EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **37**, 9–22 (2012)

Published online 29 April 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.2163

State of Science

Hydrogeomorphic processes and vegetation: disturbance, process histories, dependencies and interactions

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Received 8 December 2010; Revised 10 March 2011; Accepted 21 March 2011

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Earth Surface Processes and Landforms

ABSTRACT: Riparian vegetation and hydrogeomorphic processes are intimately connected parts of upland catchment and fan environments. Trees, shrubs and grasses and hydrogeomorphic processes interact and depend on each other in complex ways on the hillslopes, channels and cone-shaped fans of torrential watersheds. While the presence and density of vegetation have a profound influence on hydrogeomorphic processes, the occurrence of the latter will also exert control on the presence, vitality, species, and age distribution of vegetation. This contribution aims at providing a review of foundational and more recent work on the dependencies and interactions between hydrogeomorphic processes and vegetation. In particular, we address the role of vegetation in the initiation of hydrogeomorphic processes and its impact on stream morphology as well as immediate and long-term effects of hydrogeomorphic disturbance on vegetation. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: hydrogeomorphic processes; riparian vegetation; dendrogeomorphology; alluvial fans; debris-flow cones; forest management; risk analysis

Introduction

A substantive body of evidence exists for vegetation–hydrogeomorphology linkages and for the mutual implications of vegetation and hydrogeomorphology on each other. Hydrogeomorphic processes such as floods, debris floods, and debris flows (Hungr *et al.*, 2001) move water, sediment, and large woody debris (LWD) from the hillslopes of a watershed through channels to depositional areas (Wilford *et al.*, 2009). The solid charge transported by hydrogeomorphic processes is normally deposited on cone-shaped fans (the term fan is used here for both cones and fans) where streams or torrential systems exit mountain valleys (Bull, 1977). As fans commonly have unconfined channels, broadcasting of water and sediment as well as channel avulsions actively influence portions of the fan surface (Figure 1A). The zone on fans with forests influenced by hydrogeomorphic processes is generally referred to as the hydrogeomorphic riparian zone (Wilford *et al.*, 2005a) and can range in width from a few to several hundreds of metres (e.g. Stoffel *et al.*, 2008a; Mayer *et al.*, 2010), thus potentially occupying major portions of a fan. At the same time, the gentle gradients and workable materials of fans render this geomorphic feature a desirable site for residential developments and transportation corridors (Figure 1B; Wilford *et al.*, 2009) with a potential for considerable loss of life and high financial costs in the case of hydrogeomorphic events affecting the fan surface (Figure 1C; Sidle *et al.*, 1985; Jakob and Hungr, 2005). Resource development in watersheds above fans, the source of hydrogeomorphic processes, thus needs to be planned and undertaken with an understanding of the fan–watershed system and its components as well as with a critical consideration of the risks to downstream features on fans (Jakob *et al.*, 2000; Wilford *et al.*, 2009).

Fans are also seen as the expression of their watersheds because they have been created by and represent a summary of hydrologic, geomorphic, climatic, biologic, and anthropogenic processes (e.g. agriculture, forestry) in the mountains and hillslopes upstream of the fan (Shroder *et al.*, 2011). Inherited and present-day processes in the watershed actively influence water and sediment regimes and can thus lead to significant changes in the timing, frequency, and magnitude of hydrogeomorphic events (e.g. Jakob *et al.*, 2005; Densmore *et al.*, 2007; Lugon and Stoffel, 2010; Roering and Hales, 2011). Similarly, the delivery of LWD to channels can vary with time as a result of natural (e.g. wildfires, earthquakes, wind storms, snow

Figure 1. (A) The broadcasting of water and sediment influencing portions of an actively growing fan in British Columbia (Canada); (B) the gentle gradients and workable materials render fans a desirable site for residential developments (Ritigraben, Valais, Swiss Alps); (C) with a potential for considerable losses in the case of hydrogeomorphic events affecting the fan surface (Kuskanook, B.C., Canada). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

avalanches, insect infestations) or anthropogenic (i.e. harvesting) disturbances and therefore vary from high-frequency, low-magnitude delivery of dead trees to channels under normal conditions to catastrophic inputs of LWD (Braggs, 2000). The artificial removal of LWD over long time-scales has been shown to cause irreversible changes in fluvial systems and thus alters hydrogeomorphic conditions as well (Brooks *et al.*, 2003).

These first examples clearly demonstrate that grasses, shrubs and trees (hereafter referred to as vegetation) and hydrogeomorphic processes interact and depend on each other in complex ways (e.g. Darby, 2010; Marston, 2010). The presence and density of vegetation has a profound influence on hydrogeomorphic processes. Hydrogeomorphic processes also exert control on the presence, vitality and age distribution of vegetation. In high-energy watersheds, debris flows and floods can erode channel banks and thereby undercut, topple and remove standing vegetation. LWD entrained by hydrogeomorphic processes can batter riparian stands, and entire forest stands can be buried or removed (Johnson *et al.*, 2000). At the same time, riparian vegetation can also physically constrain flood flows, trap floating debris, and its roots may increase the erosional resistance of stream channel banks (Sato, 1991). The riparian forest may thus play a significant role in the storage of sediment, thereby limiting the potential for the development of new channels (i.e. avulsions) and maintaining the stream in its channel (Wilford *et al.*, 2005a). As a result, debris flows or floods are both influencing and influenced by the structure and composition of vegetation in the hydrogeomorphic riparian zone. An increasingly large number of studies have focused on the impacts of hillslope and riparian vegetation or beaver dams as influencing channel form, channel pattern and fan environments affected by hydrogeomorphic processes (Viles *et al.*, 2008). This contribution aims at providing a review of foundational and more recent work on dependencies and interactions between hydrogeomorphic processes and vegetation.

Role of Vegetation in the Initiation of Hydrogeomorphic Processes

Vegetation has long been recognized as a stabilizing force on hillslopes (Ziemer and Swanston, 1977; Sakals *et al.*, 2006; Viles *et al.*, 2008). Disturbances affecting vegetation cover will have implications on runoff (Hewlett and Hibbert, 1963) and erosion (e.g. Casermeio *et al.*, 2004) thus affecting initiation and magnitude of hydrogeomorphic processes in mountain and hillslope watersheds (Sidle and Ochiai, 2006). Trees have a more efficient protective role in erosion control than grasses (Descroix *et al.*, 2001), as they supply more abundant below-ground root biomass and may form interlocking root mats in the upper soil horizons and act as anchors into the substrata in shallow soils (Gray and Megahan, 1981). On hillslopes, root mats and root anchors reduce the risk of landslides being released. Schmidt *et al.* (2001) also illustrated that root cohesion of old-growth forests was greater than that of post-harvest, second-growth stands. Once landslides are released, forests on hillslopes provide resistance to movement, reducing velocity and enhancing sediment deposition (Irasawa *et al.*, 1991). A portion of the water (rain and snow) intercepted in forest canopies during precipitation events is typically evaporated or sublimated (Aston, 1979; Hewlett, 1982), thus reducing water availability for hydrogeomorphic processes, such as flooding or landsliding. While some of the water may evaporate, Nanko *et al.* (2004) demonstrated that 'small' raindrops tend to coalesce into much larger drops that fall to the forest floor with more energy causing more surface erosion (Figure 2C) than 'regular' raindrops. Organic litter layers on forest floors provide protection from these large raindrops, but in intensively managed forests these layers may be thin or absent.

Changes in forest canopy – through harvesting or natural disturbance agents (e.g. defoliation from insect infestations) may result in more snow and faster melt rates in the openings and immature stands of snowmelt-dominated watersheds (Winkler *et al.*, 2005) and therefore increase peak flows from seasonal snowpack melting (Schnorbus and Alila, 2004). Changes in forest canopy and the related modification of peak flow runoff may also affect in-channel mobilization of sediment. The impact of forest harvesting on peak flow response is undisputed; its quantification is challenging because of the confounding influence of roads that have a different, and generally larger, influence on the hydrology than does the felling of trees (Wemple *et al.*, 1996; Sidle *et al.*, 2006). Forest management activities commonly aggravate natural hydrogeomorphic processes and ultimately lead to increased erosion (Figure 2A) and destabilization of fan surfaces and stream channels (Wilford *et al.*, 2003). In coastal British Columbia (Canada), approximately one-half of all landslides occur in clearcuts and are not road-related (Jakob, 2000), this is why proposed harvesting should be assessed and managed accordingly.

In watersheds subject to significant forest health issues, hydrogeomorphic consequences are more likely to occur, regardless of human activities in the watershed (Winkler *et al.*, 2008). Similar effects are observed in burned areas where reduced soil infiltration, subsequent water repellency, removal of surface cover, and soil sealing (Larsen *et al.*, 2009) can cause effects (Figure 2B) comparable to, or more significant than those of clearcuts.

Figure 2. (A) Inappropriate forest management activities can aggravate natural hydrogeomorphic processes and ultimately lead to increased erosion. (B) In burned areas, reduced soil infiltration, water repellency, removal of surface cover, and soil sealing will lead to increased surface runoff. (C) Raindrops falling onto soil without a forest floor destroys soil structure and leads to surface erosion. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Riparian zones are characterized by early serial stage deciduous tree species. These species are the preferred diet of beaver (*Castor canadensis*) and given the presence of water, beaver gravitate to streams. Beaver can have a significant influence on floods, both in reducing peak flow magnitudes when flows are routed through their ponds, but also in generating catastrophic floods when dams break. Such failures may either result from the human destruction of dams, lack of dam maintenance by beaver, or the collapse of upstream dams (Hillman, 1998; Butler and Malanson, 2005; Butler, Submitted for publication).

Impact of Vegetation on Stream Morphology and Hydrogeomorphic Processes

Vegetation not only plays an important role in stream ecology but also as a geomorphic agent. Despite this fact, Osterkamp *et al.* (in press) pertinently state that the storage of LWD in stream channels and the quantification of its effects to induce either channel scour or deposition have received relatively little attention in the past. It is true that riparian forests have been shown to be significant in the development of channel morphology through maintenance of channel width (Erskine and Webb, 2003), stabilization of the hydrogeomorphic riparian zone, and as sources of LWD. LWD also plays a key role in the development of riparian forests as it provides stable sites for vegetation colonization, forest island growth and coalescence, and forest development in the active channel and adjacent riparian zone (Figure 3A; Fetherston *et al.*, 1995).

n the Yellowstone area (USA), Marcus *et al.* (2002) have shown that LWD tends to accumulate in small channels because the material is too large to be transported whereas in larger channels LWD is mobilized downstream by events. Dahlström *et al.* (2005) have demonstrated that LWD from pine trees in boreal Sweden is highly resistant to decomposition and can reside for more than 300 years in streams. According to Curran and Wohl (2003), distribution and function, not just abundance, of LWD are the critical elements in steep, step-pool channels.

Hydrogeomorphic processes in forested environments tend to incorporate wood in quantities comparable to the other constituents (Lancaster *et al.*, 2003). Wood transported in debris flows is most frequently concentrated toward the leading edge of the event (Swanston and Swanson, 1976). This material tends to result in woody debris jams, trapping sediment (Hogan *et al.*, 1998). In forested watersheds this commonly leads to a distribution of sediment deposits throughout the channel network (Lancaster *et al.*, 2003). In contrast, May (2002) found that debris flows initiating in clearcuts and mixed aged forests had less wood. The result was instances of exceptionally long runout lengths that were beyond the variability present in the data from forested debris flow initiation sites.

Woody debris derived from forests stabilizes the bed and banks of channels such that floods and debris floods transport less sediment (Lisle, 1996), thus limiting the extent of disturbance along the transport path of hydrogeomorphic events and markedly enhancing sediment deposition (Wilford *et al.*, 2003). Standing vegetation, such as dense alder stands, within the riparian zone increases channel roughness – Manning's roughness coefficient *n* – by an order of magnitude and thereby significantly reducing sediment transport capability (Ogrosky and Mockus, 1964). This leads to the deposition of suspended materials within the riparian zone (Johnson *et al.*, 2000). Riparian vegetation has also been reported to narrow impact zones of hydrogeomorphic processes (Kochel *et al.*, 1987). Riparian vegetation alone does not constrict the flows but the woody debris and uprooted trees deposited against riparian trees functioned as 'wood levees', and thus kept flood water within the stream channel (Johnson *et al.*, 2000).

Roots are another important factor in limiting bank erosion along torrent and stream channels (Smith, 1976; Abernethy and Rutherford, 2000) and in reinforcing the soil mass where avulsion tends to occur (Wilford *et al.*, 2005a). Pollen-Bankhead and Simon (2009) employed empirical data to assess the spatio-temporal stability of root networks within stream channel banks and to derive root reinforcement factors. Temporal changes in mechanical effects of root reinforcement and related bank strength have also been illustrated to influence the form of downstream hydraulic geometry relations (Eaton and Giles, 2009).

However, wood within the channel and trees delivered to channels by hydrogeomorphic processes were reported to impact against standing trees and to provide the inertia required for floods and debris flows to topple or uproot riparian vegetation (e.g. Stewart and LaMarche, 1967; Swanson *et al.*, 1998). Johnson *et al.* (2000) clearly state that fluvial disturbance alone toppled fewer riparian trees than in reaches where floods transported substantial amounts of wood. Similarly, congested wood transport resulted in higher frequency of toppled trees and greater deposition of new wood levees along channel margins.

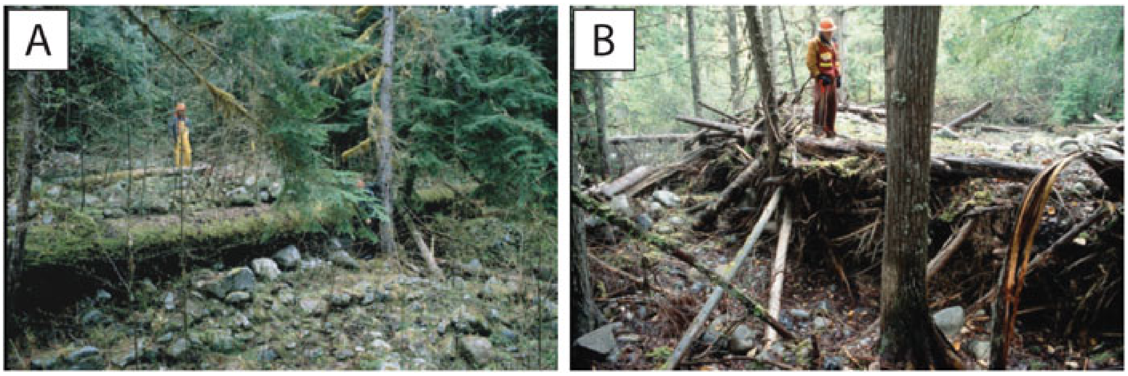

Figure 3. (A) Large woody debris (LWD) can help the development of riparian forests as it provides stable sites for vegetation colonization. (B) Wood transported in debris flows is most frequently concentrated in the frontal part of deposits as log jams. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Hydrogeomorphic Disturbance Effects on Vegetation

Reaction of trees to events

Riparian vegetation communities are determined by local ecologic conditions (Shreve, 1927; Whittaker, 1956; Zimmermann and Thom, 1982) and characteristically dominated by early serial species – a result of the high frequency of disturbance from hydrogeomorphic processes. Periodically these processes remove or kill existing trees and are therefore referred to as 'stand-replacing disturbances' (Oliver, 1981). Vegetation affected but not killed by hydrogeomorphic process activity will react to the disturbance with specific and immediate growth reactions (Baumann and Kaiser, 1999; Stoffel and Bollschweiler, 2008, 2009, and references cited therein).

Hydrogeomorphic processes in mountain and hillslope watersheds are the dominant disturbance agent to channel and riparian habitats (e.g. Hack and Goodlett, 1960; Hupp and Osterkamp, 1996; Swanson *et al.*, 1998). The soil, boulders, trees and LWD transported by hydrogeomorphic processes may physically injure the bark and wood of vegetation growing in or adjacent to their flow paths. Injured trees react upon disturbance with the production of callus tissue (Larson, 1994; Sachs, 1991) overgrowing the open wound from the sides – a process that can take decades depending on the size of the injury (e.g. Stoffel and Perret, 2006; Schneuwly *et al.*, 2009). In addition, several conifer species produce resin and tangential rows of traumatic resin ducts (e.g. Bannan, 1936; Nagy *et al.*, 2000) in the axial and vertical prolongation of the wound (Stoffel and Beniston, 2006; Bollschweiler *et al.*, 2008a; Kaczka *et al.*, 2010). Figure 4 provides examples of injuries and the responses to wounds inflicted to different types of woody vegetation by hydrogeomorphic processes.

The destabilization of trunks as well as the unilateral pressure induced by the material transported in a floods, debris flood or debris flow can lead to a tilting of the stem axis (Figure 5A; Lundström *et al.*, 2008). Trees compensate for the tilting through the formation of reaction wood (Braam *et al.*, 1987; Timell, 1986) and eccentric growth will become apparent in the tree-ring series (Figure 5B and 5C).

Trees can be partially buried by sediment (Figure 6A) in the hydrogeomorphic riparian zone, and will not die if the roots have sufficient oxygen, nutrients and water, but tend to exhibit a sudden and abrupt decrease in yearly growth-ring increment for several (usually >10) years (Figure 6B; Hupp *et al.*, 1987; Friedman *et al.*, 2005). Characteristically these trees do not have a basal or 'butt' flare, but the flare can re-establish over a period of time. While lack of butt flare and recent deposits are indications of hydrogeomorphic activity, it is possible for trees to recover after a few decades and to re-establish basal flare. Noteworthy, the sudden growth decrease reported earlier has been observed to be reduced or virtually non-existent in case (i) an abundant source of water was still available after burial, (ii) the sediment is coarse textured, and (iii) the surrounding trees were removed by the same event (thus removing competition).

Comparable growth decreases also occur when trees from the riparian zone are decapitated by the impact of the solid charge transported by hydrogeomorphic events (Butler and Malanson, 1985) or if large parts of the root system (Figure 7A) are exposed as a result of sudden channel wall erosion or gullying processes (LaMarche, 1968; Carrara and Carroll, 1979; McAuliffe *et al.*, 2006; Stoffel *et al.*, submitted for publication). Once roots are exposed morphologic changes in the wood structure occur – root rings become stem-like with more tracheid cells and a much larger latewood (Figure 7B; Corona *et al.*, 2011a, 2011b; Stoffel *et al.*, submitted for publication).

When a hydrogeomorphic event is a stand replacing disturbance a new even-aged forest or 'cohort' (Oliver and Larson, 1996) establishes and the vegetative evidence of previous events is lost. In these situations, the age of the stand plus a factor for stand establishment can be a cautious surrogate for the event return period, or the number of years between event occurrences (Pierson, 2007; Bollschweiler *et al.*, 2008b).

Dendrogeomorphology and time-series reconstruction

The study of potentially hazardous hydrogeomorphic processes using increment rings of trees growing in temperate climates with distinct seasons lies in their capacity to both preserve evidence of past events and to provide critical information on their dating (e.g. Alestalo, 1971; Shroder, 1980; Wilford *et al.*, 2005b; Bollschweiler and Stoffel, 2010c; Stoffel *et al.*, 2010). The initial employment of dendrogeomorphology in hydrogeomorphic process studies was simply as a dating tool (e.g. Sigafoos, 1961, 1964; Everitt, 1968) and rarely exploited other environmental information that could be derived from studies of ring-width variations and records of damage contained within the tree itself. However, these unique, annually resolved, tree-ring records can preserve potentially valuable archives of hydrogeomorphic events on timescales of a few decades to several centuries. As many of these processes are

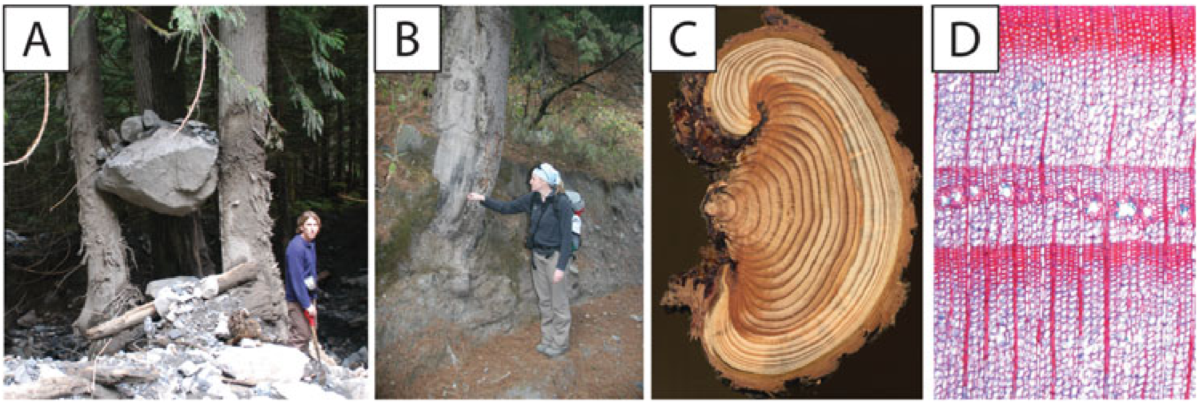

Figure 4. (A) A stand of *Thuja plicata* influences debris flow sediment movement on a fan in British Columbia. (B) *Pinus ayacahuite* trunk injured by a lahar at Huiloac gorge (Popocatépetl volcano, Mexico). (C) Cross-section of a *Larix decidua* stem injured by a debris flow. Note the callus tissue overgrowing the wound. (D) Micro-section of a tree ring with a tangential row of traumatic resin ducts (TRD) as an immediate reaction of *Larix decidua* to wounding (illustrations C and D: M. Bollschweiler, used with permission). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

significant natural hazards, documenting time series of events, understanding their areal extent and controls provides valuable information that can assist in the prediction, mitigation and defense against these hazards and their consequences on society. Time-series analyses of tree rings have considerably contributed to the endeavors of hydrogeomorphic processes in the past with annual and sometimes even monthly resolution.

Pioneering work in the field was done by Hupp (1984; Hupp *et al.*, 1987) documenting the past occurrence of debris flows in forested watersheds on the slopes of Mount Shasta, California (USA). More recently, May and Gresswell (2004) used growth-ring series of trees to estimate the time elapsed since the last debris flow and calculated rates of sediment and wood accumulation in low-order streams to describe the temporal succession of channel morphology after a hydrogeomorphic event. A current focus of contemporary dendrogeomorphic assessments of hydrogeomorphic process activity is on the European Alps (Bollschweiler and Stoffel, 2010a). Strunk (1991, 1995), for instance, has used tree rings extensively to reconstruct debris-flow activity in the Italian Dolomites. He was also the first to test initiation dates of adventitious roots in buried stems to reconstruct burial depths and the temporal occurrence of debris flows in the Southern Alps. As roots can continue to initiate for decades, the caution here is that many samples are required to adequately determine event dates using adventitious roots. More recently, the temporal frequency of past events was reconstructed for over 30 torrents in the Valais Alps (Switzerland; Bollschweiler and Stoffel, 2007, 2010a; Bollschweiler *et al.*, 2008b; Stoffel *et al.*, 2008a), including research on more frequent, yet smaller in-channel events based on growth anomalies and morphological changes in wood structure in riparian broadleaved trees (Figure 8; Arbellay *et al.*, 2010; Szymczak *et al.*, 2010).

In contemporary tree-ring research, the focus in frequency assessments has shifted from isolated at-site analyses to regional approaches (Pelfini and Santilli, 2008; Jomelli *et al.*, 2009). The integration of several torrents in a single reconstruction not only facilitates identification of spatial and temporal changes or trends in hydrogeomorphic process activity, but also assists in the reconstruction of hydrometeorological conditions leading to

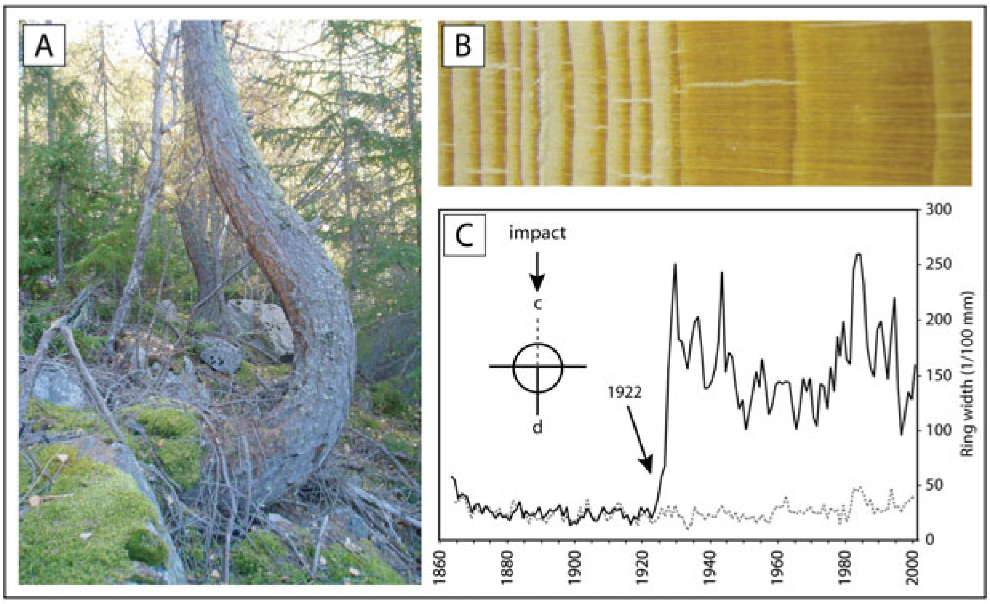

Figure 5. (A) Deformed stem and (B) cross-section of annual rings of a *Larix decidua* impacted by a debris flow (D.M. Schneuwly, used with permission). (C) Graph of annual ring widths of a *Picea abies* indicate the formation of reaction wood associated with tilting caused by a debris flow in 1922 (c = upslope core, d = downslope core; adapted from Stoffel *et al.*, 2005). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

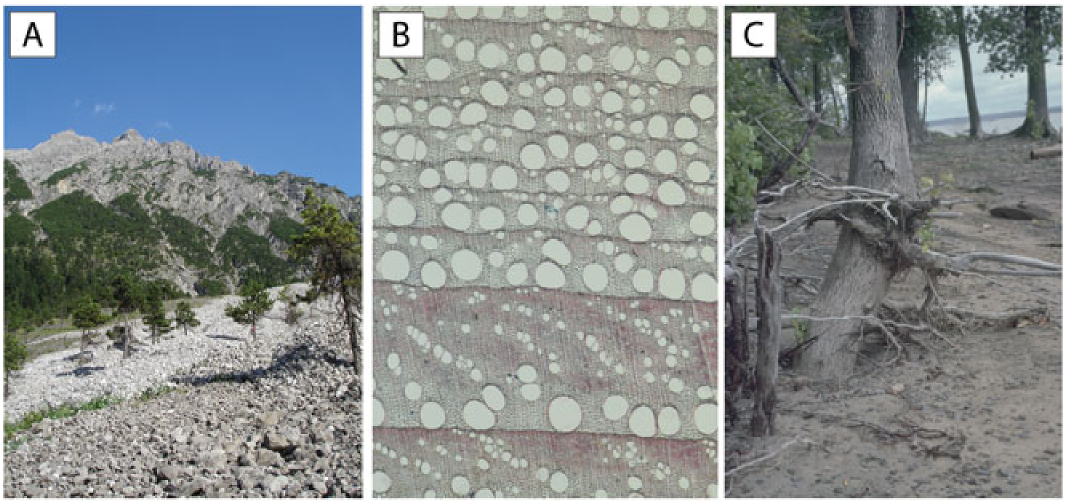

Figure 6. (A) Sedimentation and partial die-off in a stand of *Pinus uncinata* in the Austrian Alps. (B) Micro-section showing an abrupt growth decrease in *Castanea sativa* following stem burial (F.H. Schweingruber, used with permission). (C) Several levels of adventitious roots in *Populus balsamifera* growing on the debris-flow channel bank at Quesnel, B.C. (Canada) indicate cycles of sediment deposition and erosion. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

the release of events. In the southern Valais Alps (Switzerland), reconstruction of the temporal occurrence of 296 debris flows (1850–2009; Bollschweiler and Stoffel, 2010b) indicates that the temperature increase and higher summer precipitation at the end of the Little Ice Age would have caused a sharp increase in debris-flow frequency in many catchments of the Valais Alps during the second half of the nineteenth and the early twentieth centuries. Recently, changes in the seasonality and nature of rainfalls (i.e. a shift from localized summer thunderstorms to advective rainfalls in late summer and fall) have, in contrast, led to a general decrease in debris-flow frequency and, at the same time, to an increase in debris-flow magnitude over the past *c.* 15 years. Stoffel *et al.* (2011) also demonstrated that these changes in the temporal occurrence and size of debris flows were clearly the result of modified atmospheric circulation patterns (i.e. North Atlantic Oscillation or NAO) and a related decrease in the number of potentially triggering rainfall events (Schmidli and Frei, 2005) rather than reflecting sediment supply limitations in these catchments (i.e. 'transport-limited' conditions *sensu* Bovis and Jakob, 1999).

Analyses of actual triggers of reconstructed debris flows has been facilitated considerably through the fact that tree-ring dating of wounds in trees has been improved to the point that past events can now be dated with up to monthly precision. Kaczka *et al.* (2010), for instance, used 240 cross-sections of conifers impacted by a known debris-flow event in Québec to identify the timing of growth disturbances (i.e. injuries, tangential rows of traumatic resin ducts and density fluctuations) within the tree ring. In the Swiss Alps, Stoffel *et al.* (2005, 2008a) have used the intra-seasonal position of debris-flow damage in trees, local rainfall records and data on flooding to reconstruct 440 years of debris-flow history at Ritigraben with monthly resolution. Their results demonstrate that the main debris-flow season at the study location shifted from June and July during the late nineteenth century to August and September over the last 50 years. Precipitation recorded prior to debris

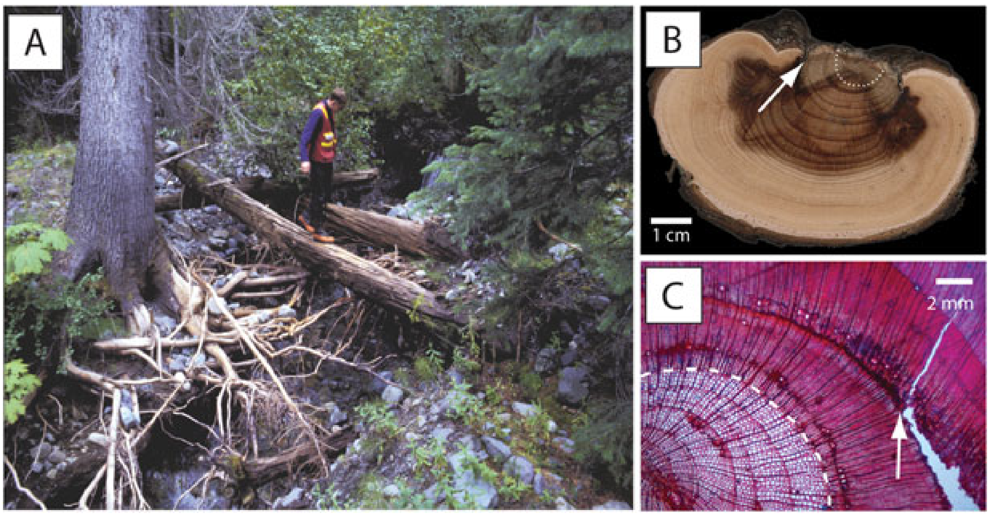

Figure 7. (A) Root systems of trees can reduce or delay erosion and channel avulsion. (B) Cross-section of an exposed *Austrocedrus chilensis* root with initial exposure signature in 1937 (changes in cell structure indicated with dashed line) and subsequent abrasion (arrow) in 1956. (C) Micro-section of a *Pseudotsuga menziesii* root with initial exposure (dashed line) in 2004 as well as an abrasion scar (arrow) and related tangential rows of traumatic resin ducts (TRD) in 2007. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

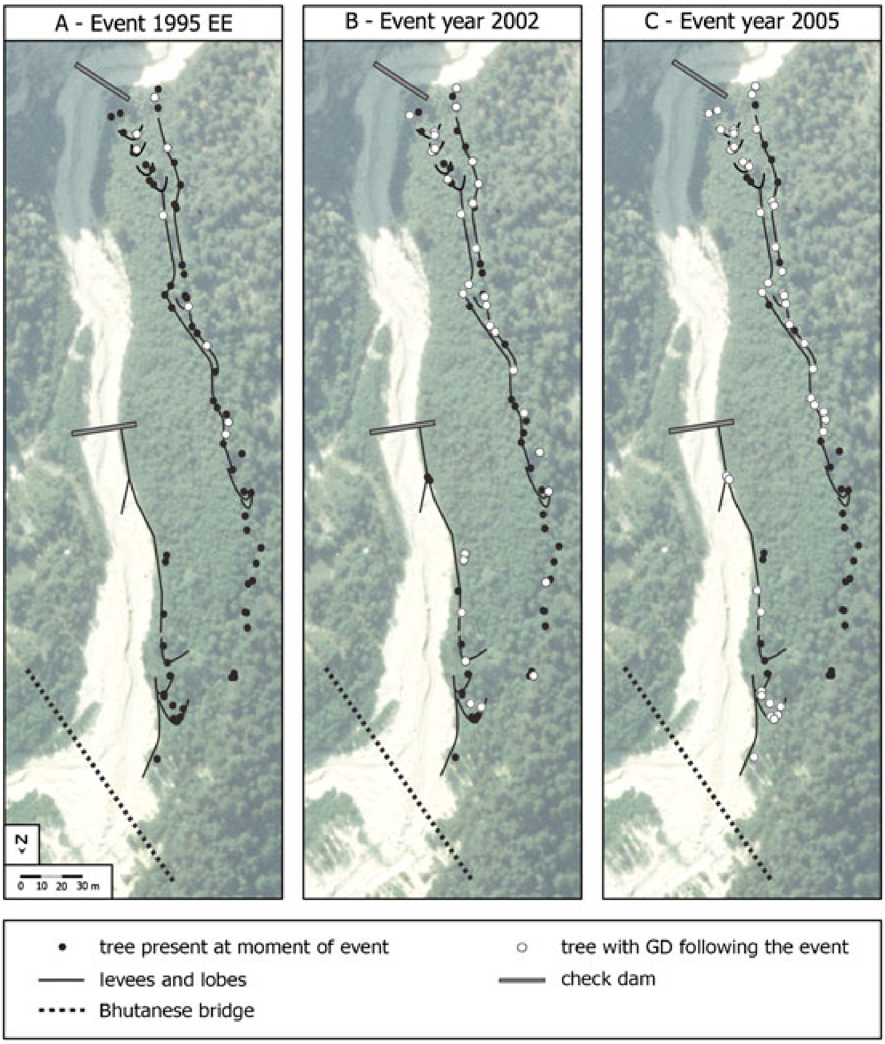

Figure 8. Location of riparian broadleaved trees (*Alnus incana*, *Betula pendula*, *Betula pubescens*, *Populus alba*, *Populus nigra*, *Populus tremula*, *Salix caprea*, *Sambucus nigra*) showing growth disturbances associated with three debris flow events at Illgraben (Valais, Swiss Alps). Abbreviation: EE = early earlywood (i.e. May and June) (adapted from Arbellay *et al.*, 2010; aerial photograph: © 2009 swisstopo - BA091308). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

flows at Ritigraben exists for the last 150 years with daily resolution; precipitation differed considerably between events and ranged from 10 to 179 mm years (Stoffel *et al.*, 2011).

When frequency records are coupled with spatial information, it is possible to reconstruct the extent of disturbance of hydrogeomorphic events or the complexity of activity in channel networks. In particular, the use of detailed geomorphic maps and accurate positioning of trees reacting simultaneously to an event provide valuable spatial data on individual events (Bollschweiler *et al.*, 2007; Stoffel *et al.*, 2008a). Similarly, the approach also allows identification specific hazardous locations such as, avulsion locations or the identification of locations experiencing frequent overbank sedimentation or erosion (Figure 9) (Stoffel *et al.*, 2008b; Mayer *et al.*, 2010; Stoffel *et al.*, submitted for publication). Breakout locations and activity in paleochannels receives key attention in hazard assessment and risk analysis on debris-flow fans (Bollschweiler *et al.*, 2008b; Wilford *et al.*, 2009).

Spatio-temporal information of debris-flow activity can also be useful for understanding depositional processes on fans. At

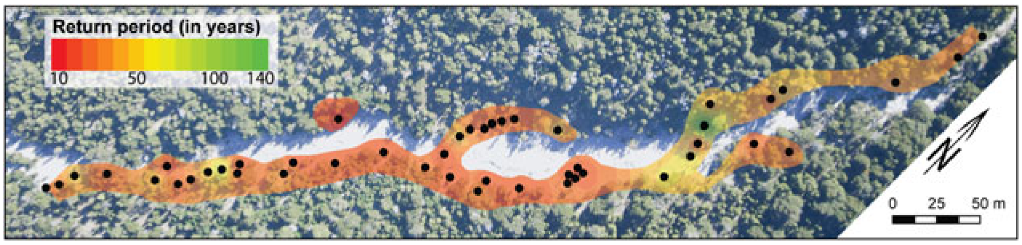

Figure 9. Spatial interpolation (inverse distance weighing) of return periods of gully wall erosion at Los Cipreses (Bariloche, Argentina) based on root exposure of *Austrocedrus chilensis*, *Nothofagus dombeyi* and *Pseudotsuga menziesii*. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

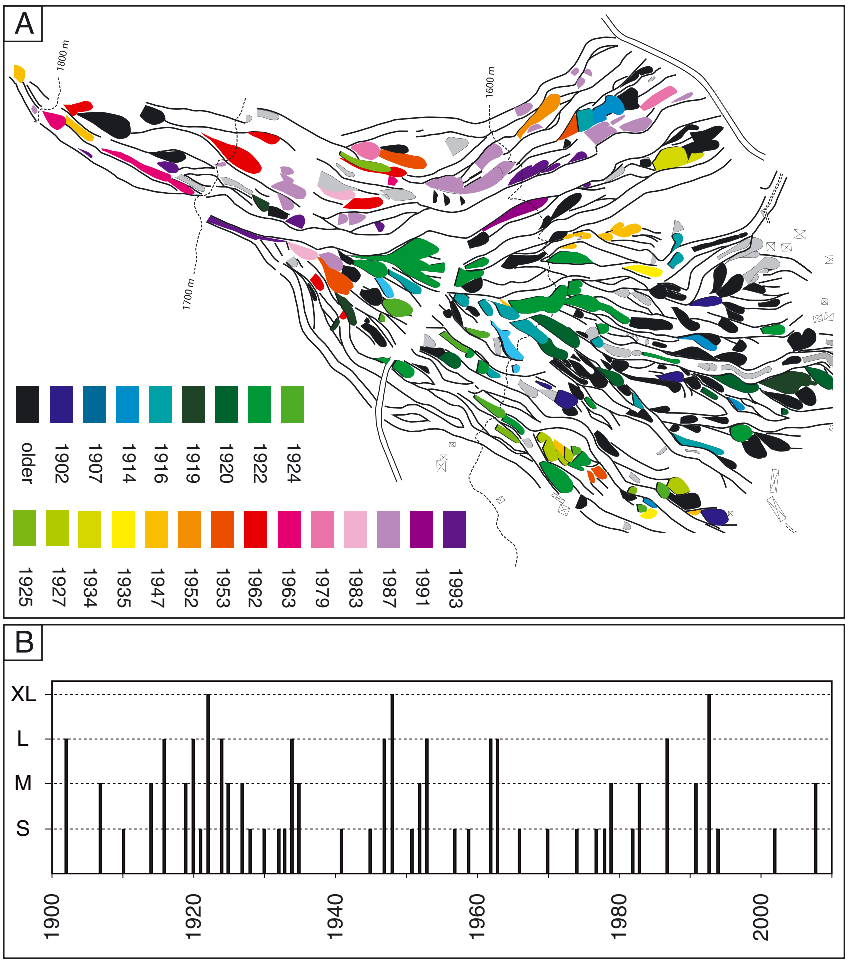

Figure 10. (A) Spatial distribution of even-aged sediment deposits on the Ritigraben fan (Swiss Alps) for the twentieth century. A majority of the fan surface has been active during the last century and – although evidence of events date back to AD 1570 – deposits on the present surface are rarely older than 150 years before they are buried (adapted from Stoffel *et al.*, 2008a). (B) Reconstructed magnitudes of twentieth century events at Ritigraben (magnitude classes: $S = 10^2–10^3\,m^3$, $M = 10^3–5 \times 10^3\,m^3$, $L = 5 \times 10^3–10^4\,m^3$, $XL = 10^4–5 \times 10^4\,m^3$; adapted from Stoffel, 2010). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Ritigraben, analysis of injured, buried or tilted survivor trees in deposits allowed dating of 249 of 291 lobes (86%) identified on the contemporary fan surface. Figure 10A illustrates that a majority of lobes visible on the contemporary fan surface were deposited during the last 70 years. In contrast, only six deposits (2%) were attributed to pre-eighteenth century events, despite the fact that one in three debris flows were reconstructed for the period AD 1570–1790 (Stoffel *et al.*, 2008a). Stoffel (2010) identifies that smaller debris flows are characterized by higher snout elevations, early deposition of material and more limited spread as compared to larger events.

Based on impact heights or on the extent of growth defects on stems, the spatial distribution of trees showing signs of disturbance and the dating of individual deposits, determination of magnitudes of past events becomes possible as well. In his pioneering tree-ring work on debris flows at Mount Shasta (California), Hupp (1984) determined that events of small magnitudes have shorter recurrence intervals than do large-magnitude events. Strunk (1988) coupled tree-ring data with stratigraphic records (i.e. layer thickness) and presented rough volume estimates for episodic debris-flow events in the Italian Dolomites. On the basis of the extent of individual surges, amount of material deposited on the fan during specific events, seasonality of incidences, rainfall intensities and sedimentology of debris-flow deposits, Stoffel (2010) attributed magnitude classes to 62 events (AD 1863–2008; Figure 10B) originating in a small peri-glacial watershed of the Swiss Alps.

The application of tree-ring techniques in hydrogeomorphic research has recently been expanded to include debris floods in the Austrian (Mayer *et al.*, 2010) and hyperconcentrated flows (i.e. debris floods *sensu* Hungr *et al.*, 2001) in the Swiss Alps (Bollschweiler *et al.*, 2007). In the Spanish Central System, Ballesteros *et al.* (2010a, 2010b) documented flash flood signatures in riparian trees to determine the occurrence of past hydrogeomorphic events. It has been assumed in the past that the extent of disturbance by hydrogeomorphic processes to vegetation can be indicative of the energy of the water and of physical impact by materials transported by hydrogeomorphic processes (Johnson *et al.*, 2000). Based on this assumption and on data on flash-flood frequency (Ruiz *et al.*, 2010) and vertical distribution of impact scars on the stem surface, Ballesteros *et al.* (2011) were able to accurately reproduce flow heights in a two-dimensional hydraulic model and to derive data on stream power, flow velocity and discharge of past flash-flood events (Figure 11). Similarly, growth-ring series from injured and buried trees were used at high-elevation sites in the Mexican Volcanic Belt [(*c.* 3300–4000 m above sea level (a.s.l.)] to reconstruct the temporal occurrence and disturbance extent of past lahars from the Popocatépetl volcano (Bollschweiler *et al.*, 2010).

The reconstruction of past hydrogeomorphic events has proven crucial for a better understanding of spatial and temporal dynamics of torrential processes in small upland catchments and to complement existing anecdotal information.

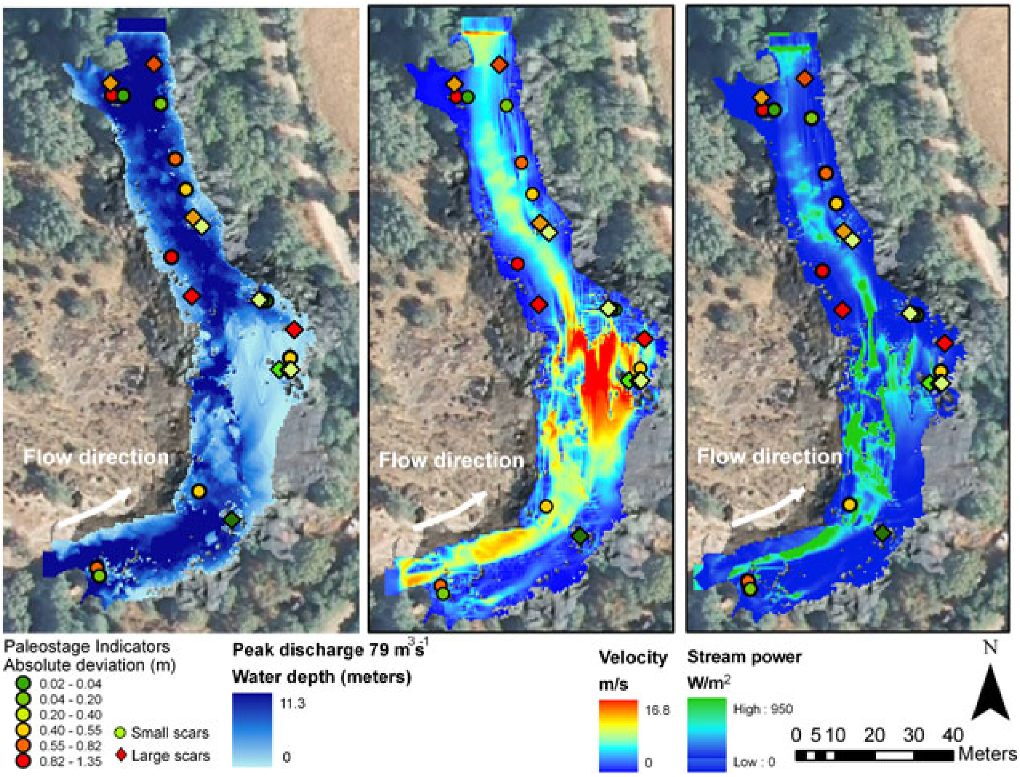

Figure 11. Deviation (in meters) between observed scar heights on tree trunks and modeled (two-dimensional hydraulic model Mike 21) flood stage. Scar data were used to calibrate peak discharge and to derive information on flow velocity and stream power of the 1997 flash-flood event at Venero Claro (Spanish Central System; adapted from Ballesteros *et al.*, 2011). *S* = small scar (<800 cm^2); *L* = large scar (≥800 cm^2). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Figure 12. Riparian plant communities affected by hydrogeomorphic processes are often distributed along gradients of flood frequency and depth, which are in turn closely related to the elevation and distance relative to the stream (flash-flood system, Venero Claro, Spain). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

While most of the earlier examples were from sites with exclusively hydrogeomorphic activity, it has been demonstrated that dendrogeomorphic work can also be performed on more complex fans where other geomorphic processes may occur simultaneously (e.g. rockfalls, snow avalanches; Stoffel *et al.*, 2006; Szymczak *et al.*, 2010; Kogelnig-Mayer *et al.*, in press).

Long-term Ecological Effects of Hydrogeomorphic Processes

The temporal occurrence, size and duration of hydrogeomorphic processes represent critical controls on riparian plant communities and their structure (Poff, 1996). It has been demonstrated that riparian plant communities on floodplains are often distributed along gradients of flood frequency and depth, which are in turn closely related to the elevation and distance relative to the stream (Figure 12; Sagers and Lyon, 1997; Merritt and Cooper, 2000). This approach, used in floodplains for hazard mapping (in terms of frequency and magnitude) can not be used on fans due to the unconfined nature of the stream channel. Normal backwater profile computational procedures are not applicable (Kellerhals and Church, 1990). In addition, when flooding begins, there is a possibility that the whole or major portions of the channel may avulse or shift laterally. Avulsions are usually much more severe hazards than normal flooding on fans (Kellerhals and Church, 1990).

The basic conical shape of the fan surface and the presence of multiple current or paleochannels will also result in complex vegetation patterns. Removal of vegetation and the creation of new surfaces for plant establishment is enhanced through scouring and deposition processes, channel migration, avulsion and channel narrowing (e.g. Everitt 1968; Burkham, 1972; Osterkamp and Costa, 1987; Friedman *et al.*, 1996; Dykaar and Wigington, 2000; Gurnell *et al.*, 2005). During high-power events swaths 20 m or wider are easily cleared by hydrogeomorphic processes and referred to as stand-level or site-level events (Figure 13A and 13B; Wilford *et al.*, 2005a). Low power events, by contrast, will not remove trees but spread sediment under a forest canopy (Figure 13C). Over time, this reshaping of channel geometry and fan topography will lead to the establishment of new growing sites as well as the maturation of some and the destruction of other vegetation communities, resulting in a mosaic of riparian vegetation patches with different structure and distinct successional stages (e.g. Cowles, 1899; Hack and Goodlett, 1960; Gregory *et al.*, 1991). The vegetation communities on fans thus reflect the complex interactions among vegetation, geomorphic processes and time (Johnson *et al.*, 2000).

The magnitude of physical stresses imposed by hydrogeomorphic processes and the frequency of hydrogeomorphic

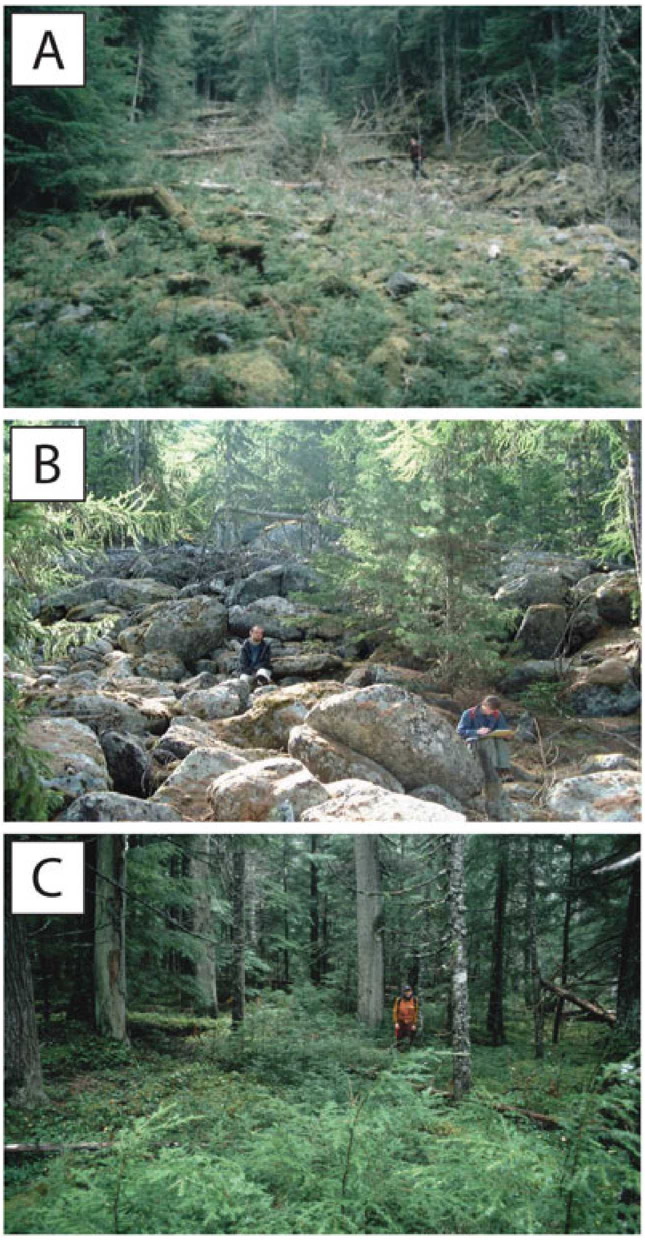

Figure 13. During high-power hydrogeomorphic events on fans swaths are cleared through forests. Depending on the size of the material deposited, surfaces are (A) recolonized quickly or (B) remain bare for decades (deposits of the 1922 Ritigraben debris flow). (C) Low power events on fans, by contrast, will not remove trees but spread sediment under a forest canopy, in this case providing a seedbed for a cohort of *Tsuga heterophylla*. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

events exert a strong selective control on species distribution and persistence (Bendix, 1999; Bendix and Hupp, 2000). The hydrogeomorphic riparian zone normally hosts the least flood-sensitive species (Hupp, 1988; Friedman *et al.*, 1996) or the youngest tree populations (Scott *et al.*, 1996; Hughes, 1997). Species less tolerant to hydrogeomorphic processes and older trees are usually located farther from the channel or scattered in the riparian zone as survivors from past events. In the case of large but infrequent hydrogeomorphic process activity heterogeneous, patchy legacies can be observed on the fan (Parsons *et al.*, 2006). Some riparian species will decrease in density because of removal by a flood, while others increased in density by post-flood recruitment or re-establishment. Post-disturbance biological responses are determined by the distribution, orientation, and size of disturbance patches and refuges in the riparian zone (Swanson *et al.*, 1998). Size of opening is particularly important as smaller openings will favor shade tolerant tree species (Coates and Burton, 1997). In confined mountain stream valleys, however, the nature and distribution of riparian species will not only be influenced by hydrogeomorphic processes, but also by enhanced moisture availability from hillslope runoff and groundwater discharge (Peters, 1995) and the coexistence of fluvial and hillslope processes, resulting in highly heterogeneous riparian vegetation communities.

Debris flows were demonstrated to be the main source of wood (58%) transported to and deposited in channels (Bigelow *et al.*, 2007) and on fans. The type and depth of material deposited on the fan as well as the intensity of scour produces differences in vegetative cover and species composition (Veblen and Ashton, 1978) and will determine the establishment of new vegetation on debris-flow deposits (Gecy and Wilson, 1989). For instance, vegetative resprouting from transported wood fragments have been reported to dominate early succession (Adams *et al.*, 1987) and Gecy and Wilson (1989) state that seedling establishment (Figure 13C) was highest on gravel and fine debris-flow deposits. While the mobilization of wood and the removal of riparian vegetation boosts ecosystem productivity in the areas where material is deposited, it has also been noted that major (negative) ecological and biotic effects can occur in the headwater streams after hydrogeomorphic process activity, with changed channel geometry, LWD being sparse in the transport zone of recent debris-flow streams and water temperatures being much higher than prior to events (Vannotte *et al.*, 1980; Stanford *et al.*, 1996; Cover *et al.*, 2010).

Hydrogeomorphic Processes and Vegetation: An Outlook and Conclusion

Riparian vegetation and hydrogeomorphic processes are intimately connected parts of upland catchment and fan environments. In this paper we have tried to illustrate the breadth of interactions and dependencies between vegetation and hydrogeomorphic processes and to provide a glimpse of recent results emerging from the various themes related to this vast research field. Nevertheless, more research is needed as to the understanding and quantification of the physical impact of hydrogeomorphic processes on riparian vegetation, particularly regarding ecophysiological drivers and wood anatomical reactions to this disturbance. One of the key implications of the vegetation–hydrogeomorphology linkages (i.e. vegetation on geomorphology as well as geomorphology on vegetation) is that trees provide an incredibly valuable means of reconstructing ecologic and hydrogeomorphic activity for the most crucial missing time scale (i.e. the last 150 years). Maintenance of forests and their associated debris in the hydrogeomorphic riparian zone is a critical element in maintaining fan stability within the natural range of variability dictated by the hydrogeomorphic process activity of its associated watershed. Both forest harvesting and lack of forest management (e.g. lack of post-wildfire rehabilitation) within a watershed can have a high likelihood of affecting the downstream fan. With an awareness of the total risk and appropriate accommodations for reducing them, forest harvesting and forest management will be able to continue in many watersheds with minimal, and potentially positive, effects.

Acknowledgements—M.S. acknowledges support from the EU-FP7 project ACQWA under contract no. GOCE-20290 and SFP-SRCE project RUFINE. The authors express their gratitude to editor-in-chief Stuart N. Lane as well as to David R. Butler and W. R. Osterkamp for insightful comments on an earlier version of this paper.

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