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## 27. Fluxes of water, sediment and dissolved substances in geomorphologically active/changing environments


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# 27. Fluxes of water, sediment and dissolved substances in geomorphologically active/changing environments

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*Swiss Geomorphological Society*

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## 27.1

# Biochar erosion: A potential threat to its suitability for carbon sequestration?

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Biochar is often considered to be a 'soft' geo-engineering option, with the potential to encourage soils to sequester more carbon (C) from the atmospheric C pool, and so increase both medium- and long-term soil C stocks. Similar to soil organic carbon (SOC), biochar has a lower bulk density than typical agricultural soils. Therefore, the question about its preferential mobilization and redistribution in the landscape has been raised in recent years. This is especially relevant on soils, which are regularly cultivated and are vulnerable to soil erosion themselves. However, so far few studies about the erodibility and fate of biochar in the landscape exist and the answer to this question is still unknown. Since the efficacy of biochar for sequestering carbon and improving soil quality depends on its amount and residential time in the upper soil matrix, it is important to further our knowledge about mobilization and transport behaviour of biochar. Moreover, such knowledge could have profound economic implications for farmers committed to its use, as a high net annual loss of biochar by erosion could exceed any net annual economic gain. The overall objective of this study was, therefore, to investigate the erodibility of biochar, when erosion events occur directly or soon after its application. The estimation of the financial value of the eroded biochar and its cost-effectiveness were scaled up from plot to field scale.

In this investigation, the biochar was applied to the soil surface of three plots on a recently cultivated sandy field near Viborg in northern Jutland, Denmark at concentrations equivalent to 1.5-2.0 kg $m^{-2}$. After application, the biochar was manually incorporated into the till-zone (20cm). Three consecutive erosion events (each lasted for 30 min. with rainfall intensity of approx. 90 mm $h^{-1}$) were conducted on both biochar and reference plots. The erosion events were generated by the 2.2 $m^{-2}$ Portable Wind and Rainfall Simulator.

The preliminary results of this study show that the sediment from plots with biochar application contains more carbon than sediment eroded from reference plots. Results based on floating biochar particles indicate that a considerable amount of biochar can be eroded from the fields within the first rainfall events after biochar application to the soil, most likely causing a reduction in the capability to sequester carbon. The economic loss of the floating biochar particles from a single event account for 3-32 €/ha, depending on the carbon content of the biochar and the erodibility of the soil. This seems to be negligible, but considering that the amount of applied biochar was very low and that erosion events occur more often than once in Denmark and most probably even more frequently under future climate conditions, the economic losses to landowners could be severe.

## 27.2

# Does the invasive plant, *Impatiens glandulifera*, influence soil flux from riparian zones? An investigation on a small watercourse in northwest Switzerland

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*Impatiens glandulifera* (common English name: Himalayan Balsam) was introduced into Europe in the mid-19th century. Its invasive tendency has facilitated its expansion throughout much of mainland Europe due to certain lifecycle traits that have facilitated its rapid establishment and have allowed it to out-compete most native floral species. Its favoured habitat includes damp, nutrient-rich soils which experience frequent natural disturbance, such as riparian zones. Once present, watercourses then inadvertently act as conduits that facilitate the downstream movement of seeds into un-contaminated parts of the catchment. Deposited seeds then germinate and form discrete mono-cultural stands of plants. These can typically range from a few $m^{-2}$ to > 400 $m^{-2}$. *Impatiens glandulifera* is cold-intolerant, however, and in temperate countries is rapidly killed by the first frosts. When die-back occurs, the dense vegetation canopy previously affording protection to the underlying soil surface from erosion processes is reduced. This can potentially increase the susceptibility of those areas to soil erosion, particularly by impacting raindrops. This paper reports the preliminary findings from on-going work conducted in a contaminated sub-catchment of the Birs River in northwest Switzerland. The investigation sought to quantify soil loss from a number of discrete riparian areas occupied by *I. glandulifera* before, during and after the die-back period. A technique using erosion pins and a profile bridge was employed to measure changes in the soil surface over a ca. 5-month period. Initial soil surface profiles were established at six contaminated sites before die-back occurred, as well as at six nearby uncontaminated reference sites. Soil surface profiles at all 12 sites were then re-measured at regular intervals. The average change in the soil surface profile was quantified for each transect and the results from both sets of transects were statistically compared. Significantly more sediment was lost from contaminated sites than from comparable reference sites. This is attributed to the presence of *I. glandulifera* and its role in promoting soil erosion along riparian zones. This finding could have important implications for water quality and for future river management strategies in all affected catchments in Europe, and be of particular relevance to European Union (EU) member states, since those countries are committed by the Water Framework Directive (WFD) to having their waterways in good ecological and chemical condition by the 2015 implementation date.

# 27.6

# Vanishing glaciers, degrading permafrost, new lakes and increasing probability of extreme floods from impact waves in cold mountain chains

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As a consequence of continued global warming, rapid and fundamental changes are taking place in high-mountain regions. Within decades only, many still existing glacier landscapes will probably transform into new and strongly different landscapes of bare bedrock, loose debris, numerous lakes and sparse vegetation. These new landscapes are then likely to persist for centuries if not millennia to come. During variable but mostly extended parts of this future time period, they will be characterized by pronounced disequilibria within their geo- and ecosystems. Such disequilibria include a long-term stability reduction of steep/icy mountain slopes as a slow and delayed reaction to stress redistribution following debuttressing by vanishing glaciers and to changes in strength and hydraulic permeability caused by permafrost warming and degradation. With the formation of many new lakes in close neighborhood to, or even directly at the foot of, so-affected slopes, the probability of far-reaching flood waves from large rock falls into lakes is likely to increase over extended time periods.

Quantitative information for anticipating possible developments exists in the European Alps. The present (2013) glacier cover is some 1700 $km^2$ with an average annual loss rate in area of about 40 $km^2$; the still existing total ice volume can be estimated at 80 ± 20 $km^3$ with an average loss rate of about 2 $km^3$ ice per year (updated from Haeberli et al., 2013). The permafrost area has recently been estimated at some 3000 $km^2$ with a total subsurface ice volume of 25 ± 2 $km^3$ (Böckli, 2013); loss rates are hardly known but are certainly much smaller than for glaciers – probably by at least a factor of 10. Based on a detailed study for the Swiss Alps, total future lake volume may be assumed to be a few percent of the presently remaining glacier volume, i.e. a few $km^3$ for the entire Alps (Linsbauer et al., 2012). Forward projection of such numbers into the future indicates that glacier volumes tend to vanish much more rapidly than volumes of subsurface ice in permafrost, and lake volumes are likely to steadily increase. Already during the second half of the 21st century, more subsurface ice in permafrost may remain than surface ice in glaciers. The new lakes will then coexist with, or even be surrounded by, largely de-glaciated/de-buttressed over-steepened slopes and mountain peaks with thermally disturbed and degrading permafrost (Haeberli, 2013).

Similar scenarios are likely to take place in many cold mountain chains. Using integrated spatial information on glacier/permafrost evolution and lake formation together with models for rapid mass movements, impact waves and flood propagation in connection with vulnerability considerations related to settlements and infrastructure, hot spots of future hazards from flood waves caused by large rock falls into lakes can already now be recognized in possibly affected regions. This enables in-time planning of risk reduction options, which may include adapted spatial planning, early-warning systems, improved preparedness of local people and institutions, artificial lake drainage or lake-level lowering (Fig. 1), and flood retention optimally in connection with multipurpose structures for hydropower production and/or irrigation.

Figure 1. Laguna Llaca near Huaraz in 2013. Since the 1960s, the level of this lake at the foot of Nevado Ranrapalca (6162 m; background) was artificially lowered by about 30 m, greatly reducing the lake volume and the potential for large impact waves

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## 27.4

# The effect of aggregation onto the fate of eroded carbon

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The effect of soil erosion on the global Carbon (C) cycle is subject of an intense debate. The controversy is mostly due to the lack of understanding of the fate of transported C from the source of erosion to the eventual site of deposition. The fate of eroded carbon is strongly influenced by the settling velocities of the eroded fractions and the corresponding transport distance and environment at the site of deposition. Some erosion/deposition models already include the settling velocity of particles to evaluate the sediment transport distance and selective redistribution after erosion. However, the settling velocities in these models are either based on grain size (e.g. the EUROSEM model) or an arbitrary number of size classes (e.g. the WEPP model and the Hairsine-Rose model). In reality, most soil is eroded as aggregates, or at least aggregates are present in the sediment, which affects settling velocity and C content of the eroded soil. Without considering the effects of aggregation on sediment movement and C content, the extent of mineralization of deposited C as well as the transfer of organic C to aquatic systems is likely to be incorrect.

To identify the effect of aggregation on the fate of eroded C, a rainfall simulation was carried out on two soils of distinct texture and structure. The eroded sediments were then fractionated by a settling tube apparatus according to their likely transport distance after erosion. The sediment of each class was incubated for 50 days to monitor the respiration rate.

Weight, total organic carbon (TOC) of the sediment in each class were also measured. The distribution of C across our settling velocity classes indicates that most of the eroded C was incorporated in coarse aggregates that would have been deposited after short transport distances. This portion likely to be deposited across the landscape carried 58.8 to 88.2% of the total organic C stock in the eroded sediment and released about 55.4 to 81.9% of the total sediment $CO_2$ emission. The fine sediment likely transferred into rivers contained 3.6 to 7.4% of the total organic C stock and produced about 6.1 to 17.3% of the total $CO_2$ emission. As a consequence, if C erosion and mineralization had been solely based on grain size and associated C, the potential release of $CO_2$ during transport would have been underestimated. Future research should account for the effects of transport processes in a real field environment.

# 27.5

# The impacts of climatically-driven hydrological flux upon coarse sediment flux in Alpine river basins

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Both future temperature and precipitation changes could have a dramatic impact upon the geomorphic response of high mountain river basins. The availability of historical climate records and aerial image archives since the 1940s now provides the opportunity to investigate over the recent past the forcing of geomorphic systems by rapid climate change, of importance because very few studies have disentangles the signature of such change in geomorphic records. Here we consider an Alpine river basin (altitude c. 1,200 m to 3,005 m), with very little direct human impact, but where there is excellent archival imagery. The imagery reveals three distinct phases of river basin change each period corresponding almost exactly to periods of known climatic warming/cooling in the last 5 decades of the 20th Century. To evaluate this climate forcing, we test a set of plausible hypotheses using mathematical modelling. To assess possible changes in sediment production activity, we apply the 1D heat diffusion equation to the basin scale, driven using historical temperature records. This shows that one plausible explanation remains decreases/increases in the percentage of the sediment supply zone that is frozen during warming/cooling periods. To assess changes in sediment transport capacity, we apply a multi-fraction sediment transport model to the predictions from a reconstruction of basin hydrological response that begins in 1940. This reveals systematic changes in hydrological response which, notably because of non-linearities in the transport equations, translates into dramatic changes in sediment transport capacity that mirror those of possible temperature driven changes in sediment production. Thus, both of these hypotheses remain plausible and it is possible that they act synergistically to cause rapid and dramatic changes in basin sediment state. Thus, understanding climate impacts on geomorphic response requires coupled temperature-precipitation effects to be considered.

## 27.6

# Investigation of mass movement and sediment flux at the decadal scale for Alpine mountain basins using archival digital photogrammetry

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Geomorphologists developed a good level of knowledge about mass movement and sediment flux at both the event scale (through direct measurement) and over longer timescales (through erosion measurement techniques such as those based upon cosmogenic methods). However, our understanding of sediment flux at the timescale of decades to centuries is still showing a deficit, especially when we try to establish a link between anthropological influence and climate change and their impacts upon geomorphic systems. Extensive coverage of mountain environments by aerial imagery begins in the 1940s, before the period of most rapid climate warming linked to human activity, and is essential to fill this gap of knowledge. The information contained in such imagery can be unlocked applying archival digital photogrammetry and producing high precision digital elevation models (DEMs) over large spatial scales. Using the appropriate data management and error propagation methods, we are able to perform quantitative comparisons of successive DEMs to build DEMs of Differences (DoD), to reconstruct histories of mass movement and sediment flux over the timescales of decades. Interpret these results with the help of geomorphological maps unveils the different ways in which climate change impacts individual landforms. Further, a proxy for mass movement behavior can be computed using multiple flow direction and flow accumulation algorithms considering sediment budget by the use of the aforementioned DoD. By doing so, we are able to investigate how the spatial arrangement of sediment system elements determines the diffusion of climate impacts through hillslopes.

Results demonstrate how, while particular elements of the sediment flux system prove to have been much more sensitive to climatic change than others, variations in high sediment production areas do not necessarily propagate throughout the hillslope because of the presence of disconnections and sediment trapping zones. As a consequence, despite a notable sediment production at the top of the sediment cascade, alluvial fans at the valley bottom seem to be stabilized and are mostly vegetation-covered. Accordingly, we suggest that warming-driven sediment dynamics on high mountain hillslopes are highly location specific and may depend more on sediment connectivity than sediment production process themselves.

## P 27.1

# Transient sediment supply in a high-altitude Alpine environment evidenced through a $^{10}Be$ budget of the Etages catchment (French Western Alps)

Delunel R., van der Beek P.A., Bourlès D.L., Carcaillet J., Schlunegger F.

Although $^{10}Be$ concentrations in stream sediments provide useful synoptic views of catchment-wide erosion rates, little is known on the relative contributions of different sediment supply mechanisms to the acquisition of their initial signature in the headwaters. Here we address this issue by conducting a $^{10}Be$-budget of detrital materials originated from the morphogenetic domains representative of high-altitude environments of the European Alps (i.e. glacial system, high-elevation periglacial domain, intermediate rock-slope of valley walls, polygenic talus and cones at the valley bottom). We focus on the Etages catchment, located in the Ecrins-Pelvoux massif (SE France), and illustrate how in situ $^{10}Be$ concentrations can be used for tracing the origin of the sand fraction from the bedload in the trunk stream. The $^{10}Be$-budget approach conducted here reveals that $^{10}Be$ concentrations vary by a factor of ca. 50 within the Etages catchment while they display consistent distributions within each of the identified morphogenetic domain. We show in this small glaciated basin $^{10}Be$ cannot be used to constrain erosion rates, as the different morphogenetic units supply sediment with a specific $^{10}Be$ concentration and do not mix with each other within the alluvial network. The averaging principle needed to calculate erosion rates is thus not fulfilled. However, we suggest that the $^{10}Be$ signature measured in different morphogenetic domains using this budget approach serve as a detrital tracer and help illustrating the origin of bedload in dynamic and changing high-altitude alpine environments.

## P 27.2

# Experimental Investigation of the Energy-Balance of an Alpine Catchment

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Water temperature is an important environmental factor, which affects the habitat suitability of many fish species and is of central interest for many ecohydrological studies. Over the past 30 years, the scientific community has focused on the understanding and modeling of the mechanisms controlling in- stream temperature. However, the thermal regime of water in the unchanneled state has been poorly studied so far, so that the mechanisms linking precipitation temperature to the water temperature in the stream channel are still unresolved. In particular, existing stream temperature models either rely on direct measurements or on simple correlations with the air temperature to estimate the temperature of stream sources and tributaries. The present study is seen as a first step towards a more physically based computation of such temperatures. The energy balance of a small alpine catchment (20 $km^2$) is investigated in detail using a set of meteorological and hydrological observations. Particular attention is given to the physical quantities, in particular ground temperature, which affects water temperature in the unchanneled state. The database used for this study was collected over the past six years and contains meteorological data from a high-density network of wireless weather stations, as well as river stage, discharge and temperature measurements. The present work lays the foundations for the future development of an energy balance model at the catchment scale, which will be able to compute the temperature of surface, interflow, and baseflow runoffs – and therefore provide some boundary conditions to the actual stream temperature models.

# P 27.3

## Sediment on Mars: settling faster, moving slower

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Using empirical approaches developed on Earth to assess Martian hydrology based on conglomerates such as those found at Gale crater may deliver false results because Martian gravity potentially alters flow-sediment interaction compared to Earth. In this study, we report the results of our Mars Sedimentation Experiments (MarsSedEx I and II) which used settling tubes during reduced gravity flights in November 2012 (and scheduled for November 2013) on board Zero g's G-Force 1. The settling velocity data collected during the flights are compared to several models for terrestrial settling velocities. The results indicate that settling velocities on Mars are underestimated by up to 30 to 50%, depending on the selected model. As a consequence, transport distances of sediment particles increase by a similar proportion in a given flow. We suspect that the underestimation of settling velocity is caused by poor capture of flow hydraulics under reduced gravity. While MarsSedEx I (and II) results are only very preliminary, they indicate that applying empirically derived models for Earth to conglomerates such as those found at Garle crater to derive properties of surface runoff carries the risk of significantly misjudging flow depth and velocities. In the light of the potentially strong influence of topography on runoff generation on Mars, we may therefore end up looking for water in the wrong place.

# P 27.4

# Modeling process chains: rock/ice-avalanche induced outburst floods at Laguna 513, Cordillera Blanca, Peru

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Changes in the cryosphere induce as much general changes in the high-alpine environment as they induce changes in specific hazard processes. One feature are new lakes that are forming in recently deglaciated glacier beds (Linsbauer et al., 2012) underneath destabilized, oversteepened slopes and that are therewith subject to impacts from rock-/ice-avalanches (Schaub et al., in press). In Switzerland many new lakes are to form in the near to middle-term future, nevertheless several new glacier lakes have already stressed attention (Grindelwald, Plaine Morte, Trift, amongst others). In other areas of the world (such as Cordilllera Blanca, Peru) several outburst floods have happened (e.g. Laguna 513, (Carey et al., 2012)) and also caused extreme damage. In 1941, an outburst flood from the lake Palcacocha caused 4000 fatalities in the town of Huaraz (Vilímek et al, 2005). Similarly to the Peruvian setting, in Switzerland the valley bottoms are also densely populated and possible hazardous glacier lake outburst floods threaten huge damage potential.

Natural hazard processes are typically assessed as single hazards. Multi-hazard assessments of entire process chains are rarely done but are important in view of the potentially devastating effects of such events. However, in order to generate intensity or hazard maps of process chains such as a rock-/ice-avalanche triggering an impact wave in a lake, which leads to a lake outburst flood, the entire process chain has to be modeled. We here present an approach on how to connect numerical process models (RAMMS and IBER) in order to reproduce the entire process chain. As a case study, the Hualcán-south face in the Cordillera Blanca, Peru, is considered. The models were calibrated with help of the 2010 outburst event (Schneider et al, in press) and then scenarios were modeled based on estimations of future ice-avalanche detachment zones and volumes. The influence of scenario definition on hazard intensities (flood inundation, flow velocity) was evaluated to better understand the importance for hazard mapping and risk reduction measures. Results indicate, that zones of high hazard are primarily located in the vicinity of the river channel. However, large or extreme events have the potential to reach the center of Carhuaz.

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# P 27.5

## Can soil biomarkers trace floodplain contributions to organic carbon export in a pristine, tropical river system?

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Floodplains represent important biogeochemical reactors for organic matter during fluvial transport. While in temperate systems most floodplains only become inundated as part of management schemes or in extreme-weather situations, some tropical floodplains still experience natural, seasonal flooding. One such floodplain can be found in the Zambezi River Basin, the fourth largest river on the African continent. Due to its location within the Inter Tropical Convergence Zone, this system is characterized by distinct dry (April-November) and wet seasons (December-March). This seasonality has marked influence on the export of organic matter and nutrients from floodplains. Since the Zambezi is the largest African river draining into the Indian Ocean, the export of organic matter and nutrients is important for understanding elemental cycles in the western part of this ocean.

With a bigger aim to reconstruct past flooding patterns, and indirectly thus organic carbon dynamics, we present here a present-day study to investigate to what extent lipid biomarkers (specifically, glycerol dialkyl glycerol tetraethers, GDGTs), which are commonly associated with soil material, can be used to trace the contribution of floodplain-derived organic material to particulate organic carbon carried by the river mainstem. The hypothesis is that during inundation soil organic matter (including the GDGT lipids) are mobilized and entrained in the suspended load. We will describe GDGT concentrations and distributions in particulate organic matter collected immediately upstream and downstream of the Barotse Plains (Zambia), one of Africa›s major wetlands that is located in the upper reach of the Zambezi River.