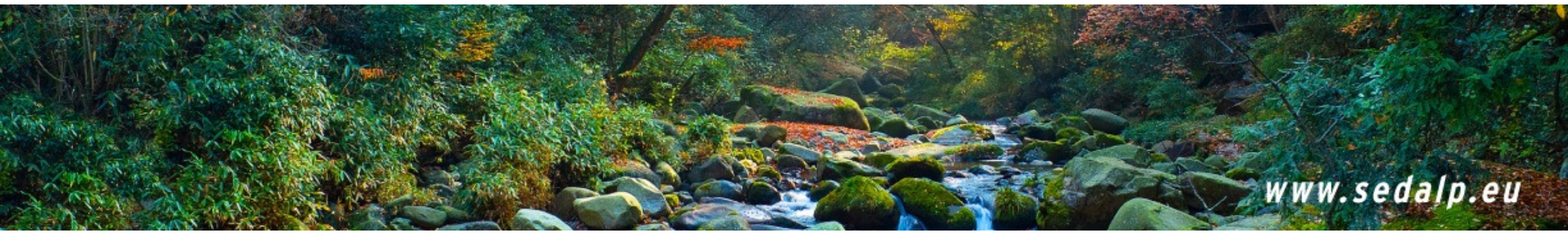

Report

Guidelines for assessing sediment dynamics in alpine basins and channel reaches

WP4 Basin-scale Sediment Dynamics

Action 4.1: Sediment sources

Action 4.2: Sediment connectivity

Action 4.3: Sediment yields

Action 4.4: Sediment cascades

Action 4.5: Historical analysis of basin responses

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May 29th, 2015

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1 Introduction

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1.1 The SedAlp project

The management of Alpine catchments requires the knowledge of sediment dynamics; it is related to natural hazards and environmental quality, it may contribute to the infilling of reservoirs, and it is useful for both investigating the need for and assessing the effectiveness of erosion-control measures. In natural catchments, and even more so in those affected by human impacts, sediment transfer is spatially and temporally discontinuous. The SedAlp project addresses issues of sediment continuity and Work Package 4 (WP4), specifically, aims at evaluating sediment transfer spatially (i.e., location of sediment sources, sinks, and pathways) and quantitatively at the catchment scale. This report collates SedAlp studies related to this topic, explains the respective methodology, and gives recommendations. While it does not present an approach to compare catchments with respect to their sediment dynamics, it outlines a conceptual and methodological framework that can be a useful basis towards such purposes.

Project partners who contribute to WP4 activities are:

- PP4: CNR-IRPI, Padova, Italy (with UNIMIB as subcontractor)
- PP5: Regione Piemonte, Italy
- PP6: LFU, Augsburg, Germany (with KU Eichstätt as subcontractor)
- PP7: Irstea Grenoble, France
- PP8: CNRS Lyon, France
- PP9: ULFGG Ljubljana, Slovenia
- PP11: BOKU, Vienna, Austria
- PP12: IZVRS, Slovenia
- PP13: AKL Klagenfurt, Austria

In section 1.2, the concept of sediment cascades is explained. Along the lines of this framework, section 1.3 provides a description of the outline of this report.

1.2 Sediment cascades and connectivity

Sediment transfer through a mountain catchment can be regarded as a cascading system (Figure 1-1). Hillslopes and channel reaches represent elementary landscape units between which a wide variety of geomorphic processes transfers sediment (e.g., slope wash, rill erosion, landslides, debris flows and fluvial processes). These processes erode or remobilize sediments from sediment sources, i.e. areas on hillslopes or within the channel network where sediments are generated or stored. Adjacent landforms, for example a hillslope and a channel reach, are coupled if sediment delivery to the latter takes place, either by sediment transfer from the hillslope to the channel, or by bank undercutting and bank failure. However, it is not uncommon that hillslopes are decoupled from the channel network because sediments are deposited within the hillslope, in storage landforms, e.g., on the footslope, or on a floodplain bordering the channel. The same concept can be applied to adjacent channel reaches; they can be decoupled where (and when) the transport capacity is too low, for example, in (natural) low-gradient sections or due to artificial structures. The transfer of sediment by multiple processes links sediment sources to storage landforms and the catchment outlet, thus forming sediment cascades.

All coupling relationships within a catchment depend among others on topography, the spatial configuration of sediment sources and sinks, sediment properties, and the type and magnitude-frequency of processes that drive sediment transfer. Coupling is subject to change, for example the construction or removal of dams, or the formation of new sediment sources following a landslide. Such changes may affect sediment transfer on a longer timescale, so that the current state of a system is the product of both current conditions and former states of the system; this includes both the impacts of historical land-use change and the heritage of the Pleistocene ice ages. While the latter can be studied using geomorphological mapping, historical data (maps, aerial photos) allow for the investigation of more recent geomorphic and landcover changes.

The degree to which a catchment is coupled is termed (sediment) connectivity. Geomorphology has related this system property to the relation of erosion within and sediment transfer out of the catchment, and with its sensitivity to change (Brunsden 2001; Harvey 2001; Fryirs 2013).

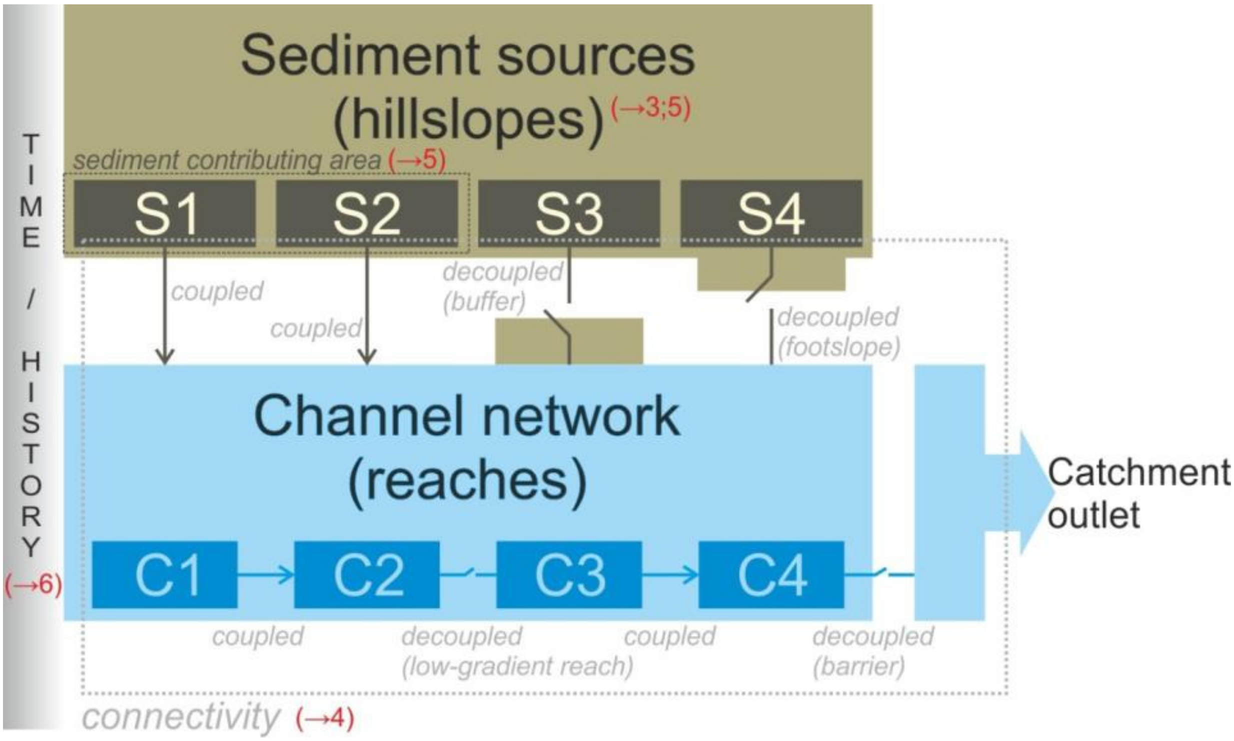

Figure 1-1: The cascading system of sediment transfers in a torrent catchment (see text for more detailed explanations). Sediment sources on hillslopes are coupled to, or decoupled from the channel network; the sum of coupled hillslope sources forms the sediment contributing area. Connectivity addresses the overall coupling state of a catchment, including also the (de-)coupling of reaches within the channel network. System structure and connectivity are subject to changes ("Time / History"). Red numbers indicate the chapter(s) that deal with the respective topic. Source: Tobias Heckmann.

1.3 Report outline

The structure of this report thematically follows the concept of sediment cascades (see references to chapters in Figure 1-1). Many of the methods presented require digital data, for example high-resolution Digital Elevation Models (DEMs), orthophotos and other remote sensing products. Chapter 2 represents a collection of such data and their acquisition. Chapter 3 then deals with sediment sources and their identification using geomorphological mapping, digital orthophotos (visible light and infrared) and DEM analysis. Chapter 4 focuses on the assessment of geomorphic coupling at the catchment scale and introduces an integrated index of sediment connectivity that is based on a high-resolution DEM. As a logical follow-up, chapter 5 deals with the assessment of sediment delivery and geomorphic changes on different spatial scales (local to catchment) and chapter 6 focuses on the importance of considering the time variability of system structure and properties (e.g., connectivity) for predicting geomorphic trajectories associated with global and local changes.

2 Preparing an overview of the catchment

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Assessing sediment dynamics of alpine basins can be made using a great variety of data, depending on the specific objective and the spatiotemporal framework of the study. A compilation of data used in WP4 of the SedAlp project is proposed in Table 2-1. This table gives references of case studies where more specific information can be found about the sources and the nature of these data, as well as the data processing methods that can be implemented. The emerging pattern from this compilation clearly shows that the best way to achieve a comprehensive understanding of alpine basin sediment cascades relies upon integrating approaches based on the combination of field observations and remote sensing data. The SedAlp project clearly illustrates the increasing use of high-resolution LiDAR derived topographic data. Examples of applications of such data are provided for each thematic field of the WP4, and were used in 7 different case studies.

Table 2-1: Inventory of data used for basin-scale sediment dynamics assessment during the SedAlp project; numbers refer to case studies presented in the annex of the report

	Sediment Sources	Sediment Connectivity	Sediment Yield	Historical Analysis
Historical aerial photos	8.2	8.2	8.2	8.7
Historical maps				8.3
Historical archives				8.3
Airborne LiDAR survey	8.1-8.2-8.3-8.6	8.2-8.3-9.1	8.1-8.4-8.6	8.7
Terrestrial LiDAR survey	8.1		8.1	
Satellite imagery	8.5			
Digital orthophotos	8.3-8.5-9.2	8.2-8.3		8.7
Field surveys	8.2	8.3	8.2	8.2
Stream network geodatabase		9.2		
Low-resolution DEM (>10 m)		9.1-9.2	8.8	
Land cover maps		9.1	8.4-8.8	
Hydrometeorological data	8.3		8.3-8.4-8.8	
Sediment transport data			8.4-8.8	

It is important to start all work concerning sediment dynamics with some overview in the beginning. In this first step, it is important to gain some (first) idea of the whole catchment, potentially main areas concerning sediment balance, the most relevant processes andto screen the existing data. Of course, these first assessments have to be reviewed after all following steps.

For the further assessment procedure it is essential to document all relevant steps and especially important decisions. By this it is to ensure, that later on it is possible to follow the whole assessment process and to prove the results. Only by a sufficient documentation a high quality of the assessment can be ensured and it is a real benefit for practical use.

3 Identification and delineation of sediment sources

Francesco Brardinoni, University of Milano-Bicocca

3.1 Introduction

A key methodological component for assessing geomorphic activity and hazard potential in Alpine mountain drainage basins is the identification and delineation of sediment sources. These are sites in which sediment is produced directly from bedrock (e.g., rockfalls and rock avalanches from valley walls), or detached from relict sedimentary landforms (e.g., debris slides from moraine bodies and bank collapses from fluvial terraces), and then is transferred downslope (or downstream) through discrete mass-wasting processes or via chronic surficial erosion.

Sediment sources constitute the triggering sites of the sediment cascade (Allison and Burt, 2010) and distribute sediment supply across landscape components. In so doing, their effects on the landscape may be amplified by peculiar process-disturbance sequences (Nakamura et al., 2000), for example this is the case of a debris slide that entering a steep low-order stream transforms into a debris flow and propagates sediment evacuation all the way to the basin outlet. The spatial and temporal variability of sediment sources in Alpine basins is the result of the complex interactions between hydro-meteorological forcing (extrinsic thresholds), sediment recharge mechanisms (intrinsic thresholds) (Schumm, 1973; Bovis and Jakob, 1999), land-use dynamics (Sidle and Ochiai, 2006), and boundary conditions including lithology and Quaternary sedimentary cover (Stirling and Slaymaker, 2009; Brardinoni et al., 2012).

The ability to quantify sediment supply to the Alpine channel network has important implications for understanding sediment dynamics hence for undertaking suitable strategies of sediment management. Specifically, the spatial and temporal distribution of sediment delivery to streams controls in-channel storage and channel bed texture, which in turn modulate channel morphology (Montgomery and Buffington, 1997), flow resistance (Hassan et al., 2005), bedload transport (Lisle and Church, 2002), as well as in-channel habitat conditions (Church, 2002).

In recognition of the impacts of colluvial disturbance on channel morphodynamics, mountain streams are classified on the basis of the structural arrangement of the bed sediment into: colluvial (water flows on colluvial valley fills), alluvial (water flows on alluvial morphological channel units such as step pools, plane beds, and riffle pools) (Montgomery and Buffington, 1997), and semi-alluvial channels (Halwas and Church, 2002). Semi-alluvial channels are considered as transitional typologies in which coarse bed material is mobilized only by infrequent, extreme floods (e.g., recurrence interval greater than 50 years). This classification scheme has been developed further for formerly glaciated mountain settings (Brardinoni and Hassan, 2006; Weekes et al., 2012) in which the inherited glacial topography (e.g., cirques, hanging valleys, valleys steps, and troughs) (Figure 3-1) imposes peculiar configurations of hillslope-channel geomorphic coupling (*sensu* Brunsden and Thornes, 1979). Accordingly, colluvial channels are classified into subcategories depending on how these are spatially connected to landslides and debris flows: source and sink colluvial channels (Figure 3-1). Source colluvial channels are steep, first- and second-order streams, typically located on valley walls and cirque walls. They are longitudinally scoured by debris flows and may receive lateral secondary inputs (e.g., debris slides and avalanches) from adjacent hillslopes (Figure 3-2a). Sink colluvial channels are steep second- and higher-order streams, flowing along valley steps (i.e., VS zone in Figure 3-1a) and glacial troughs whose floor is not wide enough to disconnect the channel main stem from lateral colluvial inputs (i.e., GT zone in Figure 3-1a). They receive exclusively lateral colluvial inputs (as opposed to colluvial inputs from upstream), including debris flows at tributary junctions (Figure 3-2b). In extreme rainfall events sink colluvial channels may transform temporarily into source colluvial one, and experience debris-flow scouring.

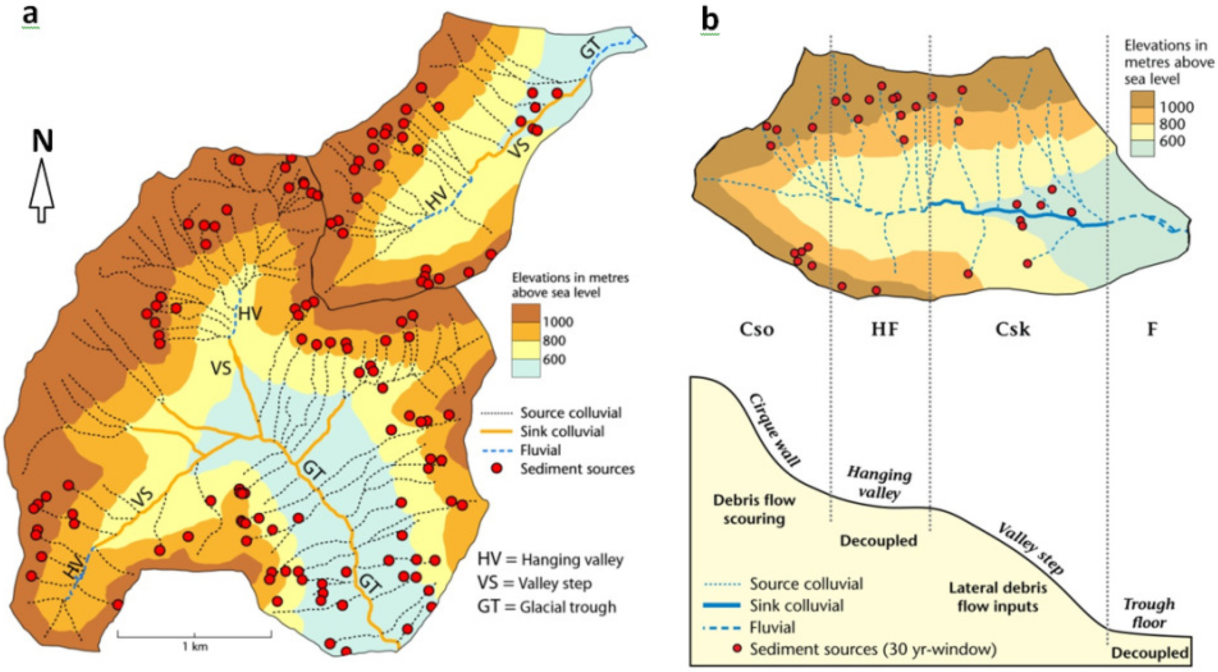

Figure 3-1: Formerly glaciated mountain drainage basins: a) contour map showing the spatial distribution of colluvial and alluvial channels in relation to sediment sources (modified from Brardinoni and Hassan (2006)); and b) schematic representation combining the plan view and the longitudinal profile. Cso = source colluvial; HF = hanging fluvial; Csk = sink colluvial; F = distal fluvial. Red circles indicate the initiation sites of landslides and debris flows inventoried in a 30-year time window from aerial photo interpretation and complementary fieldwork (modified from Brardinoni et al. (2009)).

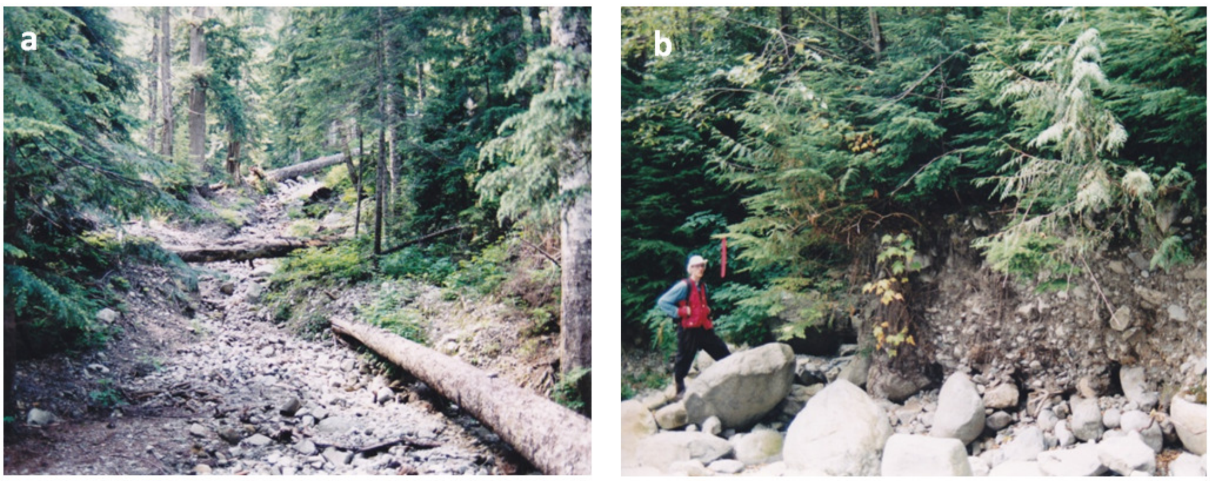

Figure 3-2: Examples of: (a) source colluvial channel; and (b) sink colluvial channels. Note lateral channel levees in panel (a) consequence of channel longitudinal debris-flow scouring (channel width = 3.70 m). In panel (b) the person is standing on the bed of a sink colluvial channel at the confluence with a source colluvial channel. To the left, note the presence of the truncated debris-flow fan testifying to the lateral colluvial inputs that the sink channel receives at tributary junctions. Photos by F. Brardinoni.

In the context of WP4, the identification and delineation of sediment sources has involved: (i) the characterization of source-to-sink colluvial pathways in relation to the spatial distribution of moraines and rock glaciers in the high mountain terrain of the Saldur River basin (Italy, PP4); (ii) the evaluation of sediment source activation and delivery potential to stream channels in relation to different hydro-meteorological scenarios in the Maira River basin (Italy, PP5); (iii) the detection of sediment sources through repeat terrestrial and/or airborne laser scanning in the debris flow-dominated basins of Gadria-Strimm, Moscardo (Italy, PP4), and Réal (France, PP7); and (iv) the semi-automated detection of active surficial erosion sites in the Bléone River Basin (France, PP7).

3.2 Methods

The choice of the methodology for mapping sediment sources is tightly related to the spatial and temporal scales of interest, as well as to the time and the financial resources available for pursuing specific research or management objectives. In Table 3.1 are reported the set of methods employed in the SedAlp case studies. Undoubtedly, the most versatile method in terms of target spatial and temporal scale is the compilation of multitemporal sediment source inventories (Figure 3-3). This is performed via stereographic inspection of sequential photosets. Each sediment source is classified in terms of: (i) photoset of first detection; (ii) state of activity through sequential photosets; (iii) dominant type of slope movement; (iv) morphology at initiation site; and (v) morphology at deposition site (Box 3.1). The last attribute is extremely important in that it allows assigning to each sediment source a sediment delivery potential to perennial streams, as detailed in Box 3.2. Typical obstacles to sediment delivery potential in Alpine mountain settings include hanging valley floors (e.g., either structurally- or glacially-derived), moraines, glaciers, rock glaciers, alluvial fans, debris cones, fluvial terraces, floodplains, lakes and artificial reservoirs, check-dams and similar engineering structures.

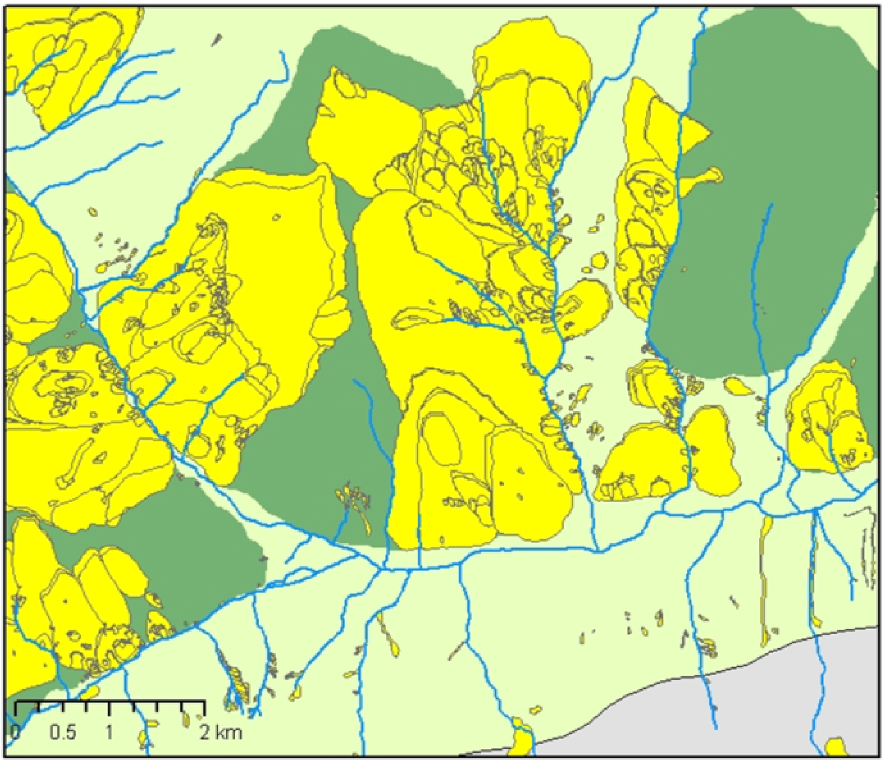

Figure 3-3: Detail of a multitemporal sediment source inventory map in the Noce River basin (Autonomous Province of Trento, Italy). The inventory was compiled through interpretation of historical aerial photosets and delineated on a high resolution (2m grid) LiDAR-derived DTM. Yellow polygons indicate deep-seated landslides and colluvial sediment sources. Grey and light green indicate respectively intrusive (tonalite) and metamorphic (paragneiss and orthogneiss) lithologies.

BOX 3.1. Example of Classification Scheme for Colluvial Sediment Sources

MOVEMENT TYPE: shallow and deep-seated failures including slides, flows, avalanches, slumps, falls, and topples

MORPHOLOGY AT INITIATION POSITION (OR INITIATION SITE)

<u>UNCHANNELED TOPOGRAPHY</u>:	(os) open slope (nearly planar slope) (sw) subvertical wall (ef) escarpment face (break in slope along the valley side) (m) moraine (kt) kame terrace (rg) rock glacier (gf) glacier front
<u>SEASONAL CHANNELS</u>:	(gh) gully headwall (hillslope-channel transition, hollow) (gs) gully sidewall (gc) gully channel
<u>PERENNIAL CHANNELS</u>:	(rb) river bank (ft) fluvial terrace

SEDIMENT DELIVERY SITE

<u>UNCHANNELED TOPOGRAPHY</u>: (on-site, low deliverability to perennial streams)	(s) slope (ts) talus slope (co) talus cone (rg) rock glacier (m) moraine (kt) kame terrace (glaciofluvial)
<u>SEASONAL CHANNELS & TRANSITIONS</u>: (moderate deliverability to perennial streams)	(f) fan (gc) gully channel (ephemeral channel) (cg) connected gully channel (directly connected to a perennial channel) (r) road (ft) fluvial terrace (fp) floodplain (lk) lake or reservoir (permanent freshwater sink)
<u>PERENNIAL CHANNELS</u>: (high deliverability to perennial streams)	(mc) main channel (river mainstem) (ct) connected tributary (stream connected to the river mainstem) (ut) unconnected tributary (connected to another tributary and not directly connected to the river mainstem)

BOX 3.2. Example of Classification for Sediment Delivery Potential (or Deliverability)

Ranked from lowest (1) to highest (4) deliverability:

(1) on-site:	lowest delivery potential; e.g., open-slope in close proximity to source; not near any drainage line.
(2) gully channel:	moderately to steeply sloping ephemeral/seasonal channel (colluvial) confined in a steep-sided ravine. Delivery potential is highly dependent on the status of gully sediment recharge and as such it is subject to decade-to-century fluctuations.
(3) tributary channel:	low-gradient perennial channel which drains directly to the (semialluvial) river mainstem draining a valley. Delivery potential is subject to seasonal fluctuations.
(4) main channel: (alluvial)	active bed of the river mainstem. Delivery potential is about homogeneous.

Limitations associated with aerial photo interpretation are especially high in densely forested terrain in which a visibility threshold for landslide identification must be derived via complementary fieldwork. In particular, the forest canopy hides a population of not visible sediment sources (Robison et al., 1999; Turner et al., 2010), that can account for as much as 30% of the total volume of debris mobilized (Brardinoni et al., 2003) (Figure 3-2). Fieldwork is also conducted for estimating the thickness of material mobilized. Specifically, field measurements on sediment source geometry are instrumental to derive sediment source area-volume relations (Guzzetti et al., 2009; Larsen et al., 2010) that allow to convert each sediment source area (i.e., polygon) mapped from aerial photo interpretation into a volume of mobilized/deposited material. The integration of volumes enables to constrain envelopes of colluvial sediment flux across single drainage basins (Brardinoni et al., 2009; Guzzetti et al., 2009) and across regions (Brardinoni et al., 2012). For completeness, we report a sample chart for field data collection on sediment sources (Box 3.3). The temporal resolution of the inventory is imposed by the time interval occurring between available historical photosets, which typically spans from 5 to 10 years. This methodology, which in this contribution has been employed by PP4 and PP5, is especially well suited for detecting discrete slope movements such as debris slides and debris flows but cannot be used for change detection of areas undergoing chronic surficial erosion.

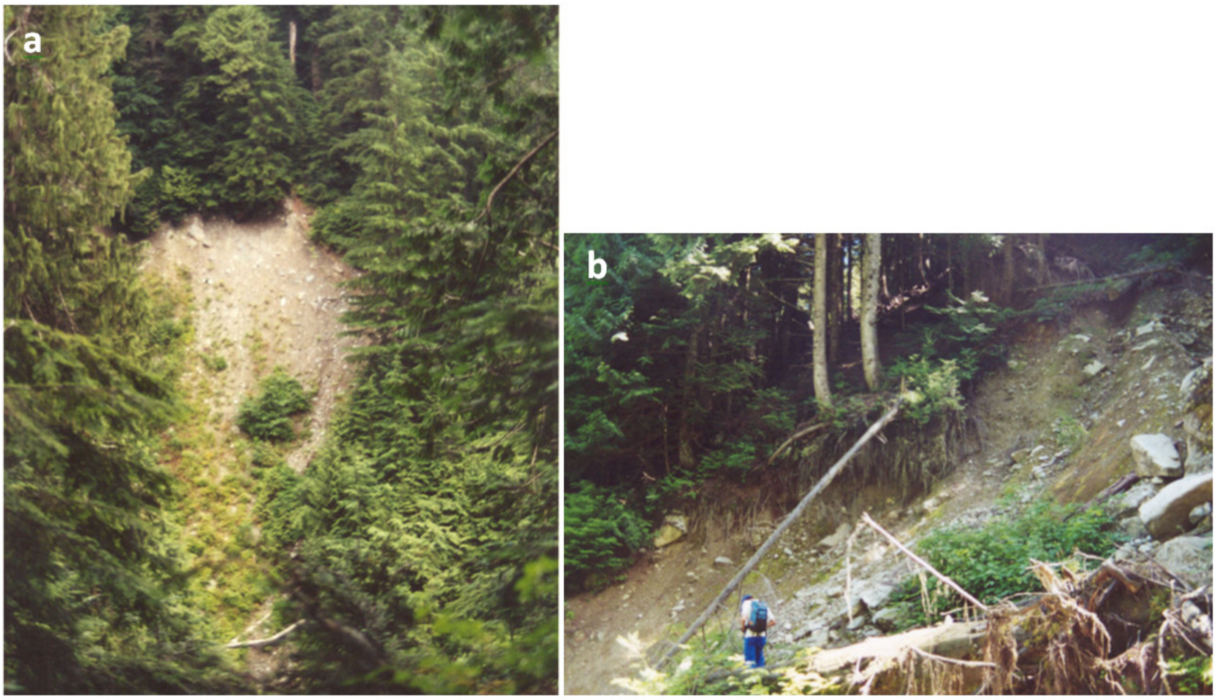

Figure 3-4: Sediment sources not visible from aerial photographs: (a) debris slide at open-slope location (headscarp width = 12 m); (b) debris slide originating at gully sidewall. Photos by F. Brardinoni.

During the last decade, the development of airborne LiDAR and Terrestrial Laser Scanning (ALS and TLS, respectively) has allowed to increase the spatial resolution of topographic change to the decimetric level (Theule et al., 2012; Blasone et al., 2014). Specifically, repeated scans allow to map the dynamic evolution of sediment sources, transport zones, and the corresponding deposition zones. In so doing they provide a reliable tool for extracting sediment yields related not only to discrete slope failures but also to chronic surficial erosion, as it has been shown in debris-flow dominated basins of the French (PP7) and the Italian Alps (PP4). More recently, oblique, close-range photogrammetry, termed structure-from-motion (Westoby et al., 2012), promises to obtain high resolution DTMs at significantly lower costs in comparison to LiDAR or TLS based surveys, provided that one does not work in forested terrain. A description of this last methodology is beyond the scope of the present report, also in consideration that it has not been applied by any Project Partner. For a thorough review on the techniques available to compile landslide inventories the reader should refer to Guzzetti et al. (2012).

BOX 3.3. Template for Field Data Collection on Colluvial Sediment Sources

Failure Type: (e.g., slide, flow, avalanche, fall)

Land cover: (e.g., grass, bushes, trees)

Morphological position at initiation: (e.g., open slope, escarpment face, gully headwall, gully sidewall, stream bank, rock glacier front, moraine ridge)

Headscarp height* (cm): Seepage from headscarp? Y/N

Regolith depth (cm):

Type of material mobilized*: (e.g., till, colluvium, bedrock)

Texture (clay, silt, sand, gravel, rubble, boulder)*:

Average sidescarp height (cm):

Initial scar width (m): Average scar width (m):

Scar length (m) a) initiation zone (till where sidescarps are visible):

b) transport zone: c) deposition zone:

Distance from ridge top (or from major change in slope) (m):

Slope upslope from failure (percent):

Scar slope (%) a) initiation zone: b) transport zone: c) deposition zone:

Scar cross section: (straight, concave, convex, complex)

Scar longitudinal profile: (straight, concave, convex, complex)

Nature of slip-plane*:

Sediment delivery site: (e.g., perennial stream, gully, talus slope, fan, moraine, rock glacier)

Vegetation on scar*: a) quality (grass, saplings, trees)

b) diameter (cores or sections)

Estimated age of failure: Visible from aerial photos: Y/N

Similar events or signs of instability?

*Need for close-range photographs

Table 3-1: Summary information of the methods adopted in this report for the identification and quantification of sediment sources.

Survey method	Spatial scale	Temporal scale	Limitations
Expert-based stereographic examination of sequential photosets Automated detection on orthophotos and satellite imagery	from single hillslopes to the regional scale (e.g., 10^3 km^2).	up to several decades (e.g., 70 years)	- some degree of subjectivity in the expert-based case - forest cover imposes a threshold on the size of visible sediment sources - availability of historical aerial photos/imagery determines the temporal resolution - the automated procedure does not allow to classify sediment sources in terms of typology and morphology
Terrestrial laser scanning	from the plot scale to the small drainage basin scale (e.g., 10 km^2)	seasonal to annual and decadal	- the time window is typically limited by the time of the first survey performed - only accessible areas can be surveyed
Airborne LiDAR	from the small drainage basin up to the regional scale (e.g., 10^3 km^2)	seasonal to annual and decadal	- the time window is typically limited by the time of the first survey performed - High costs typically prevent to run seasonal surveys.

3.3 Results and interpretation

Sediment sources in mountain drainage basins may be subdivided into two major categories, sources associated with surficial chronic erosion that in extreme cases produces badland-like morphologies and discrete sources in time, related to mass movement events. In turn, mass movements can be classified in relation to the velocity of the failure type and the mobility of the detached material (Cruden and Varnes, 1996). In the Alpine context of the estimation of sediment production and delivery to stream channels, mass wasting-related sediment sources can be classified in a further simplified way including full-mobility failures (e.g., rock falls, debris slides, debris flows), and slow, partial-mobility failures such as deep-seated rotational and translational landslides (e.g., Brardinoni et al., 2013). For the former typology, it is possible to evaluate volumetric sediment yields across a wide range of temporal and spatial scales via delineation of initiation, transport and deposition zones and through field estimation of eroded/deposited depths. For the second source type, which generally presents a well-defined source niche, but an unclear and poorly-developed deposition zone, the associated depth of the mobilized material and the discrete travel distances cannot be estimated in the field unambiguously, and therefore quantifying current rates of movements would imply detailed and costly monitoring efforts (e.g., Colesanti and Wasowski, 2006). Efforts that nevertheless would remain limited to single, site-specific case studies and that would not allow extrapolations at the drainage basin or at the regional scales.

The five case studies of interest reflect variability associated with: (i) the different nature of the sediment sources that dominate different study basins across the Alps; (ii) the availability and resolution of historical (numerical and/or graphical) data; (iii) the resolution of single or sequential DTMs; and (iv) the specific goals that motivated each work. In this sense, the Saldur River (PP4, case study 8.2, see Annex) and the Maira River (PP5, study 8.3) case studies represent basin-scale inventories conducted at a similar spatial resolution. In the Maira River basin, the authors compiled a sediment source inventory including all those sediment sources that were considered capable of delivering material to the drainage network. Sediment sources included not only areas undergoing surficial erosion, and rapid full-mobility and slow partial-mobility slope failures, but also landforms that could potentially act as sediment sources (i.e., moraines, rock glaciers, and talus slopes) (Figure 3-5). Potentially active sediment sources, which include currently quiescent landslides, are considered capable of delivering material to the drainage network in dependence of three broadly-defined scenarios of meteorological forcing labeled as frequent, occasional and rare, associated with return periods of respectively 2, 20 and 50 years. The study does not involve direct measurements of sediment volumes and relies on volumetric relations taken from the literature.

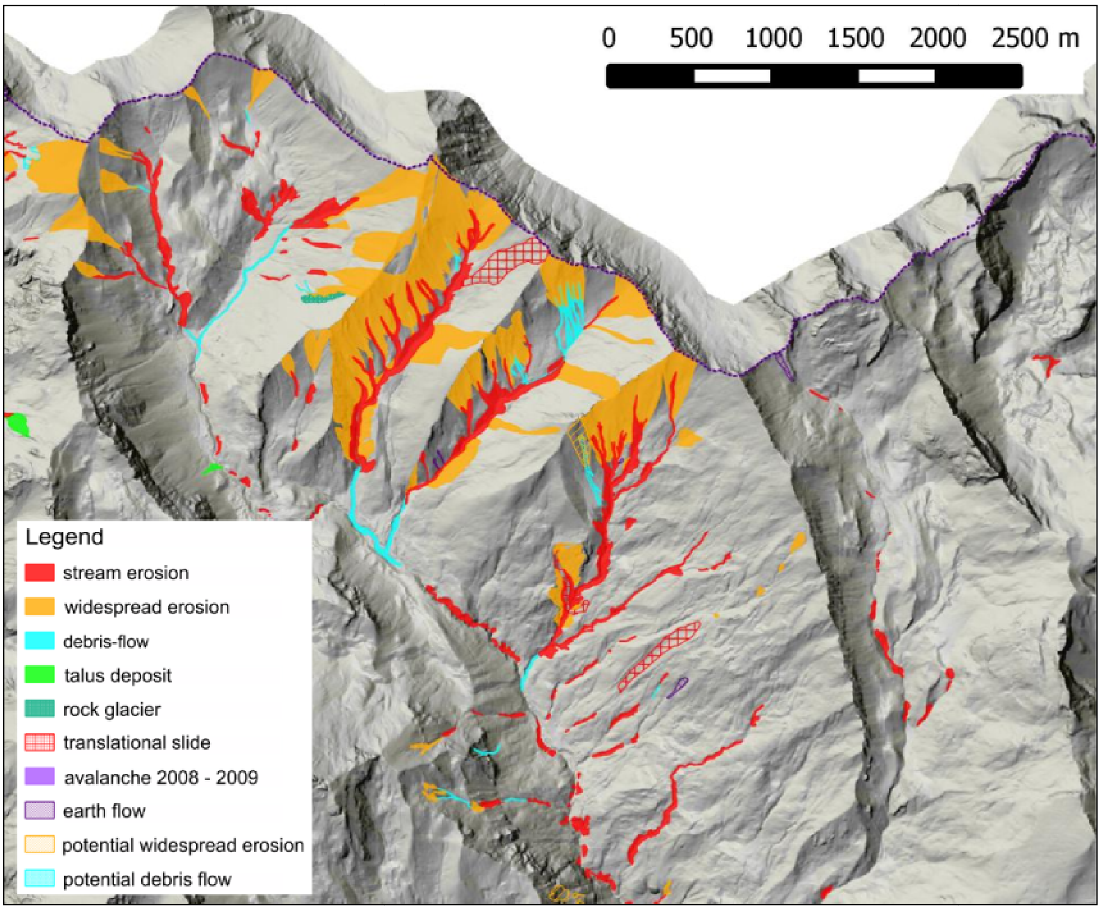

Figure 3-5: Example of the sediment source mapping conducted in the Maira River basin. Figure taken from case study 8.3 (Annex).

The Saldur River case study deals with a multi-temporal inventory of sediment sources that focuses on areas of chronic surficial erosion and rapid, full-mobility slope failures. The inventory, which is the result of stereographic inspection of sequential photosets and fieldwork, has recorded 998 rapid, full-mobility slope failures that have mobilized an estimated volume of 997,000 m^3 of colluvial material. This volume corresponds to an average rate of colluvial sediment yield equal to 1.41 m^3/ha/yr within a 75-year time window. In comparison with the Maira River study, this work does not consider potential sediment sources, but identifies slow (e.g., active rock glacier conveyor belts) and fast (e.g., debris flows) source-to sink colluvial pathways and estimates the degree of sediment redistribution across key landscape components characterized by different transport regimes. Accordingly in the Saldur River basin, 39% of the sediment mobilized has been delivered to the ephemeral-colluvial channel network (e.g., gullies and ravines), 22% has remained on unchannelled topography including hillslopes, moraines and rock glaciers, 20% has reached the perennial channel network, and 19% has made it to coarse-textured sedimentary linkages such as debris-flow fans and talus cones. Particular emphasis is placed on the conditioning that the spatial distribution of moraines and rock glaciers exerts on the distribution of active sediment sources hence on the general spatial pattern of sediment connectivity. In this sense, the case of the Upper Saldur basin is instructive (Figure 3-6b) in that it was observed how moraines and rock glaciers are located preferentially on the western valley side. The spatial and temporal resolution of the methodology used in this case study did not allow to constrain volumetric estimates of erosion for the 697 polygons (0.51 km^2) classified as sediment sources undergoing chronic surficial erosion. In this context, the Bléone River case study (PP7, see Annex 8.5) is complementary in that it tackles specifically areas dominated by distributed surficial erosion (Figure 3-7).

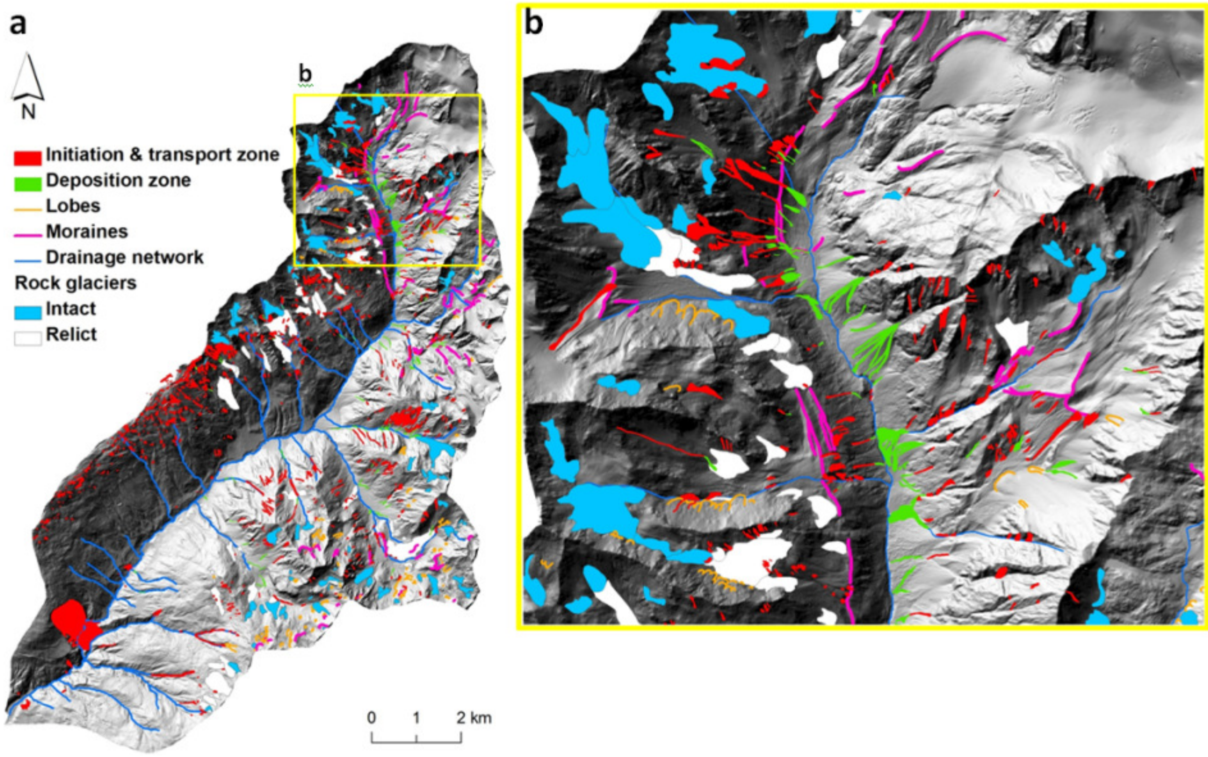

Figure 3-6: Mapping of sediment sources, glacial, and periglacial depositional landforms in the Saldur River Basin. (b) Close-up view of the Upper Saldur River basin in which are apparent differences in the spatial distribution of mapped landforms and deposition zones between the two valley sides. Figure modified from case study 8.2 (Annex).

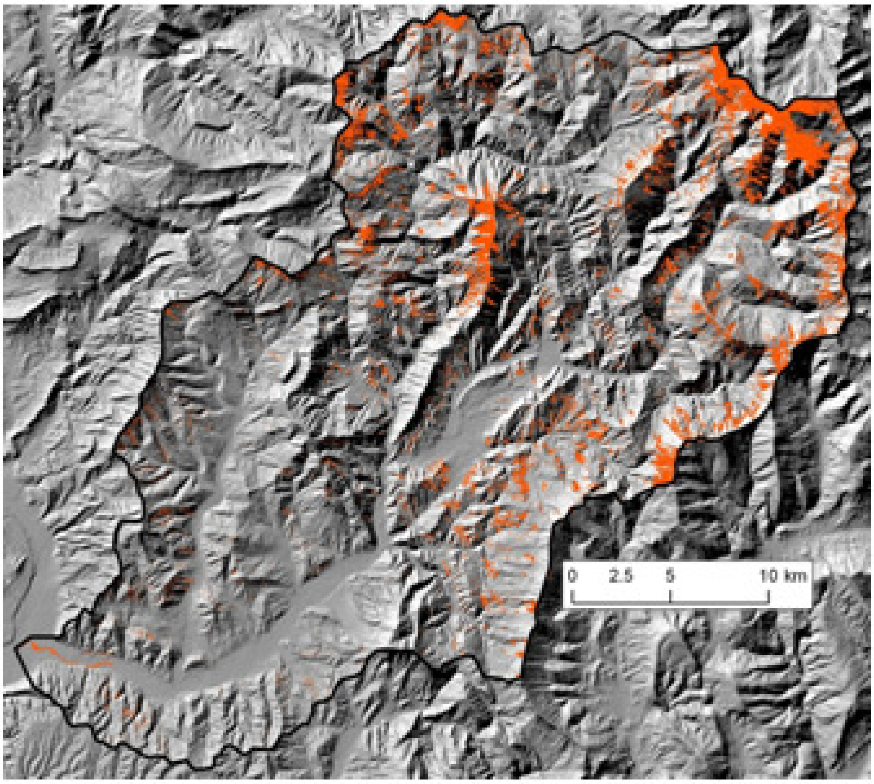

Figure 3-7: Map of the Bléone River basin showing automatically-detected active erosion patches (orange polygons) in 2001-2009 period. Figure taken from case study 8.5 (Annex).

In the Bléone River basin, the authors implement an automated procedure that by integrating infra-red aerial orthophotos and satellite (Landsat 7 ETM+) imagery is able to identify and delineate, across large spatial scales, areas undergoing diffused surficial erosion. An independent expert classification conducted on 500 random points and compared with the automated outcome yielded a 96% success rate, indicating the high reliability of this automated procedure. At the moment, the methodology does not allow to distinguish between different sediment source typologies (e.g., debris slides/flows occurring within a given identified erosion patch).

The three remaining case studies (Gadria-Strimm (PP4, Annex 8.1), Moscardo (PP4, Annex 8.1), and Réal (PP7, Annex 8.6)) are concerned with topographic change detection through repeat (terrestrial or airborne) laser scanning in debris flow-dominated drainage basins. They are characterized by notably higher spatial resolution (submetric DTMs) and much smaller uncertainty in comparison with the case studies involving the use of aerial photography. These improvements, which enable to decipher geomorphic dynamics at an unprecedented degree of resolution, are achieved at the expense of the spatial and temporal scales of interest, which are respectively smaller than 10 km^2 and range from seasonal (or annual) to decadal. Accordingly, the main limitation of this approach arises from the fact that reduced spatial and temporal scales do not allow to capture adequately high-magnitude low-frequency events. The reduced time scales (3-5 years) pose also a serious question on how representative are the sediment yields derived from similar surveys. It follows that any inference on dominant source-to-sink patterns and trajectories of postglacial landscape evolution should be made with extreme care. The identification and delineation of sediment sources is indirect: it is inferred from DoD (DEM of Difference) analysis (e.g., Figure 3-8).

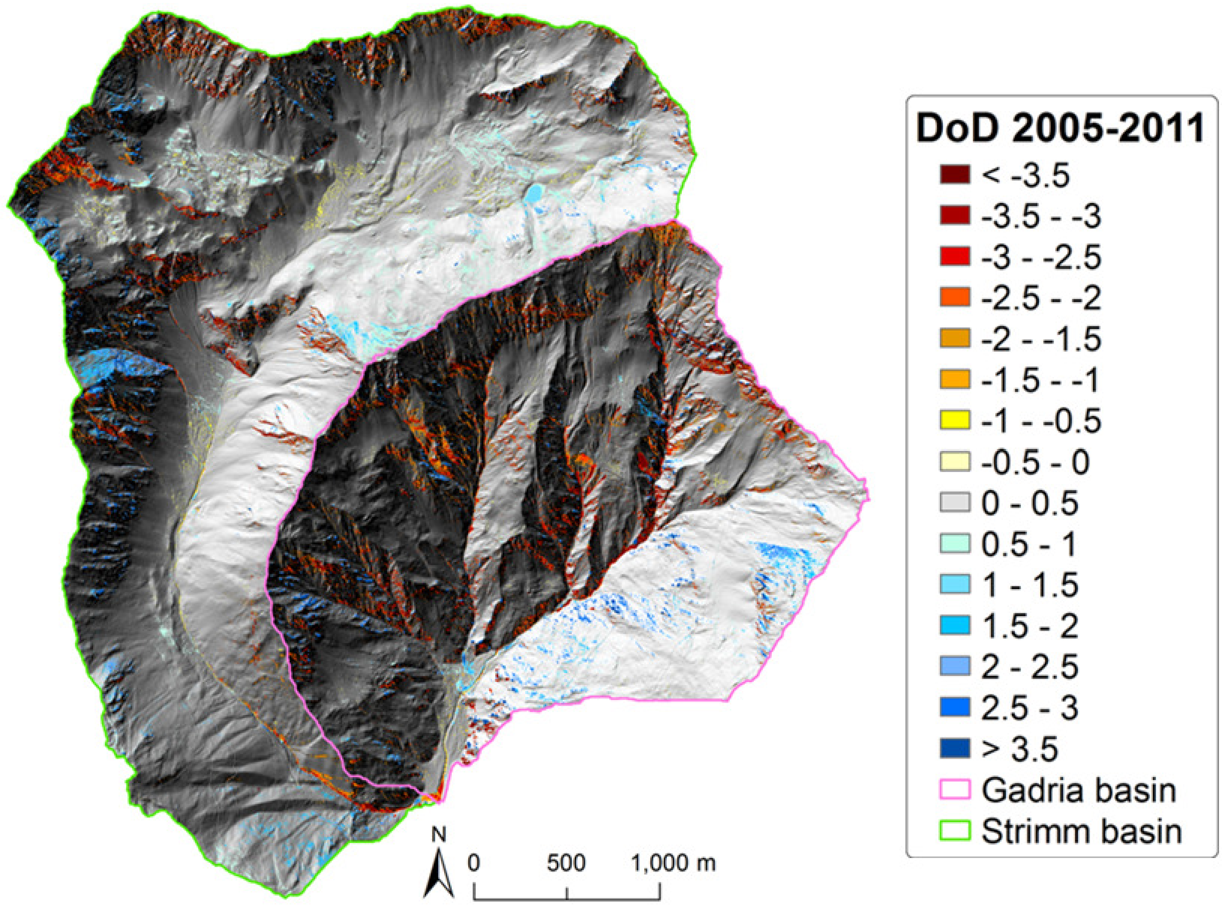

Figure 3-8: DEM of difference (DoD) map expressing the change in elevation (in m) in the 2005-2011 time window of the Gadria-Strimm system, Eastern Italian Alps. Figure taken from case study 8.1 (Annex).

3.3 Recommendations and future work

The identification and delineation of sediment sources for quantifying sediment dynamics and propose sustainable management strategies are difficult tasks to pursue in Alpine drainage basins. This is mainly a consequence of difficult access and ground cover conditions (e.g., vegetation and snow) that can limit visibility. In this chapter we have reviewed some of the currently-available methods for identifying and mapping sediment sources. In principle, we reckon there is no intrinsically better or worse method for compiling the ideal sediment source inventory. Rather, we think that any methodological choice depends on the specific objectives addressed (e.g., static vs multitemporal assessment; numbers vs volumetric estimates) and on the typology of sediment sources considered (e.g., slope failures vs surficial erosion), which in turn dictate the required spatial and temporal resolutions. For example, techniques involving the use of sequential aerial photographs and satellite imagery are well-suited for working over large drainage basins and across regions dominated by discrete mass-wasting processes. By contrast, techniques involving repeat terrestrial or airborne laser scanning are capable of resolving more complex geomorphic dynamics such as the headward migration of landslide scarps, the emplacement (or fluvial reworking) of in-channel debris-flow deposits, the amplification of existing bank failures. On this premise, we think that the best and more versatile solution would arise from adopting an integrated approach between airphoto-based and laser-scanning techniques. The former would provide an overall mapping of historically active (e.g., Saldur River basin) and potentially unstable sites under constrained hydro-meteorological forcing conditions (e.g., Maira River basin). The identification and delineation procedures could be manual (e.g., Saldur and Maira River basins) or automated (e.g., Bléone River basin), depending on photo quality and size of the study area. This first step when coupled to fieldwork and repeated across sequential photosets (e.g., Saldur River basin) can provide not only first-order estimates of colluvial sediment flux across basins and regions, but also can identify particularly critical sub-areas that merit higher resolution work, as it is the case of steep Alpine basins undergoing chronic surficial erosion and/or intense debris flow activity (e.g., Gadria-Strimm and Réal catchments). Future work should aim at a better integration (ideally a process-based one) of the methodologies encompassed in this chapter across spatial and temporal scales.

4 Assessment of hillslope-channel and within-channel coupling on the catchment scale

Marco Cavalli, CNR-IRPI, Padova

4.1 Introduction

In mountain catchments, sediment supply to downstream areas is often due to spatially limited sediment source areas where geomorphic processes occur with high intensity. The identification of the type, extent and location of sediment sources in a catchment (see previous chapter) is a fundamental requirement to predict sediment fluxes and calculate sediment yield at the catchment scale. Nevertheless, catchments can be considered very inefficient systems since sediment output at the outlet is much lower than the total sediment eroded within the catchment (Slaymaker, 2006). The discrepancy between sediment erosion and sediment yield, termed by Walling (1983) as the "sediment delivery problem", can be explained by sediment deposition and temporary or permanent storage occurring within the catchment in low gradient slope, floodplain or along the channel. Thus, a key role is recognized to storage areas in attenuating sediment delivery to the basin outlet. The pioneering work of Walling (1983) stressed the importance of improving understanding and representation of sediment supply, transport and storage in catchments in order to try to address the sediment delivery problem.

The linkage between the component parts of a geomorphic system is termed coupling (Harvey, 2001, 2002). In particular, when the sediment produced on the hillslopes directly reaches the channel network a hillslope\channel coupling relationship is identified. Conversely, a decoupling relationship refers to the case where the supplied material stops on the hillslope before reaching the channel (Savi et al., 2013). At catchment scale, the main active geomorphic zones are hillslopes and channels and the main fluxes are inside and between these two components (Bracken et al., 2015). The degree of geomorphic coupling, i.e. linkages between system components, is termed (sediment) connectivity (Heckmann and Schwanghart, 2013). Thus, sediment connectivity can be defined as the degree of linkage that controls sediment fluxes throughout landscape, in particular between sediment source and downstream areas. The conceptual model of sediment catchment (dis)connectivity developed by Fryirs (2013), that expresses the degree to which any limiting factor constrains the efficiency of sediment transfer relationships (Fryirs et al., 2007), takes into account lateral (hillslope-channel), longitudinal (between river reaches) and vertical (surface-subsurface) sediment transfers. Different types of blockages, termed buffers (e.g, alluvial fans, broad floodplains), barriers (e.g., valley constrictions, dams) and blankets (e.g., bed armouring), can disrupt lateral, longitudinal and vertical connectivity in catchments. According to this conceptual model it is fundamental to spatially identify sediment sources and transport pathways in a catchment in order to spatially characterize sediment (dis)connectivity. A measure to quantify the degree to which the catchment is longitudinally, laterally and vertically connected is given by the ‘effective catchment area’ (Harvey, 2002). The effective catchment area considers the catchment spatial extent constituted by only those areas that are active in contributing sediment downstream to the channel network or in transporting sediment along it. Those areas are part of the sediment cascade due to the absence or to the breaching of blockages. Since sediment dynamics are not uniform over time, another important issue that has to be considered in connectivity analysis is temporal scale (Harvey, 2001; Lane et al., 2008; Reid et al., 2007a, 2007b). Accordingly, sediment storage in catchments can be divided into sediment stores, temporary storage areas (e.g., bars, benches), and sinks, more permanent areas of storage where sediments can reside for a long time (Fryirs and Brierley, 2001).

Geomorphic coupling and connectivity have important implications for the behaviour of geomorphic systems and have become key issues in the study of sediment transfer processes. Starting from the 1980s, the role of geomorphic coupling and its importance for the landscape functioning for the establishment of sediment budgets have been continuously stressed (e.g., Dietrich and Dunne, 1978; Roberts and Church, 1986; Caine and Swanson, 1989; Slaymaker, 2003; 2006; Schrott et al., 2002). In the more recent years, literature has shown an increasing attention for the geomorphic coupling in catchments with particular regard to lateral connectivity (Baartman et al., 2013; Cavalli et al., 2013; Foerster et al., 2014; Heckmann and Schwanghart, 2013; Messenzehl et al., 2014) and important steps have been carried out in order to provide a solid theoretical approach (Bracken et al., 2015; Brierley et al., 2006; Fryirs, 2013). In these recent works, spatial and temporal variability factors are specifically included into the connectivity framework. The increasing interest in connectivity issues is also reflected in the recent implementation of an EU-funded COST Action (ES1306: Connecting European Connectivity Research) which aims are to form an EU-spanning network of scientists and to share expertise and develop a consensus on the definition and scientific agenda regarding the emerging field of water and sediment connectivity in Europe.

The assessment of the degree of hillslope-channel coupling and decoupling is of particular importance in alpine catchments, in which both complex and rugged morphology, and heterogeneity in type, extent and location of sediment sources cause large variability in the effectiveness of sediment transport processes.

In this context, highly efficient sediment transfer processes, such as debris flows and mud flows (Figure 4-1), can favour an effective linkage between hillslopes and the channel network while some morphological settings and landforms, such as glacial cirques and hanging valleys (Figure 4-2) can play an important role in decoupling hillslopes from channels excluding large portions of the catchment from sediment delivery to its downstream parts. This results in an effective sediment contributing area lower than the total catchment area. Moreover, an efficient lateral connectivity (hillslope-channel) does not always ensure an effective downstream transfer of sediment (e.g., low-slope channel reaches causing sediment deposition).

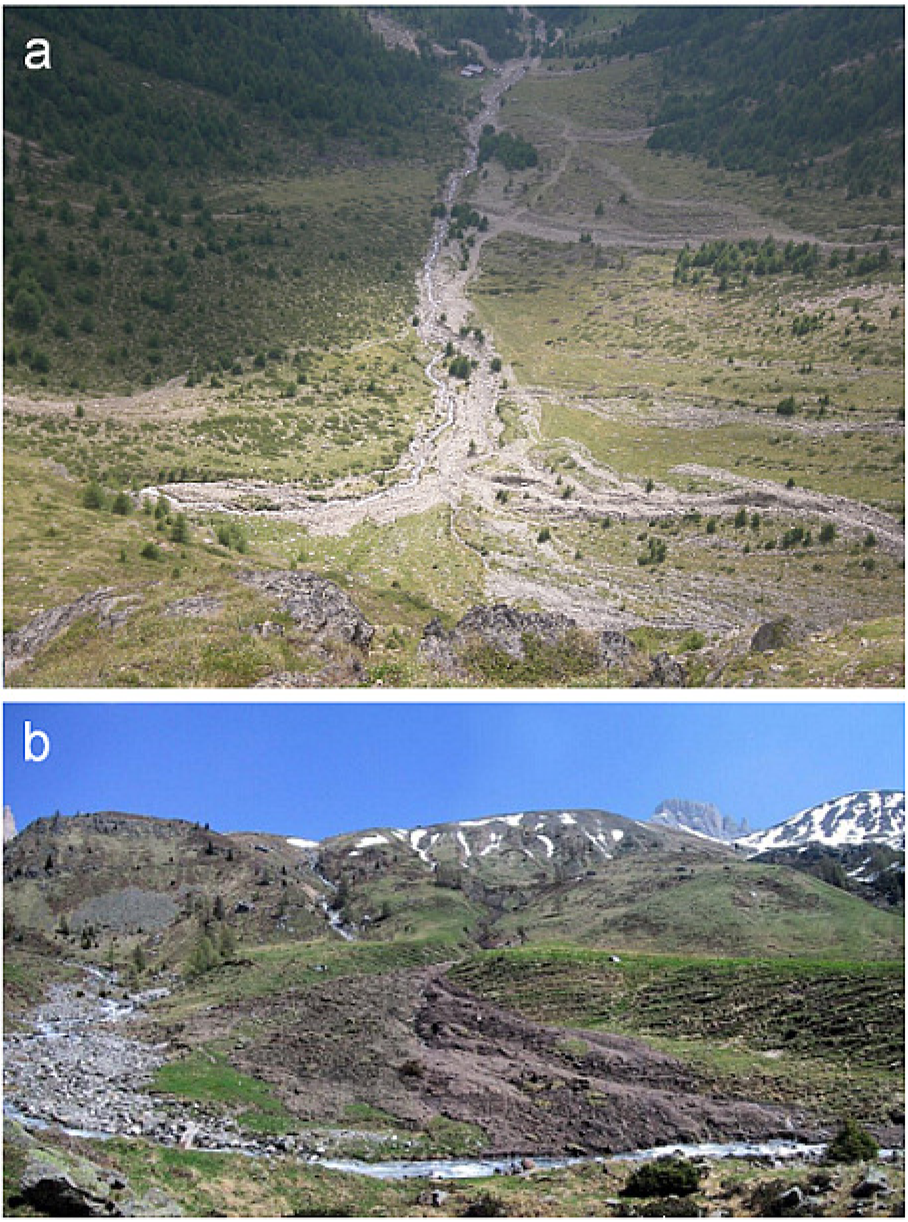

Figure 4-1: Debris flows create the conditions for hillslope-channel coupling a) Strimm catchment, Italy b) Rio Cordon catchment, Italy. Photos 4-1a by M. Cavalli and 4-1b by L. Marchi.

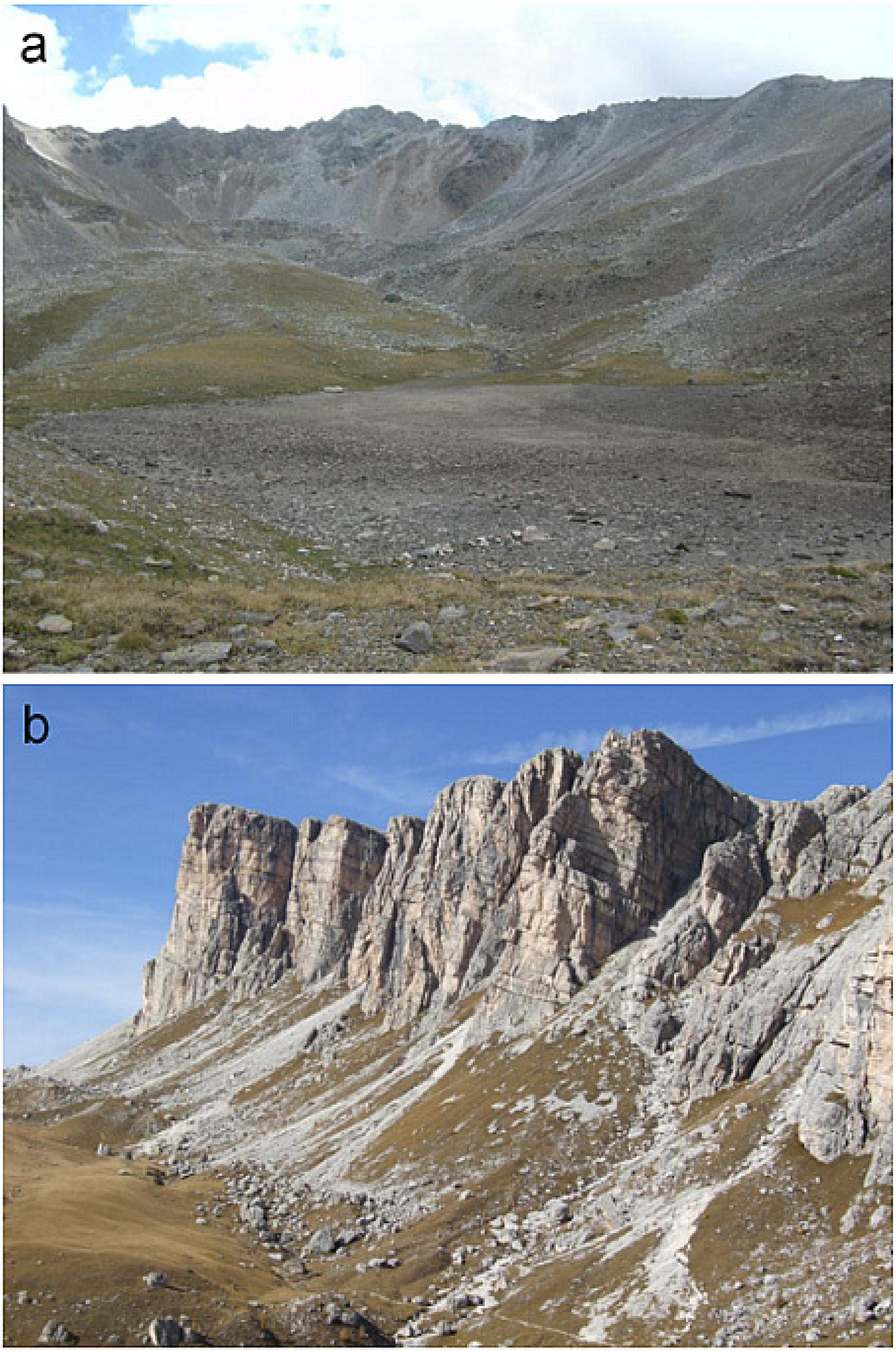

Figure 4-2: Examples of morphological landforms and settings decoupling hillslopes from channels: a) Glacial cirque (Strimm catchment, Italy); b) Hanging valley (Rio Cordon, Italy). Photos by M. Cavalli.

The spatial characterization of connectivity patterns in the catchment allows estimation of the contribution of a given part of the catchment as sediment source, and defines sediment transfer paths. A reliable assessment of sediment connectivity is especially useful for giving management priorities (e.g., not all sediment sources are relevant for chosen point of view). This is a key issue when dealing with sediment management and has an important linkage with hazard assessment and in relation to priorities of intervention at catchment scale.

4.2 Methods

The methods most commonly used for the analysis of sediment connectivity include geomorphological and sedimentological field observations, and monitoring of sediment fluxes by means of field instrumentation. Recently, several approaches have been developed in order to qualitatively address connectivity based on geomorphometry (Borselli et al., 2008; Cavalli et al., 2013) and graph theory (Heckmann and Schwanghart, 2013).

In the framework of WP4, several GIS-tools have been developed for sediment connectivity and sediment management of river basins:

- Two utilities for the derivation of the Index of Connectivity (IC), as expressed in Cavalli et al. (2013) developed by CNR-IRPI Padova (PP4), see Annex 9.1;
- The Fluvial Corridor Toolbox, developed by CNRS UMR5600 Lyon (PP8), see Annex 9.2.

The Index of Connectivity tools aim at evaluating the potential connection between hillslopes and features of interest (e.g., catchment outlet, main channel network, a given cross section along the channel) or elements acting as storage areas (sinks) for transported sediment (e.g., lake, retention basin) through a topography-based approach. It is mainly focused on lateral connectivity assessment.

The Fluvial Corridor Toolbox (Roux et al., 2014) provides a tools package allowing a planimetric and downstream characterization of fluvial corridor networks at multiple scales (i.e. from meter-scale to large regional scale issues). This toolbox can be very useful to characterize fluvial corridors and to automatically identify buffers (e.g., valley bottom) and blockages (e.g., longitudinal discontinuities location).

For further details on the developed tools see section 9 in the Annex.

In the context of WP4, the characterization of geomorphic coupling and sediment connectivity has involved: (i) application and testing of the GIS-based sediment connectivity index in the Venosta valley (Italy, PP4); (ii) characterization of source-to-sink colluvial sedimentary pathways through aerial photographs interpretation and supplementary fieldwork, and the Index of Connectivity in the Saldur River basin (Italy, PP4); (iii) evaluation of sediment sources coupled to the main channel in the Maira River basin (Italy, PP5); and (iv) investigation of the dependence of sediment yield on the size of Sediment Contributing Area in Isar catchment (Germany, PP6).

Table 4-1: Summary information about WP4 studies on geomorphic coupling and sediment connectivity.

Study site	Spatial scale	Objectives	Connectivity assessment methods	Main Outcomes
Venosta Valley	Regional scale (1096 km^2)	- test the applicability of index of connectivity at regional scale - investigate the effect of DTM resolution, weighting factor and catchment size on index results	- geomorphometric index of sediment connectivity	- the index has proved very promising for a rapid spatial characterization of sediment dynamics in a complex and large mountain watersheds; - It appears slightly dependent from DTM resolution and strongly from catchment size; - the index can provide useful information on the dominant processes affecting catchment of different size.
Saldur catchment	Catchment scale* (drainage area 97 km^2)	- spatial characterization of colluvial sediment cascade - integration and comparison of methods for sediment connectivity assessment	- multitemporal aerial photographs interpretation and field observations - geomorphometric index of sediment connectivity	- agile and integrated approach for identifying dominant source-to-sink colluvial sedimentary pathways; - the mapping of periglacial depositional landforms to obtain a more realistic assessment of sediment connectivity; - the integrated approach allows assessing the geomorphic response potential in future scenarios.
Maira catchment	Regional scale (574 km^2)	- identification of sediment sources coupled with the main channel	- geomorphometric index of sediment connectivity - field observation	- geomorphometric approach useful to limit the sediment source inventory only to effectively connected area; - at the scale of single sediment source, a critical evaluation of index results is required.
Isar catchment	Hillslope scale	- investigating the relationship between sediment yield and sediment contributing area (SCA);	- DEM-based approach to compute SCA; - sediment yield measurement through sediment traps	- Results confirm the dependence of mean annual sediment yield on the size of the SCA observed in a previous study (Haas et al., 2011); - DEM-based delineation of SCA represents a good proxy of lateral and longitudinal sediment connectivity.

* Catchment scale = drainage area < 100 km^2

4.3 Results and interpretation

PP4 applied the sediment connectivity index (IC) (Cavalli et al., 2013), originally developed at catchment scale, to the upper and middle sectors of the Venosta Valley in Italy (1096 km^2) to test the applicability of the geomorphometric index to a regional context which encompasses areas with a large variability in topography and land-use. A LiDAR-derived DTM with a resolution of 2.5 m covers the territory under study. The aim was also to investigate the effect of DTM resolution on index results and the comparability in terms of connectivity values between catchments of different size. The latter issue was analyzed by selecting 22 catchments characterized by different size, mean slope, shape and sediment transport dynamic (Figure 4-3a).

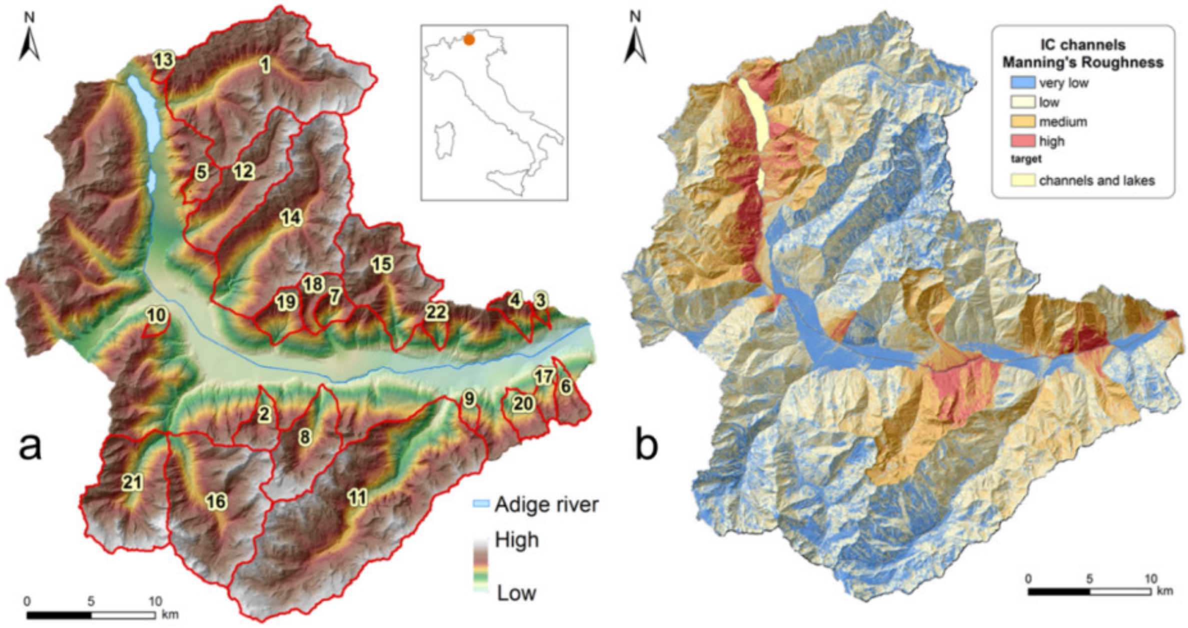

Figure 4-3: a) Location map of the Venosta Valley and the 22 selected catchments; b) Map of the Index of Connectivity calculated with respect to the Adige river. IC values are classified in four classes with the Jenks Natural Breaks algorithm.

Results (Figure 4-3b) show that the application of the model over a large spatial scale gives a realistic spatial characterization of sediment connectivity with very low values of IC in the Adige floodplain and highlights the role of most of the alluvial fans in decoupling upstream catchments from floodplain. Conversely, steep and large alluvial fans that occupy the valley floor favour the coupling of the upstream catchments and of the opposite hillslopes to the Adige River.

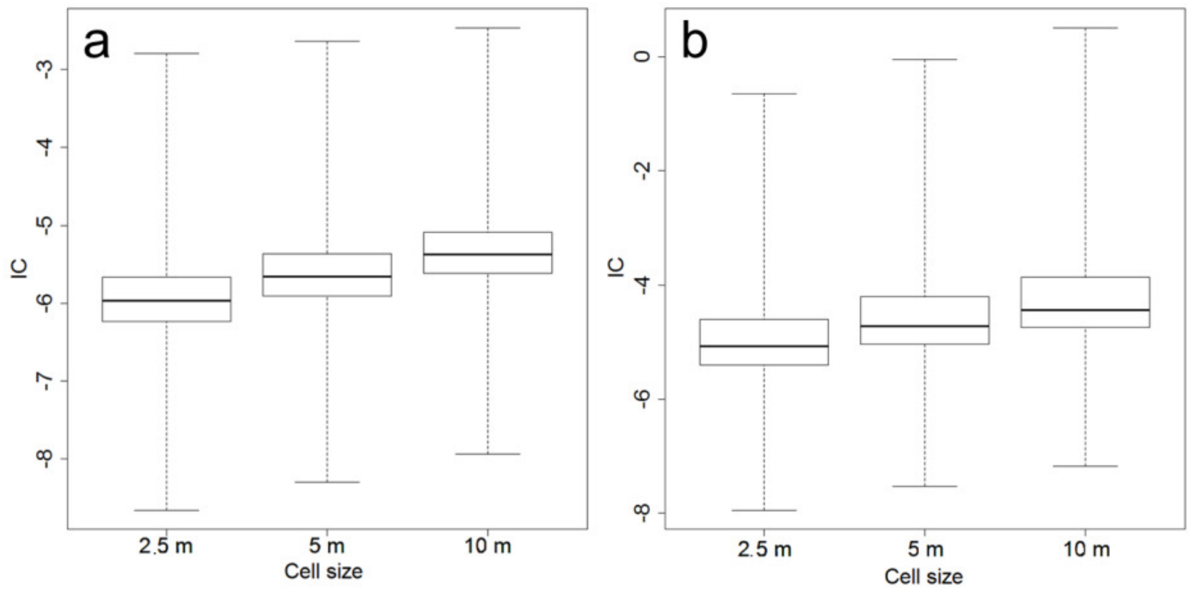

Figure 4-4: Boxplots of IC values of the Venosta Valley with 2.5, 5 and 10 m DTM resolution. IC was computed with respect to a) the valley outlet; b) to the Adige River.

Figure 4-4 shows boxplots of IC values calculated in the study site using three different DTM resolutions (2.5, 5, 10 m) in order to investigate the relationship between IC and DTM resolution. A slight increase in IC values with decreasing resolution can be observed. The increase is more evident for the application of IC with regard to the Adige River. The explanation can be found in the simplification of the flow paths due to increased cell size. The reduction of the length that the sediment has to travel to reach the selected target leads to an increase of IC values.

In the application to the Venosta valley two different impedance factors in IC calculation were tested: one based on the surface roughness (Cavalli et al., 2013) and one derived from tabled values of hydraulic roughness (Manning's n). The main outcome of this analysis is that using different impedance factors leads to different IC patterns and values. Generally, overall lower IC values are achieved when using Manning's n as weighting factor (Figure 4-5). Surface roughness can be used as weighting factor in those areas (e.g., high-altitude headwater catchments) characterized by homogeneity in land-use or absence of vegetation. On the contrary, a weighting factor based on Manning's n can be useful to characterized impedance to sediment fluxes in large areas of where land-use is very heterogeneous.

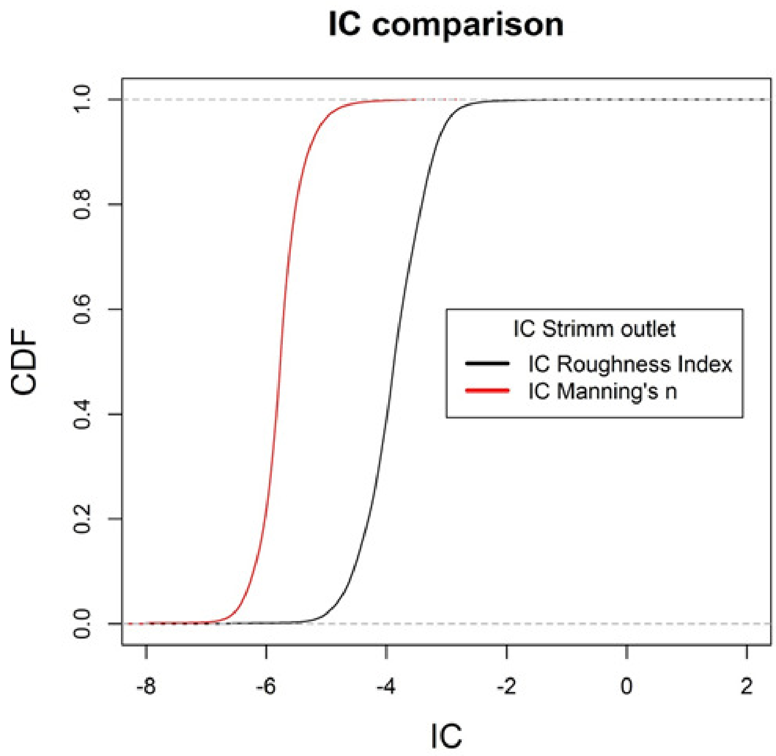

Figure 4-5: Cumulative distribution functions of IC values computed using two different weighting factors in a selected catchment (Strimm catchment).

A strong dependency on catchment size is evident when plotting the mean value of IC against catchment area for the 22 selected catchments (Figure 4-6). IC mean values tend to decrease for higher catchment sizes: this is accordance with what found also for the sediment delivery ratio. Moreover, large basins are usually characterized by a lower average slope and a higher amount of sediment storages between sediment sources areas and the outlet than small catchments. Selected catchments have been classified into three classes (i.e. debris flow, mixed and bedload) according to the dominant process affecting the main channel identified from historical data and field observation. IC values are higher for debris flow basins (drainage area from 1 up to about 10 km^2) whereas lower IC values characterize larger basins whose main channel is mostly affected by bedload sediment transport. Medium size basins (drainage area from 6 km^2 to 30 km^2) are located in the central part of the plot where different type of processes occurred.

In conclusion, the index has proved very promising for a rapid spatial characterization of sediment dynamics in a complex and large mountain area. The proposed sediment connectivity appears slightly dependent from DTM resolution, whereas a strong dependency on catchment size is observed. Nevertheless, when used to compare basins of different sizes, it can provide useful confirmation on the dominant processes affecting them.

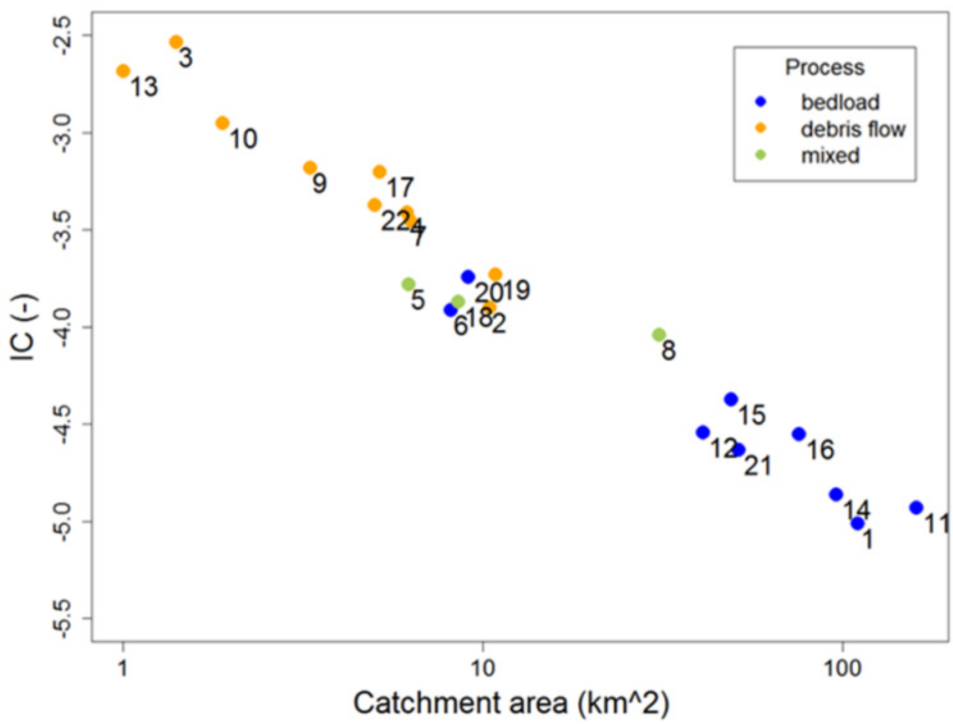

Figure 4-6: Relationship between IC calculated with reference to the fan apex of the basin and the catchment area. Numbers refer to catchment numbers in **Figure 4-3**.

The activities carried out by PP4 in the Saldur River basin (97 km^2) were focused on the compilation of a multitemporal inventory of colluvial sediment sources and of glacial and periglacial depositional landforms (e.g., rock glaciers, protalus ramparts, moraines) in order to characterize the spatial organization of the colluvial sediment cascade. Source-to-sink colluvial sedimentary pathways were mapped with an integrated approach involving aerial photo interpretation and supplementary fieldwork, and the topography-based index of sediment connectivity (i.e., Cavalli et al., 2013) (Figure 4-7).

In light of the results (for details, see case study 8.2 in Annex), the integration of multitemporal mapping of sediment sources, of the identification of glacial and periglacial depositional landforms, and the spatial characterization of topography-based sediment connectivity is considered fundamental to obtain a more realistic assessment of sediment connectivity in high mountain basins similar to the Saldur River basin. Moreover, this integrated approach holds critical implications for evaluating landscape response to climate change in steep, permafrost-prone areas, as well as for assessing mass wasting-related hazard. For example, intact rock glaciers and creeping debris lobes located within the domain of discontinuous alpine permafrost are characterized by high IC values due to particular topographic conditions (e.g. high slope, high drainage area) that might favour slope instability and catastrophic in-channel sediment evacuation where climate scenarios foresee fast permafrost degradation and glacial retreat.

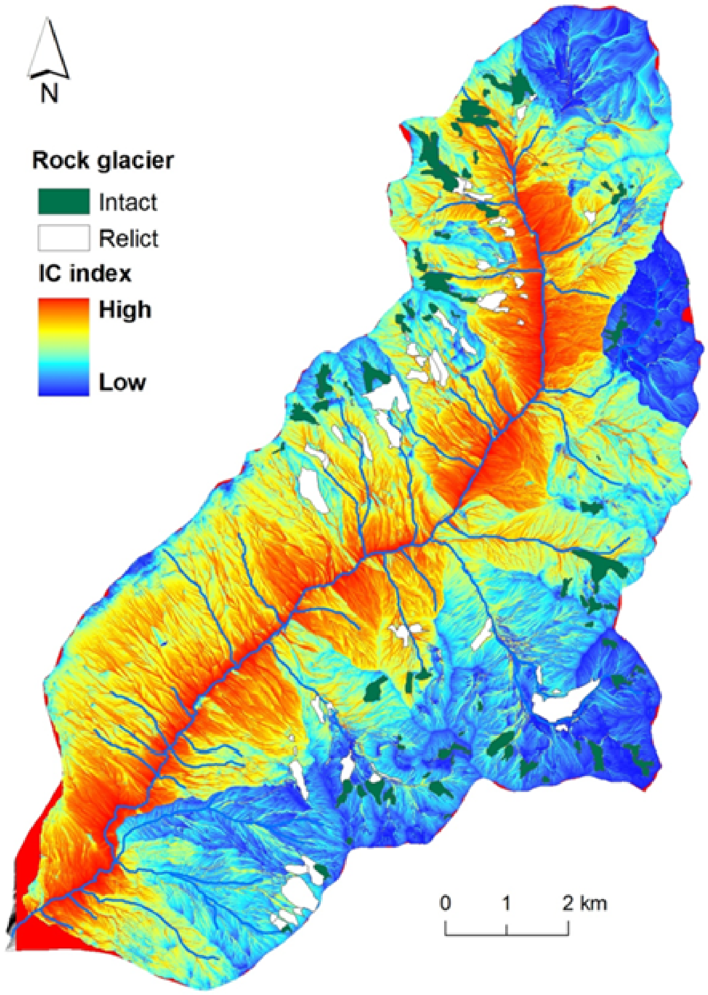

Figure 4-7: Index of connectivity, with superimposed sediment sources (filled red and green polygons), rock glaciers and protalus ramparts (filled green (intact) and white (relict) polygons), creeping permafrost-rich lobes (black linework), and moraine ridges (ginger pink linework). Figure modified from case study 8.2 (Annex).

The general objective of the study conducted by PP5 in the Maira catchment (Italy) was to estimate the volume of the sediment produced in the catchment and compare the result with the volume of sediment deposits in two reservoirs for hydropower production (see case study in Annex 8.3).

Sediment source areas were identified by means of aerial photo interpretation combined with field survey. In order to limit the inventory only to the source areas that are effectively coupled to the main drainage system, an estimate of sediment connectivity has been carried out by means of field observations and interpretation of the topography-based sediment connectivity index (Cavalli et al., 2013) map. The connectivity analysis was carried out in the upper part of the catchment (574 km^2) using a 5 m resolution LiDAR-derived DTM and considering the main channels (Maira River and major tributaries) as the target of the analysis.

The comparison between IC map classified into four classes (Jenks Natural Breaks algorithm) with the final sediment source database (Figure 4-8) highlights that most of the sediment source areas (>80%) are located in the Medium-High and High Connectivity classes. Only less than 20% of the areas was considered to be coupled to the hydrographic network by field observations even if belonging to the Medium-Low IC class.

In the application to the Maira Valley, the IC has proven useful in supporting the expert judgment and saving time in the inventory compilation process. It's worth noting that if on the one hand the index is able to characterize in a realistic way sediment connectivity pattern at catchment and sub-catchment scale, the assessment of geomorphic coupling at single sediment source scale still requires a critical expert interpretation.

A complete presentation of the study case is available in section 8.3 of the Annex.

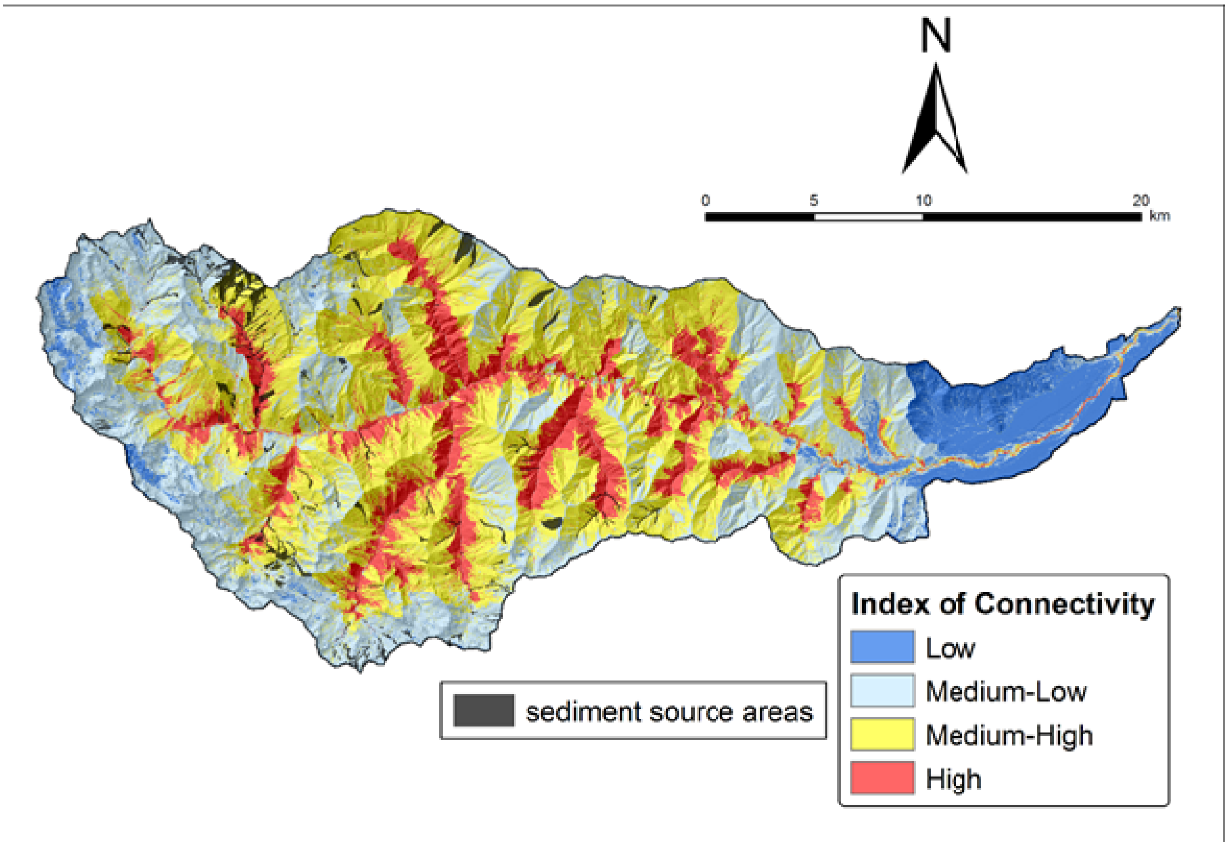

Figure 4-8: Sediment source areas superimposed to the Index of Connectivity output map in the Maira River basin, Italy.

The study in the Isar catchment (Germany) by PP6, investigates the relationship between sediment yield and sediment contributing area (SCA) (i.e., possible area providing sediment input from hillslopes into the channel) (see case study 8.4 in Annex). In order to identify sufficiently steep terrain sections directly adjacent to the channel network, under the hypothesis that these are geomorphically coupled and hence provide sediments to the channel network, a set of rules is applied to a high-resolution DEM (Figure 4-9). Moreover, this DEM-based approach, on the base of slope analysis, identifies torrent reaches decoupling sediment pathways from downstream sections. At the end, the cumulative size of the SCA is calculated for each raster cell that is part of the channel network. In order to account for different rates of sediment mobilization, a different weight (0.2 in vegetated areas and 1.0 in areas characterized by missing or sparse vegetation cover) was assigned to raster cells belonging to the SCA. The rules forming the basis of this delineation represent an implementation of lateral (hillslope-channel) and longitudinal (within-channel) sediment connectivity.

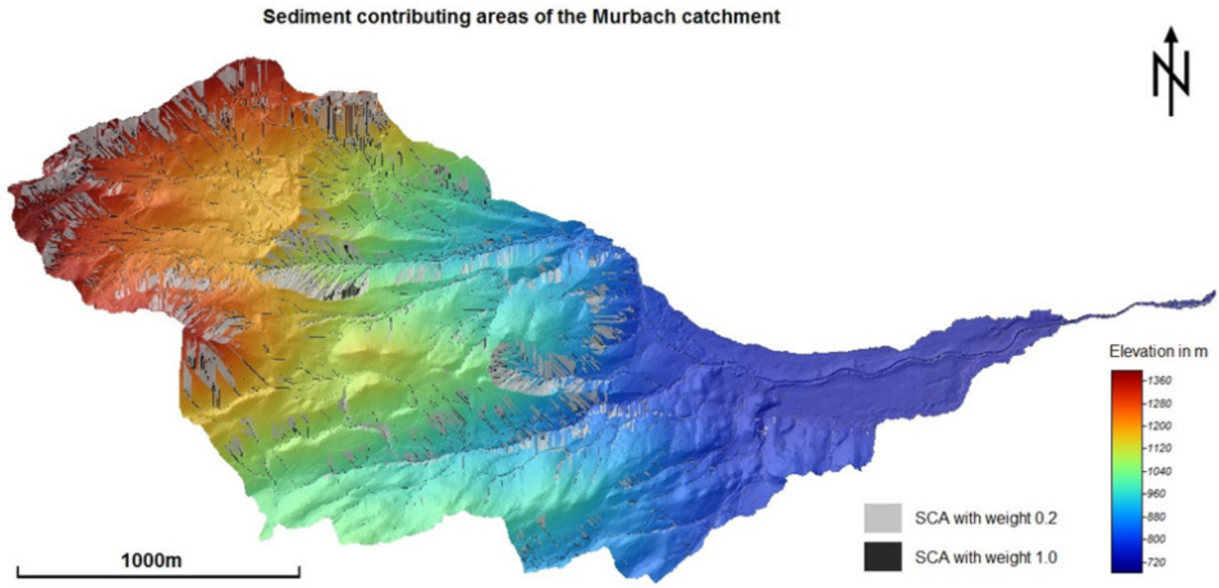

Figure 4-9: Sediment contributing areas of a subcatchment of the Isar (Murbach catchment) as delineated from the DEM. The geomorphological/landcover map was used to weight the sediment contributing areas. Figure modified from case study 8.4 (Annex).

Sediment yield was measured by weighting the content of several sediment traps deployed in selected hillslope channels (see the following section for further details on sediment yield measurements).

Results confirm the findings of a previous study by Haas et al. (2011): a power-law dependence of mean annual sediment yield on the size of the SCA even if, in this study, data derived from a shorter measuring periods were used (about 1 year vs. 5 years). It must be noted that this analysis is best suited for long-term average sediment yield whereas the estimation of event-based sediment yields appears to be infeasible using this approach. In general, the estimation of average sediment yields from hillslope tributaries to channels in the study area has proven feasible using the DEM-based delineation of sediment contributing area highlighting the importance of connectivity analysis. More details on this case study can be found in section 8.4 of the Annex.

4.4 Achievements and Recommendations

- The possibility to relate a quantitative estimate of sediment connectivity to sediment sources databases can improve hazard and risk assessment in order to mitigate the effects of dangerous phenomena like debris flows. With an integrated approach, which encompasses sediment sources mapping and connectivity assessment, it is indeed possible not only to evaluate the general availability of sediment but also to estimate the potential for this sediment to reach specific targets;
- GIS-based approaches applied in WP4 case studies (i.e. Index of Sediment Connectivity and Sediment Contributing Area) have proved very promising for a rapid spatial characterization of lateral and longitudinal sediment connectivity both at catchment scale and when applied in a complex and large mountain watersheds;
- The integration of multitemporal mapping of sediment sources, of the identification of glacial and periglacial depositional landforms, and a spatial characterization of sediment connectivity using a geomorphometric approach is considered fundamental to obtain a more realistic assessment of sediment connectivity in high mountain basins;
- An integrated approach for delineating sediment connectivity across landscape components could allow assessing geomorphic response potential in peculiar future climate scenarios at distinct locations of a given study basin;
- The DEM-based delineation of Sediment Contributing Area has proven useful in order to estimate average sediment yields from hillslope tributaries to channels highlighting the importance of connectivity analysis. Anyway, long time series of measured sediment yield are needed for the calibration of the regression function.

5 Sediment delivery and yield

Tobias Heckmann, University of Eichstätt-Ingolstadt

5.1 Introduction

Sediment is routed through a mountain landscape along sediment cascades, i.e. pathways of sediment transport by different geomorphic processes. The identification of potential sediment sources and the assessment of hillslope-channel and within-channel coupling form an important basis for the spatial delineation of these sediment cascades. Many problems in basin management, however, require an estimate of sediment dynamics and yield at some point(s) of the catchment, for example at the outlet.

This chapter deals with the assessment of sediment delivery and geomorphic changes; it focuses on the application of high-resolution DTMs for measuring and modeling morphodynamics and sediment transfer on different spatial scales (local to catchment).

5.2 Description of methods

5.2.1 Measurement of geomorphic change and sediment budgets

Depending on the spatial scale, a number of methods are available that enable a quantification of change in surface elevation that is effected by geomorphic processes through erosion and deposition. The previous decade has seen the emergence of revolutionary tools that can be used to survey the Earth surface at an unprecedented level of detail/resolution and accuracy (c.f. Tarolli 2014). When applied at successive points in time, the techniques of "scour-and-fill" analysis can be used to detect and quantify surface changes and the associated erosion, (re-)distribution and deposition of sediment (e.g. Fuller et al., 2003; Wheaton et al., 2010). The subtraction of DEMs representing the surface at different points in time yields a DEM of difference (DoD); in case of raster DEMs, the elevation difference on each raster cell is multiplied by the raster size squared in order to compute the volume of sediment that has been eroded or deposited, respectively. Establishing such morphological sediment budgets, however, is more complex than just the computation of a DoD. It has been stressed that this technique requires, besides an accurate coregistration of the DEMs, a rigorous treatment of uncertainty. As all measurements are subject to errors, these errors are propagated to the results of all computations that are based on the measurements. An approach that has been widely adopted assumes normally distributed errors with an expected value of 0; it computes the uncertainty *U* of the DoD from the squared errors of each DEM (see e.g. Lane et al., 2003):

$$U_{DoD} = \sqrt{(\delta z_{new})^2 + (\delta z_{old})^2}$$

The error δz of each DEM can be estimated by surveying an area twice, with no surface changes between the two measurements, and evaluating the differences between the two surveys; the standard deviation of errors is then taken as the DEM error. Another possibility is the evaluation of "stable" sections of a DoD, i.e. the computation of statistics on the DoD where real changes can be excluded: while the mean should be zero (otherwise indicating a systematic error), the standard deviation can be regarded as a measure for the DoD uncertainty.

The latter can be multiplied by a value taken from the t distribution, for example with t=2 representing a confidence level of ca. 95%. The resulting 2σ error is considered as the level of detection (LoD) of the technique (Bennett et al., 2012, use t=1); differences in the DoD below that level can be masked:

$$LoD = t\sqrt{(\delta z_{new})^2 + (\delta z_{old})^2}$$

Many studies have used uniform DoD errors (and, hence, LoD), although it has been shown that DEM uncertainty strongly depends, among others, on slope, terrain roughness and point density (Scheidl et al. 2008; Milan et al. 2011).

For the estimation of volumetric errors from a scour-and-fill analysis, Lane et al. (2003) recommend to consider all differences and to calculate the error of the volume as

$$\sigma_{Vol} = d^2\ U_{DoD}\sqrt{n}$$

where *d* is the raster size and *n* is the number of raster cells used to compute the volume (of erosion, deposition, or the net balance, respectively).

DEM-based investigations on the local scale, for example on a hillslope, aim at measuring where, and how much, sediment is mobilised and transferred to the channel network from hillslope and riverbank sources by different geomorphic processes. On the catchment scale, the spatial pattern of sediment sources becomes more relevant. Investigations seek to understand coupling relationships by documenting coupled and uncoupled sediment sources, i.e. cases where sediment from the respective sources is delivered to the channel network, or redistributed on the slope without entering the channel, respectively.

On the local scale, multitemporal surveys by terrestrial LiDAR can be employed for such investigations. Recently, inexpensive software tools have been developed that allow for the construction of high-resolution DEMs from non-metric photos taken from the ground or from unmanned aerial vehicles (UAV), using the Structure-from-Motion technique (SfM, see e.g. Westoby et al., 2012; Fonstad et al., 2013). Using ground-control points surveyed with differential GNSS, the data generated using these techniques can be transformed to a coordinate system and coregistered with other DEM data. Catchment-scale investigations rely on multitemporal airborne LiDAR data (see Annex 8.6; Scheidl et al., 2008) and on DEMs generated from aerial photos using techniques of stereophotogrammetry. The latter make it possible to use historical aerial photos for the reconstruction of past surfaces, and the quantification of changes (e.g. Schiefer and Gilbert, 2007). Finally, high-resolution DEMs form the basis of multi-scale digital geomorphometry and index-based assessments of sediment connectivity on the catchment scale (see chapter 4; Cavalli et al., 2013)

5.2.2 Model-based estimation of erosion and sediment delivery

Multitemporal surveying of whole catchments is now possible using airborne LiDAR, however it is expensive and therefore prohibitive for large-scale monitoring purposes, especially if a high temporal resolution is required. Where a high-resolution DEM from airborne LiDAR data exists, localised geomorphic changes and the associated amount of sediment eroded or deposited can be quantified using terrestrial LiDAR (see Bremer and Sass 2012, Heckmann et al., 2012). The most recommendable solution is the measurement of sediment transfer on the local scale, and the regionalisation using various types of models.

The case studies within WP4 have used a variety of models, among them the empirical "revised universal soil loss" (RUSLE) and Gavrilovic equations, and the physically-based model WATEM/SEDEM (see Annex 8.8).

The RUSLE, for example, predicts only erosion; in complex relief, however, different coupling relationships (hillslope-channel, but also within-slope, i.e. between crest and footlslope) strongly modify the relationship of gross erosion and sediment yield, i.e. sediment transfer to the channel network and to the catchment outlet. This is why the WATEM/SEDEM model predicted lower rates of sediment yield in the aforementioned case study. Another issue with modelling is that neither WATEM/SEDEM nor the RUSLE or Gavrilovic equations take into account all processes that are active within the study areas, for example landslides; in addition, the RUSLE does not account for gully erosion, a process that is deemed dominant in the study area of the case study.

5.2.3 Scaling sediment yield using empirical relationships between sediment contributing area and measured sediment yield

Another method that has been employed in a WP4 case study is based on measurements of sediment yield in small hillslope channels that can be regionalised using empirical relationships.

Plastic troughs with a volume of ca. 90 l are deployed in a number of small hillslope channels within a study area; rugged foils are used to ensure that the complete runoff on the channel is forced to pass through the trough that acts as a sediment trap for bedload (grain sizes > 2 mm).

The basis for regionalising the mean annual sediment yield measured in these traps is their sediment contributing area (SCA), i.e. that fraction of the hydrological catchment that effectively delivers sediment to the sediment trap. The SCA is delineated from a high-resolution raster DEM and is related to those raster cells that represent the channel network. The latter can be mapped manually or derived automatically from a DEM (see Haas et al., 2011). A set of rules is applied to the DEM, marking those raster cells as SCA that connect to the channel network along flow pathways that are (i) continuously steeper than a user-specified slope gradient and (ii) not longer than a user-specified maximum distance. Moreover, sediment pathways that belong to the channel network are interrupted (decoupled) when (iii) the channel gradient falls below a user-specified threshold. Using a standard flow-accumulation routine, the size of the SCA is calculated for each raster cell. In this procedure, SCA cells can be weighted, for example in relation to vegetation cover; for example, bare areas are fully counted (weight = 1.0), while a factor of 0.2 may be applied to SCA cells covered with vegetation. In applying these simple rules, the method implements the concepts of lateral (i.e. hillslope-channel) and longitudinal coupling (within-channel coupling; c.f. chapter 4).

Initially, this method was used to identify points in the channel network that had a high potential sediment delivery, forming part of a susceptibility model for (torrent bed – type) debris flows (Heinimann et al., 1998). Haas (2008) and Haas et al. (2011) found that the mean annual sediment yield measured in sediment traps was highly correlated with the size of the corresponding SCA. The statistical relationship between SCA and mean annual sediment yield has the form of a power law; for simplicity, it is derived using least-squares linear regression of log sediment yield on log SCA. Using a regression equation whose parameters were estimated with data from 17 sediment traps in the Lahnenwiesgraben (Northern Calcareous Alps), mean annual sediment yield could successfully be predicted in another catchment (Reintal, Northern Calcareous Alps; Haas et al., 2011) and in a study on enhanced sediment yield on steep slopes that were affected by wildfires (Sass et al., 2012).

5.3 Achievements and Recommendations

5.3.1 Quantification of geomorphic changes and sediment delivery from sediment sources

Some of the case studies contained in this report (see Annex) make use of multitemporal DEMs for (i) the identification of sediment sources and (ii) the quantification of surface changes and the underlying sediment transfer using the technique of "morphological budgeting".

Case study 8.1 uses two high-resolution DEMs (2 m raster size, generated from airborne LiDAR data) of two catchments in the Italian Alps. In the Gadria-Strimm area, the focus is on the spatial pattern of active sediment sources at the basin scale, specifically fluvial processes and debris flows. Uncertainty of the DEMs of difference (DoD) is assessed using the fuzzy approach (Wheaton et al., 2010) that also takes into account the spatial coherence of depositional and erosional units. In the Moscardo torrent case study, terrestrial laser scanning (TLS) was applied on a more local scale on three areas of interest (a channel section at the apex of the Moscardo alluvial fan that is affected by debris flows, a landslide in the central part of the catchment, and major sediment sources in the upper part). This case study exhibits the advantages of TLS surveys that (i) can be conducted more often due to the comparatively low cost, in order to reach a much higher temporal resolution and (ii) yield a higher spatial resolution (0.2 m in the case study). Moreover, TLS outperforms airborne LiDAR in steep areas due to the favorable acquisition geometry. However, the advantages of TLS surveys come at the expense of a smaller range and areal coverage as they are not feasible on the catchment scale.

Measurements of landslide volume, for example, are useful for the fitting of area-volume relationships (c.f. case study 8.2) that are needed for the estimation of historical geomorphic activity on the basis of aerial photos, from which only the areal extent of landslides can be mapped.

In case study 8.6, two epochs of airborne LiDAR data were used to identify active sediment sources and the complex pattern of sediment transfer along the main channel of a very active debris-flow torrent in the Southern French Prealps. In this study, the level of detection for surface changes has been determined to be 0.13 m. The study shows that, while the spatial pattern of erosion and deposition is complex, the net budget is positive, i.e. the studied torrent section is aggrading. The difference between the budgets of the catchment (~ 15,000 m^3) and the main channel (~ 10,000 m^3) indicates that erosion within ravines directly contributed to sediment yield at the catchment outlet, i.e. the system was well connected during the study period. The (average) erosion rates determined by the measurements are in the same order as the highest rates worldwide.

Case study 8.7 shows that even single high-resolution DEMs can be valuable for the quantification of surface changes: in cross-sections extracted from airborne LiDAR DEMs, remnant surfaces (e.g. fluvial terraces) dated using historical aerial photos allow for a reconstruction of the long-term evolution of the long profile – revealing a significant channel incision accompanying channel narrowing during c.a. 60 years.

5.3.2 Assessment of (potential) sediment yield

In case study 8.4, Huber et al. (PP6, see also 5.2.3) tested the statistical relationship between the size of the sediment contributing area (SCA) and measurements of sediment yield in 16 sediment traps deployed in zero-order channels within the upper Isar study area. A comparison of the spatial extent of the SCA and a map of sediment sources that was based on aerial photos shows that the model identifies sediment sources (potentially coupled to the channel network) that are not visible due to forest cover, for example. Despite being subject to caveats (extrapolation of comparatively short-term measurements), their results compare favourably with those published by Haas et al. (2011), indicating that the delineation of SCA and the application of a power law-type equation may yield an effective first-order estimation of mean annual sediment yield. Future work is needed to investigate:

- the range of spatial scales across which SCA is an effective predictor of sediment yield;
- the validity of empirical relationships in different lithologies;
- the opportunity of weighting the SCA according to lithology and/or vegetation has not yet been rigorously evaluated. This could form a link between the statistical method and existing approaches to assess

potential sediment delivery using field mapping and expert knowledge;
- while the SCA approach already implements concepts of hillslope-channel and within-channel coupling, combinations with approaches to identifying sediment sources (chapter 3) and assessing connectivity (chapter 4) should be tested and developed further;
- the relevance of the SCA approach for the estimation of the potential sediment yield of high-magnitude events (as opposed to long-term average rates) remains to be studied.

Case study 8.3 includes an estimation of potential sediment yield based on a classification of mapped sediment sources and specific thresholds of hydrometeorological trigger events for each geomorphic process; thus, a semi-quantitative estimation of potential mobilisable sediment volumes can be undertaken for three scenarios (frequent = return period < 10 years vs. occasional = return period ~ 10 years vs. rare = return period >50 years). Other statistical and rule-based methods exist for the prediction of sediment yield of a catchment on different time scales (i.e. either for a specific event, say, a HQ100 flood, or for the long-term average). Gertsch et al. (2012) published two methods for estimating sediment yields. For example, catchments are classified, using a decision tree and various criteria, in five categories of potential specific sediment yield; more detailed estimations require field-based assessment of sediment potential for channel reaches using empirical formulae. Peteuil et al. (2012) presented the ECSTREM approach that relates, among others, the catchment area and morphometric parameters to the 10 years and 100 years sediment supply to a torrent (see also Bovis & Jakob 1999, for example). These relationships are moderated by the type and intensity of the geomorphic processes (debris flows- vs. bedload transport-dominated catchments), and by the area of active sediment sources that are coupled to the channel network. In the ECSTREM approach, the latter is delineated manually through mapping; it would be interesting to compare these areas with those delineated by the semi-automated and automated approaches described in this report. It can be stated that the modern techniques of quantifying surface changes and sediment budgets may form a basis for evaluating and/or calibrating the existing empirical, rule- or model-based approaches. The DEM-based assessment of connectivity may add important information as to the (potential) coupling of sediment sources to the channel network, sediment continuity within the channel network, and sediment transfer to the catchment outlet.

Case study 8.8 uses empirical (RUSLE, Gavrilovic equation) and physically-based models (WATEM/SEDEM) to identify sediment sources and to estimate potential sediment yield. A comparison between the model results showed considerable differences, attributed in part on the inability of RUSLE and Gavrilovic equation to model deposition – hence, the sediment yield as predicted by the WATEM/SEDEM model is also lower. Due to the inability of the RUSLE approach to model gully erosion, a process deemed dominant in the study area, the RUSLE approach should not be used. The authors call for a better calibration of models using field measurements.

6 Historical analysis of alpine basins

F. Liébault, IRSTEA, Grenoble

6.1 Introduction

Alpine river basins can be viewed as physical systems with a memory, in the sense that their present-day functioning may be more or less influenced by past events. This is particularly true when a catastrophic flood occurs in a mountainous catchment. These floods may induce such a high geomorphic disturbance that it can take several decades for the alluvial system to recover its pre-event morphology and sediment regime. It is for example well known that a shift of the sediment rating curve may occur after an extreme flood, under the effect of enhanced sediment supply conditions after the event (Pitlick 1993). At a longer timescale, it is also recognized that imprints from the Last Glacial Maximum (LGM) generally exert a primary control on current geomorphic responses. This is for instance the case of debris-flow sediment dynamics, which can be modulated by the availability of Quaternary sediment deposits (Brardinoni et al., 2012). In alpine basins, geomorphic responses are also integrating a complex history of human disturbances, from the widespread deforestation of the 18 and 19th centuries to the recent impacts from engineering works, gravel mining, or dam construction (Liébault et al., 2005; Comiti 2012). It is therefore very challenging to deconvolve the respective contribution of past and present conditions in the geomorphic signal, although this is generally important for sediment management issues in alpine basins.

One way to handle this issue is to read the historical record of alpine basins and to combine this information with theoretical or conceptual laws available for interpreting the data. This is the key objective of the historical analysis, which proved to be very helpful for the comprehensive understanding of complex responses of fluvial systems (Piégay and Schumm 2003). This approach was particularly effective for determining the causes of the geomorphic trajectory of several gravel-bed rivers in SE France (Liébault and Piégay, 2002). By reading the evolution of channel morphology through time, it is possible to infer time fluctuations of water and sediment fluxes, and to test hypotheses related to external forcings (e.g. climate and land-use changes). In absence of long-term hydrological and sediment transport monitoring data, channel morphology can be used as a proxy for inferring time fluctuations of these fluxes (Figure 6-1).

Figure 6-1: Example of channel changes of the braided Bléone River in the Southern French Prealps detected by comparison of past and present aerial photographs. This river shows a strong active channel narrowing under the cumulative effect of gravel mining and catchment reforestation (data from IGN).

The historical investigation of alpine basins is of great interest for the definition of strategic policies related to sediment management issues. By looking at alpine rivers at the historical timescale, it becomes possible to evaluate present-day conditions in the light of the time variability of the system, and to better understand the respective legacy of human impacts and climate changes, as well as extreme events. This kind of approach can be very useful for predicting geomorphic trajectories associated with global and local changes observed in the Alps (e.g. increased frequency of extreme events, permafrost degradation, glacier retreat, reforestation on hillslopes, torrent-control works) (Figure 6-2). Historical records can also be used to reconstruct the flood history of a river, or the geomorphic effects and inundation area of historic floods (Arnaud-Fassetta et al., 2005).

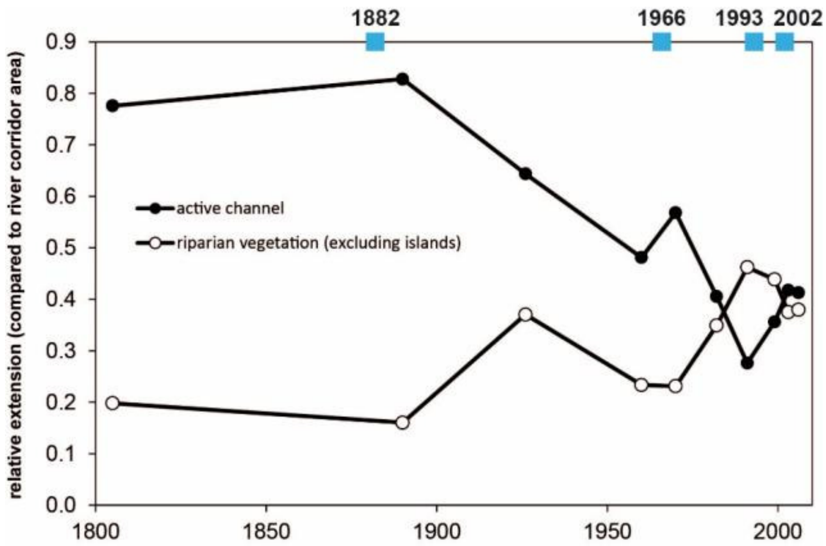

Figure 6-2: Proportion of the fluvial corridor occupied by the unvegetated active channel, and riparian vegetation (excluding islands) throughout the last two centuries along the Piave River, Eastern Italian Alps. Flood events that exhibited relevant effects in terms of channel adjustments are marked in blue (modified after Comiti et al., 2011).

These different topics have been addressed in the SedAlp project by several case studies in France (Bouinenc Torrent), Italy (Saldur River basin, Maira River basin), and Slovenia (Bistricica) (Table 6-1). In the Bouinenc Torrent, historical data was combined with a recent airborne LiDAR survey for reconstructing the timing of channel incision associated with reforestation. In the Saldur valley, historical data were used to reconstruct a catalogue of mass wasting activity and to analyse the effect of glacial and periglacial imprints on the sediment cascade. In the Maira River basin, historical data were used to reconstruct the effects of a catastrophic flood which occurred in June 1957. In the Bistricica Torrent basin in Slovenia, the present-day sediment source map was compared to an historical erosion map produced in 1939 to assess the evolution of sediment supply conditions.

Table 6-1: Summary information about WP4 historical studies (A_d: drainage area)

Study Site	Spatial Scale	Timescale	Historical Data	Outcome
Bouinenc Torrent	3-km river reach (A_d = 39 km²)	1948-2010	• historical aerial photographs (9 sets) • airborne LiDAR data (2 coverages)	• Terrace dating • Long profile evolution • Time evolution of active channel elevation over 50 years
Maira River	1-km river reach (A_d ~ 110 km²)	June 1957 catastrophic flood	• historical oblique pictures and maps of the June 1957-flood consequences	• Flooding map of the June 1957 event in the village of Acceglio (Upper Maira River valley)
Saldur River	A_d = 97 km²	1950-2012	• historical aerial photographs (8 sets) • airborne LiDAR data (1 coverage)	• Inventory map of dated colluvial sediment sources • Inventory map of glacial and periglacial landforms
Bistricica Torrent	A_d = 9.6 km²	1939-2013	• historical erosion map (1939) • 2013 aerial photographs	• Qualitative information about changing sediment supply conditions

6.2 Description of methods / results / interpretations

6.2.1 Bouinenc Torrent (Irstea Grenoble)

This study case was dedicated to the reconstruction of channel changes of the Bouinenc Torrent, a tributary to the Bléone River in the Southern French Alps, from the systematic analysis of historical aerial photos available since the late 1940s. This information was combined with a high-resolution digital elevation model of the floodplain to study the formation of recent terraces associated with the evolution of the active channel of the torrent. A general description of the study site is available in the Annex of the report (8.7).

The historical analysis of channel changes was conducted in the last 3 km of the Bouinenc, where the stream develops a wandering pattern in a 200-m-wide floodplain, at the exit of a confined gorge. A multi-thread, braided channel is observed locally. The overall channel slope is 0.016 and the mean active channel width is 24 m (range: 10–45 m). Channel reach morphology is a riffle-pool-bar system entrenched in a floodplain.

The active channel width (unvegetated gravel bars and low-flow channels) of the Bouinenc Torrent was systematically measured at 10-m regular intervals along the 2.9-km alluvial downstream reach of the torrent, on 9 historical aerial photographs between 1948 and 2004. This was completed with two recent airborne LiDAR surveys in 2008 and 2010. Aerial photos before 2000 were georectified with ArcGIS before active channel analysis. Active channels at all dates were also manually digitized for overlaying on a high-resolution DEM derived from the airborne LiDAR survey acquired in 2010. This gives the possibility to investigate the relative elevation of the terraces formed since 1948, and to reconstruct the long profile evolution of the channel during the last 60 years.

Historical aerial photos revealed dramatic changes of the active channel during the last 60 years. A very strong active channel narrowing is observed between 1948 and 1975, followed by stable conditions 1975 onwards. The mean active channel width decreased from 85 m to 22 m between 1948 and 1975 (74% decrease). During this 30-yr period, the channel pattern shifted from braiding to single-thread wandering, with a strong vegetation encroachment in the former braided plain.

The manual editing of active channel boundaries on each set of aerial photographs was used to produce a map of the age of surface formation for the forested floodplain of the Bouinenc (Figure 6-3A). This map gives for each point of the floodplain the last date at which the point was included in the active channel. A mosaic of dated remnant surfaces was provided and used to characterize the active channel elevation at each date. The systematic analysis of remnant surfaces elevations allowed for the reconstruction of the long-profile evolution of the 3-km reach (Figure 6-3B). This analysis revealed that channel narrowing was associated with a substantial channel incision along the entire reach.

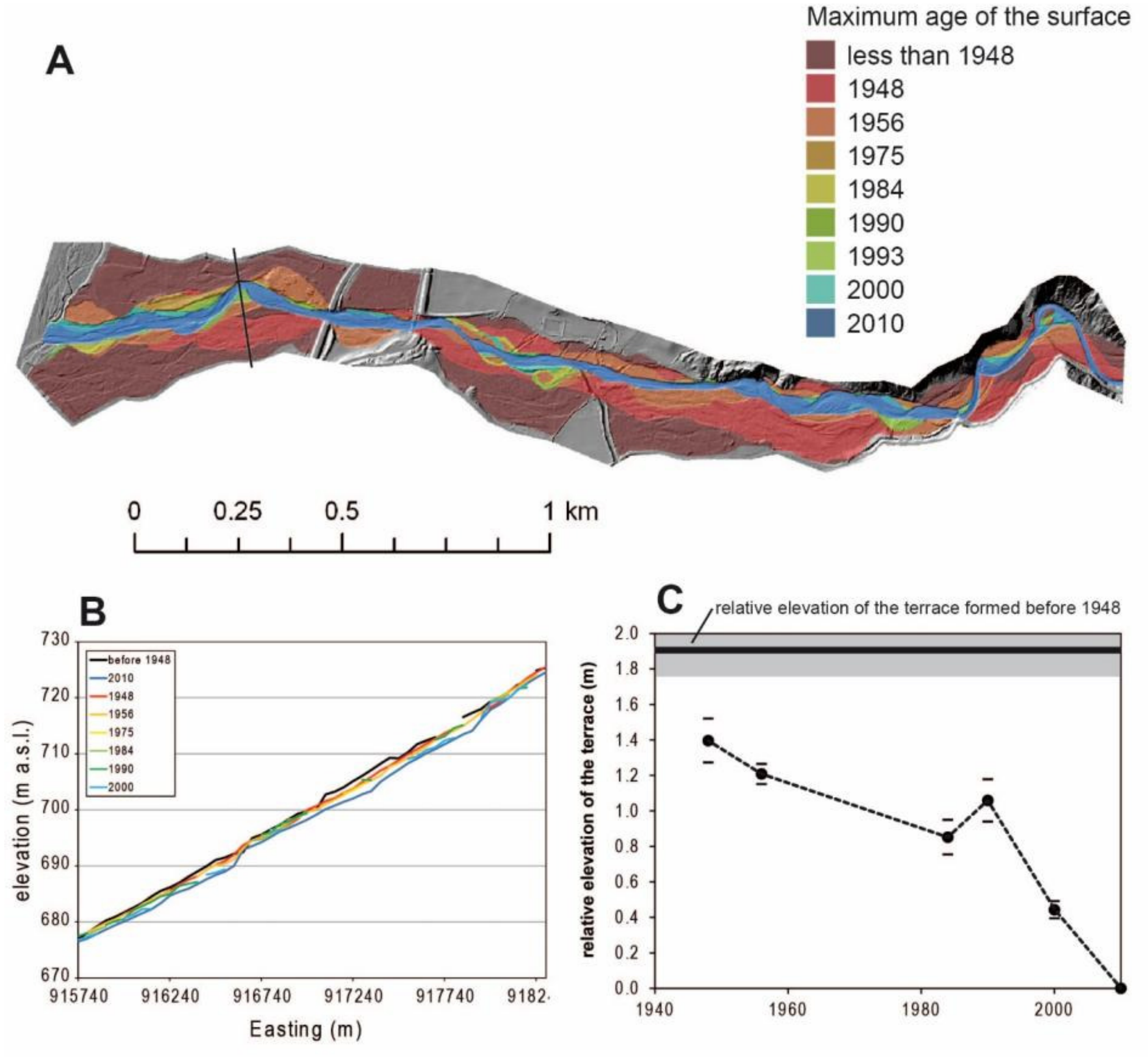

Figure 6-3: Historical analysis of channel changes for the Bouinenc Torrent: (A) dating of terrace formation from historical aerial photographs (background: hillshade view of the LiDAR derived 2010 DEM); (B) long-profile evolution of the Bouinenc Torrent derived from historical aerial photos and LiDAR data; (C) relative elevation of remnant surfaces as a function of time; the black solid horizontal line shows the relative elevation of the surfaces abandoned before 1948; the grey rectangle shows one standard error buffer around the line; error bars of points correspond to one standard error from the mean. Figure modified from case study 8.7 (Annex).

The combination of historical aerial photographs and high-resolution LiDAR data proved to be an efficient method for the reconstruction of channel changes of the Bouinenc Torrent during the last 60 years. A strong active channel narrowing was detected during the 1950s and 1960s, which was associated with a shift from braided to wandering pattern. This is in perfect agreement with channel changes observed along other torrents in the Southwestern Prealps (Liébault et al., 2005), where a downstream progressing channel narrowing was associated with the effect of spontaneous reforestation due to rural depopulation. This is also the case in the Bouinenc, where the forest cover increased due to both torrent-control works and a decreasing demographic pressure. It is also interesting to see that the active channel of the torrent did not increased during the recent period, under the effect of large floods in 1962, 1986 and 1994. This can be explained by the decreasing sediment supply from the catchment, which prevents the reactivation of a braided channel pattern.

The long-profile extraction from LiDAR points on dated remnant surfaces revealed at least two periods of channel incision (Figure 6-3C). The one observed during the 1950s and 1960s can be clearly associated with the effect of reforestation after the Second World War, already demonstrated in the Southern Prealps (Taillefumier and Piégay, 2003). The second phase of incision, which started in the 1990s, is more difficult to explain. One possibility is that it corresponds to the recovery of a possible aggradation following the 1986 and 1994 large floods (attested by the comparison of 1984 and 1990 remnant surfaces). If this scenario is correct, it implies that the present-day entrenchment was already reached in 1975. This is partly suggested by the lack of remnant surfaces of the 1975 active channel.

6.2.2 Saldur River basin (CNR-IRPI Padova and UNIMIB)

The Saldur River basin is a 97-km² glacier-fed drainage basin located in the Mid-Venosta valley where a specific analysis of landscape history imprints on present-day sediment cascade was implemented. Historical information was used to gain a better picture of the colluvial sediment cascade in a formerly glaciated environment, recently affected by glacial retreat and permafrost degradation. The spatial distribution of glacial and periglacial inherited landforms was used to assess their influence on the colluvial sediment cascade. Historical aerial photographs were used to reconstruct source-to-sink colluvial sedimentary pathways and to compare them with a geomorphometry-based sediment connectivity map using the tool developed by Cavalli et al. (2013).

Eight sets of aerial photographs dating from 1959 to 2012 were used to produce a compilation of colluvial sediment sources, including debris slides, debris flows, surficial erosion patches, and bank collapses. For each sediment source, a binary subdivision into initiation-transportation and deposition zones was done, following the procedures detailed in Brardinoni et al (2003, 2009). Simultaneously, via visual inspection of aerial photos and a LiDAR-derived shaded relief map, an inventory of glacial (moraine ridges) and periglacial (rock glaciers, protalus ramparts, creeping debris lobes) imprints was done. This photointerpretation analysis was complemented by field surveys in summer 2013 and 2014. Technical specifications about these procedures are available in the Annex section of the report (8.2).

The exploitation of historical aerial photos resulted in a spatial inventory of 998 discrete mass wasting events during a 53-yrs period (Figure 6-4), which mobilized an estimated volume of ~1 Mm^3. The mapping of source-to-sink sedimentary pathways indicated that about 59% of this volume reached the ephemeral or perennial stream network.

Geomorphic mapping revealed that periglacial depositional landforms are major landscape components in the Saldur River basin, where 126 rock glaciers, 28 protalus ramparts, and 209 creeping debris lobes were identified (Figure 6-4). In addition, 101 segments of moraine ridges were mapped. The qualitative analysis of the effect of these inherited landforms on colluvial sediment sources revealed a variety of situation: partial sedimentary disconnection between hillslopes and valley floor by the Little Ice Age moraines (Site 1 in Figure 6-4B), complete sedimentary disconnection by older and larger lateral moraines (Site 2 in Figure 6-4B), and funnel effect by moraine structures associated with tributary glaciers (Site 3 in Figure 6-4B).

Testing of the topography-based sediment connectivity index's ability to detect these contrasting imprint effects on the colluvial sediment cascade was done using the Saldur River mainstem as the sedimentary sink (a detailed presentation of the results is available in the Annex 8.2). A comprehensive analysis of the results revealed that to obtain a more realistic assessment of sediment connectivity in high mountain basins similar to the Saldur River basin, it is critical to combine the multitemporal mapping of sediment sources, the mapping of glacial and periglacial depositional landforms, and the geomorphometry-based, spatially-distributed index of sediment connectivity. Equally important, this approach holds critical implications for evaluating landscape response to climate change in steep, permafrost-prone areas, as well as for assessing mass wasting-related hazard. In particular, those sites that today lie well within the domain of discontinuous alpine permafrost and that display counterintuitive medium-to-high sediment connectivity values, such as intact rock glaciers and creeping debris lobes, are characterized by topographic conditions (high slope, high drainage area, and/or high stream power index) that might favour slope instability and catastrophic in-channel sediment evacuation where climate scenarios foresee fast permafrost degradation and glacial retreat.

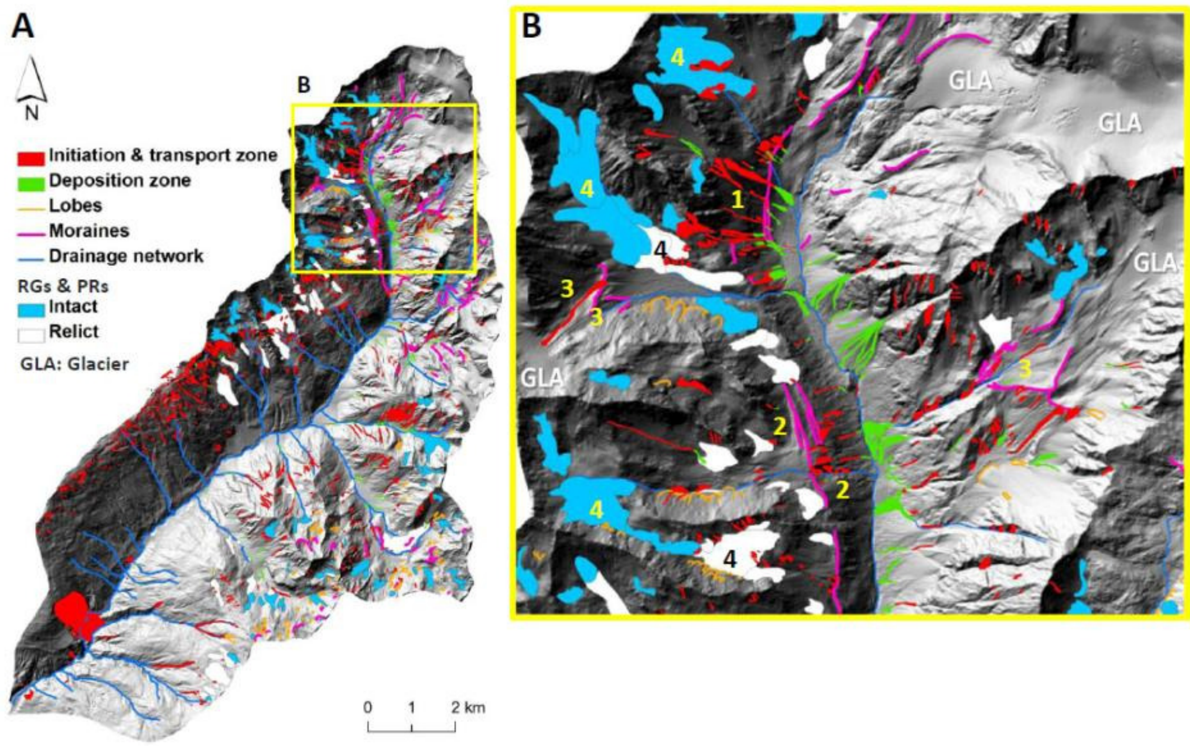

Figure 6-4: Saldur River basin: (A) Mapping of sediment sources, glacial and periglacial depositional landforms; (B) close-up view of the Upper Saldur River basin in which are apparent differences in the spatial distribution of landforms and deposition zones between the two valley sides. Figure taken from case study 8.2 (Annex).

6.2.3 Maira River basin (Piemonte Region)

An historical analysis was conducted on the Upper Maira River basin in the Piemonte Region, Italy, to study the effects of an extreme flood which occurred in June 1957. A general presentation of the study site is available in the annex of the report (8.3). We know from historical data about extreme floods in this valley that the 3 main damaging events occurred in 1900, 1948, and 1957. In 1957, between June 12th and 15th, a major rainfall event affected almost all the Piemonte Region, and induced a dramatic flood in the Maira River valley, as well as several significant landslides on the hillslopes. For some of the western Piemont valleys (Stura di Demonte, Maira, Varaita and Susa valleys), the 1957 flood event is the largest event recorded for the 20th century. The historical reconstruction of the flood was only documented for the Acceglio village where damaging effects were mainly induced by the Mollasco Torrent, a left-bank tributary to the Maira River which joins the mainstream just upstream from the Acceglio village.

According to the available historical information, it has been possible to show that coarse sediment coming from several debris flows of the Mollasco Torrent play a critical role during the flood, notably be inducing channel defluviation on the alluvial fan of the torrent, but also on the mainstream (Figure 6-5A). Dramatic active channel aggradation and widening along the Maira River can be detected downstream of the Mollasco confluence on old pictures taken just after the flood (Figure 6-5B). Most of the damages on buildings as well as bankfull overflooding can be clearly associated with the sediment wave coming from the Mollasco Torrent (Figure 6-5C and D). All these information were used to reconstruct the flooding area of the 1957 event.

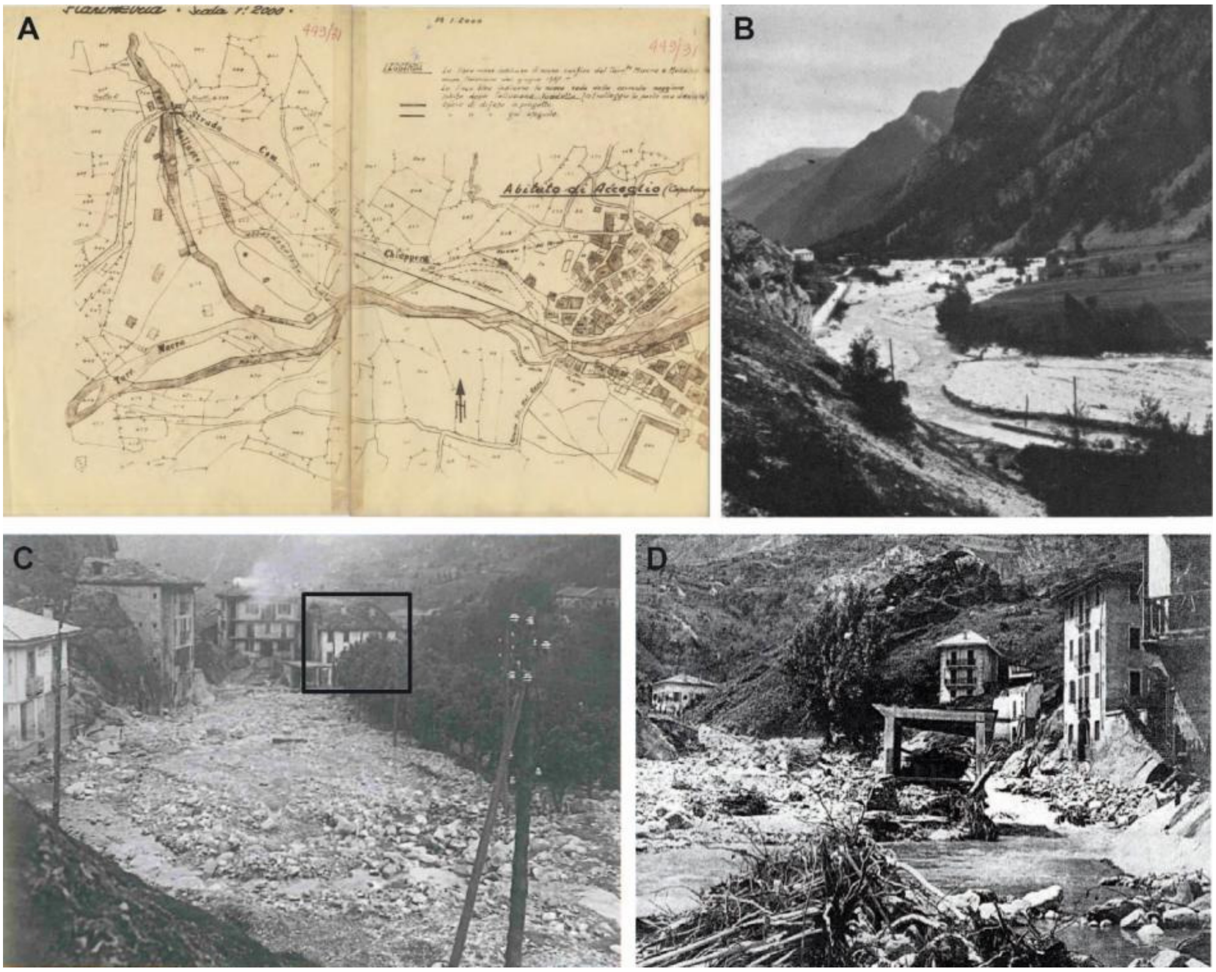

Figure 6-5: Historical data collected for the reconstruction of the June 1957 extreme flood of the Maira River in the village of Acceglio, Piemonte Region, Italy: (A) Map of the Maira-Mollasco confluence showing defluviations of river courses during the flood (light grey: river courses before the flood, dark greys: river courses after the flood); (B) active channel widening and aggradation of the Maira River downstream from Acceglio, with important bank erosion and road destruction on the left side of the valley (view looking

downstream); (C) Maira River in Acceglio after the 1948 flood; the underlined building was destroyed during the 1957 flood; (D) Damages induced by the 1957 flood in Acceglio.

6.3 Recommendations / Perspectives

- Small alluvial alpine streams (tributaries to large alpine rivers) are excellent field laboratories for looking at the effect of land-use and climate changes on sediment regime alterations. Such effects are much more difficult to detect in large alpine rivers, where the channel history also integrates the impact of gravel mining, dams, and embankments
- The fusion of historical aerial photos and recent lidar surveys proved to be an effective way for dating recent terraces and reconstruct the time evolution of active channel elevation (and detect the critical periods of channel incision/aggradation)
- A general decline of sediment supply is observed in unglaciated prealpine torrents in France and Italy, under the effect of reforestation (rural depopulation, torrent-control works) and climate change (end of the Little Ice Age). Downstream progressing incision on these torrents sustained the sediment supply to large alpine rivers, and the impact of sediment supply decline on large rivers may have not yet been observed due to time lag effect
- Recent geomorphic trajectories of active channels reconstructed with aerial photos and lidar surveys are excellent indicators of recovery potential of impacted river channels (gravel mining, power plants), notably in case of recent large floods
- To obtain a robust assessment of sediment connectivity in high mountain basins, it is critical to combine the multitemporal mapping of sediment sources, the mapping of glacial and periglacial depositional landforms, and the geomorphometry-based, spatially-distributed index of sediment connectivity

7 Conclusions and outlook

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This chapter consists of two sections that summarise WP4-related work developed in this report. In section 7.1, the main scientific results from the case studies and their implications are summarized. Based on these results, section 7.2 lists a series of recommendations for policymakers (7.2.1), practitioners (7.2.2) and research (7.2.3).

7.1 Summary of WP4 key outputs

7.1.1 Erosion and sediment production

A significant step forward in sediment source mapping for alpine environments

A comprehensive analysis of the sediment cascade in alpine river basins should start by the detection and characterization of sediment sources. Several original methods were implemented during the project to capture the spatial and/or temporal variability of sediment sources, at local and regional scales. Four illustrative sediment source maps of large and small alpine basins (from around 10 to 1000 km²) were provided and give to practitioners some examples of products that can be achieved using the different approaches used by the project partners. The automatic detection of active erosion on hillslopes from a remote-sensing approach was proved to be an efficient way for constraining sediment supply conditions at the regional scale. Several applications of change detection using sequential LiDAR surveys illustrate how such data can be useful for capturing the most active sediment sources over short timescales. The stereographic inspection of sequential aerial photosets provided multitemporal sediment source inventories for a larger time window, and can be complementary to recent LiDAR data for obtaining a more comprehensive picture of sediment supply conditions.

New high-resolution observations of erosion rates from active sediment production zones of the Alpine Space

Change detection from sequential terrestrial or airborne LiDAR data was implemented in several active sediment production zones of the Alpine Space to provide new data on time-integrated erosion rates of hillslopes feeding stream channels with sediment. Several case studies from the project illustrate how these data can be processed to isolate geomorphic changes from noise, to characterize the spatial variability of uncertainty for change detection, and to provide a sound catchment-scale sediment budget. Results indicate that punctual hot spots of erosion in the Alps (like gully complexes entrenched into deposits from the Last Glacial Maximum) are of critical importance for assessing the sediment input to alpine rivers, since they can erode at rates exceeding 10 cm/yr (measured over a 3-yr period). A regional inventory of such landforms could be of great interest for the assessment of their contribution to the sediment supply of large alpine rivers.

7.1.2 Integrated sediment cascade

Fluvial Corridor Toolbox: a new GIS-tool for characterizing fluvial corridor networks

Both for scientists and river basin managers, development of automated GIS tools is essential today to characterize riverscape and explore biogeomorphic processes over large channel networks and notably connectivity. Since the 1990s GIS toolboxes and add-in programs have been used to characterize catchments. However, there is currently no equivalent to a planimetric and longitudinal characterization of fluvial corridor networks at multiple scales. This is why the Fluvial Corridor toolbox has been developed within the project. This package allows (i) to extract a large set of riverscape features such as the main components of fluvial corridors from DEM and vector layers (e.g. stream network or valley bottom), and (ii) to provide spatial aggregation into homogeneous segments and metrics characterizing each of them.

The Fluvial Corridor Toolbox is described in Annex 9.2.

A new GIS-tool for assessing sediment connectivity in alpine basins

Connectivity information is useful for understanding, predicting, and managing sediment dynamics at the catchment scale, e.g. by identifying areas effectively supplying sediment to the channel network. For this reason, a reliable assessment of sediment connectivity has important implications on hazard assessment, also in relation to priorities of intervention at the catchment scale. GIS-based tools (both for proprietary software suites and as a free toolbox) have been developed during the project and are made freely available to assess the spatial pattern of connectivity based on a spatially distributed index that can be computed on a high-resolution DEM (see Annex 9.1).

Historical analysis of alpine basins: exploring the time dimension of the sediment cascade

Alpine river basins can be viewed as physical systems with a memory, in the sense that their present-day functioning may be more or less influenced by past events. Geomorphic responses of these basins are also integrating a complex history of human disturbances, from the widespread deforestation of the 18th and 19th centuries to the recent impacts from engineering works, gravel mining, or dam construction. It is therefore very challenging to isolate the respective contribution of past and present conditions in the geomorphic signal, although this is generally important for sediment management issues in alpine basins. One way to handle this issue is to read the historical record of alpine basins and to combine this information with high-resolution DEMs derived from LiDAR data. Some examples of such approach are provided in the project, for reconstructing the time evolution of channel incision subsequent to catchment reforestation, or for looking at the effect of glacial imprints on source-to-sink colluvial pathways in a formerly glaciated setting.

7.2 Recommendations

7.2.1 For policymakers

Promote a basin-scale approach of sediment management issues

This is needed for understanding the geomorphic evolution of a river channel (e.g. aggradation/degradation) through geomorphological mapping and analysis of historical maps and aerial photos, and proposing reliable solutions for both natural hazard and environmental management.

Support the collection of high-resolution LiDAR surveys of alpine catchments, and make data available at no or low cost

The present-day situation within the Alpine Space is extremely heterogeneous on the regional level with respect to data coverage (none, patchy, complete), availability (data should be acquired for and distributed by official authorities), and cost (ranging from free distribution to rates that are prohibitively high for universities and small enterprises). A first priority is to achieve complete areal coverage in order to enable mapping of sediment sources, connectivity assessment, and modelling of sediment transfer. A second priority is to establish regular repeat surveys (e.g. every 3-5 years); multitemporal surveys are indispensable tools for change detection and quantification, and finally for prioritization of management decisions.

Establish and maintain accessible archives of historical aerial photographs in digital form

Digital archives of historical maps, aerial photos and other documents serves not only the conservation of historical data for future generations; such data have proven to be of great interest for reconstructing the long-term evolution of catchments, representing strategic material for the interpretation of present-day observations and for supporting management decisions. The application of cutting-edge digital techniques for the generation of historical orthophotos and for the extraction of multitemporal DEMs requires the use of high-quality scanners for digitizing.

Promote research on sediment continuity in alpine basins

The scientific understanding of sediment transfer in the alpine environment is facing the extreme complexity of fluvial systems inside which these processes operate. Several research gaps are identified, notably concerning the sediment connectivity between hillslopes and channels, the discontinuous nature of sediment transfer along the stream network and its consequence on the response time to disturbances related to climate or land-use changes. It is also imperative to improve the understanding of interactions between sediment transfer and ecological continuity of alpine rivers. This is a prerequisite for the emergence of sustainable river restoration programs. It is therefore recommended to maintain a substantial level of scientific investment in this field, notably by promoting collaborations between river ecologists and specialists of sediment transport and river morphology.

7.2.2 For practitioners

Sediment management strategies of alpine rivers must be based on a comprehensive basin-scale analysis of the sediment cascade

This cannot be achieved without a strong background in geomorphology (a "cookbook" approach is not appropriate for dealing with complex fluvial system).

Promoting GIS and remote sensing approaches for sediment management in the Alpine Space.

Data from leading-edge technology (LiDAR, high-resolution imagery…) are becoming more and more common and this project provides many examples of the practical applications of these data for sediment management issues. However, these data are not easy to use and a strong background in remote sensing and GIS sciences is necessary before producing relevant information for sediment analysis (e.g. uncertainty analysis of change detection and quantification of sediment yield).

The possibility to relate a spatial characterization of sediment connectivity to sediment sources inventory can improve hazard and risk assessment of catastrophic processes like debris flows

With this integrated approach, it is indeed possible not only to evaluate the general availability of sediment but also to estimate the potential for this sediment to reach specific targets of interest. For a reliable assessment of sediment connectivity in high mountain basins, GIS-based connectivity approach should be complemented with the mapping (or at least the identification) of glacial and periglacial depositional landforms since their distribution strongly influences the distribution of active sediment sources and connectivity pattern (i.e., source-to-sink colluvial pathways).

Integrating present-day sediment dynamics within the historical dimension of alpine basins

Several case studies of the project highlighted the importance of glacial and periglacial imprints in the present-day sediment dynamics of alpine basins. A better integration of these heritages from the past can be done by a systematic geomorphological mapping of catchment in practical studies of sediment-related issues. The project also claims for a better integration of the recent history of alpine rivers in practical studies, since this analysis provides some critical insights into the geomorphic trajectories of fluvial systems. This is the best guarantee against failure of management actions related to stream restoration and against undesirable impacts of protection measures against floods and sediment disasters.

7.2.3 For research

Promoting integration of GIS and field-based approaches of the sediment cascade

Future research needs include an improved field parameterization /calibration of GIS-based indices and sediment fluxes across spatial scales. For example, there is a general lack of empirical data for translating remotely-sensed sediment source areas in rates of mobilized volumes at the regional scale (e.g., area-volume relations for different physiographic regions). This in turn would allow compiling and constraining envelopes of measured sediment yield as a function of sediment contributing area. The expected increasing availability of high-resolution DEMs at regional scale would also require new research efforts on the development and field calibration of new simple and fast geomorphic indicators, applicable at the regional scale, for sediment cascade analysis.

8 Annex: Case studies

The Annex contains eight detailed case studies that form the basis for this report. In addition, two chapters describe software tools related to the analysis of digital spatial data that were developed and/or used in the SedAlp framework.

9 References

This chapter contains the list of references for the report. See the Annex for literature cited in the case studies.

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