphic and mechanistic features of mass flows based on two examples: debris flows and earthflows. In a last part, we present the characteristics of risks related to mass flows.

1 Tentative typology of mass flows

Several classifications of mass flows and other hillslope processes do exist (e.g. Hungr et al. 2001). Most of them are imperfect and may be criticized (Germain and Ouellet, 2013), highlighting the difficulty to sort Nature into boxes. Nevertheless, probably the most useful and widely accepted are the classifications elaborated by (1) Varnes (1978), which covers all kinds of movement types, basically by crossing the type of material type (earth, debris, and rock) with the type of movement (fall, flow), and (2) Costa (1984) who provides a classification focusing on the flow type and mechanical behavior.

In the context of mass movements, it is widely recognized that material of a same origin, which starts to move following similar processes, may evolve towards different types of phenomena according to its size (e.g. volume of material set into motion) (e.g. Dussauge et al. 2003, Guthrie and Evans, 2004, Guzzetti et al. 2002, Hovius et al. 1997). These changes in the behavior are partly due to the mechanical processes becoming dominant (e.g. pore fluid pressure, fragmentation) depending on the size of the mass in motion. This is particularly obvious for large rock avalanches, but also true for other phenomena like mudflows and debris flows.

The classification adopted here is based on Varne's classification and its subsequent critics (Hungr et al., 2014). Broadly ranking phenomena based on the volume of material set into motion, flows we consider are (in increasing size) erosion, solifluction, mudflow, debris flow, earth flow and debris avalanches. In the perspective of this chapter, we also try to emphasize the dynamics of flow propagation. In practice (Figure 1 hereafter), for each type of flow mentioned above, we focus on the typical range of propagation distance, considered as representative for the size, as well as the typical range of velocity.

Figure 1 hereafter shows, as for any tentative classification of natural phenomena that there are some overlaps between considered categories. The size appears as the parameter allowing the most pertinent distinction. The velocity especially allows to distinguish two classes of movement: the extremely slow flows (solifluction and earthflow) and the rapid ones, with the rock avalanches displaying the highest velocities. Indeed, combined geomorphic and dynamic considerations help distinguishing categories that we will analyze later in more details under the perspectives of geomorphology and mechanics.

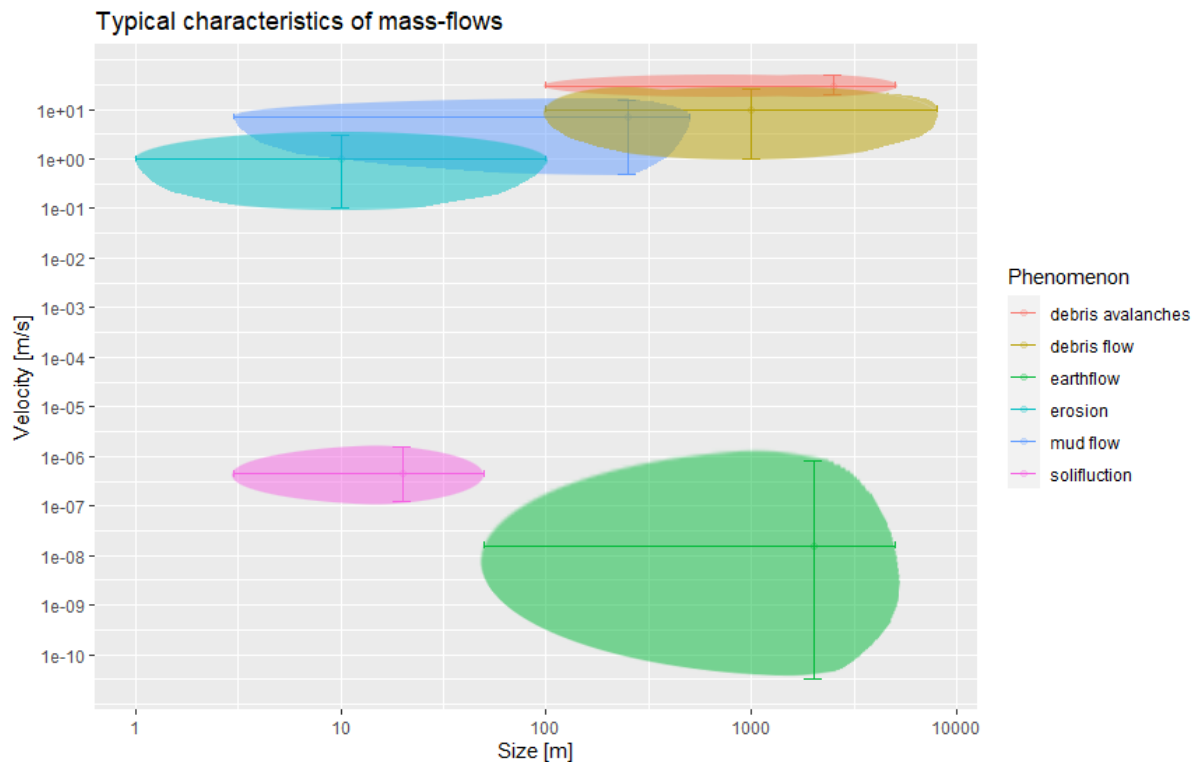


Figure 1 Overview of the characteristics of mass flows with reference to typical size (propagation distance), and velocity

We briefly present here below the main features of the flows considered above (Figure 1 here before). In Nature, phenomena may evolve from one type to another in a continuum of cascading effects, which highlights once again the difficulty to establish a classification.

Sheet erosion, and its extension: the rill and gully erosion, is not a mass flow as defined in the introduction. The flow is generally biphasic and the concentration not high enough to consider it as a mass flow. Here the sediment grains are detached by the splashes of raindrops, mainly on hillslopes and displaced by the film of running water down to the hydrographic network. In the perspective of this chapter, we consider sheet erosion as it is an important process involved in the triggering of some mass flows under the effect of water precipitation and surface runoff (see section 2.2).

Solifluction or the creep of soil is the imperceptibly slow, steady, downward movement of the slope-forming soil or rock. The movement is caused by a shear stress sufficient to produce permanent deformation, but too small to produce shear failure. Creep may be seasonal due to temporary increase of soil moisture or soil temperature (also named gelifluction). In the landscape, this creeping phenomenon develops in lobate masses, highlighting their similarity with other flowing processes (e.g. debris flows).

Debris flow is a rapid mass movement in which a combination of loose soil, rock, organic matter, water, and small amount of air mobilizes as a highly concentrated mixture that flows downslope. Debris flows include <50% fine particles. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt that erodes and mobilizes loose soil or rock on steep slopes. River jamming by a landslide or a rock avalanche, followed by a sudden collapse, may also be the cause of a debris flow. The prominent mark of a debris flow in the field is the large and steep alluvial fan at the mouth of the main gully, and the levees

(longitudinal ridges, more or less parallel to the slope), which are a typical sign of debris flow activity. Debris flows are presented in more details in section 3.1.

Mudflow is a rapid mass movement issuing from the complete liquefaction of a landslide or an earth flow. In general, it mobilizes a smaller volume than a debris flow and consists of material that is wet enough to flow rapidly. In general, it contains >50 % fine particles (sand, silt, and clay-sized particles). The word mudflow can be confusing as, for example in newspaper reports or in other languages, it is often used as a generic term to mention any type of rapid hyperconcentrated or mass flow. In terms of mechanics, mudflows are rather similar to debris flows (at least of the viscous type). In terms of cascading effects, a mudflow entering the hydrographic network may be the cause of a debris flow downstream.

Earth flow is a slow mass movement. It has a characteristic "hourglass" shape. The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongated and usually occurs under saturated conditions in fine-grained materials or clay-bearing rocks on moderate slopes. The clues in the field are often a bumpy surface lower than the surrounding area. The geological settings are at the origin of the movement, but underground water (whatever its origin) is the trigger of what one calls a crisis (acceleration of the movement). In regions where extensive loess accumulations exist, earth flows may liquefy and turn into a kind of debris flow. Such events cause widespread damages and casualties (e.g. Zhang et al., 2015). In the context of climate change, the thaw of permafrost areas may increase the velocity of the moving mass (Jermyn and Geertsema, 2015). Earth flows are presented in more details in section 3.2.

Debris avalanche (named also *Sturtzstrom* in the past) is a large volume of rock beginning its movement as a fall and for which the dissipated energy induces huge fragmentation. Due to the intense fragmentation, an important volume of fine particles (dust) is released. The phenomenon is not well understood yet, but it seems that these fine particle clouds act as a fluid matrix, providing the mass in movement the behavior of a flow, the dusty interstitial fluid supporting the debris. Such process explains the impressively long run out distance of such events. In parallel of this fragmentation there is the development of frictional heating which is sufficient for melting large amount of ice or snow (Mergili et al., 2020; Shugar et al., 2021) if present within the moving mass or on the path of the phenomenon. Debris avalanches produce deposits displaying typical flow structures (e.g. Bertran, 2003; Hsü, 1975).

The mass flows presented so far are the most common, but the list is not exhaustive. Other phenomena are mass flows as defined in the introduction, like peatflows (e.g. Dykes and Warburton, 2007; Davies et al., 2013), or present similar characteristics. For instance, volcanic lava flows have similar propagation features. Moreover, such processes are not limited to Nature, as flows of liquefied artificial landfills (mine tailing) material may present similar characteristics (Grebby et al., 2021) as well.

2 Common processes involved in mass flows

Slope flows range in size from the avalanching of a few cubic centimeters of sand down the slip face of a dune, to the collapse of several cubic kilometers of a volcano, such as the Mt. St. Helens debris avalanche in 1980 (Sousa and Voigt, 1995; Major et al., 2005). We recognized in section 1 the influence of size on mass movement processes, but intriguingly, the geomorphic outcomes have similar geometric characteristics across large differences of scale and materials. Thus, despite the large variety of phenomena observed in the field, basic processes governing mass flows are apparently common and lead to similarities in the mechanical behavior of constitutive material, and subsequently on characteristics of the flow propagation. Initiation processes and triggering factors are also common to many mass-flow phenomena. Furthermore, initiation of major events often combines several triggering mechanisms.

Nevertheless, scale effects may be present. In the case of granular flows (dry and grain-in-fluid flows), at larger scales (and, therefore, larger flow depths and intergranular stresses) individual grains are more likely to be crushed (or fragmented) during the flow, and this has a dramatic effect on the flow behavior (e.g., Davies and McSaveney, 2009). This effect appears to be limited for flow depths under a few meters.

2.1 Mechanical behavior of grain-in-fluid flows

Most flows involve fluids; however, some of the geophysical phenomena commonly classified as flows may in fact involve combinations of flowing and sliding, particularly where the lower boundary is weak. In addition, many natural flows involve rigid or breakable solids as components of the flowing material, and some dry granular flows involve no truly fluid components at all. Thus, the mechanical description of mass flows is not simple. However, a brief summary of the main characteristics of flows is useful to conceptualize phenomena. We mainly focus in this chapter on grain-in-water flows, which are the most common in Nature.

A fluid is strictly a material that is unable to resist some level of applied shear stress. When the critical stress level - if present - is exceeded, this material moves by distributed internal deformation. By contrast, a solid responds to excess stress by localized deformation on a failure surface. A commonly encountered fluid is water, which cannot resist any shear stress at all, so it settles to a horizontal surface in the absence of lateral stress. In fluid flows, stress transfer depends on fluid viscosity, which is the relation between deformation rate and excess shear stress and is generally a macroscopic property as well as a micromechanical property.

At the other extreme from water, is the bulk flow of non-cohesive solid grains (Figure 2 hereafter) down a slope with no water or other fluid present (apart from ambient air). In dry grain flows, stress transfer occurs by grain contacts (sliding or collisions). Macroscopic activity is commonly described by a coefficient of dynamic friction (e.g. Jop et al., 2006), which is the ratio of shear to normal stresses and is generally assumed independent of the strain rate, except at high velocity. In contrast with fluid flows, the characteristics of the grains that constitute the flow are important, especially grain size distribution, grain shape, and intergranular friction. Again, in contrast with fluid flows, grain flows can be extremely sensitive to boundary conditions. Air, which is of low density, generally has insignificant effects on flows of Earth materials (in large collapses like rock avalanches the presence of air, as well as thermal effects, is probably not negligible)

The mechanical behavior of slurries (e.g. Pierson and Costa, 1987), constituted of highly concentrated mixtures of water and fine cohesive particles – typically clay – is again different (Figure 2 hereafter). Viscosity is the main factor of energy dissipation within the flow, but still, it is not purely a liquid. Shear is dependent on the strain rate, but the cohesion induces a behavior that is generally non-Newtonian, in between a solid and a liquid. Effective shearing of the material can occur only when a minimum value of shear stress is applied.

The complexity of natural grain flows saturated by a fluid is notably the result of the high solid concentration – generally > 40-50 % in volume, and often more - and the generally large grain-size distribution of the bulk material. When large amounts of fine particles – clay and silt – are present, the interstitial fluid is not only water but rather a slurry with properties introduced here before. In fact, whatever the size of the bulk material, large zones inside the flow may appear either as rigid or liquid. Ancey (2007) notably provided a synthetic analysis of the physical processes at the origin of such behavior. Schematically, the friction between grains governs the rigid-liquid behavior of the mixture when the concentration of fine particles is low (left side of Figure 2 hereafter), while cohesion and lubrication of contacts by the interstitial slurry dominates when the concentration of fine particles is high (right side of Figure 2 hereafter).

Whatever the physical process at work, the liquefaction – the transition between rigid and liquid behavior - that strongly influences the mobility of the material and may be an important process in the initiation of slope flows, is still difficult to evaluate. This transition is very sensitive to the water content. It is notably influenced by local variations of the interstitial pressure – of water or any other interstitial fluid – during the flow, which tends to reduce the contact forces between grains and consequently the friction. Iverson and Denlinger (2001), for instance, have pointed out the paramount role played by the interstitial pressure. At the macroscopic scale, the transition from the rigid to liquid behavior is generally abrupt and leads either to a quick collapse of a large mass of material – when shear stress or water content increases even slightly – or to *en masse* deposition – when applied shear stress decreases.

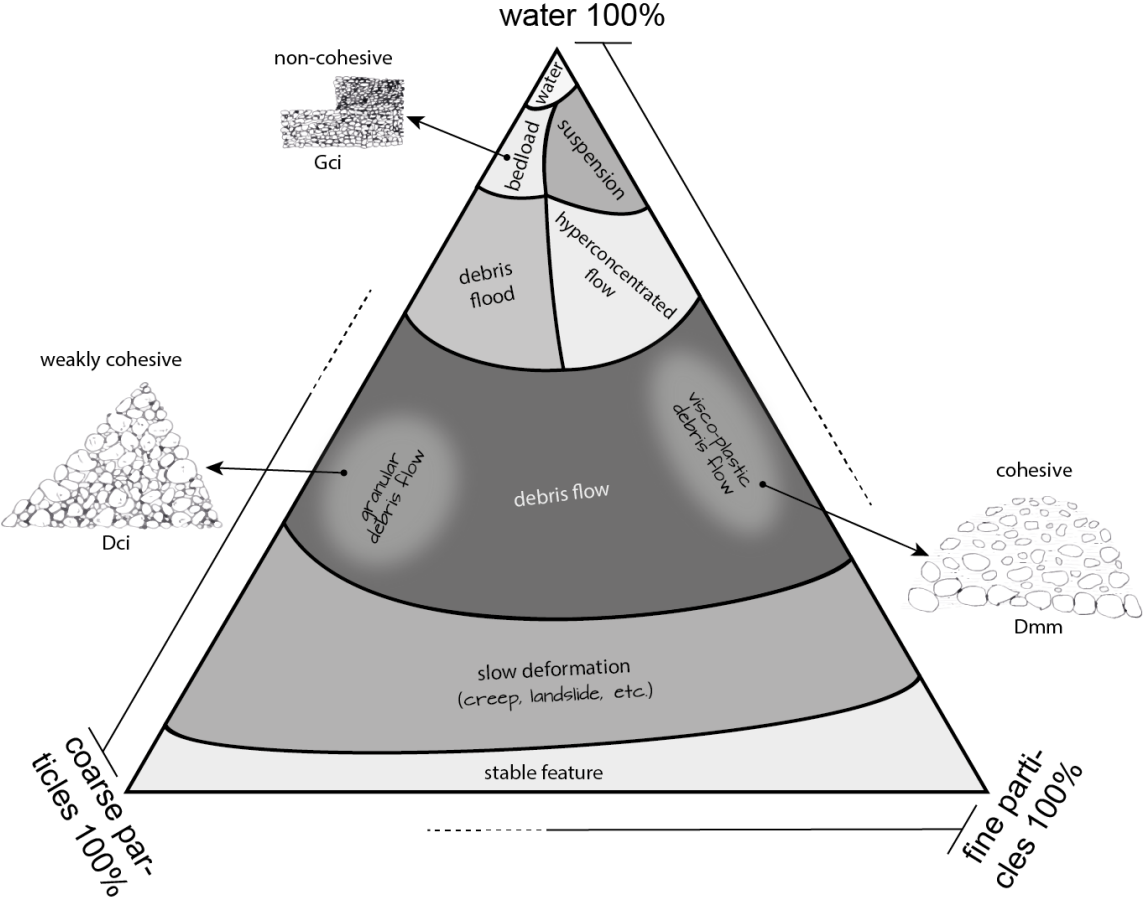


Figure 2 Synthetic overview of mechanical properties of grain-in-water mixtures. Given the multiplicity of terms, sometimes covering similar processes, it is quite difficult to represent all categories on a single sketch. In the perspective of this chapter, phenomena belonging to the top part of this diagram (water, bedload, and to a lesser extent hyperconcentrated flow) are clearly biphasic and not considered as mass flows. Features of typical deposits of the phenomenon are according to the sedimentological description (e.g. Miall, 1996) and in coherence with Shultz (1984).

2.2 Initiation of Mass Flows

Mechanistic theories for mass flow initiation can be grouped into two main categories (Takahashi, 2014): (1) surface erosion responsible for grain-by-grain bulking of the flow (e.g. Cannon et al., 2003), most often observed

in the hydrographic network; (2) mass failure that evolve into flow by liquefaction (e.g. Malet et al., 2005), most often observed on hillslopes. The first mechanism is the extension of bedload theory in steep-slope hydraulics. The second derives from the slope stability concept in soil mechanics. In fact, these mechanisms are often interconnected. Hillslope phenomena are a major source of sediment to the hydrographic network, and channel erosion can contribute to hillslope toe destabilization.

Two levels of short and long-term forcings influence mass-flow occurrence. Predisposition factors are those related to the antecedent conditions that favor the flow initiation. The presence of large quantities of loose solid material on steep slopes is the most obvious and is the result of complex geomorphic processes. Mechanical properties of this material, and thus stability, may depend upon climatic factors such as antecedent rainfall. Triggering factors are those that directly initiate the flow. Several major triggering factors can be at the origin of mass flows: heavy precipitations (tropical cyclone, monsoon, convective rains in a temperate climate), which are the most frequent, melting of the snowpack or permafrost, glacier outburst, earthquake, or impact of another slope movement such as boulder falls, or even volcanic activity. In alpine environment, the variety of sediment and water sources – other than precipitation - that can contribute to mass flows is illustrated in Figure 3, hereafter.

Figure 3 hereafter also illustrates the complex environment where mass flows initiate and propagate most of the time. In such environments, not all processes are mass flows, but multiple processes can lead to mass flows, and in turn, some localized mass flows may evolve to other processes in a series of complex cascading effects. It is therefore of interest to analyze processes at the scale of the steep mountain catchment.

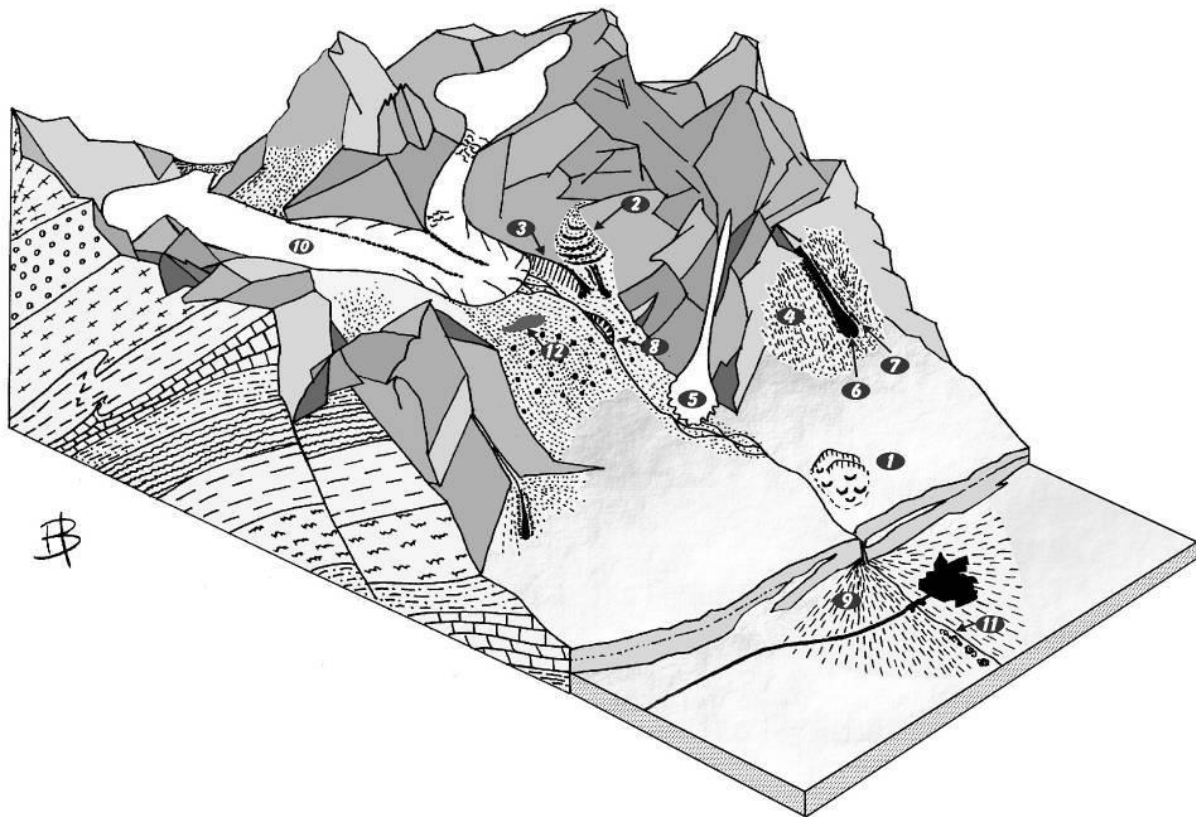


Figure 3 In the mountainous context, the main sources of sediment and water that can contribute to mass flows are: 1) landslide ; 2) rock glacier ; 3) ice inside moraines ; 4) screes ; 5) snow avalanche deposits ; 6) stream ; 7)

fresh or old debris-flow deposits ; 8) glacier front covered by debris ; 9) springs ; 10) glacier ; 11) water table raise ; 12) glacier lake.

2.2.1 Initiation of mass flows on hillslopes

Any material initially at rest on a hillslope must have the ability to resist to shear (i.e. shear strength), and this must be overcome before any motion can occur. A mass movement can be triggered by sliding along a slip plane or by liquefaction of the saturated (or nearly saturated) mass. Such processes - slide and liquefaction - are mainly caused by the development of positive pore-water pressures that accompany saturation rise during water infiltration or water table rise. Indeed, the high-water content of the mass increases its weight and in particular reduces its effective shear strength, which leads soil particles to lose coherency. Pore pressure buildup is thus a key component of the triggering mechanisms, which is a main focus in research (Bogaard and Greco, 2016). The incorporation of water supply by runoff, as well as the agitation of debris flowing downslope along rough surfaces may also play an important role in the mass liquefaction (Iverson et al., 1997). Indeed, the mass movement may start as a slip and the material rapidly liquefies, leading to a mass flow. Furthermore, when earth or rock masses are "flowing" on the ground, it is not clear if the movement at the base is sliding or not.

A second way to initiate mass flows is the direct water runoff on the surface sweeping away small particles (erosion process). Increasing viscosity of the flowing fluid will in turn increase its capacity to drag coarser grains. The forces tending to cause motion (gravity, runoff/seepage dragging, excess pore-pressure, seismic wave) are unlikely to be uniformly distributed within the material mass and neither is the shear strength. Therefore, motion will start at the specific location where stress first exceeds strength. The subsequent flow may either remain on the slope or reach the hydrographic network where it will contribute to the sediment accumulation (see section 2.2.2 below).

2.2.2 Initiation of mass flows in the low-order hydrographic network

Mass flows, and notably debris flows, can trigger in the upper hydrographic network (Coe et al., 2008), even in the channel of a steep mountain stream by water runoff, when large amounts of loose sediment are stored, notably in gullies of the upper catchment. Runoff can transform loose sediment into mass flows either by progressive erosion responsible for sediment enrichment of the flow, or through mass failure of colluvial and/or alluvial deposits. For example, Kean et al. (2013) proposed a physical-based model that focuses on the triggering of debris flows. This model assumes that low-gradient sections act as a "sediment capacitor" which (1) temporarily stores incoming sediment from bedload and (2) releases flow surges once the Mohr-Coulomb static force balance is broken. A similar concept was proposed by Pech and Jomelli (2001).

2.2.3 The cascading processes of sediment transfer at the mountain catchment scale

The analysis presented here is not specific for mass flows. It may even involve no mass flow at all! It must be seen as a tentative analysis of the complex interactions between processes in steep mountain stream catchments and the place of mass flows when present.

Sediment production and transfer are some of the key factors of both geomorphic evolution of mountain catchments and development of mass flows. Sediment sources - i.e. the areas where sediments are generated or temporally stored - generally consist of unconsolidated material overlying bedrock. They are supplied by (1) the

weathering of the bedrock from frost cracking (Matsuoka, 1990) and (2) the remobilization of the loose debris accumulated in the colluvial channels through hillslope processes (e.g. rockfall, debris slide, slope failure or gully erosion). The geomorphic response of steep mountain stream catchments is strongly linked to the condition of sediment recharge. The transfer of sediment between the geomorphic zones – on hillslopes, between hillslopes and the hydrographic network, and within the main channel - can be regarded as a cascading system. Sediment recharge within the catchment is provided by the hillslope-hydrographic network coupling (figure 4 hereafter), which integrates complex interactions between sediment detachment and transport processes.

The efficiency of sediment transfer between two compartments of the catchment sediment cascade corresponds to the degree of sediment (dis)connectivity (Fryirs, 2013). These compartments may act as sediment stores or sinks to which sediment is added or removed over time. Approaches for quantifying connectivity, and system behavior and dynamics have been developed based on geomorphometry (Cavalli et al., 2013) or graph theory (Heckmann and Schwanghart, 2013). Sediment connectivity is influenced by the magnitude and frequency of sediment supply and flood events, in conjunction with the form of the landscape (Bracken et al., 2015). Thus, hillslope-hydrographic network coupling and sediment transfer are highly conditioned by seasonal hydro-climatic factors. In particular, the sediment coming from hillslopes may accumulate during winter in the first-order channels and be transferred to the next higher order reaches during the spring and summer storms (Theule et al., 2012). During a significant rainfall event, sediment volumes coming from individual channels coalesce in the upper part of the main channel in which the resulting flow acquires enough mass and energy to propagate over long distances.

We tentatively synthesize these complex interactions in Figure 4, hereafter. Initiation of the motion of solid material may occur either on hillslopes or in the low-order hydrographic network. In both, erosion plays a significant role in the first movement, and is an evolution factor of hillslope material, together with weathering. Erosion tends to accumulate material into the colluvium, which may be seen as a tank, temporally storing sediment.

Mass wasting processes initiate on hillslopes (hillslope process in figure 4 hereafter). Mobilized material may stay on the hillslope, but generally, these processes transfer sediment to/from the colluvium, or to the gullies of the low-order hydrographic network. Depending on the intensity of phenomena or the location of the hillslope, these processes may transfer material directly to the main channel of the hydrographic network (Benda et al., 2005), evolving towards sediment transfer, notably when diluted by the main stream. The material may also not be mobile enough for flowing downstream and thus jam the main channel. This dam may then collapse quickly as a debris flow.

The gullies of the low-order hydrographic network, where runoff is channeled, experience erosion in their talweg. This sediment transfer (noted with an * in figure 4 hereafter) is here used as a generic term covering the whole spectrum of possible phenomena from bedload to hyperconcentrated flow, immature debris flow, and debris flow (McCoy et al., 2012). Sediment may be directly transferred to the main channel or stored temporarily on the colluvium.

Once in the main channel, sediment transfer can propagate downstream over a long distance, or stop in the channel (it will be remobilized later on), or form terraces if channel banks are overflowed. The latter may store the sediment for an extended period of time.

Sediment yield in Figure 4 hereafter stands for the material exported from the basin at the outlet of the main channel. There, depending notably upon the sediment concentration, the material may flow downstream to the valley stream or stop on the alluvial fan, or a combination of both.

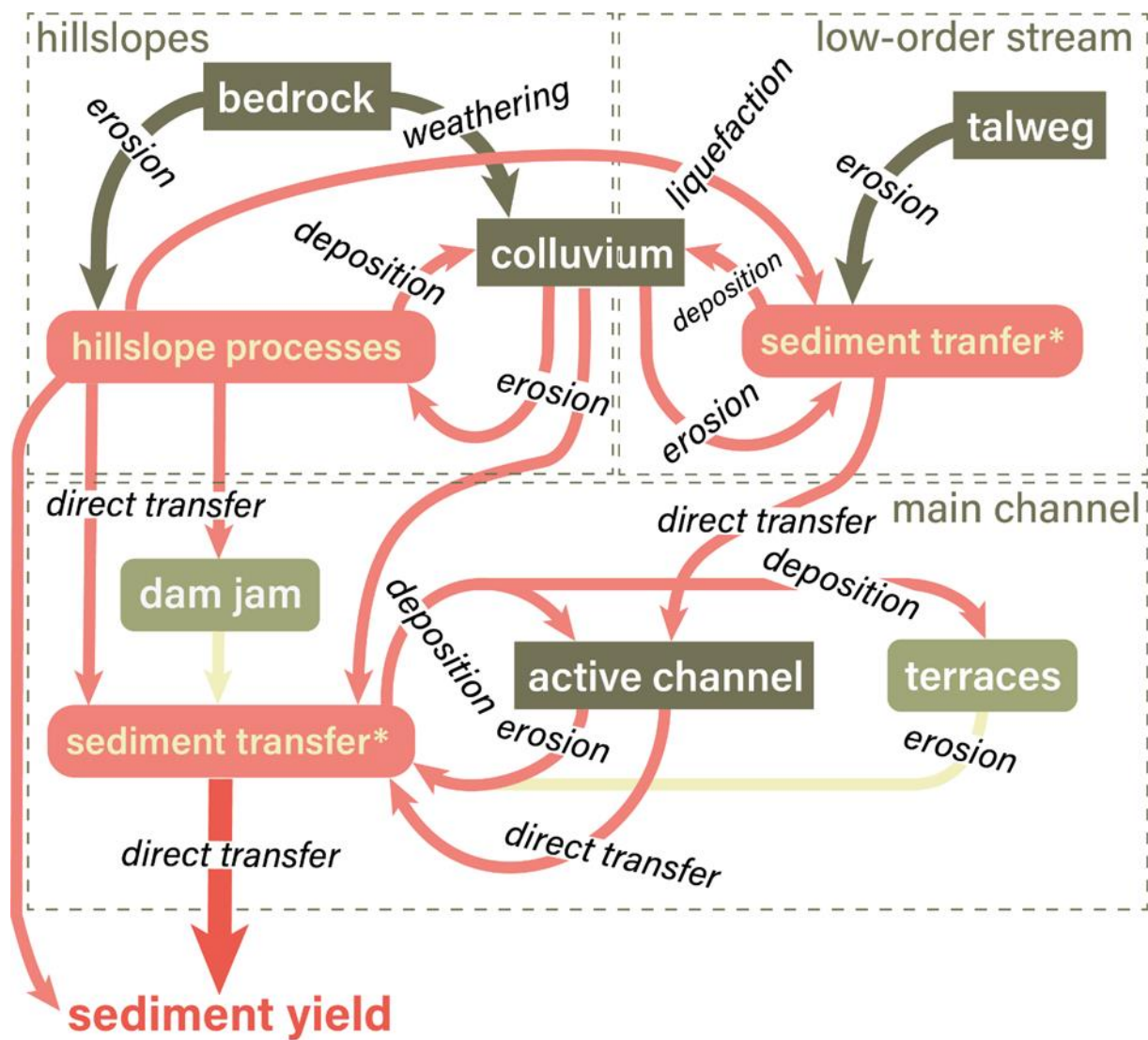


Figure 4 Sediment cascade: diagram of the hillslope-channel coupling (inspired by Liébault, 2015). Sediment transfer* is a generic term covering the whole spectrum from bedload to hyperconcentrated flow, immature debris flow, and debris flow.

In terms of cascade processes not presented so far, we can also mention a series of other phenomena. For instance, natural earth dams built up by a lateral rock avalanche that clog the stream. The collapse of such dams can trigger large debris flows (e.g. Schuster, 2000). Similar events occur in case of glacial lake outburst flood (GLOF, e.g. Carrivick and Tweed, 2016) that, by eroding the hillslopes flanks, often transforms into a debris flow (e.g. Ancey et al., 2019). Finally, we stress here the abundant literature linking mass wasting as a whole to the earthquakes (Keefer 1984). This is the so-called co-seismic landslide (in the sense of mass movements), some of which are mass flows (e.g. Fan et al. 2017).

2.2.4 Climatic factors

A review of the climatic factors that can significantly influence mass-flow triggering is provided by Wieczorek and Glade (2005). Heavy precipitation - intense or long-lasting rainfall - is the most prevalent cause. Flow triggering can also result from rapid snow/ice melting due to rainfall and/or sudden temperature rise. Both factors - rainfall and snowmelt - are responsible for the hydrologic forcing by infiltration and runoff (Reid et al., 1997). Infiltration develops perched aquifers or raises groundwater level by saturating the soil, which increases the pore-water pressure and the slope instability. In alpine permafrost areas, melting in summer is sufficient for creating such conditions (e.g. Bardou et al, 2011). Surface runoff supplies the water discharge, favors the soil liquefaction and leads notably to surficial erosion. Subsurface flow exfiltration may also enhance slope failure potential (Montgomery et al., 2002). Water input can arise from outburst flood during the collapse of an artificial or natural dam (e.g. landslide dam lake, glacial lake or cavity; Costa and Schuster, 1988). In particular, glacier-related debris flows in the European Alps were documented in Chiarle et al. (2007). Such a triggering process often leads to more catastrophic events (e.g. Ancey et al., 2019) and tends to be more frequent under the influence of climate change (Gilbert et al., 2012).

The amount of rain needed to trigger a mass flow at a given location depends on the antecedent conditions, and is different from one event to another. However, as rainfall is recognized as the main mass-flow triggering factor, efforts to develop prevention strategies relied on characterizing minimum conditions of precipitation required for flow initiation. Caine (1980) introduced the concept of critical threshold combining rainfall intensity and duration (ID) for the occurrence of debris flows and shallow landslides. Since then, rainfall thresholds have been defined worldwide using different approaches at the local scale (e.g. Wieczorek, 1987; Marchi et al., 2002; Coe et al., 2008; Bel et al., 2017) or regional scale (e.g. Caine, 1980; Guzzetti et al., 2007; Baum and Godt, 2010; Pavlova et al., 2014; Peruccacci et al., 2017). Figure 5 hereafter shows such a threshold.

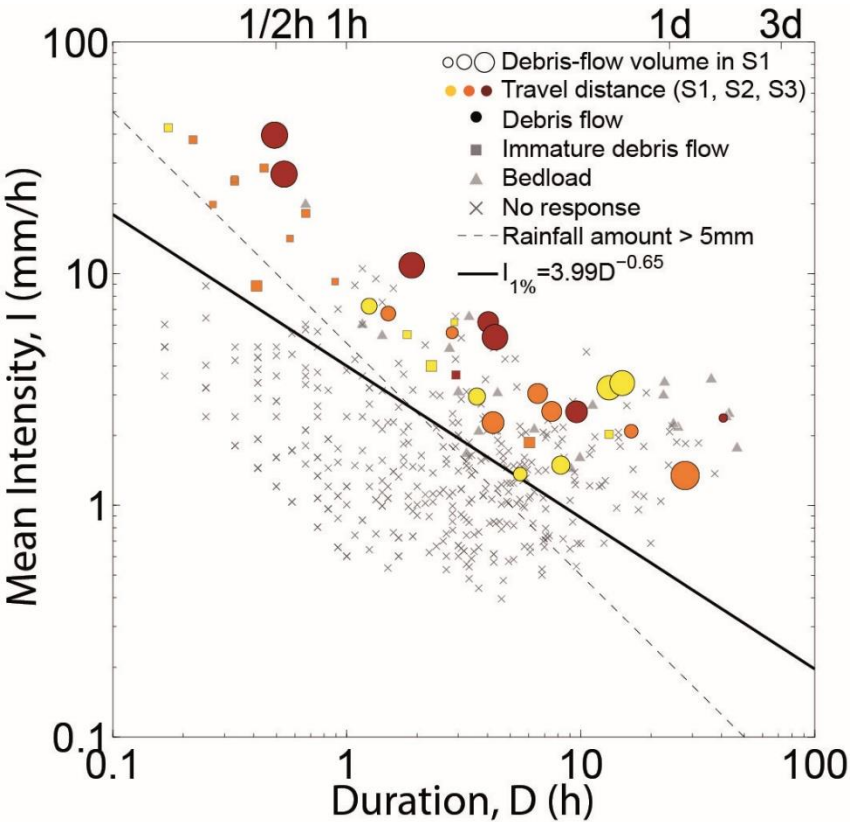


Figure 5 Example of rainfall Intensity-Duration threshold developed for debris flows after Bel et al. (2017)

2.3 Flow characteristics

Of the complete range of materials available, mass flows are most likely to comprise (1) quartz-density solids with grains ranging from clay to at least sand size, and sometimes to boulder size and (2) water. In some circumstances (e.g., rock avalanches, earthquake-triggered landslides; Kieffer et al., 2006), the quantity of water present may be negligible, but generally this is not the case. Particularly for rainfall-generated flows, the material is likely to be at least partly saturated. Organic material is unlikely to significantly affect the dynamics except when present in large quantities. Flows triggering or propagating in forest areas may carry logs or other woody debris and require specific hazard assessment and management. Flows on volcanic slopes, not presented in this chapter, may have specific features, notably with a large mobility as proven by several historical catastrophes (e.g. Sigurdsson and Carey, 1986; Major et al., 2005; Carrivik and Tweed, 2019).

The high solid concentrations considered herein imply a rigid-liquid mechanical behavior of the flowing material. Whatever the physical process involved in this transition, the flow can only occur if the effect of gravity - the shear stress - is sufficient. As a first approximation, the factors that will contribute to the applied shear stress at the bottom of the flow are the density of the mixture, slope gradient, and flow thickness. The capacity of the material to resist a given shear stress depends on the mechanical properties of the material, and therefore relies mainly on the composition of the bulk material – notably its grain-size distribution – and concentration (or water content). The absence of balance between the shear stress and the material resistance may explain triggering – as mentioned earlier - or deposition processes. During the flow, additional resistance comes from internal energy dissipation by grain friction or collision, or viscous effects. The shear stress exerted by the flow at the bottom may contribute to the entrainment of slope or channel bed material.

2.3.1 Propagation

Despite the presence of two phases in the highly concentrated natural grain-fluid mixtures considered herein, the flow remains roughly monophasic when observed at the macroscopic scale, as the matrix – water and fine sediment, if present – remains trapped between the grains. Water and grains flow at the same velocity, and only partly flow apart when the material is at rest. This is again a consequence of the high solid concentration, and generally large grain-size distribution. Grain-size sorting remains generally limited, and even inverse-sorting can be observed with large clasts present at the surface of the flow and travelling longer distance.

One other consequence of high concentration is the laminar regime of most natural grain-fluid flows with generally little development of turbulence, and often no turbulence at all. In fact, internal dissipation of energy is mostly due to viscosity, friction between grains, or a combination of both processes. The dominant process is determinant over the whole flow and leads to granular flows, or viscous and cohesive flows, with well-defined shapes of deposits when the material comes to rest (Figure 2 here before, and Figure 8 hereafter).

Another obvious consequence of the high concentration is the high density of the mixture, intermediate between those of water and bulk material. The resulting high buoyancy partly explains the capacity of such flows to carry large-size grains. In flows with large clasts present, the intergranular contact stresses also have the effect of causing large grains to rise through the flow, whereas surrounding smaller grains move down to replace them (e.g., Davies, 1988). This can also be the result of kinetic sieving (Gray et al., 2006), in which small particles move down through the necessarily large interstices formed by two adjacent large particles. The result is an apparent proclivity for large clasts to occupy the upper regions of the flow and to be advected to the front of the

flow. Deposits of mass flows can give the impression that the whole flow is made of coarse grains (e.g., Figure 8 hereafter), but finer material is generally present below the coarse surface layer.

Outside of a pre-existing channel, the flow may form its own channel on the slope, by either eroding the hillslope and growing in volume, or as the front part of the flow builds levees that confine the following material (Figure 6 hereafter). This occurs for instance on hillslopes or after channel banks are overflowed and the material freely spreads on an alluvial fan. Although this reduces the flow volume, it prevents the following debris from spreading and allows it to flow faster than the front, which is overtaken and travels farther it would if levees were not built. The lack of confinement of a flow consequently means that the course of the flow down the slope is hardly predictable. The course is set by the path of the flow front as it moves downslope; this will generally be close to the fall line; but for small flows, small-scale topography can cause appreciable deviations. Even in pre-existing channels, provided they are not deep compared to the flow thickness, some material can slightly overflow the channel banks. With little transverse slope gradient and thin flow thickness over the banks, the applied shear stress becomes smaller than the internal resistance of the material and the flow quickly stops. This process contributes to build lateral levees.

Rapid grain-in-fluid flows tend to develop roll waves that stabilize as a series of discrete pulses with low velocity or even no flow at all between them. This can be the result of a positive feedback between grain concentration and flow resistance. A slight random increase in concentration causes a slight local slowing of the flow, which causes grain concentration to increase further. It was also established (Coussot, 1994) that free-surface flows of such mixtures tend to be intrinsically unstable, except at low velocity. The consequence is that flows observed in the field are generally unsteady by nature, and propagate in series of pulses, at least when the volume of the whole event is sufficiently large. This propensity of rapid mass flows to break up into discrete surges gives these surges a rolling motion in which the surface material is continuously advected to the front of the surge and overrun (e.g. Davies, 1988). Accordingly, the mean velocity of the surge is lower than the surface velocity. Hence, field flows – with, for example, a wide variety of grain sizes and shapes, an interstitial fluid that itself comprises a slurry of fine grains in water, and a series of pulses each with spatially varying grain concentrations, flow depth, and degree of saturation – can be very complicated.

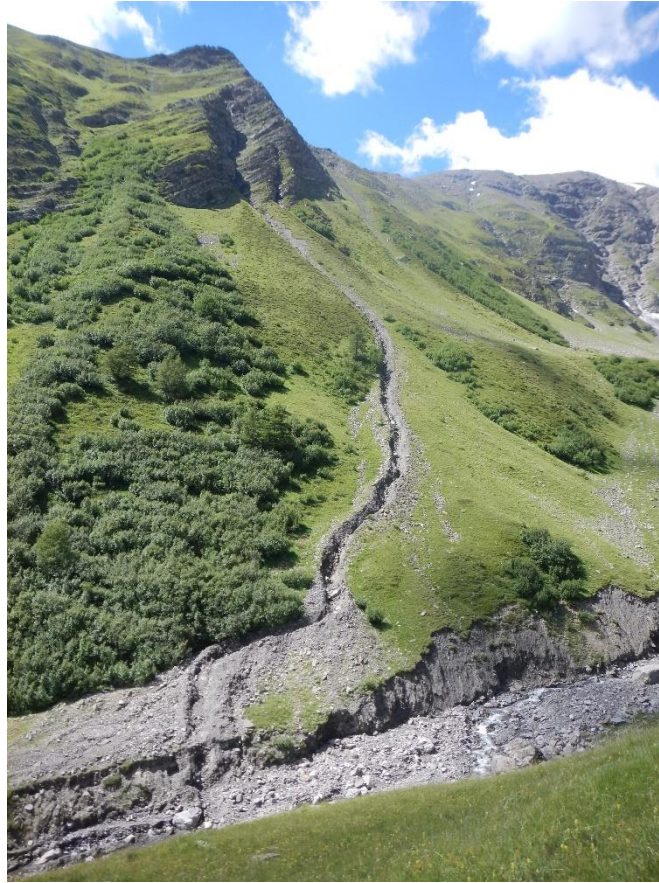


Figure 6 Flow that formed its own channel on hillslope by a combination of erosion and formation of lateral levees (Photo F. Liébault)

2.3.2 Entrainment and Deposition

Mass flows can erode material from the slope or channel along their path and increase the flowing volume; they can also deposit flow material as they pass (e.g. as levees and lag deposits). Both processes alter the mass in motion, and possibly its composition (e.g. if the eroded or deposited material is wetter or drier than the rest of the flow).

The erosion of material by the flow not only increases the volume, but it also alters the mass in motion, its momentum, and possibly its composition. Processes at work are similar to those contributing to the initiation of flows in the upper part of the hydrographic network (as seen in 2.2.2 here before) but are generally more intense and mobilize more material at a time as illustrated by Figure 7 hereafter. Consequently, the bulking of debris flows or landslides from erosion and incorporation of runout path material can be extremely important. For one of many examples, the Casita landslide in Honduras increased its volume by a factor of >4 during its passage down the volcano slope to transform from a slope failure to a debris flow that killed 2,500 people (Scott et al., 2005). Erosion, reaching a 5-10 m depth in the main channel, may be observed after a single debris-flow event (Figure 7 hereafter; King, 1996; Shugar et al., 2021). Predicting the volume of erosion during a given flow is still difficult, notably because quantifying the bed destabilization processes requires data regarding bed stratigraphy, bed material, substrate strength, drainage characteristics that are difficult to obtain (Hung et al., 2005). For such evaluation, methods based on the concept of yield rate – volume eroded per meter of channel length - and erosion depth (Hung et al., 1984) applied on successive channel reaches, present the best practical interest.



Figure 7 Entrainment of material: example of a mountain stream reach before (left) and after (right) a single debris flow event that affected this catchment for 3 days (Illgraben, Valais, Switzerland)

Final deposition of mass flow material occurs when the flow resistance overcomes the effect of gravity, and therefore the shear stress. Generally, the material deposits quite suddenly when the flow reaches a zone of lower slope gradient. For hillslope flows, this is usually at the foot of the slope. Deposition also occurs when the flow thickness diminishes as a given volume of material elongates or spreads on a surface of constant slope gradient. Other factors can affect the flow resistance. In channels, the presence of a narrow section increases the surface of contact between the flow and the boundary and tends to slow down the flow possibly to stoppage. More rarely, modifications of the material composition – slight decrease of the water content, entrainment of dryer material – can stop the flow. These deposits are characteristically lobate – each lobe being the deposit of a single flow surge – with well-defined boundaries and quite high thickness (Figure 8 hereafter). Large events with many surges can rapidly build up massive conical deposits.



Figure 8 Typical lobate shape of viscous debris-flow deposit after spreading on gentle slope (Valgaudemar, French Alps; Photo M. Bonnefoy)

3 Examples of mass flows

We recognized in section 1 the large diversity of mass flow processes. In this section, we illustrate this diversity in more details with two examples: (1) debris flow, which is rapid a mass flow, most often observed in mountain stream channel, and (2) earth flow, which is a slow mass flow, generally observed on hillslope.

3.1 Debris flows

Debris flows are a phenomenon clearly recognized as being very destructive (e. g. Surell, 1841; Skermer and VanDine, 2005) and have only been systematically investigated since the 1980s. Current knowledge about debris flows - from geomorphology to mechanics and countermeasures - is exhaustively described in several reviews (e.g. Jakob and Hungr, 2005; Takahashi, 2014). Debris flows relate essentially to mountain stream catchments and channels where they can travel long distances (several km) and are likely to encounter infrastructures in the form of bridges, roads, or buildings, with a great destructive potential. Debris flows are remarkably mobile, given that they may contain 50 – 75% by volume of solids, some of which can be exceptionally large – up to several meters - relative to flow depth. Their density is roughly twice that of water.

Debris flows can trigger by all initiation processes presented in section 2.2 here before, either on hillslope, in the hydrographic network, or even in the channel, and often a complex combination of these processes. Even though heavy precipitations are the most frequent triggering factor, the melting of "alpine permafrost" and glaciers is often the cause of debris flow (Kääb et al., 2005), even without rainfall (Bardou et al., 2015). Other cascading mechanisms can be observed, like a large rock avalanche falling on a glacier, entraining ice, and turning into a debris flow (Mergili et al., 2020; Shugar et al., 2021). Entrainment of channel bed and bank material is often an important process contributing the volume mobilized during a debris-flow event (e.g. King, 1996; Bardou et al.,

2011). The combination of these processes leads to huge volumes for a single debris flow event, typically ranging from a few thousand to a few million cubic meters in alpine environment (e.g. Skermer and VanDine, 2005 for a historical perspective), and sometimes much more if we integrate for instance outburst floods transforming into debris flows (e.g. Carrivick and Tweed, 2019). Debris flows trigger on steep slopes, but the minimum gradient value is unclear as thresholds can reach down to 16-20 %. (e.g. Theule et al., 2012). Wildfires that denude slopes of vegetation intensify the susceptibility of debris flows (Cannon and Gartner, 2005), as well as ash deposits in volcanic settings producing very fluidic debris flows called lahars (e.g. Pierson, 1986; Major et al., 2005).

Debris flow propagation is unsteady and appears as a surge – several surges are often observed within the same event. In channel, each surge is typically several meters thick and travels at a speed ranging from 1 to 10 m.s⁻¹, sometimes much more, with maximum discharge at the surge front. No flow is generally observed before the first surge, and the flow slows down and often stops between two surges. Schematically, each surge constitutes a steep snout where large clasts are generally particularly present, followed by a body with a large grain-size distribution (Figure 9 hereafter). The surge often presents a rear tail with less concentrated flow – sometimes turbulent – marking a transition to other processes as immature debris flows (Takahashi, 2014) or bedload transport. When the surge stops in the channel and is not removed by subsequent flows, it keeps the same shape (Figure 10 hereafter). For several reasons – limited channel section, presence of obstacles like bridges, lower slope gradient – the debris flow may overflow the channel banks and begin to spread. This situation is frequently encountered on the mountain stream alluvial fan where the flow is no longer confined by boundaries. However, the material generally does not spread completely freely as the flow tends to build up lateral levees and define its own channel. Even on gentle slopes, the flow keeps its capacity to travel quite long distances depending on the volume. Conditions of flow stoppage and material deposition have already been introduced in section 2.3.2 here before.

After the debris-flow passage, the flow path is highly eroded and generally flanked by levee deposits notably made of boulders that were pushed aside by the moving mass (Johnson and Rodine, 1984). When not diluted by subsequent flows, typical debris-flow deposits generally show a lobate form (Figure 8 here before) with unsorted material, often cemented (Figure 11 hereafter) when fine particles are present. Deposits can also present very large clasts (Figure 12 hereafter), which would not be carried away by any other liquid natural flow. These elements constitute the typical geomorphic signature of a debris flow. However, a debris flow is rarely the only phenomenon present in a given mountain stream where other liquid flows may alter the field evidence of the debris flow. This makes post-analysis of a debris-flow event particularly difficult. Additionally, a debris-flow catchment generally presents a large and steep alluvial fan.

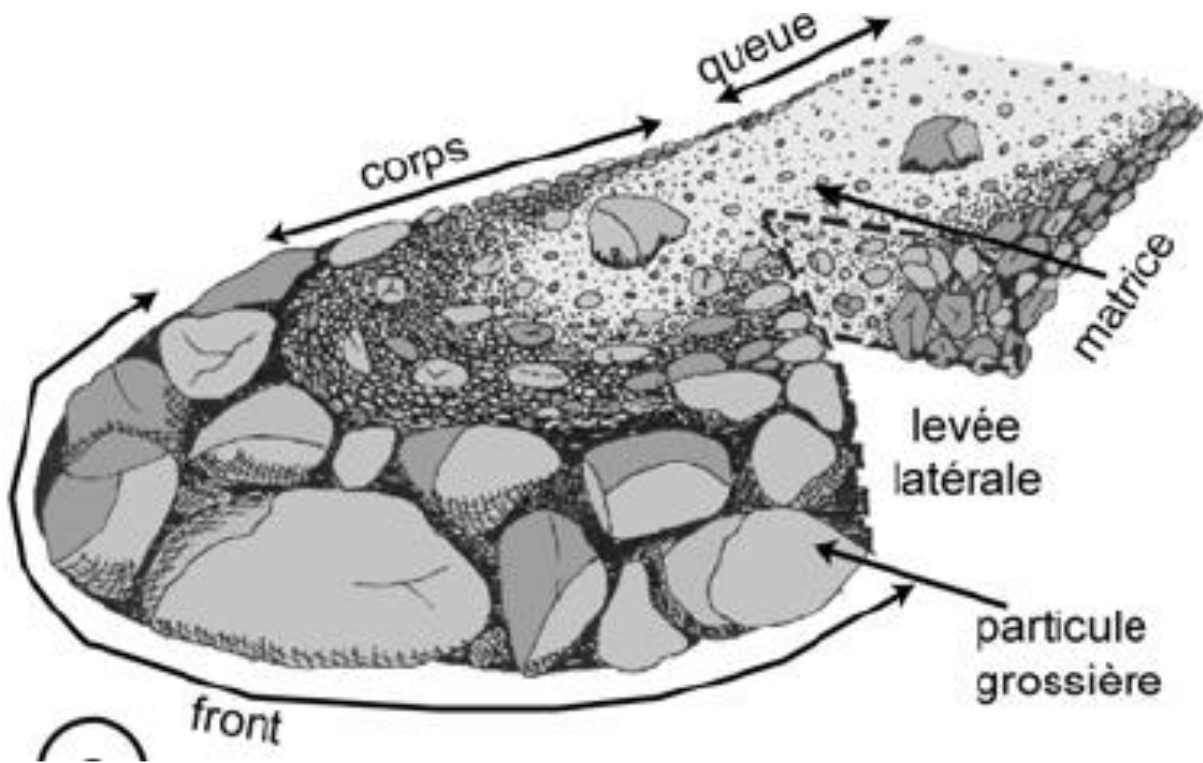


Figure 9 Schematic view of a debris-flow surge. Note that the body is longer than appears on the figure.



Figure 10 Debris flow front at rest (Southern French Alps; Photo F. Liebault)



Figure 11 Unsorted and cemented material in a debris-flow deposit where large amount of fine sediment is present (Photo F. Liebault)



Figure 12 Presence of big boulders in a debris-flow deposit (Photo J. Theule)

From a mechanical perspective, debris flow is generally defined as "a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel" (Hung, 2005; Iverson, 2005)). Non-plastic debris refers to loose unsorted coarse material consisting of a mixture of sand, gravel, cobbles, boulders and organic material (e.g. large woody debris). However, debris flow may also contain a muddy matrix made of fine sediment like silt and clay (i.e. plastic debris). Although strict mixtures of water and sediment, they can be realistically considered as comprising coarse solids in a dense, high-viscosity slurry of fine sediment in water (Davies et al., 2013) which is likely to impact the bulk flow behavior (e.g. Phillips and Davies, 1991; Jan and Shen, 1997; Iverson et al., 1997; Ancey, 2007). This led authors (e.g. Coussot and Meunier, 1996; Bonnet-Staub, 1999; Ancey, 2001) to propose two main categories: (1) muddy and (2) granular debris flows - lahars (i.e. volcanic debris flow; Vallance, 2005) constituting a very specific third category. According to this classification, the geomorphic signature and notably the appearance of debris-flow deposits and stopping slope would be different (Bardou et al., 2003): (1) viscous debris flow presents cohesive deposits (figures 8 and 10 here before) once dry with round-shape levees and stopping slope generally $> 5\%$; (2) granular debris flow presents non-cohesive deposit (Figure 12 here before) once dry with triangular-shape levees and stopping slope generally $> 15\%$.

3.2 Earth flows

Earth flows (or earthflows) are generally slow mass movements of mostly fine-grained materials or highly weathered loose rocks (Varnes, 1978; Keefer and Johnson, 1983; Iverson, 1986; Zhang et al., 1991; Malet et al. 2005). Several kinds of lithology seem prone to produce earth flows like fine-clayey material, loess deposits or black marls. They are among the most common hillslope mass-movement phenomena, but classification becomes confusing when including the nature of the processes during movement (flow, slide, or a combination of

both), the type of materials involved (earth, debris, or rock), and the velocity of the failed moving mass (rapid or slow) (Varnes, 1978). Earth flows may be long-lived features with movement occurring over seasonal to decadal timescales (e.g. Mackey et al. 2009). In the perspective adopted in this chapter, flow-like landslides and slow earth flows (exhibiting movement of creep type, which is a non-recoverable delayed deformation) are considered as earth flows.

Earth flows are generally initiated or remobilized when pore-water pressures increase sufficiently on potential or existing shear surfaces (Keefer and Johnson, 1983; Bechini, 1993) or when clay-rich fine materials swell, reducing interparticle friction. After initial failure, an earth flow may move seasonally in response to increasing saturation caused by rainfall and/or groundwater (Iverson, 1986, 2000; Iverson and Major, 1987; Zhang et al., 1991a, 1991b, 1993; Bovis and Jones 1992; McConchie, 2004).

Earth flows commonly exhibit both flowing and sliding (Zhang et al., 1991a, 1991b, 1993). They notably may present some compartments that are mostly sliding, or localized liquefaction that may be the source of mudflows or debris flow (e.g. Malet et al. 2005; Bernardie et al. 2015). Movement in earth flows tends to be intermittent. They may show seasonal variations in activity and can reactivate after years of stability. Movement rates vary from < 0.5 to > 25 m.y⁻¹ (Keefer and Johnson, 1983). In addition to slow, persistent or intermittent movement, some earth flows can exhibit surges lasting for a few minutes to several hours. Then, the velocity increases drastically, going from dozens of meters per year to meters per second. In such case, the motion of the completely liquefied mass may be more adequately defined as a mudflow or debris flow. This was for instance the case in several places of Fergana Loess Belt in Kyrgyzstan (e.g. Havenith et al. 2017) or in Afghanistan (Zhang et al. 2015) inducing heavy fatalities.

Earth flows may extend from the drainage divide down-slope (Figures 15 and 16 hereafter) to terminate at a stream, and normally have a pair of flanking lateral ridges (levees) and a set of discrete boundary shear surfaces, commonly showing slickenside-like features (Figures 13, 14, 15, 16 hereafter). Hummocky surfaces and tension cracks are common. Earth flows may be shallow to deep seated (<1 – 2 m to tens of meters, typically 3–5 m; Marden et al., 2008). Deep-seated earth flows typically occur on slopes between 10° and 20° and can cover large areas (hundreds of square meters), whereas smaller shallow earth flows are more common on slopes $> 20^\circ$.

Earth flows generally show dish-shaped scars, bulging toes, and long narrow tongue- or teardrop-shaped planforms (Keefer and Johnson, 1983; Figure 13 hereafter). An earth flow has a well-defined source or initiation zone, a transport zone and a deposition zone (Figures 13 and 16 hereafter) with associated processes of motion and material mixing (Varnes, 1978; Baum et al., 2003). Sometimes, due to the surplus of cohesion offered by tree roots, "floating" rafts of vegetation surf on the surface of the flowing mass (Figure 14 hereafter). Sliding blocks can often be seen against the main scarp on the upper part of the earth flow (Figure 17 hereafter) and the flowing mass is generally able to entrain coarse rocks (Figures 14 and 15).

Due to their size, the energy involved and the complexity of the geomorphology, earth flows are difficult to stop. When entering the main hydrographic network, the massive input of material becomes problematic (Bertolini and Pizzolo, 2008). One of the most common ways to mitigate the risk related to earth flows is monitoring (Teshebaeva et al. 2015; Bernardie, 2015; Mondini et al., 2019).

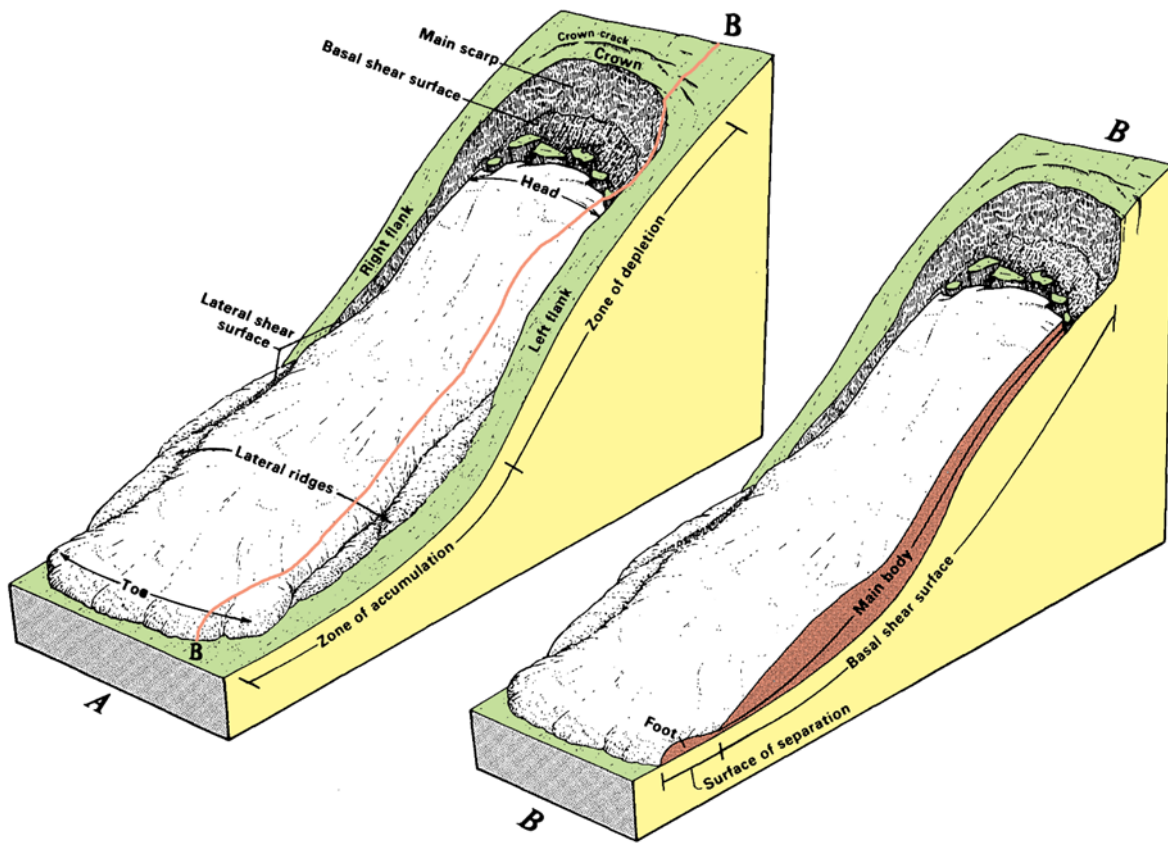


Figure 13 Typical features of earth flows (adapted from Keefer and Johnson, 1983)



Figure 14. Vegetated raft, with an apparent cohesion due to the roots, "floating" on the surface of the Pravochin earth flow (Southwestern Swiss Alps).



Figure 15 The Super-Sauze earth flow (Southern French Alps) depressed flowing mass is well visible in the middle of the image; this earth flow is prone to mudflows after partial liquefaction



Figure 16 Boup's earth flow (Valais, Switzerland). The retrogressive erosion due to the flowing part (in dark grey) reaches the upper plateau (collecting the water); the light grey part in the middle of the image is the rock cliff, partially destabilized by normal weathering and probably enhanced by the removal of mass at its foot.



Figure 17 The ridge on the left is the top of the main scarp of an earth flow, with just below (in the middle) some blocks still recognizable, and separated by cracks

4 Mass-flow risk

Mass flows can develop in any area where loose sediment is present on slopes. Risk to population and human structures is directly connected to the vicinity between the phenomenon and human stakes. Obviously, events mobilizing small volumes of material on hillslopes are likely to affect only stakes – if present - at the slope toe. Events mobilizing large volumes of material, are likely to propagate over large distance, and can affect remote populations, sometimes tens of kilometers away from the triggering area. As a first approximation, any hilly or mountainous area exposed to hydro-climatic, seismic or volcanic hazard may be affected. The most impacted areas worldwide, in terms of victims, are China, Andean countries, Caucasian countries, Japan, India, USA and Canada. In Europe, mainly countries of the Alpine arc, the Apennines and the Pyrenees are concerned.

Most destructive impacts are related to thick and rapid flows, and reinforced by the presence of blocks and boulders if entrained by the flow. Dynamic pressure (due to either high velocity or high density of the flowing mass, or both) exerted on any obstacle can be extremely high and destructive. Such flows can destroy roads, bridges and buildings (e.g. Ratto et al. 2003), even killing people inside dwellings. Less dynamic flows may however be more destructive than expected (1) as the pressure exerted by high density material, even at relatively low velocity, may be important (e.g. Laigle and Labbé, 2017) or (2) after acceleration due to complete liquefaction (e.g. Havenith et al., 2015). Figure 18 hereafter gives an example of destruction caused by a debris flow.



Figure 18 Example of destructive impact of debris flow that overflow its channel banks and spread on alluvial fan (photo G. Piton)

4.1 Examples of historical events

Mass flows affect most of the mountain ranges all over the globe. There are few accounts of mass flow events in the past, compared to large floods. Interestingly, in the Alpine countries and in Japan, the first laws for the conservation of forested area in order to protect the surrounding villages date back as early as the 15th Century. During the 19th century, the development of infrastructures across the Alps increased the probability of damage. In consequence, several European countries created public agencies to deal with erosion and mass flow risks. For instance, Surell (1841) wrote one of the first handbooks on erosion and mountain streams management, based on the experience of the black marl basins of the Southern French Alps.

Reports on catastrophic mass flow events become abundant since the beginning of the 20th century. We give here a few examples in different contexts. In volcanic environment, often related to the most catastrophic phenomena, the city of Armero (Colombia) was devastated in 1985 by the lahars of the Nevado del Ruiz volcano, causing the death of 23,000 people (Sigurdsson and Carey, 1986). In 1999, the state of Miranda in Venezuela was devastated by particularly deadly debris flows, causing roughly 30,000 casualties (Garcia-Martinez and Lopez, 2005; Perez, 2001). In May 1998, a series of debris avalanches and debris flows struck the Sarno-Quindici area in Southern Italy, and led to 161 casualties (Guadagno et al., 2005). In July 1996, a large debris flow swept away a campsite in Biescas, Spanish Pyrenees causing the death of 87 people (Alcoverro et al., 1999). In 1987, a widespread (in time and in space) severe weather hit Switzerland and Northern Italy causing many debris flows and other mass flows (e.g. Rickenmann and Zimmermann, 1993). This event and subsequent ones in 1993, 1994 and 2000 triggered a large impetus for the research on mass flows in Europe (Crosta, 2001; Kunz and Rey, 1995; Ratto et al. 2003). The situation in the Caucasus (Seinova et al., 2003) and Asia became similar towards the end of the 20th Century, pushing the scientific community to perform real size experiment on debris flow (Khegai et al. 1999), as well as in Japan (Sassa 1984). Large scale mass flows can issue from glacial outburst floods, like in Gietro, (Switzerland, 47 fatalities) in 1818 (Ancey et al., 2019) or in St-Gervais (France, 175 fatalities) in 1892 (Vincent et al., 2012). Mass flows can also be related to human activities like the collapse of a large landslide induced by the presence of a reservoir of a recently built dam in Vajont (Northeastern Italy) in 1963. The collapsing landslide impacted the reservoir, issuing a water wave that caused more than 2,000 fatalities (e.g. Semenza and Ghirotti, 2000, Crosta et al. 2016).

4.2 Risk mitigation

Large mass of dense material travelling at high speed develops a large energy. In the case of mass flows, this energy is sufficient to destroy most of the infrastructures human can built in a reasonable manner. In this perspective, mass flows become a natural hazard that, if entering in contact with infrastructure, creates a risk. The risk can be defined as a combination of the hazard, the exposure and the vulnerability (e.g. Cardona et al., 2012). As for any other kind of natural risk, mitigation can (and preferably should) act on all these components of the risk, following a multidisciplinary approach. The presentation of the integral risk management concept is beyond the scope of this chapter, but the reader may refer to the Sendai UN Conference (<https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030>). This concept relies on risk governance (e.g. Renn and Schweizer, 2009).

Defining a protection strategy requires first to assess the hazard. A comprehensive review of the mechanisms ruling the triggering and propagation of phenomena is a key for defining the type of measures needed, as well as to design appropriate technical and non-technical countermeasures. We do not give here details about methods and tools to carry out such assessments and designs as the literature on the topic is abundant (e.g. Jakob, 2005;

Bergmeister et al., 2009; Deymier et al., 1995; López Cadenas de Llano, 1992; SABO, 2007) and beyond the scope of this chapter.

4.2.1 Reducing hazard

Reducing the hazard mainly consists in applying techniques that aim at reducing the intensity and/or frequency of occurrence of phenomena. For all kinds of surface flows, this can be achieved by application of so-called blue and green measures. Blue measures mostly consist of watershed management, preventing for instance water to reach sensitive areas of unstable material. Green measures mostly consist in revegetation techniques and forest management. These measures are very efficient and cost-effective (e.g. United Nations, 2017; de Risi et al., 2018). The so-called grey measures, a term that covers all civil engineering protection works, may complement the blue and green measures, when necessary. For mass flows, men have successfully developed technics (green, blue, and grey) to prevent hazards mostly since the 19th century. Pioneering work was carried out mainly in Alpine countries in Europe (e.g. Piton et al., 2016), and in Japan (e.g. Ikeya, 1979). Technics have constantly evolved since and have been applied worldwide. These mitigation measures may apply either on the initiation, propagation or deposition process.

Mitigation of the initiation process consists in stabilizing terrains in areas where events can be triggered, to reduce the volume and/or the probability of occurrence of a mass flow event. Afforestation and bioengineering have been extensively used for more than 150 years, and are effective against erosion runoff (e.g. Delsigne et al. 2001). On steep and very instable slopes, building small civil engineering structures may be necessary before bioengineering techniques can be effectively deployed. On slopes prone to landslides, drainage or slope toe stabilization can be effective. In gullies and channels, check dams – often series of them – contribute to reduce erosion by stabilizing the bed and banks. They also contribute to reduce the slope and thus the propagation speed, sometimes favoring deposition.

Mainly since the 1970s, protection techniques acting on propagation and deposition processes have been developed. Several kinds of open check dams – or debris-flow breakers or SABO dams – have been deployed in mountain streams, often in combination with a retention basin located immediately upstream (Figure 19 hereafter). The objective of such protection structures is to let small, rather liquid floods pass through, and to stop all or part of the debris-flow volume during large events, so that the flow intensity is reduced near human stakes. These dams can contribute to the sorting of material by retention of the large – most damaging – clasts (Huebl and Fiebiger, 2005). Deflection structures and artificial channels are other kinds of countermeasures that aim at letting the flow pass through without overflow and impact on stakes. Woody debris rakes are also a rather classical structure that aims at sorting this kind of material particularly prone to bridge clogging.



Figure 19 Slit dam closing the downstream extremity of a retention basin (Photo G. Piton)

4.2.2 Reducing exposure and vulnerability

Reducing exposure mainly consists in avoiding the presence of human beings and settlements in areas potentially affected by hazards. The vulnerability, or the fragility, of a community has several dimensions. For example, a wooden house may be more fragile than a reinforced concrete designed one. The vulnerability notably considers the coping capacity of the community to withstand an adverse situation, and the level of preparedness (e.g. organization and training of rescue staff) of the community/municipality at risk. Protection measures aiming at reducing exposure and vulnerability are not specific to mass flows as their principle can be applied for any kind of natural hazards.

Among these protection measures, maps of standardized hazard levels for predefined probabilities of occurrence allow to issue regulations for hazardous areas. Based on different legal and administrative procedures, expert opinions lead to decisions being made by the authorities. Notably, urban planning consists in series of rules that apply on a given territory and prohibit new building construction or impose architectural reinforcement in areas prone to damaging phenomena with a given intensity and/or probability (Huebl and Fiebiger, 2005).

For very rare events (therefore the ones with the higher magnitude), urban planning may be insufficient (or so imposing that it obliterates the normal socio-economic life). The only solution is to detect the early warning signs of an event and anticipate its potential damaging consequences. Together with the civil protection and search and rescue specialists, it is possible to define an adequate early warning system. Figure 20 hereafter shows an example of monitoring, integrated into a warning system, applied to an earth flow (Bernardie, 2015). The

monitoring system is not only constituted by the sensors installed in the field, it fully involves human actors able to interpret the warning according to the contingency/emergency plan, and take actions once the alert is triggered (<https://www.ccohs.ca/oshanswers/hsprograms/planning.html>).

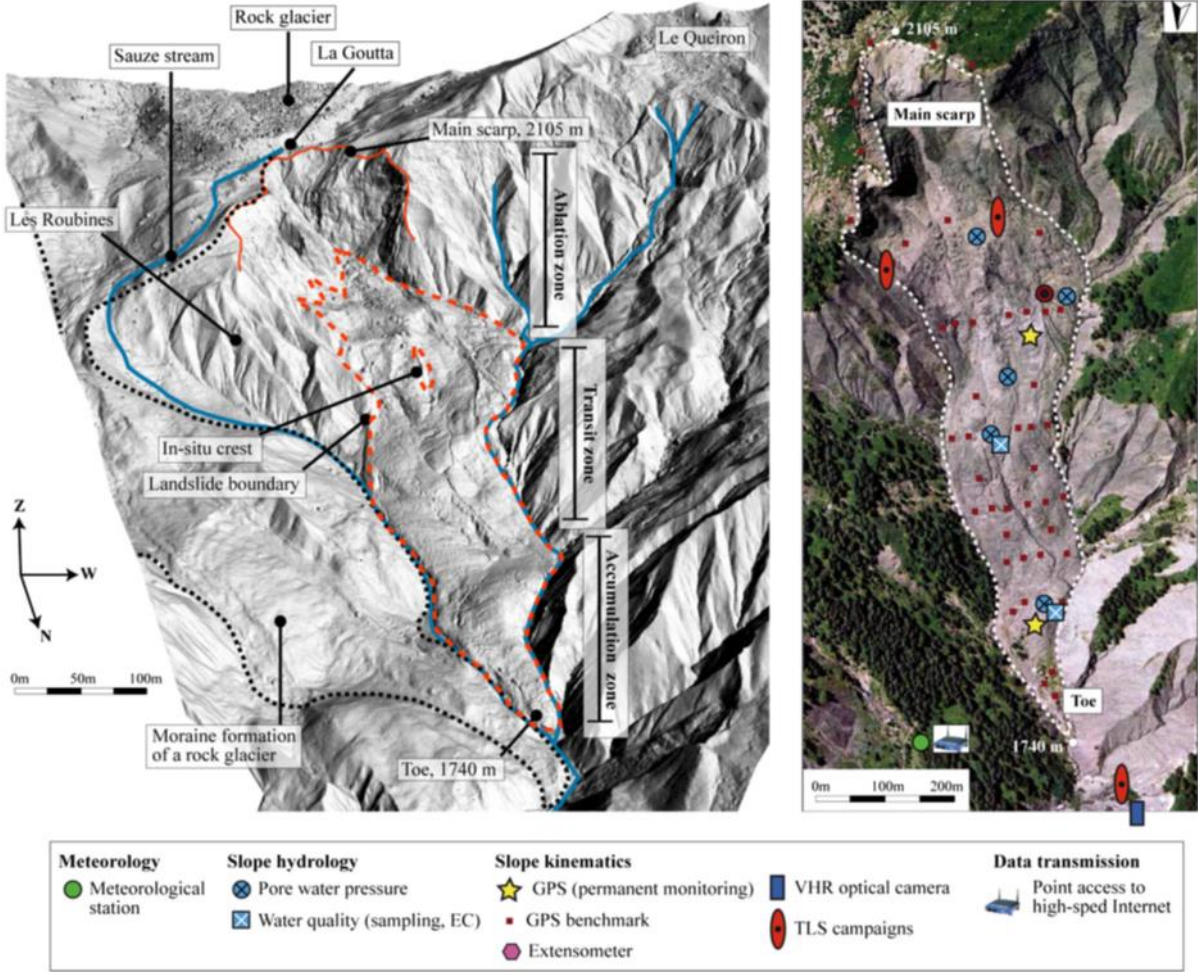


Figure 20 The super-Sauze earth flow (Southern French Alps) and the monitoring instrumentation deployed in the framework of a warning system (Bernardie et al. 2015)

Concluding Remarks

This chapter is a tentative synthesis of both geomorphic and mechanistic features of mass flows. Despite the large variety of expression in Nature, in terms of size and velocity, such phenomena present common characteristics. We have defined mass flows as subaerial highly concentrated grains-in-fluid mixtures. These phenomena occur on hillslopes or in steep mountain stream channels, and are often the result of complex interactions between hillslope and hydrographic network processes. Initiation processes are quite similar from one phenomenon to another and include either liquefaction or erosion and bulking. Most mass flows involve water and are triggered by similar climatic factors. Similarities in the material composition lead to similarities in the mechanical properties and propagation features: unsteady flows of Non-Newtonian fluid, propagating in surge, and stopping *en masse*. Such similarities lead to common features in the geomorphic signature, like typical lateral or frontal levees or ridges, with generally a lobate form of the material deposits. We detailed these features for two examples: debris flow, a rapid mass flow mostly observed in channels, and earth flow, a slow flow mostly

observed on hillslopes. We finally evoked the specific features of mass flow risks, and the main concepts of protection strategies against these phenomena prone to catastrophic events. Some of the processes involved in mass flows are not fully understood yet. However, knowledge, identification, and assessment of phenomena, with appropriate existing tools and methods, are the first and compulsory step to coping with mass flow risk.

List of relevant websites

Sendai framework <https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030>
accessed 23/06/2021

Emergency planning <https://www.ccohs.ca/oshanswers/hsprograms/planning.html> accessed 23/06/2021

Interpraevent <http://www.interpraevent.at> accessed 29/06/2021

USGS <https://www.usgs.gov/natural-hazards/landslide-hazards/> accessed 29/06/2021

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