NGU Report 2007.053

Analysis of Source-to-Sink-Fluxes and Sediment Budgets in Changing High-Latitude and High-Altitude Cold Environments:

SEDIFLUX Manual

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REPORT

Report no.: 2007.053	ISSN 0800-3416	Grading: Open

Title:
Analysis of Source-to-Sink-Fluxes and Sediment Budgets in Changing High-Latitude and High-Altitude Cold Environments: *SEDIFLUX Manual*

Authors: **Achim A. Beylich & Jeff Warburton (Eds.)**	Client:
County:	Commune:
Map-sheet name (M=1:250.000)	Map-sheet no. and -name (M=1:50.000)
Deposit name and grid-reference:	Number of pages: 158 Price (NOK): 200,- Map enclosures:

Fieldwork carried out:	Date of report: 01.09.2007	Project no.: 307500	Person responsible:

Summary:

This *First Edition of the SEDIFLUX Manual* is an outcome of the *European Science Foundation (ESF) Network SEDIFLUX – Sedimentary Source-to-Sink-Fluxes in Cold Environments* (2004 - 2006) (http://www.ngu.no/sediflux, http://www.esf.org/sediflux). The development of this publication has been based on four ESF SEDIFLUX Science Meetings, which were held in *Saudarkrokur (Iceland)*, June 18th – 21st, 2004, *Clermont-Ferrand (France)*, January 20th – 22nd, 2005, *Durham (UK)*, December 16th – 19th, 2005 and *Trondheim (Norway)*, October 29th – November 2nd, 2006.

The aim of this Manual is to provide guidance on developing quantitative frameworks for characterising catchment (field-based) sediment budget studies, so that: (1) *baseline measurements at SEDIFLUX/SEDIBUD key test catchments are standardised thus enabling intersite comparisons*, and (2) *long-term changes in catchment geosystems as related to climate change are well documented*. The main focus is on non-glacial processes, although within the context of glacierised catchments glacial sediment transfer processes are assumed as inputs/outputs of the periglacial / paraglacial system.

This *First Edition of the SEDIFLUX Manual* will be further developed within the *I.A.G./A.I.G. Working Group SEDIBUD – Sediment Budgets in Cold Environments* (http://www.geomorph.org/wg/wgsb.html).

Keywords: Source-to-Sink-Fluxes	Sediment Budgets	Changing Cold Environments
Catchment	Standardised Quantitative Analysis	Monitoring and Intersite Comparisons
Guidelines	Protocols	SEDIFLUX / SEDIBUD

Sedimentary Source-to-Sink-Fluxes in Cold Environments

(SEDIFLUX)

http://www.ngu.no/sediflux, http://www.esf.org/sediflux

Sediment Budgets in Cold Environments

(SEDIBUD)

http://www.geomorph.org/wg/wgsb.html

Analysis of Source-to-Sink-Fluxes and Sediment Budgets in Changing High-Latitude and High-Altitude Cold Environments

SEDIFLUX Manual

First Edition

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Preface

This *First Edition of the SEDIFLUX Manual* is an outcome of the *European Science Foundation (ESF) Network SEDIFLUX – Sedimentary Source-to-Sink-Fluxes in Cold Environments* (2004 – 2006) (http://www.ngu.no/sediflux, http://www.esf.org/sediflux) (Beylich et al., 2005; 2006). The development of this *publication* has been based on four *ESF SEDIFLUX Science Meetings*, which were held in *Sauđárkrókur (Iceland)*, June 18th – 21st, 2004, *Clermont-Ferrand (France)*, January 20th – 22nd, 2005, *Durham (UK)*, December 16th – 19th, 2005 and *Trondheim (Norway)*, October 29th - November 2nd, 2006.
The aim of this *Manual* is to provide guidance on developing quantitative frameworks for characterising catchment (field -based) sediment budget studies, so that: (1) *baseline measurements at SEDIFLUX/SEDIBUD key test catchment are standardised thus enabling intersite comparisons*, and (2) *long-term changes in catchment geosystems as related to climate change are well documented*. The main focus is on non-glacial processes, although within the context of glacierised catchments glacial sediment transfer processes are assumed as inputs/outputs of the periglacial / paraglacial system.

We would like to thank all contributing authors for their work on this *First Edition of the SEDIFLUX Manual*. We also would like to acknowledge the critical comments by numerous colleagues, which have helped to improve this *First Edition*.

This *First Edition of the SEDIFLUX Manual*' will be further developed within the *I.A.G./A.I.G. Working Group SEDIBUD – Sediment Budgets in Cold Environments* (http://www.geomorph.org/wg/wgsb.html).
Comments and suggestions for improvement of this *SEDIFLUX Manual* are very welcome.

Achim A. Beylich

Chairman

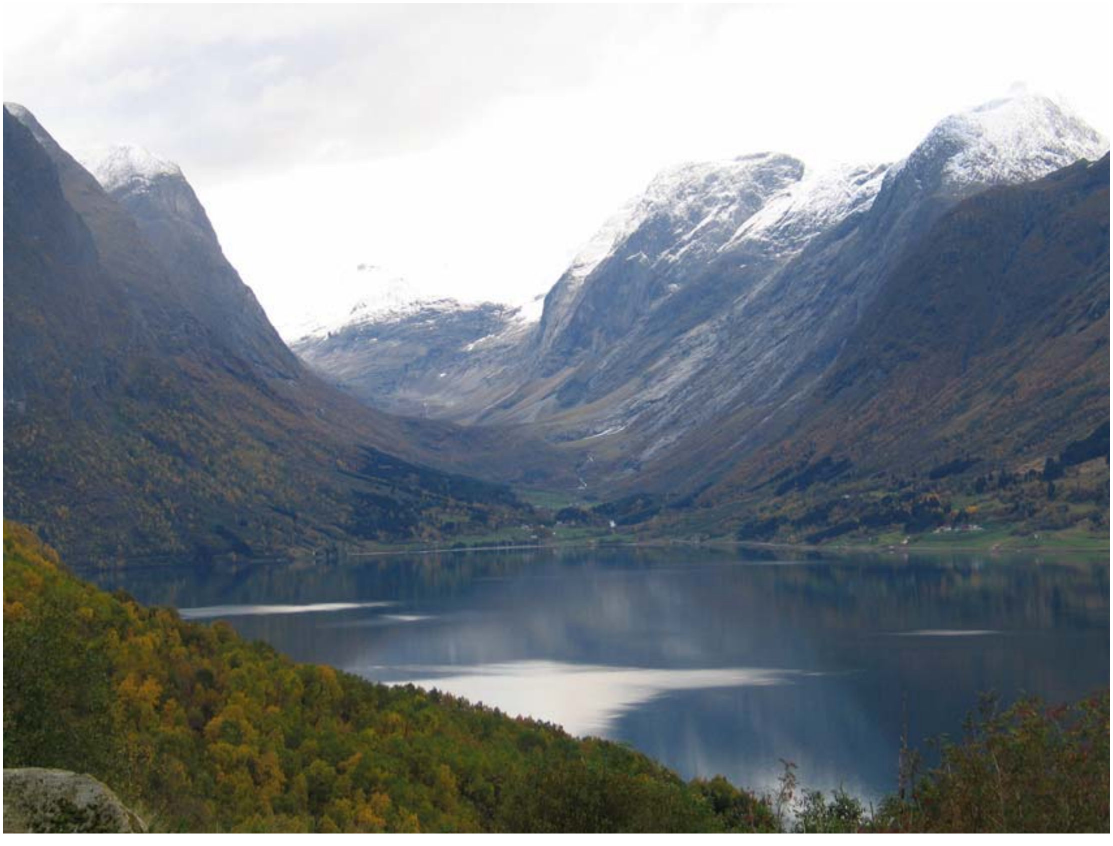
Trondheim, August 2007

ACKNOWLEDGEMENT

Thanks to Sarah Verleysdonk (University of Bonn) for assisting with several literature searches and to Rosemary Duncan (Staffordshire University) for her help with Figure 1.1.

Part A

Sediment Budget Frameworks and the Quantification of Sediment Transfer in Cold Environments



SEDIBUD Key Test Site: Erdalen (Nordfjord, Norway) (Photo by O. Fredin, NGU)

Chapter 1 – Introduction and background:

Sediment fluxes and sediment budgets in changing cold environments – a summary of key issues

1.0 SUMMARY OF CHAPTER CONTENTS

This chapter 1 provides an introduction to the *SEDIFLUX Manual*, constituting a brief review of key research on sediment budgets in cold environments. The context of, and justification for such research is explained and key terms presented and defined. The review identifies and summarises holistic issues that frame research on sediment budgets in cold environments and highlights the current state of research on sediment transfer studies in Polar, sub-Polar, alpine, fringe and glaciated catchments. The main focus is on non-glacial processes (periglacial and paraglacial sediment systems), although within the context of glacierised catchments direct glacial sediment transfer processes are treated as a separate subsystem with inputs into the larger ctachment. Glacier sediment systems are dealt with already in a range of excellent texts documenting conceptual approaches to glacial landsystems (Evans, 2003) and methods of studying these important sedimentary environments (Hubbard & Glasser, 2005).

1.1 KEY ISSUES AND CONTEXT

Geomorphologic processes, responsible for transferring sediments and effecting landform change, are highly dependent on climate, vegetation cover and human activities. It is anticipated that climate change will have a major impact on the behaviour of Earth surface systems and that the most profound changes will occur in high-latitude and high-altitude environments (Beylich et al., 2005; 2006), where rapid temperature increases could lead to potentially irreversible shifts in hydrologic regime and geomorphologic processes. Given these expected changes, it is critical to develop a better understanding of the mechanisms of sedimentary transfer processes currently operating in cold environments, their likely controls and the expected nature of responses to changing climate (e.g. Allard, 1996; Haeberli & Beniston 1998; Lamoureux, 1999; Boelhouwers et al., 2001; Ballantyne, 2002; Holmes et al., 2002; Matmon et al., 2003; Slaymaker et al., 2003; Gebhardt et al., 2005; Beylich et al., 2003; 2005; 2006). Quantitative analyses of sediment transfers have largely been confined to other climatic zones (e.g. Dunbar et al., 2000; Thomas, 2003), and therefore integrated studies of source-to-sink sediment fluxes in cold environments are overdue. Collection, comparison and evaluation of data and knowledge from a range of different high-latitude and high-altitude environments are required to permit greater understanding of sediment fluxes. Given the diverse nature of existing research in cold environments, it is also vital to develop standardised methods and approaches for future research on sediment fluxes and relationships between climate and sedimentary transfer processes. Studies of the impacts of such change over contemporary and historic timescales will provide valuable input into debates on land and resource management in cold environments and permit modelling of the effects of climate change, and related changes in vegetation cover, through space-for-time substitution (Beylich et al. 2005; 2006).

This *SEDIFLUX Manual* summarises our current understanding of sediment budgets in cold environments and provides guidelines for the monitoring of sediment budgets in small catchments. Although modelling of sediment budgets is a fundamental part of research in changing cold environments, a strong framework of monitoring and the development of standardised methods of operational data collection constitute the baseline for such modelling. Therefore, this manual focuses on the selection of critical test catchments for effective monitoring, analysis of sediment storage, analysis of present-day sediment fluxes and the integration and synthesis of data using standardised protocols (Beylich et al., 2005; 2006).

1.2 THE SIGNIFICANCE OF SEDIMENT BUDGET STUDIES

Research on sediment budgets in a variety of different environments is represented by a substantial body of literature (e.g. Rapp, 1960; Oldfield, 1977; Swanson et al., 1982; Gallie & Slaymaker, 1984; Foster et al., 1985; Gurnell & Clark, 1987; Caine & Swanson, 1989; Warburton, 1990; Jordan & Slaymaker, 1991; Caine, 1992; Beylich, 2000; accepted; Beylich et al., 2005; 2006; Holmes et al., 2002; Johnson & Warburton, 2002; Slaymaker et al., 2003; Otto & Dikau, 2004; Vezzoli, 2004; Habersack & Schober, 2005; and Nichols et al., 2005). The ‘first’ sediment budget study was developed by Jäckli (1957) working in the catchment of the Upper Rhine. The fundamentals of this approach and methodologies for the development of a sediment budget are best summarised in Reid & Dunne (1996).

A sediment budget is “an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin” (Reid & Dunne, 1996, p. 3). The development of a sediment budget necessitates the identification of processes of erosion, transportation and deposition within a catchment, and their rates and controls (Reid & Dunne, 1996; Slaymaker, 2000). The fundamental concept underpinning sediment budget studies is the basic sediment mass balance equation:

$$I = O \pm \Delta S \qquad \text{Eq. (1)}$$

Where inputs (I) equal outputs (O) plus changes in net storage of sediment (ΔS). Sediment budget studies permit quantification of the transport and storage of sediment in a system (Warburton, 1990; 1992; Reid & Dunne, 1996). A thorough understanding of the current sediment production and transport regime within a system is fundamental to predicting the likely effects of changes to the system, whether climatic-induced or human-influenced. Sediment budget research therefore enables the prediction of changes to erosion and sedimentation rates, knowledge of where sediment will be deposited, how long it will be stored and how such sediment will be re-mobilised (e.g. Gurnell & Clark, 1987; Reid & Dunne, 1996). A key utility of such research is that the empirical results of sediment budget studies can be applied to other catchments with similar land-use, geology, soils and climate providing that processes are sufficiently understood and the results recognised as estimates (Reid & Dunne, 1996).

1.3 SEDIMENT BUDGETS IN COLD ENVIRONMENTS

Geomorphological processes are dependent on climate and will be significantly affected by climate change, especially in high-latitude and high-altitude environments. Integrated research on sediment budgets has to-date been undertaken chiefly in other climatic zones; therefore understanding of sediment transfer processes is needed to determine the consequences of climate change in cold environments and the potential impacts of such changes on other parts of the Earth's surface (Beylich et al., 2005; 2006).

For the purposes of this manual, definitions of key terms are crucial. In using the term 'cold environments', we are referring to areas of the Earth's surface that show evidence of frost processes and seasonal snow cover; Tricart (1970, p.12) defined cold environments as those in which the conversion of water to the solid state plays an important role. This definition effectively delimits high-latitude and high-altitude regions, or polar, sub-polar, alpine and 'fringe' upland environments. Cold environments therefore encompass glaciated terrain and areas with frequent diurnal freeze-thaw cycles or intense seasonal frost, with or without permafrost. Such a definition is easy to apply in a broad qualitative sense, a chief distinction frequently being made between zonal (latitudinal) cold regions and azonal (altitudinal) cold environments (Hewitt, 2002). However, detailed differentiation of cold environments can be problematic as zonal and azonal cold areas can be temporally and spatially heterogeneous (Zhang et al., 2003); this has led to further distinctions, based primarily on process regime, between, for example, mountainous and lowland relief and glaciated and non-glaciated areas. Shifts in zones of continuous, discontinuous and sporadic and isolated permafrost, seasonal changes in frost activity and freeze-thaw frequency also make the accurate demarcation of cold environments somewhat difficult.

The key characteristics of sediment transfer in cold environments include: phase changes of water resulting in sediment mobilisation, seasonal transfer of sediment, glacial processes and processes intrinsic to past glaciation, ground ice dynamics and associated sediment mass transfer and direct transport processes related to frozen water (for example, avalanches, slush flows). Indirect effects of cold also act to subtly modify common weathering, fluvial, aeolian, slope and coastal process regimes (Hewitt, 2002). In cold environments, climate change influences earth surface processes not just by altering vegetation and human activities, but also through its impact on frost penetration and duration within ground surface layers. Climate change also exerts a strong control on cryospheric systems, influencing the nature and extent of glaciers and ice sheets, and the extent and severity of glacial and periglacial processes. Changes within the cryosphere have consequences for glacifluvial, aeolian and marine sediment transfer systems. All of these factors influence spatial and temporal patterns of erosion, transportation and deposition of sediments (Beylich et al., 2005; 2006).

There is often a significant imbalance between material production and transport in cold environments because of former glacial activity. The presence of glaciers and ice sheets results in the over-steepening of relief due to glacier erosion and paraglacial slope readjustment produces large sediment stores available for erosion (e.g. Ballantyne, 2000). Extensive reworking of glacigenic sediments is reported from a range of cold environments (e.g.

Barnard et al., 2006). In mountainous terrain, recent research suggests that landsliding both produces and retains large volumes of sediment accounting for partial regulation of catchment sediment flux (e.g. Korup, 2005). Research in the Himalayas, Tien Shan and New Zealand has demonstrated that rockslide and moraine dams in mountainous terrain have marked impacts on sediment budgets following failure (e.g. Cenderelli & Wohl, 2003; Korup et al., 2006). Increasing formation and drainage of moraine- and rockslide-dammed lakes is predicted to accompany climate change (e.g. Richardson & Reynolds, 2000; Chikita & Yamada, 2005). Short-term storage and release of sediment in proglacial channels controls the pattern of suspended sediment transfer from Alpine glacial basins in which significant sediment source and storage areas are exposed by glacial retreat (e.g. Orwin & Smart, 2004).

Changing hydrological regimes have implications for channel erosion, storage and aggradation in cold environments. The presence of water is as important as the severity of cold in determining sediment transfer rates through for example, the generation of excess moisture during surface thaw and melt (e.g. Matsuoka & Sakai, 1999; Hasholt et al., 2005). However, the geomorphic significance of the phase change of water from liquid to solid is still poorly understood because of the lack of data (Warburton, 2007). This has implications for the understanding of climate change impacts on cold environment sediment budgets.

There have been very few truly integrated studies of sediment transfer in cold environment catchments; exceptions are provided by Maizels, 1979; Hammer & Smith, 1983; Gurnell & Clark, 1987; Warburton, 1990; 1992; and Beylich, accepted. There is some knowledge of discrete processes and landforms in cold environment systems, but less understanding of the nature of the links between systems and their variability (e.g. Korup, 2002; Harris & Murton, 2005). This constitutes a research gap that should be addressed, especially given the backdrop of climate change.

1.3.1 THE LANDSYSTEMS FRAMEWORK

A landsystem is an area with common terrain attributes different to those of adjacent areas, and as such, is scale independent (Cooke & Doornkamp, 1990; Evans, 2003). The landsystems approach constitutes a holistic form of terrain evaluation and is useful for a variety of purposes (e.g. Cooke & Doornkamp, 1990). Landsystem classifications are usually derived from mapping where both topography and geomorphology constitute the primary differentiating criteria for assigning landsystems, each of which should, in theory, contain a predictable combination of landforms, soils and vegetation. Landsystems are divided into smaller areas termed units and elements.

In glacial, high-mountain and cold climate geomorphology, landsystems have traditionally been used as a tool for reconstruction of past glacial processes and the dynamics of ice sheets and glaciers as well as providing engineers with process-form models of glacigenic landform-sediment assemblages. The high mountain landsystem is summarized by Fookes et al. (1985); highlighting five major terrain zones: high altitude glacial and periglacial; free rock faces and debris slopes; degraded middle slopes and ancient valley floors; active lower slopes and valley floors (see Chapter 2).

Evans (2003) synthesises definitive research on glacial landsystems, building on earlier work by Clayton & Moran, (1974); Fookes et al., (1978); Eyles (1983); Brodzikowski & van Loon (1987) and Krüger (1994). A series of landsystems are presented by Evans (2003), constituting process-form models relating to specific glaciation styles and dynamics. Ancient and modern glacial landsystems are represented on a continuum of scales, from valley glaciers to ice sheets. Ballantyne (2002) applies a landsystems approach to paraglacial landforms and sediment assemblages, enabling the identification of six paraglacial landsystems, based on locational context.

A possible weakness of most landsystems classifications, and one explicitly identified by Ballantyne (2002) in the context of paraglacial landsystems, is that they do not identify the fact that different elements of the landscape evolve over different timescales or the nature of the connections between particular landsystems. The approach however, does permit the characterization of process interactions between parts of each landsystem and is therefore useful for characterising different cold environments.

1.3.2 SEDIMENT SOURCES

Sediment sources in cold environments are diverse and subject to variation in response to changing climate. Climatic warming results in the loss of glacial ice, which in turn increases avalanching, landslides and slope instability caused by glacial de-buttressing, and flooding from glacial and moraine-dammed lakes (e.g. Evans & Clague, 1994; Ballantyne, 2002). All of these processes redistribute sediment and operate at different rates as a result of change to the system. Glaciers and ice sheets exert strong controls on the supply of sediment to catchments in cold environments. Knight et al. (2002) identify the basal ice layer of a section of the Greenland ice sheet as the dominant source of sediment production. There is, however, limited knowledge of debris fluxes from ice sheets and glaciers and its variability.

1.3.3 SEDIMENT TRANSFERS

Some drainage basins are well coupled with efficient sediment transfer. The Ganges catchment is a tightly coupled source-to-sink area, the catchment basin to the coastal and marine sink, with sedimentary signals being transferred rapidly from source to sink with little attenuation (Goodbred, 2005). The tight linkage of source-to-sink component is a function of the monsoon's control of the hydrology of the region. Gordeev (2006), using models developed by Morehead et al. (2003), estimated the increase in sediment load in Arctic rivers in reponse to a rise in surface temperature of the catchments. Based on this model, concomitant increases in river discharge lead to an increase in the sediment flux of the six largest Arctic rivers, predicted to range from 30% to 122% by 2100.

1.3.4 SEDIMENT STORES/SINKS

The identification of storage elements is critical to the effective study of sediment budgets (Reid & Dunne, 1996). The setting of a particular catchment defines the boundary conditions for storage within that catchment. Within a given catchment, the slope and valley fill elements constitute the key storage units and individual landform storage volumes are important for addressing time-dependent sediment budget dynamics. Dating of storage in sediment budget studies is employed to determine the ages and chronology of the key storage components within a system; the type of dating used and the nature of the approach adopted depend on the characteristics of the catchment. Dating usually defaults to the application of relative dating methods to identify the chronology of sedimentation rather than the absolute age.

Several issues are apparent in considering the identification and quantification of sediment storages in cold environments for integration into sediment budget studies. Understanding of the nature of primary stores, secondary stores and the potential storage capacities of different types of catchment is critical along with knowledge of sediment residence times. The development of effective and innovative field methods, such as geophysical techniques for estimating sediment storage volumes in cold environments (e.g. Schrott et al., 2003; Sass, 2005) is also becoming increasingly important.

1.3.5 TIMESCALE ISSUES

Timescales exert important controls on the nature and rates of earth surface processes. Sediment output is not uniform in time; on short timescales, variability in catchment conditions causes variability in sediment production and supply (e.g. Trustrum et al., 1999) which is a product of the stochastic nature of geomorphic systems (Benda & Dunne, 1997). Despite the apparent simplicity of the sediment mass balance equation (see 1.2) characterising the sediment budget of even small catchments is difficult and extrapolating results from year to year and to other areas in similar environments even more so.

In paraglacial environments, accumulations of coarse clastic debris from the Holocene are stored in many basins and therefore the contemporary rates of sediment production are not reflected in sediment yields from such catchments (Ballantyne, 2002; Caine, 2004). There is an inverse relationship between basin area and denudation rates in numerous catchments, especially those in mountain areas, which can be attributed to increased sediment storage in large basins. Basins in unstable tectonic settings have denudation rates that are an order of magnitude higher than those in more stable tectonic settings (e.g. Ahnert, 1970). Estimations of denudation rates can be derived by other methods; for example, by examining sedimentation rates in lakes and in coastal and continental shelf environments (e.g. Dearing & Foster, 1993; Buoncristiani & Campy, 2001; Carter et al., 2002; Slaymaker et al., 2003).

There is concern over use of denudation rates for extrapolation over longer time periods, as most records of river flow and sediment yields are short (*c.* 50 years) and seldom include large events (Caine, 2004). These events are significant, particularly in mountainous environments (Beylich & Sandberg, 2005; Beylich et al., 2006). Warburton (1990) emphasises the importance of event duration in determining the final sediment budget for a system; an important consideration is the length of the study period and whether this represents processes in the catchment. For example, Walling (1978) recommended that 10 years of monitoring are required before the sediment transport system can be adequately understood, yet more recent research suggests that study periods need to be much longer to fully understand the relative importance of different processes and the magnitude of differences in sediment transfer between different cold environments (e.g. Ballantyne & Harris, 1994). Further research on lag times in different types of catchment is critical in this respect; for example, Johnson & Warburton (2005) found that steep upland catchments do not liberate eroded sediment immediately to lower elevations therefore implying that sediment yield from some systems might be less severe or more lagged than expected.

Average values for sediment fluxes neglect both the inter-annual variability in such systems and do not reflect the magnitude and frequency of geomorphic events (Wolman & Miller, 1960) leading to sediment transfer variation. The relative importance of continuous versus episodic sediment supply processes in different catchments needs to be better understood. Episodic events exert profound control on sediment budgets in cold environments, especially in high mountainous regions; for example, outburst flows from ice-, moraine- and landslide-dammed lakes can mobilise large quantities of sediment over short time periods. However, quantification of the contribution of such debris pulses to long-term sediment budgets is difficult to determine because of limited data on their recurrence and the lack of knowledge of the extent of upstream sediment input (e.g. Korup et al., 2004).

Benda & Dunne (1997), working in the Oregon Coast Range found that short-term and inter-annual variability of sediment load decreases with increasing catchment size, emphasising shifts from high-magnitude, low sediment discharge events to intermediate magnitude and frequency. Lewis et al. (2005) comment on the fact that even short-term variability in suspended sediment concentrations is seldom resolved in catchments; *ergo*, sediment fluxes from large but short-lived events are poorly documented. An understanding of the longer-term dynamics of change is necessary; in order to evaluate the significance of such change longer-term sediment budget studies need to be developed (e.g. Braun et al., 2000).

1.4 HOLISTIC FLOW MODEL

The conceptual diagram presented in Figure 1.1 illustrates primary and secondary sediment stores and identifies key sediment transfer processes, sources, transfers, sinks and linkages and sediment storage associations in cold environments. The Figures 1.1 and 1.2 provide an assessment and overview of the areas that are understood and those on which more research is required.

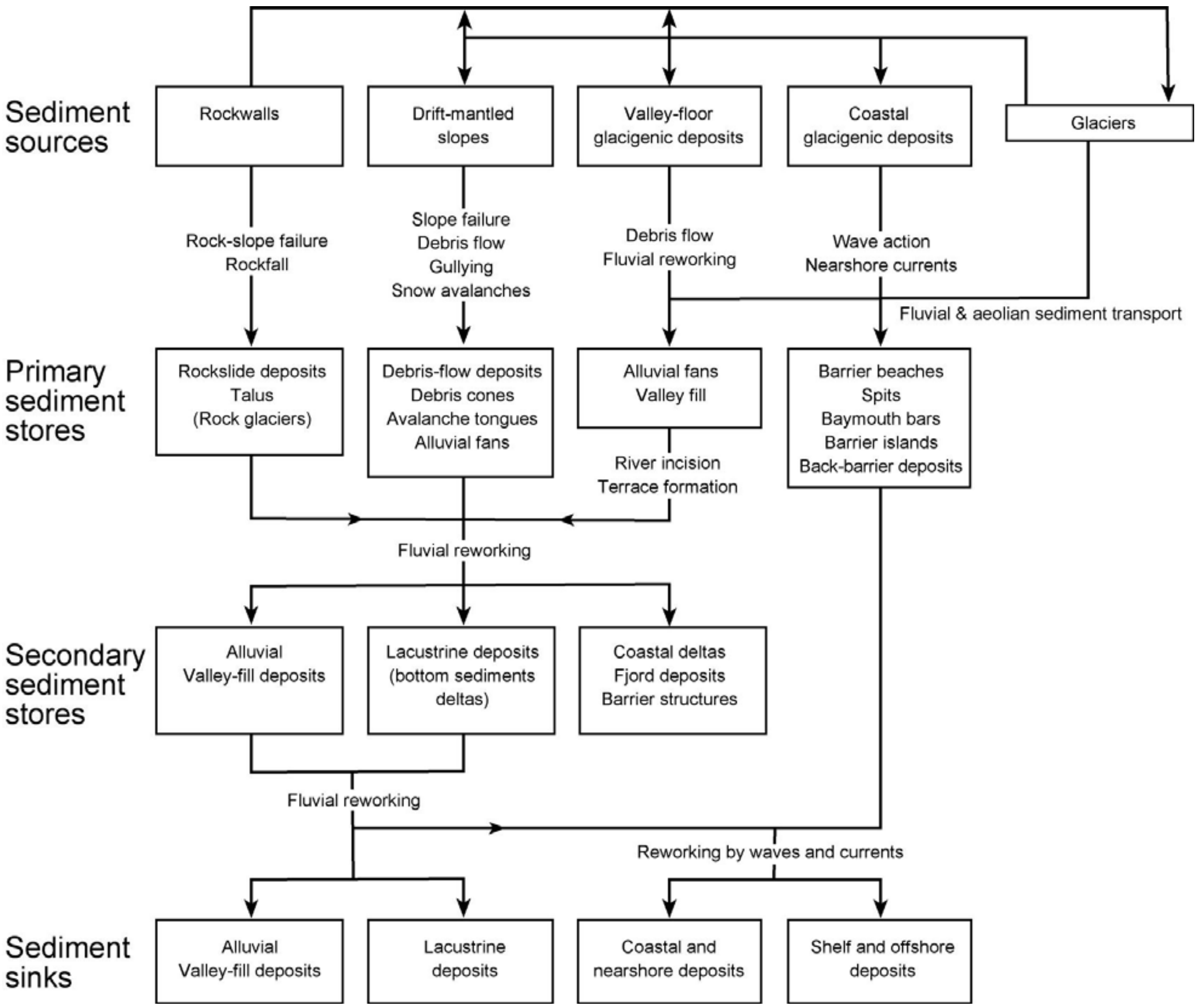


Figure 1.1. *Cold environment sediment cascade, illustrating primary and secondary sediment stores and key sediment transfer processes. Modified from Ballantyne (2002, p. 2004, Fig. 54)*

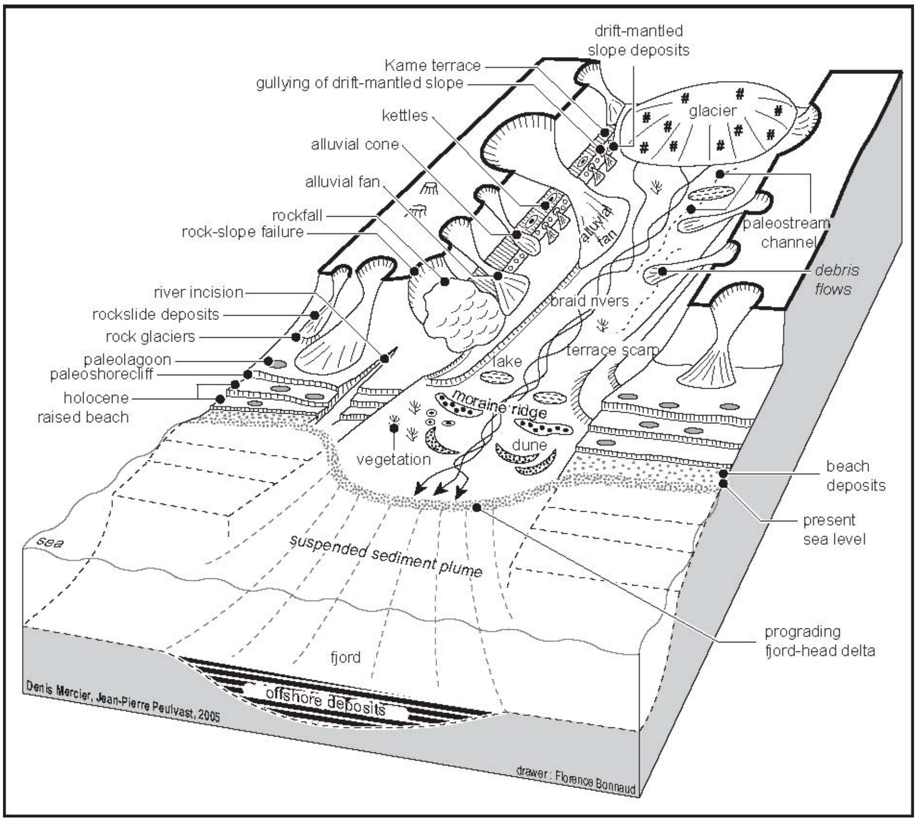


Figure 1.2. *Paraglacial landforms, fluxes and deposits in a polar environment. Modified from Mercier (2007, p. 347, Fig.3)*

1.5 CONCLUSIONS

This Chapter, by briefly summarising key conceptual issues on sediment budgets in cold environments, has provided an introduction to the main ideas, which underpin this SEDIFLUX Manual. The review has identified issues that frame research on sediment budgets in cold environments. Several important research issues and gaps have emerged from this review. Firstly, cold environments are especially sensitive to climate change has been forecast, but the nature of, and the spatial and temporal variations in, such sensitivity are the most pressing questions facing our understanding of the potential impacts of climate change in cold environments. It is apparent that there are few integrated studies of sediment transfer and that this is especially true of cold environments. Research needs to better identify the nature of the links between different landsystems, especially with regard to periglacial and glacial sediment systems. There is concern over the use of denudation rates for extrapolation over longer time periods (Beylich & Sandberg, 2005; Beylich et al., 2006) and longer-term sediment budget models need to be developed to facilitate the prediction of future sediment fluxes. Field monitoring is crucial to cold environment sediment budget investigations, and the development of effective and innovative field methods, such as geophysical techniques for estimating regolith thickness and sediment storage volumes (e.g. Schrott et al., 2003; Beylich et al., 2003; 2004), better dating techniques for determining long-term changes in sediment delivery (e.g. Blake et al., 2002) is vital to further research. Sediment budget studies have tended to concentrate on small scale catchments as units of assessment; additional upscaling from small-scale studies to larger scale sediment systems coupling headwaters to oceanic sinks is needed to further improve knowledge on the relative importance of sediment transfer processes and the potential impact of climate change on cold environment sediment fluxes (Warburton, 2007).

It is necessary to collect and to compare data and knowledge from a wide range of different high latitude and high altitude environments and to apply more standardised methods and approaches for future research on sediment fluxes and relationships between climate and sedimentary transfer processes in cold environments. Previous sediment budget studies can provide base-line data for comparison with further sediment budgets or for predictions of future changes in sediment fluxes. Strong monitoring, operational data collection and more standardized methods will provide a baseline for the development of reliable models and for future research in cold environments (Beylich, accepted; Beylich et al.; 2005; 2006). The remainder of this *SEDIFLUX Manual* will examine the key areas by which research on sediment budgets in cold environments can be advanced making recommendations for such research.

Chapter 2 –

Analysis of sediment storage:

Geological and geomorphological context

2.0 INTRODUCTION

The overall aim of this chapter is to provide a geological and geomorphologic context for considering sediment storage in cold environment small catchment geosystems. Consideration is given to the definition of basic catchment characteristics, including geology, topography and relief, and frozen ground conditions (Section 2.2). This is considered within a landsystem framework (Figure 2.1). Guidance is given for the best way to recognise the key storage elements in both slope and fluvial settings and evaluating them within the overall sediment budget framework (Section 2.3). Methods for quantifying storage elements are described in Section 2.4. The key measurements involve the two-dimensional (2D) and three-dimensional (3D) definition of storage volumes, classification of storage types and materials, dating of storage units (chronology of storage), and assessment of the stability (activity) of storage elements through both contemporary process measurements and dating. The stability of storage elements can be defined in terms of active sediment stores - frequently reworked by contemporary geomorphic activity, semi active stores – only activated during extreme events, and inactive stores – sediment which is stored in the landscape from processes and events that no longer occur. Key issues surrounding the best ways of characterising the temporal and spatial variability in storages are evaluated in Section 2.5. For each sub-task minimum requirements are outlined and recommendations for additional investigation techniques are given (dependent on catchment size). Methods are summarized in a look-up table at the end of the chapter. Much of the information presented is well suited for incorporation into a Geographical

Information System (GIS) and a brief note, advising on the best approach in doing this, is outlined.

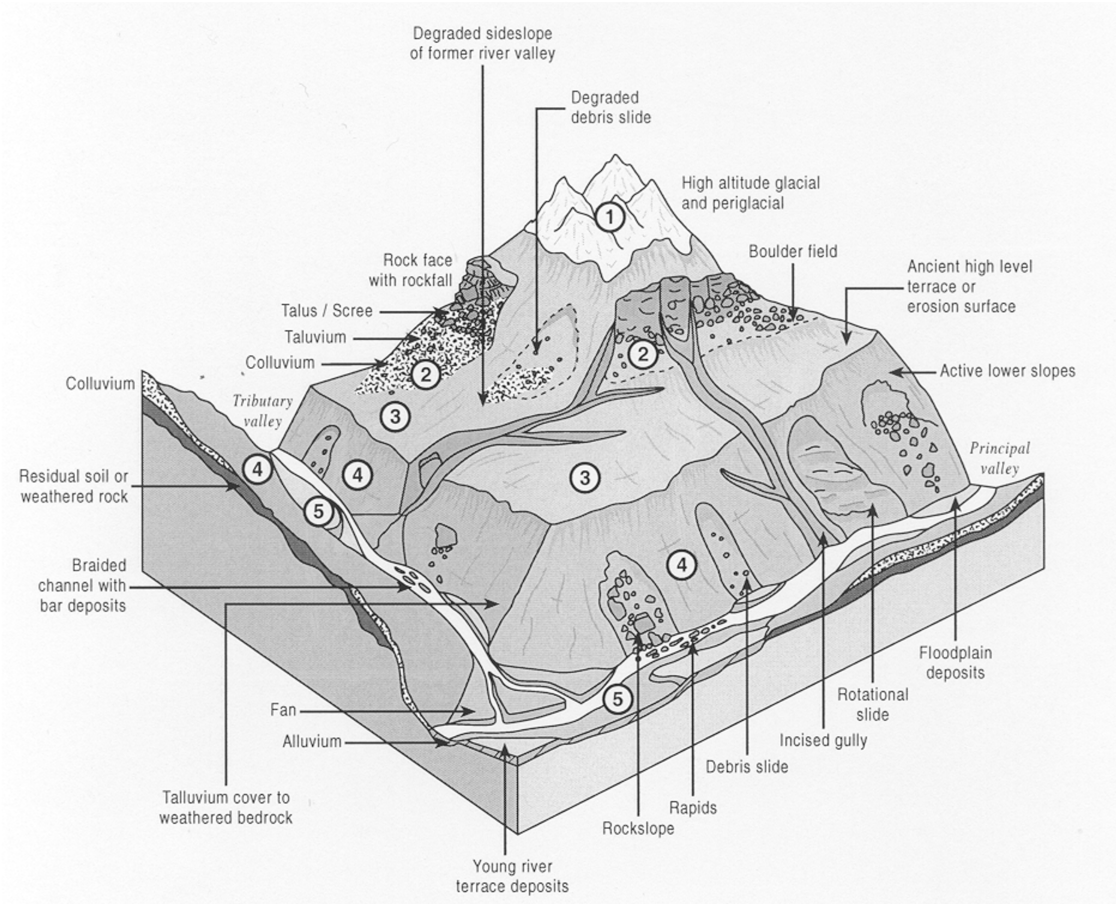


Figure 2.1. *Land system diagram of a high mountain environment showing five major terrain zones: (1) High altitude glacial and periglacial; (2) Free rock faces and debris slopes; (3) Degraded middle slopes and ancient valley floors; (4) active lower slopes; and (5) valley floors. (Source: Fookes et al. 1985)*

2.1 CATCHMENT DEFINITION

A catchment is defined as a fundamental hydrological and geomorphological unit. A major goal of SEDIFLUX and SEDIBUD is to address sediment fluxes integrated over catchment areas (Beylich et al. 2005; 2006). S*mall catchments* are in general restricted to areas of less than 30 km^2 (Chapter 4). This is an operational definition, which is suited to the scale of sediment budget studies. Consideration of scale and its implication in controlling sediment flux is addressed in Chapter 1 and will be considered by selecting a number of larger drainage basin key test sites with nested small catchment key test sites (Chapter 4). Quantitative measurements of sediment transfer processes operating in small catchments are described in Chapter 3, hence the focus of this Chapter 2 is to address conditions governing these processes at a similar scale.

2.2 GEOLOGICAL AND GEOGRAPHICAL SETTING (BOUNDARY CONDITIONS)

2.2.1 BEDROCK AND SURFICIAL GEOLOGY

Bedrock geology, both solid and surface sediments act as important controls on geomorphic processes. The implications of this should be considered in all sediment budget studies. This requires definition of the major bedrock types in a catchment and the distribution of superficial deposits. These units should be mapped at a scale appropriate to the objectives of the sediment budget study e.g. susceptibilities for landsliding, rock fall and frost action. Such information can be obtained from the best available geological maps. It is important that the major bedrock types and faults/thrusts within the catchment can be identified. Where such information (i.e. maps, third party data) is not available, a reconnaissance survey should be undertaken. Such a survey must include careful characterisation of the superficial deposits and local soils because the surficial materials have the most direct bearing on the geomorphic processes present, and in themselves, provide a historical record of sediment storage.

2.2.2 TECTONIC, SEISMIC AND VOLCANIC CONSIDERATIONS

Historic and recent large geological events have very significant impacts on local relief, sediment supply and erosion rates. Every effort should be made to establish the recent geological history of the study area because this often provides the context for recent geomorphic activity e.g. high fluvial sediment transport rates, large recent landslide events and extensive re-working of stored sedimentary deposits. Records of earthquakes and volcanic events should be obtained from documentary evidence or sought in local sediment archives. In cold environments, volcanic events are particularly significant due to the thermal instabilities that they generate in the snowpack or ice cover, which can lead to rapid snow/ice melt, jökulhlaup dynamics, etc. Similarly, avalanche activity may be triggered by seismic and tectonic disturbance – often incorporated with debris avalanches, examples of such interactions are e.g. Huascaran, Yungay, Peru 1970 (Plafker & Eriksen, 1978).

2.2.3 RELIEF CHARACTERISATION

A fundamental part of any sediment budget study is the general characterisation and quantitative description of the catchment topography and relief, including vertical zonation of major cold climate processes (Figure 2.1). This is most easily achieved using a Digital Elevation Model (DEM) from which various terrain parameters can be easily calculated. The resolution of the DEM is in many ways critical to the objectives of many detailed sediment transfer studies because it is used to define a baseline for assessing changes in sediment storage or automatically define sediment transport pathways. It is also a fundamental component of spatially distributed DEM-based models, which consider sediment transport, soil loss and shallow landsliding. A basic hypsometric curve of the catchments is a very useful tool particularly for comparison of different catchments. Basic data on catchment relief should be tabulated, including: maximum and minimum altitude, total relief, average catchment slope, etc.

2.2.4 PERMAFROST GROUND ICE CONDITIONS

In addition to characterising the general variability in surface air temperatures, the thermal state of the sub-surface is of fundamental importance for geomorphological processes. Permafrost, defined as frozen ground over two consecutive years, may stabilise sediment magazines (landforms), thereby reducing their susceptibility to erosion, while thawing of ice-rich permafrost may destabilise the same landforms. It is therefore important to address the possible permafrost distribution in the catchment (permafrost existence), model the active layer thickness and assess the thermal properties of the ground at selected sites (permafrost characteristics). In addition, knowledge of the existence of excess ground ice is important (solid ice lenses, etc.). Out side of permafrost areas active layer depths should be monitored in order to assess the seasonal significance of ground freezing.

There exist a variety of broad-scale models of permafrost distribution over many areas in the northern hemisphere, which give an indication about where permafrost has to be expected in a catchment and where not. If the modelling results suggest permafrost, several steps should be carried out additionally: (1) simple surveys like the BTS (Bottom Temperature of winter Snow) measurement should be carried out (see Brenning et al., 2005; Hoelzle et al., 2001; Etzelmüller et al., 2001). (2) Surface and sub-surface temperatures in different elevations and surface cover types should be continuously measured, applying inexpensive miniature data loggers (resolution ± 0.25 degC), and (3) the active layer thickness should be measured at selected sites, particularly addressing different surface sediment cover conditions. These data sets, in combination with a DEM, open up the opportunity for the application of a multitude of spatial modelling, addressing permafrost and active layer distribution (see also Hoelzle et al., 2001; Heggem et al., 2006). Direct monitoring, if possible, is always desirable because of the inherent uncertainties in zonal permafrost prediction and the natural local variability in the ground thermal regime, especially in mountain catchments.

2.2.5 VEGETATION AND SOILS

Spatial variability in vegetation and soil patterns are important in conditioning geomorphic processes in many cold environments. With the advent satellite images and aerial photographs, a normalized difference vegetation index (NDVI) can be rapidly calculated using the spectral signatures from the different Thematic Mapper bands (e.g. Thermal band). In the field, ground-based botanical investigations of plant colonization patterns should be obtained using a sampling protocol designed to determinate heterogeneous density of plant cover. Small 1 m^2 quadrates collected along transects following established spatial survey protocol, such as an unaligned systematic sampling scheme can be used (ITEX Manual). Such schemes are used to record the most common plant species on the surface and use a local well-documented flora. This is useful in distinguishing phanerogames, bryophytes and lichens.

Plant physiognomy and composition often reflects geomorphological dynamics, slope stability or instability, age of deposits, etc. For example: stable moraines could be identified by *Carex* or *Polygonum*; pioneer species (*Salix*) in the first time of deglaciation; wet lands or dry lands with hygrophilic species (*Cochlearia*), mesophilic species (*Saxifraga*) and xerophilic species (*Arenaria*).

In the field, basics soil properties should be described and granulometric composition, pH, organic matter, organic carbon, total nitrogen should be measured. The color of the soil can be determined from standard Munsell color charts and photograph and descriptions of each soil profile should be undertaken prioir to sampling. It is advisable to follow local soil survey practices so that catchment field data can be placed in broader soil classes determined from published soils maps. This can be important when using soil classes to drive upland erosion models.

2.3 RECOGNITION OF STORAGE ELEMENTS

The identification of the main storage elements is a central task for the sediment budget approach. Two main storage units are identified: (1) the slope and (2) valley fills. Main slope features are related to accumulations from gravitational processes such like rock glaciers, talus, debris cones, solifluction lobes and solifluction sheets and alluvial fans. The valley fill and related landforms like kames and eskers form another major storage unit, and must be adequately charcaterised. Other landforms, superimposed over these basic units, are landforms derived mainly from glacial processes, such as moraines. In this context, landsystems models are particularly valuable in defining the range of landforms and sedimentary deposits under consideration, in order to give a 3D representation of the sediment storage inventory.

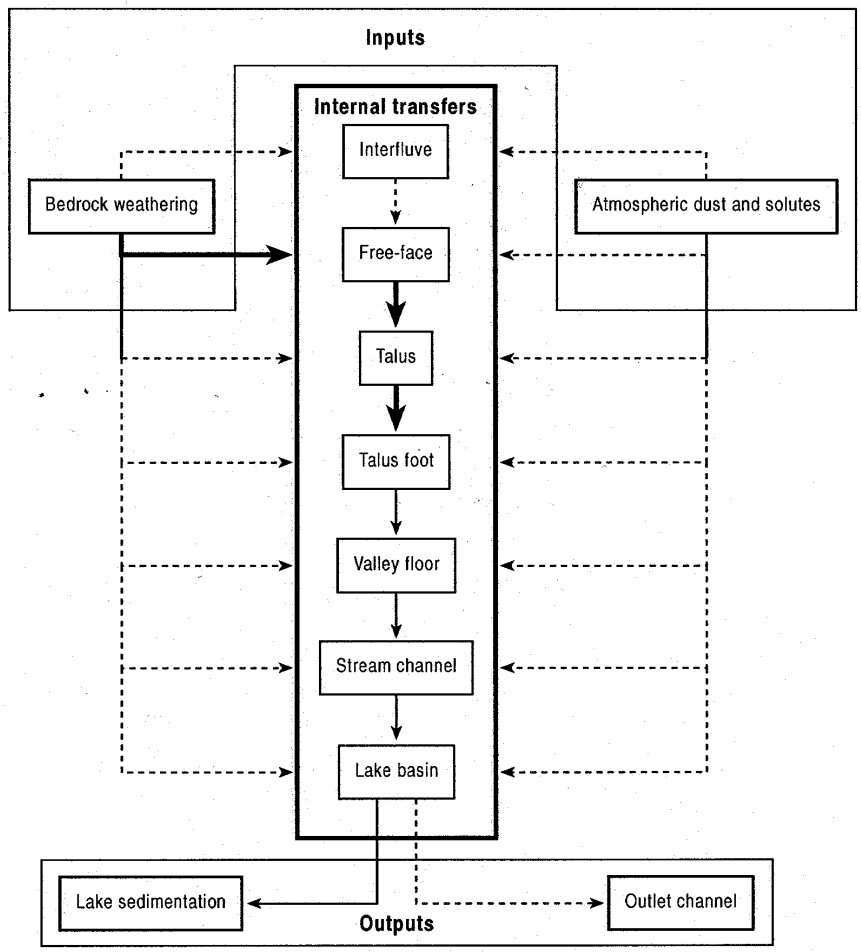


Figure 2.2. *The alpine sediment cascade process system proposed by Caine (1974)*

The identification and mapping of these units is mainly achieved through air photograph and satellite image interpretation, with subsequent ground truth fieldwork. Most of the key landforms used in the sediment budget approach are easily derived using these tools. If minor landforms, such as certain smaller scale glacial or periglacial forms are of importance (e.g. definition of fluvial terrace forms), field investigations with GPS or electronic theodolite are necessary, for measurement of location and elevation variation.

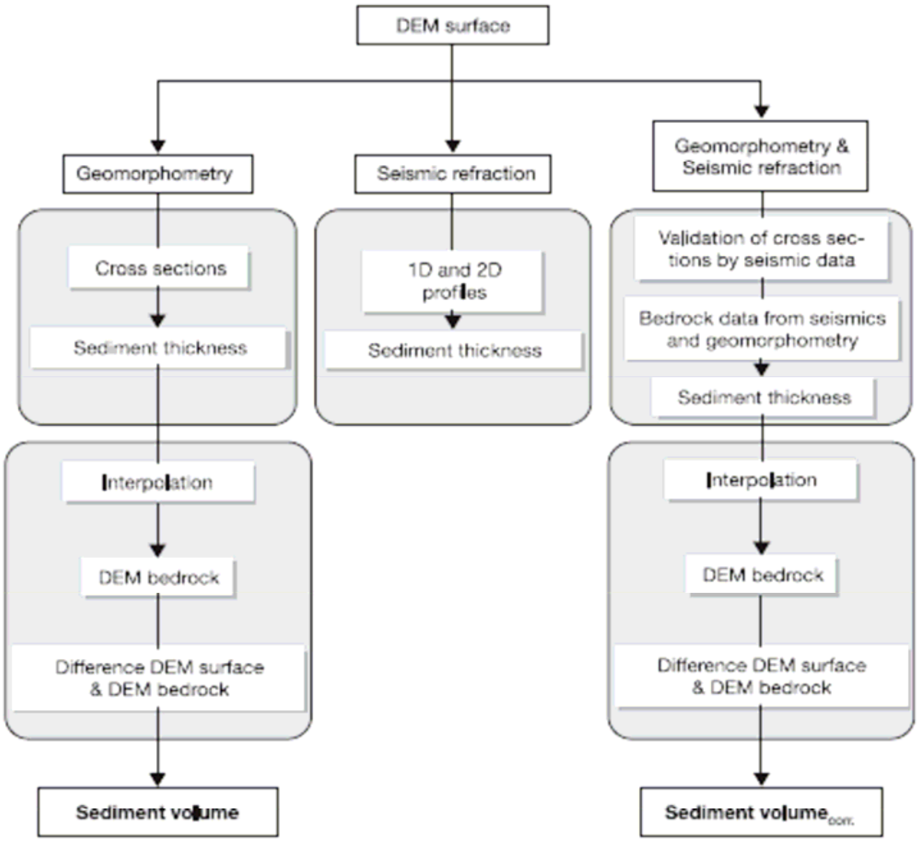
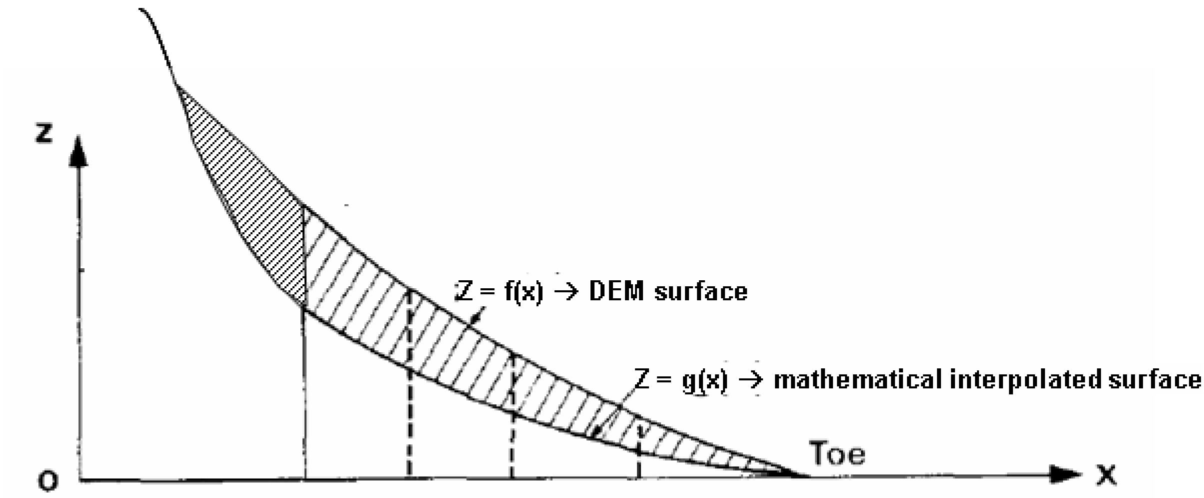


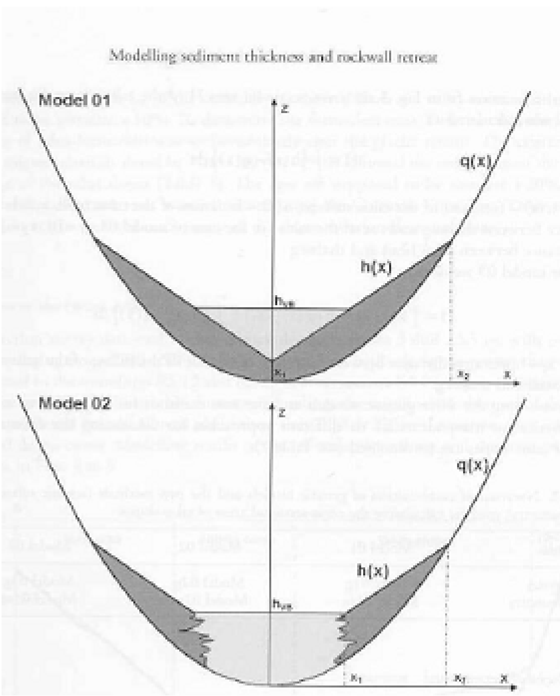
Figure 2.3. *Principles of volume calculation of storage elements (after Schrott et al., 2003)*

2.4 QUANTIFICATION OF STORAGE ELEMENTS

2.4.1 DEFINITION OF STORAGE VOLUMES

The storage volume of a landform is a critical measure for addressing time-dependant sediment budget dynamics. A major aim for a sediment budget model is to quantify the volume of the major storage elements, or at least a representative sub set of the landforms, present in a partcular catchment. The topographic variability of the landforms can be represented in a digital elevation model, depending on its resolution. To define landform volume, we have to determine the lower limit of the landforms. There are two main approaches (Figure 2.4, Schrott et al., 2003).





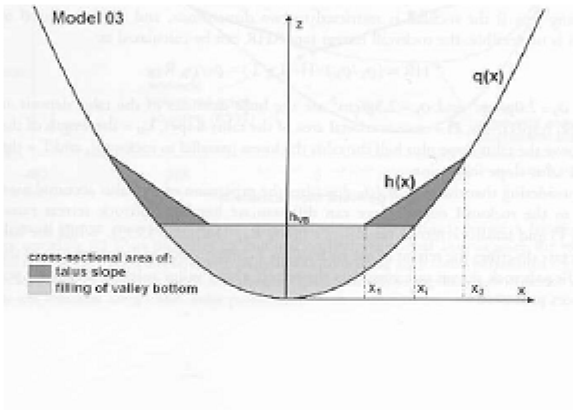


Figure 2.4. *Estimation of slope cover and valley fills. F(x) denotes the surface function obtained from a DEM. G(x) has to be defined, e.g. through trend surface analysis, thessalation or other deterministic interpolation methods. U-shaped valleys are successfully estimated through higher-order polynomial surfaces, while v-shaped valley bottoms demands linear interpolators. Based on Hoffmann & Schrott (2003)*

1. We can interpolate sub-storage element topography by interpolating a trend surface based on points sampled outside the landform (Figure 2.4). The trend surface is then subtracted from the original digital elevation model. What type of trend surface is chosen depends on the landform. Schrott et al. (2003) and Hoffmann & Schrott (2002) illustrate these different approaches. Valley fills might be quantified by a third- or forth-order polynomial, while back walls covered by talus forms might be interpolated using linear trend surfaces.

2. Sediment thickness can be obtained using geophysical soundings, using seismics, GPR (Ground Penetrating Radar) and DC electrical tomography. These tools are expensive and require specialist knowledge for application, but should be applied at least at some locations to validate calculated sub-landform topography.

Hoffmann & Schrott (2002) clearly demostrate that there might be large discrepancies for the polynomic-derived surface and geophysical soundings, especially for valley fill analysis. For each landform analysed, the realism of the calculated surface has to be assessed, either by field observations (bedrock outcrops, etc.) or some selected geophysical investigations. In both cases, the interpolated sub-landform topography is subtracted from the DEM on a cell-by-cell basis, resulting in total volume in m^3 or km^3, depending of the landform size. This value should be converted into metric tons in order to allow the assessment of specific erosion rates lateron.

2.4.2 CLASSIFICATION OF STORAGES

For estimation of specific erosion rates and metric weights of storage elements, sub-surface characteristics of these landforms have to be evaluated. Basic measurements of bulk density of the local bedrock and surficial deposits are fundamental in the accurate determination of sediment mass. First order approximations may be derived from the literature but for detailed sediment budgets field sampling schemes must be undertaken. The design of such a scheme should take into account the major storage elements within a particular catchment and sampling should be stratified within this. All bulk density values should be accompanied by an error margin, which can be used in sediment budget caculations. Sediment packing and porosity can be derived from thses basic measurements especially when grain-size analysis is carried out on the same suite of sediments. Many coarse deposits require large sample sizes and can only be adequately measured using a combined field and laboratory approach. For slope deposits, fabric should also be measured in the field (distinguish openwork texture, partially openwork, clast-supported texture, matrix-supported texture). Material arrangement (orientation, plunge of the longest particle axis), debris shape (length, width, thickness), and sorting of deposit (graded bedding, lateral sorting) should be measured as well, using 1-m^2 quadrats, along transects to measure fabric and particle morphology. Such measurements are useful in correctly assigning particular sedimenatary units to specific geomorphic processes, e.g. in fan stratigraphy debris flow deposits and slope wash units are often distinguished using such measurements.

2.4.3 DATING OF STORAGES (CHRONOLOGY OF STORAGE)

In sediment budget studies the minimum requirement is the application of relative dating methods to identify the chronology of sedimentation rather than absolute age. However, advanced dating methods are desirable particularly when quantifying rates of change and trying to correlate between different sediment systems. In addition, geoecology can provide important information about relative-age of geomorphologic features (see Matthews, 1992), however, this is not considered in detail here. The overall aim is to determine ages and chronology of the key sediment storage components. In this section we briefly outline the main methods that should be considered in cold climate catchment sediment budget studies.

2.4.3.1 Relative age dating

A full range of relative-age dating methods should be considered within a small catchment area. The most appropriate ones should be used in combination to assess areal chronologies at the highest resolution time scale possible. Such dating tools should be calibrated, i.e. objects of a known age must be used to calibrate time-curves of the dating methods used. For example, lichenometry can offer numerical ages of a morainic deposit with a good accuracy when lichen growth is calibrated on tombstones, farms walls, etc. in the surrounding area of the research site. Relative-age dating methods include biological dating (use of lichen thallus, *Silene acaulis* cushions or tree trunks (dendrochronology)), physical and chemical dating (use of rock weathering characteristics: oxidation rind, hydration rind on obsidian, soil maturity, rock surface strength (Schmidt hammer)) or sedimentological dating (tephrochronology, fine particle translocation, varve chronology).

Lichenometry. Measurements of *Rhizocarpon geographicum* thallus diameter provide a relative-age estimate based on the assumption that the longer a fresh rock surface is exposed to the atmosphere the larger the lichen thallus will grow. Field sampling, statistical data analyses are well documented in an abundant bibliography. Even if individuals might live for many millennia, it must be born in mind that the stability of the rock surface under the lichen cover is expected to be unstable over a shorter timescale as a consequence of biological weathering. Therefore, lichenometry should be restricted to the last 500 years.

Silenometry. This is based on the same principal as lichenometry but here *Silene acaulis* cushion diameters are measured. Limitations are greater than lichenometry due to a strong environmental susceptibility of this phanerogam. However, good results can be expected over a shorter time scale dating (i.e. 10-50 years).

Dendrochronology. The longest chronology currently available is the Hohenheim oak chronology which contains an annual record back to 10`480

BP, but a pine chronology which overlaps the oak chronology might extends the total annual record back to 12000 BP. Study of tree ring morphology (asymmetry, reaction wood, thickness variability) also gives an indication of possible perturbing environmental events (glacier advance, earthquakes, storms, tsunamis).

Corticometry. Weathering rinds developing at the surface of rock surfaces or boulders are more or less time-dependent. Oxidation rinds are strongly related to time. Thickness of the weathering rind is usually a good indicator of the age of the surface but, paradoxically, the integrity of the alteration halo becomes very sensitive to weathering processes. Under these conditions, two sampling strategies must be adopted depending on the dating goal: surface sampling is convenient with short-time exposure (e.g. 30-150 years for basaltic moraines in Iceland, i.e. post-LIA dating), whereas larger time exposure surfaces (i.e. thousand years or post-Weichselian dating) require subsurface sampling (usually in the *Bt* horizon of soils).

Obsidian hydration. Adsorbed water diffusion in obsidian fragment creates a weathering rind with particular optical properties. Rate of diffusion can be calibrated using industrial obsidian. Sampling should be done at a minimum depth of 1 m depth to reduce daily thermal fluctuation interferences on the diffusion rate.

Soil chronology (chronosequences). A sequence of soils developed on similar parent materials and relief under the influence of quasi-constant climate and biotic factors will show differences that can thus be ascribed to lapse of time since the initiation of soil formation (Matthews, 1992). The Profile Development Index (Harden, 1982) helps to combine qualitative (texture, color, etc.) and quantitative (pH, organic matter content, etc.) properties of soil to obtain useful relative age dating.

Schmidt hammer. This concrete-testing tool has been transferred into the geomorphological dating research field by McCarroll. It measures the rebound (r-value) of a steel hammer from the rock surface, the rebound being proportional to the compressive strength of the rock surface. Fresh surfaces have high rebound values whereas weathered surfaces have low r-value. Degree of weathering increases with time and the r-value consequently diminishes. Comparison of surfaces of different ages should give discriminating r-values but operating procedures are difficult and can greatly affect the measurements.

Tephrochronology. Tephra are pyroclastic elements ejected into the atmosphere during volcanic eruptions. Large pyroclasts (blocks, bombs) fall around the emitting volcano but fine ash can travel all around the globe before falling down and being trapped into continental sinks. Each volcano has a unique geochemical and exoscopical signature, which allows the identification of the origin of volcanic fallout. Knowing the volcanic history of an area, it is then possible to date the tephra layer in a sequence (future advances in tephrochronology will come from direct dating of tephra by $^{40}Ar/^{39}Ar$). A sedimentary sequence embedded into two dated tephra layers can be converted into rates of accumulation. Icelandic tephras (e.g. Vedde Ash, 12`000 BP) are widespread in continental Europe sinks (lakes, peatlands, river terraces, moraines).

Fine particle translocation. This is a micromorphological method based on soil characteristics, which provides good relative age estimates. Silt transfer is the quickest process of transformation of soil matrix in high latitudes areas. Under optical microscopy, soil thin-sections reveal translocation of fine particles and changes can be linked to an approximate timescale.

Varve chronology. Varves are lacustrine sediment couplets consisting of relatively coarse-grained layer alternating with a relatively fine-grained layer or organic laminae alternating with inorganic laminae. A couplet is deposited annually and provides the basis for absolute dating by counting varve sequences (Lamoureux, 2001). Calendar timescale can be achieved when varved deposits include organic materials for which radiometric is possible. This has been used to good effect in alpine and glacierised mountain catchments (Tomkins & Lamoureux, 2005), as well as boreal and tundra settings (Zolitschka, 1996; Lamoureux, 2000).

2.4.3.2 Absolute age dating

Absolute dating can be achieved using documentary records (aerial photographs, historical tourist pictures and written evidence) but such sources are usually scarce in cold regions. Alternative absolute dating methods include the range of radiometric dating techniques including: radiocarbon, long-lived and short-lives radioactive isotopes and radiation exposure dating.

Radiocarbon dating is based upon the decay of radioactive ^{14}C isotope stored by living organisms (plant, animal). After the death of the organism, storage of ^{14}C ceases, then replenishment cannot take place and the amount of ^{14}C decreases steadily (by convention half-life of ^{14}C is 5570 years). The limit of measurement of ^{14}C activity is eight half-lives, so radiocarbon dating is limited to the last 45`000 years. Any object with carbon in it can be dated, according to the age range of the method. In cold environments radiocarbon dating provides good dating where organic material is present.

Lead-210 and Caesium-137 are two short-lived isotopes commonly used in geosciences for dating purposes. ^{210}Pb has been widely used to estimate sediment accumulation within lakes. This isotope is part of the atmospheric uranium-series decay chain leading from radon (^{222}Rn) to lead (^{210}Pb). ^{210}Pb is removed from the atmosphere by precipitation and accumulates in the sediments where it decays to a stable isotope ^{206}Pb (half-life is 22.3 years). By measuring the ratio between ^{210}Pb and ^{206}Pb in a lake-sediment sequence, the time of deposition can be determined, and subsequently, the rate of accumulation of the sediments. The time span for using ^{210}Pb is restricted to approximately 150 years, so it can easily be used for post-Little Ice Age dating in High Arctic catchments (e.g., Lamoureux, 2000). Attention should be given to the nature of the lake sediments: if minerals containing small amounts of uranium are present, they will supply ^{210}Pb, and then measurements should be corrected. Caesium-137 (half-life 30 years) has been actively released in the upper atmosphere after World War Two and the campaign of thermonuclear weapon testing programmes and been deposited worldwide as fallout. A peak of ^{137}Cs "production" is 1963, which is clearly recorded in lake sediments and constitutes a good marker horizon. It is assumed that ^{137}Cs deposition within fine particles at the ground surfaces is uniform (although regional incident like 1986 Chernobyl accident might modify locally the input), so any deviation in the measured distribution from the local fallout inventory represents the net impact of sediment redistribution (upslope soil erosion and downstream sedimentation) during the period since ^{137}Cs deposition.

2.4.4 ASSESSING THE STABILITY OF STORAGE ELEMENTS

The main aim is to give an estimate of landform stability in terms of their likely contribution to sediment transfer. This could include geotechnical, thermal and erosional stability. Also are there stores in active, semi-active or inactive zones in the catchment. The stability of storage elements can be defined in terms of active sediment stores - frequently reworked by contemporary geomorphic activity, semi active stores – only activated during extreme events, and inactive stores – sediment which is stored in the landscape from processes and events that no longer occur. A convenient way of assessing this is to produce a matrix listing the potential processes leading to storage instability (sediment transfer) and the sediment storage zones activated by such processes (Warburton, 2006; Figure 2.5)

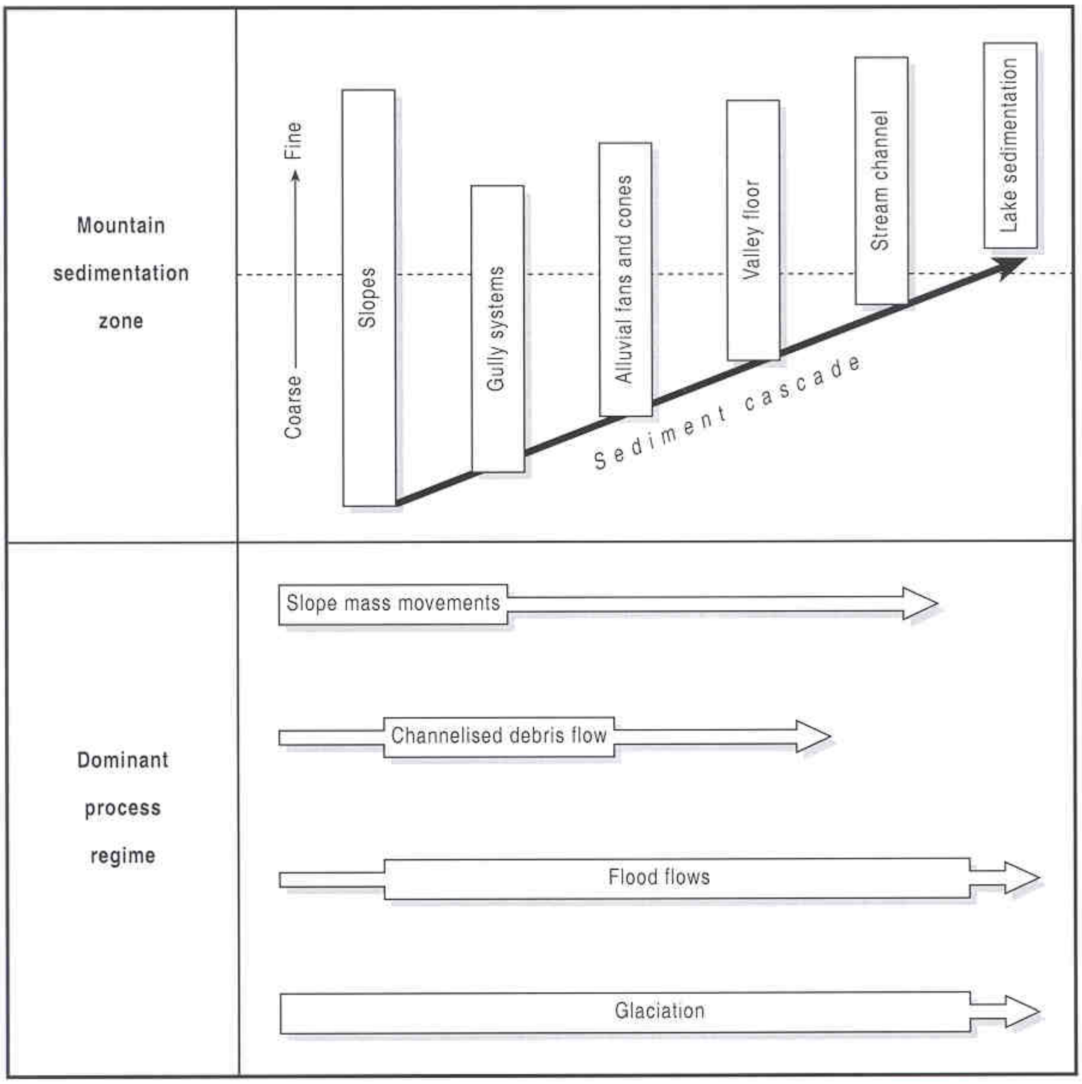


Figure 2.5: *Relationship between mountain sedimentation zones and potential sediment transfer processes in steepland environments (Warburton, 2006)*

2.5 INTEGRATING THE APPROACH INTO A GIS

The key to integrating catchment characteristics and sediment storage data into a Geographical Information System is defining the scope and resolution of the system prior to primary data collection. It is far easier to establish a clear spatial references system prior to data collection than trying to incorporate disparate data sets collected in different coordinate systems at a later date! The other key factor is the quality of available background data (e.g. DEM resolution) and access to suitable data acquisition systems (e.g. LIDAR, terrestrial laser scanning, differential GPS) because this will determine the precision and quality of the data collected. It is recommended that prior to any sediment budget study the following procedure is followed:

1) Assess the availability of spatial data and whether this data can be obtained in a digital data format.
2) Obtain relevant data coverage, which as a minimum should include: DEM-topography (at a scale relevant to the overall catchment and objectives of the study), and drainage. Geology, soils and vegetation should be included.
3) Determine position of benchmarks and ground control within the study area.
4) For small catchments sediment budget studies, a 1-10 m DEM with geo-referenced colour air photographs provides usually a feasible starting framework. A 25 m model is the coarsest acceptable for catchment sizes up to around 30 km^2.

2.6 CONCLUSIONS

The catchment is the fundamental unit of study in meso-scale sediment budget studies. Defining the characteristics of such units require a quantitative description of the overall geometry (topography) of the unit, its constituitive materials (bedrock, superficial geology, soil and surface cover), the condition of those sedimentary units (physical, chemical and thermal character) and the age of these basic building blocks. The methods outlined here should be considered when trying to define these properties in a cold climate sediment budget study. The exact nature of the approach adopted will depend on the nature of the catchment, the objective of the sediment budget approach and the resources available to carry out the study. As a first approximation, most properties can be determined from documentary evidence and remotely sensed data. However, for detailed sediment budget work systematic field survey and sampling is required.

Table 2.1. *General recommendations*

Chapter	Small catchment	Large catchment
2.1. Geological and geographical setting (boundary conditions)		
2.1.1. – Bedrock geology	Geological map, 1:50000 if available	Geological map, 1:250000
2.1.2. – Tectonic, seismic and volcanic considerations	Literature review of the area, with emphasize on tectonical setting, volcanic activity (time of eruptions etc), modern land heave/isostasy. For glacierized catchments large events like jokulhaups should be investigated.	Geological map, 1:250000 Maps of seismic activities (e.g.
2.1.3. – Surficial material	Identification of major genetic components of surficial material and major grain size composition. Delineated into: *Glacial, fluvial, glacio-fluvial, Aeolian, in-situ weathered material (block fields etc), bare rock (no sediment cover), organic (mire), gravimetric (slopes).* Thickness of material should be given where available. If maps better than 1:50000 are available, they should be used, and otherwise air photo interpretation and field ground truth. Landforms in sediments must be mapped (talus, glacial landforms, terraces, rock glaciers etc) as sediment magazines.	Maps of Quaternary surface cover, 1:50000-1:250000
2.1.4. – Relief characterisation	DEM, 25-50 m ground resolution. For catchments below 5 km^2, refine with tachymetry or DGPS (Ground resolution < 10 m). From the DEM calculate terrain parameter like slope, aspect, curvature, wetness index, potential short-wave radiation, river network and sub-basin borders within a GIS. Major structural landform must be described (arête, cliffs, valley form) If available: high-resolution DEM using digital photogrammetry based on air photos (< 5 m) or satellite images (radar, ASTER) or LIDAR	DEM, 50 m. 90 m DEM available for 60 N/S (SRMT-data).
2.1.5. – Permafrost and ground ice conditions	a. Bottom temperature of winter snow cover (BTS) – along elevation profiles in different aspect, 2-3 measurements per point, GPS localisation, average for each location, snow cover >0.8 m. At least 100 points within a catchment. Measurements before spring melting (late Feb. to early March) b. Monitoring of ground surface temperatures and air temperatures (1 m in air) in selected sites (4 hour interval) (differences in elevation, land cover and aspect) (accuracy ±0.25 ºC). At least five loggers in different positions representing elevation range and aspect dependency. Evaluation of surface offset values. c. Map of permafrost existence (statistical methods, correlation matrix between BTS, snow	Results from BTS can normally be up-scaled to a total catchment level.

	thickness and topographic parameter, multiple logistic regression) d. One to two shallow boreholes with temperature measurements (at least two different elevations, min. 4 m depth, Temperatures measured at least 4 times a year (each season) in 0, 0.2, 0.5, 1, 1.5, 2, 3, 4 m depth. (accuracy ±0.1 ºC). Evaluation of thermal offset. e. Active layer (AL) monitoring (digging and probing). Works well in organic material, often difficult without bore hole as AL can be very thick under permafrost degradation. f. Ground ice in alpine catchments is normally related to rock glaciers, ice-cored moraines and palsa. Rough estimates for these landforms are 40-80% ground ice content. Evaluate in natural sections if available. **If available**: Combined DC resistivity tomography over boreholes and at selected sites. Deeper boreholes with continuous ground temperature measurements.	
2.1.6. – Vegetation	Vegetation is important both in terms of vegetations coverage of the ground and major type of vegetation. Distinguish into recognised vegetation classes used in regiobal vegetation surveys or classifications used in airborne remote sensing surveys Use either maps in scale 1:50000 or better. Alternatively use aerial photographs. Calculate NDVI as proxy for biomass based on available satellite image (ASTER, SPOT, LANDSAT)	Vegetation associations (forest ????) should be estimated. Use existing maps or classification of available satellite images (Landsat 7). Calculate NDVI as proxy for biomass based on available satellite image (ASTER, SPOT, LANDSAT)
2.1.7. – Human impact	Mapping of a) infrastructure, b) river dams, c) agriculture/pasture use of the area	Land-use survey data
2.1.8. – Climate conditions	Instrumentation scheme included in chapter 4	
2.1.9. – Hydrography	DEM-based mapping: river network Topographic map/pictures: lake coverage (m^2), Glacier coverage (m^2), perennial snow patches (m^2), classification of main river types . Field mapping: springs, and local drainage features	River network from DEM, glacier and lakes from topographic maps pr satellite images.
2.2. – Recognition of storage elements		
2.2.1. – Slopes	Mapping of talus, scree, fans, rock glaciers, slope cover, blockfields, landslide deposits, Aeolian deposits. (See table 5 for pictures for many of these elements)	
2.2.2. – Fluvial channels	Identify point bars, flood plains, lake deltas, how the riverbed is connected to the hillslope (good, poor). Carry out fluvial geomorphology river reconnaissance survey.	
2.3. Quantification of storage element		
2.3.1. – Storage volumes	DEM-based analyses are required. DEM resolution 5 m or better.	

	Simple approach (minimum): 1. Define points (x, y, z co-ordinates) outsite the landform along the slope and evt plain. 2. Adopt a second order polynom plane thorugh these points (ArcGIS, Surfer etc). 3. Calculate the mean difference between surface of landform and the plane and multiply with the landform area (m^3). Advanced approach (which not necessarily give better results) : 1) Define thickness of landform using geophysical soundings (GPR, Geoelectrics, seismics) 2). Define the sub-landform topography based on thee results 3) Calculate the difference between this plane and the surface	
2.3.2. – Classification of storage elements	1) Morphometric characteristics of the landform based on DEM (mean elevation - m, elevation range - m, area – m^2 , mean slope (º), max llength (m), max width (m) 2) Sedimentological description based on cross section investigation (if available): (grain size – coarse/fine or amount of pebbles, sand, silt/clay). Grain shape (counting), Genetic type. Use standard sedimentological techniques and collect bulk properties in particular bulk density and packing densities of sediments in the main storage elements. If available: GPR to identify internal stratigraohy etc.	Classify genetic type based on satellite image or air photos, existing maps
2.3.3. – Dating of storage elements	Required: Relative dating methods - Lichenometry - Schmidt Hammer - Aerial photo sequences/photo archives (if available) - Look for soil chronologies Advanced: Exposure dating, OSL, ^{14}C, ^{137}Cs, ^{210}Pb	
2.3.4. – Stability of storage elements	Stability is addressed by observations in field and from air photo. Look especially for disturbance of vegetations cover and fluvial erosion of landforms. (see Table 3)	

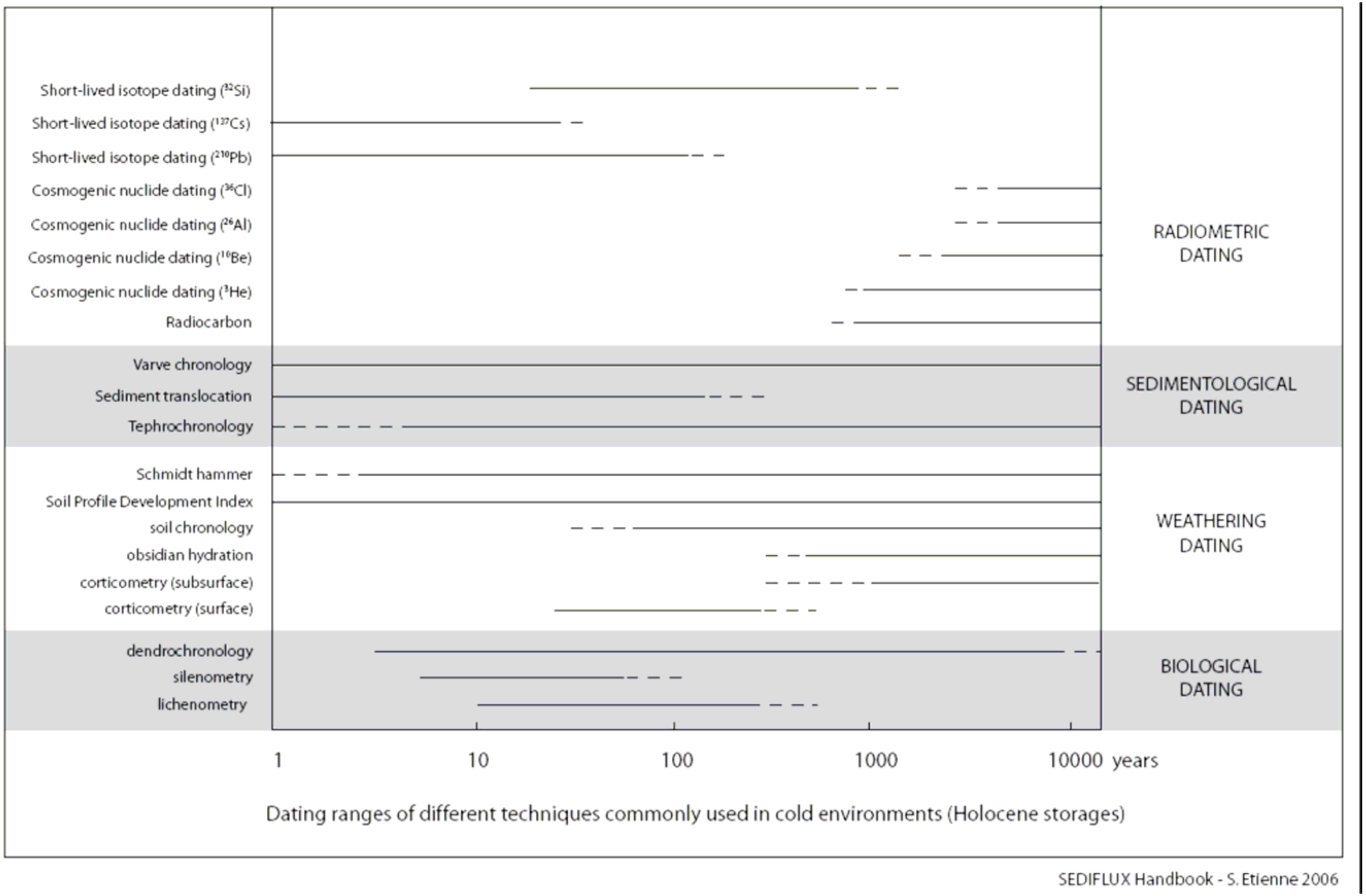
Table 2.2. *Bedrock type classification in the investigated catchment*

Major bedrock component	**Susceptibility for gravitational processes**			**Susceptibility for frost processes**		
	Non-competent lithologies (high)	Competent well-jointed lithologies (inter-mediate)	Competent massive lithologies (low)	Massive (low porosity), low joint density (low)	Massive (low porosity), well-jointed	Weak, high porosity, jointed (high)
SEDIMENTARY						
Shale	X					X
Mudstones	X					X
Sandstones		X				X
Breccia conglomerate						
Limestone						
Evaporite						
IGNEOUS						
Intrusive (gabbro, diorite, granite)						
Extrusive (basalt, andesite, rhyolite)						
METAMORPHIC						
Slate						
Schist						
Gneiss						
Quartzite / marble						

Table 2.3. *Stability consideration of sediment storage elements*

Geomorphic activity / stability	Key Characteristics	Typical age and frequency of reworking	Example landforms
Inactive – stable	No disturbance of vegetation or lateral erosion soil development with infilling of sedimentary framework May contain well developed mature vegetation	100 – 1000 years Partial reworking only during extreme events (1:100 year)	High-level valley terraces Vegetated debris cones Moraines
Semi-active – intermediate stability	Local disturbances, minor erosion scars Vegetation and signs of soil profile development (pioneer species still present) Mosaic of partially vegetated and bare areas	10 -100 years Reworked and reactivated during moderate events (1:10 to 50 years)	Talus and debris cones Alluvial fans Fluvial islands
Active – unstable	No vegetation cover, fresh stones, little lichen cover, heavy lateral erosion. Steep non-vegetated cliffs.	Recent deposits regularly reworked by contemporary geomorphic processes	Stream channel bars Active rockfall talus Avalanche debris tracks

Table 2.4: *Dating techniques and time-scale application*



Chapter 3 –

Measurement of present-day sediment fluxes

3.0 INTRODUCTION

The aim of this Chapter 3 is to provide an overview over recommended methods and techniques for the quantitative investigation and the long-term monitoring of present-day sediment fluxes in cold environment small catchment (less than 30 km^2 catchment area) geosystems.

Consideration is given to weather stations for monitoring of meteorological parameters (section 3.1), to fluvial sediment transport (section 3.2), including suspended load (section 3.2.1), bedload transport (section 3.2.2) and dissolved load (section 3.2.3), to slope wash (section 3.3), solifluction (section 3.4), aeolian processes (section 3.5), and to mass movement processes (section 3.6) including debris flows (section 3.6.1), snow avalanches (section 3.6.2), rockfalls (section 3.6.3). Additional comments are made on extreme events (section 3.7) and on magnitude and frequency as well as on magnitude-frequency-relationships within process geomorphologic studies (section 3.8).

3.1 WEATHER STATIONS

For all SEDIFLUX/SEDIBUD field sites standardised equipment and recording methods are needed with the aim to establish fundamental measurements and data acquisition to characterize the SEDIFLUX/SEDIBUD sites.

Selection of sites for weather stations

The climate stations should be located in open terrain where the measurements are representative for the SEDIFLUX /SEDIBUD key test site. The position of the climate stations should be within an area of uniform surroundings, and with an adequate distance to obstacles. No hidden, highly wind exposed or high topographic relief locations should be chosen.

Level 1 weather stations

(Levels defined after Molau & Mølgaard, 1996)

Meteorological measurements with a Level 1 climate station may choose any field site for a temporary installation in the initial phase. A Level 1 climate station is entirely manual, and the following parameters are to be measured inside a shelter cage (Stevenson Screen):

1. Air temperature thermometer installed horizontally in the cage
    a) Spirit minimum thermometer: 2 m above ground; accuracy 0.1 °C
    b) Mercury maximum thermometer: 2 m above ground; the bulb end tillted somewhat downwards; accuracy 0.1 °C
    c) Precipitation: 1m above ground, 2 m above ground in mountain regions; accuracy 0.5 mm; daily reported; note type of precipitation
2. Thermohygrograph THG and psychrometer for calibration THG

Instrumentation of Level 2 weather stations

(Levels defined after Molau & Mølgaard, 1996)

All SEDIFLUX/SEDIBUD field sites should establish Level 2 measurements of climatic parameters, if possible on a continuous annual basis. The following parameters are to be measured:

1. Air temperature: sun protected at 2 m above ground
2. Precipitation: 1m above ground, 2 m up to 4 m above ground in mountain regions; depending on the system used
3. Wind velocity: 2 m above ground
4. Global solar radiation: 2 m above ground
5. Relative humidity

These Level 2 climate stations can be entirely automatic, and require a data logger configurated to store hourly means, and daily maximum and minimum values for all parameters. Entirely automatic climate stations will need a heating system or an anti-freezing compound (depending on the system used) for the precipitation bucket recorder. During summer the precipitation gauge should be filled with an oil-layer to minimize the evaporation loss (only by precipitation measurements with a scale system). The precipitation gauge should be protected from the influence of wind eddies by a shield.

3.2 FLUVIAL SEDIMENT TRANSPORT

3.2.1 SUSPENDED LOAD

In mountain environments and in many arctic and polar basins suspended load is the main constituent of sediment export. Unlike dissolved sediment concentration the concentration of suspended sediment is characterised by a high spatial (cross-sectional) and temporal variability. A common way to calculate annual suspended sediment load and the load of individual flow classes is by using flow duration curves and rating curves for the relation between suspended sediment concentration (SSC) and discharge. Campbell and Bauder (1940) developed a simple but reliable and often used method for calculating suspended sediment transport, the so-called rating curve technique, which allows the extrapolation of field measurements with the help of regression equations. It has the general form of a power function regression relating suspended sediment concentration (SSC: mgl^{-1}) to discharge (Q: m^3s^{-1}): $SSC=aQ^b$. The results must be multiplied with discharge (Q) to get the values for sediment load (SSL: kgs^{-1}). In small polar or mountainous catchments, however, the general correlation between suspended sediment concentration and discharge is generally poor. Peak concentrations frequently occur prior to peak discharge and concentrations on the falling limb of the hydrograph are often smaller than on the rising limb, which results in hysteresis loops in the discharge/concentration graph (Schmidt, 1996). Sometimes it is necessary to calculate polynomial rating curves or separate rating curves for individual discharge classes, for the different limbs of the hydrographs or for different types of events or even event specific rating curves (Schmidt & Morche, 2006). Nonetheless the scatter in the relations is frequently considerable and estimates are often liable to large errors. The variable delivery of sediment sources in the catchment is generally much more important than the hydraulic attributes of channel flow.

The difficulties of obtaining reliable time series of suspended sediment concentration can be overcome by frequent sampling and interpolation calculations for the time between the sampling intervals. Turbidity measurement is an often used indirect method for continuous monitoring of the concentration of suspended solids. Yet the turbidity signal is influenced not only by sediment concentration, but also by its grain size distribution, colour and content of organic material, which may be a major constituent in arctic regions. The relation between the turbidity units and SSC must be calibrated for each individual measuring station. Very little information exists on the spatial variation of SSC in the cross section. There is a striking dicrepancy between the number of theoretical and laboratory models and empirical field measurements. Multi-point sampling in mountain torrents has shown that even in highly turbulent flow there are remarkable differences in the cross profiles (Schmidt, 1996).

A greater number of studies on sediment load calculations have been carried out in high-altitude environments (e.g. Schmidt & Morche, 2006) than in high-latitude locations, where the use of monitoring equipment and the accessibility is much more restricted (Beylich & Gintz, 2004; Beylich et al., 2006; Gintz & Schmidt, 2000). Measuring methods ranged from integrated sampling to multiple point samples and on-line turbidity registration. Only major floods transported remarkable amounts of suspended sediment. In Russia about 75 % of the total annual sediment load were transported in a few days during snowmelt runoff or during rare rainfall induced floods and in events when sources of material were made available by thermokarst induced bank collapse. In the course of flood events significant temporal and spatial variations of suspended sediment concentration and grain size composition were observed.

3.2.2 BEDLOAD TRANSPORT

The SEDIFLUX / SEDIBUD test sites cover a wide range of high-latitude and high-altitude cold environments. The amount of bed load to be expected at these sites is highly variable. To aggravate the situation bed load transport is the most complex fluvial-sediment transport process with respect both to measurement and quantification. This complexity is due to a combination of factors, which are related to (i) the spatial and temporal variability of the bed load transport process, (ii) the morphometric and hydraulic conditions of the site, (iii) the grain size and shape characteristics of the bed load and the bed surface particles. Additionally, limitations occur in the sampling techniques and the personal resources available to collect accurate bed load data sets.

Several field techniques are used to qualify and quantify the bed load transport rates with different success. They can be categorized into direct (Tab. 3.1) and indirect methods for measuring bed load (Tab. 3.2). Of these, none can clearly be preferred. In some cases a combination of different measuring approaches will lead to satisfactory results.

Prior to the bed load measuring itself the following fieldwork should be carried out:

i) The first step is to identify a representative part for the measuring site (cross profile). For example, a bridge will usually provide a good location to install the measuring equipment.

ii) The second step is geomorphic mapping (terrestrial or by air photography) and additional geodetic surveys of the bed morphology with respect to riffle-pool, step-pool sequences, bedrock outcrops large woody debris and channel gradient (Chin & Wohl, 2005; Lenzi, 2001; Morche et al., 2007; Morche et al., submitted).

iii) Detailed grain size analyses of the surface (by pebble count/grid by number) and subsurface material (by volume, by weight) should be carried out according to the guidelines of Bunte & Abt (2001) to get information on grain roughness and the grain size distribution. Grain size distribution is necessary for calculationg the sorting and to decide the relation between bed material size and the "Helley Smith" sampler intake width (trap efficiency obviously goes to zero when the particle size is the same as the samplers intake). It appears that the sampler intake opening has to remain greater than 5 times the diameter (conservatively of the a-axis) of the largest particle apt to move in the stream (Vericat et al., 2006).

Table 3.1. *Methods of direct bed load measurement*

Sampling Device	Advantages and disadvantages	Useful for
Permanent sediment traps, non recording ore continuously recording traps by weight (Bunte, 1996) ore ultrasonic sensors (Lenzi et al., 1999)	Provide representative measurements of instantaneous transport rates of bed load, expensive to construct, difficult to install and maintain. (Bunte, 2001); The bed load has to be removed, sieved and weighed after the chosen interval, depending on the capacity of the trap, and of the research question (e.g., event or seasonal data)	- Permanent measuring sites with moderate transport rates - U-shaped concrete canals as measuring site to weigh the passage of bed load
Small non-recording portable pit trap samplers (Bunte et al., 2004)	Can be installed in a streambed by a small field crew. Provides accurate samples of coarse bed load and can be related to flow (Bunte et al., 2004).	- Measuring sites with moderate transport rates and "low" water level. A person should operate in the stream.
Pressure-differential bedload samplers, e.g. Helley-Smith-Type Sampler with a defined opening area and mesh size (Bunte & Abt, 2001; Helley & Smith, 1971; Ryan & Porth, 1999, Ryan & Troendle, 1996; Vericat et al., 2006)	Inherent instrumental and process errors (Emmett, 1980), sampler has to be calibrated to determine their hydraulic and sampling efficiencies under a range of operating conditions.	- Wadable measuring sites or cross sections with a kind of bridge and moderate transport rates.

Table 3.2. *Methods of indirect bed load measurement*

Sampling Device	Advantages and disadvantages	Useful for
a) Hydrophones (Krein et al., 2006; Rickenmann, 1993) b) Shock sensors (Vatne et al., subm.) c) scour chains (Laronne et al., 1994; Leopold et al., 1964), d) Cut and fill analysis of DEMs from geodetic or laserscanning surveys (Fuller et al., 2003; Morche et al., 2007)	a), b) Highly resolved transport rates can be determined. The difficulties in calibration of the given signals and the high cost factor are shortcomings of these interesting techniques.	- Budgeting sediment transfer (over different time scales) (a) - Detecting the passage of bed load (a, b) - Determining the entrainment of particles (a, b) - Indicating transport rates of fine grained bed load during high discharge (a, b)
Tracer techniques Natural tracers Tracing with color, numbers, magnetic or radioactive coating (see Bunte, 1996) Natural and artificial particles with iron or magnetic cores (Gintz et al., 1996, Schmidt & Gintz, 1995) Active radiotracer (Schmidt & Ergenzinger, 1992)	The quality of tracer studies is directly linked to the recovery rate of the traced particles (Wilcock, 1997)	- Examining the active river bed cross section at several stages in small rivers and tributaries as well as in braided rivers. - Determining the entrainment of transport - Detecting the travel lengths of coarse particles, - Investigating the depth of scour layer, the transport, rest times and step length of active tracers

For the SEDIFLUX/SEDIBUD catchments in a range of 10 - 30 km² we prefer a combination of different methods in addition to the preparatory steps (see above): i) selection of cross profile, ii) riverbed morphology and iii) grain size analyses.

In addition to the direct or indirect methods of measuring bed load transport, it is possible to calculate rates of transport by using so-called bed load formulae. Their application might be successful but remains insecure. For detailed reviews of bed load formulaes see Gomez & Church (1989) and Martin (2003). In a paper proposing practical methods for estimating sediment transport Wilcock (2001, p. 1395) stated that formulae are “notoriously inaccurate”. This especially applies to coarse material torrents.

3.2.3 DISSOLVED LOAD

Runoff from glaciers as well as polar streams and rivers provides the principal routes of export of matter in the form of solutions and solids from glaciated and non-glaciated catchments. The load leaving a catchment is calculated from measurements of discharge, concentrations of solutes and suspended matter, and the rate of bedload transport (see above).

Fluvial transport can be studied by different approaches:

- At a site,
- In a profile, cross-section, or transect,
- In taxonomic units of various hierarchical orders, e.g. valleys, slopes, erosional gullies,
- In a river catchment, and
- In a catchment's buffer zone.

Discharge measurement and monitoring: Discharge is indispensable variable for calculating a sediment balance. The best solution is to install a permanent weir with a recording instrument to monitor the water stage on a continuous basis. The water stage is measured in carefully selected cross-sections of the river channel, so-called water-gauging sections. At these gauging stations water level is recorded with the help of recording instruments (recording gauges / water level recorder / electronic sensors), or by an observer's reading a staff gauge. Recording gauges produce an analogue record of the results of measurements on a paper tape, while water level recorder and sensors collect the digital data in a memory block called data logger.

The fluctuation pattern of water stages in a river varies diurnally and seasonally, and the type of alimentation that moulds it is surface and subterranean ablation. If there is no electronic recording, the number and time of measurements taken per day are adjusted to the current hydrological situation:

- Four times a day at 0:00, 6:00, 12:00 and 18:00 GMT,
- Twice a day at 6:00 and 18:00 GMT, and
- Once a day at 6:00 GMT.

If possible, the mean daily discharge should be calculated from the stage/discharge relationship for the given hydrometric profile. At rainfall-induced high stages and in glacier catchments responding quickly to changes in ablation measurements must be taken more frequently, even at hourly or shorter intervals.

The site of water sampling for analyses of physico-chemical properties should be located near the weir / hydrometric profile. In the absence of a weir, water is sampled in the current of the stream, at mid-depth, with the help of a bathometer. In shallow streams where the use of a bathometry is impracticable, a sample should be taken in such a way as to minimise the risk of its contamination. The samples should be preserved immediately. It is also recommended that they should be filtered as soon as possible through membrane filters with a pore diameter of 0.40-0.45 µm (e.g. Whatman 42 or GFC) washed with de-ionised water.

The time of transport and storage should be reduced to a minimum. In the case of some 'sensitive' determinations, e.g. alkalinity, the maximum period between sampling and lab analyses should not exceed 24 hours. To avoid chemical changes resulting from microbial activity and impurities, the bottles with samples should be transported in sunlight-blocking plastic bags and, if possible, in isothermal containers. Until the start of analyses, the bottles should be stored in the dark at 4ºC.

Table 3.3. *Measurement parameters of fluvial transport and some recommended field and analytical methods*

Parameter	**Unit**	**Accuracy** (Decimal places)	**Frequency of measurement**	**Basic method**	**Alternative method**
			Field methods		
Precipitation	Mm	0 or 1	1/day (dt-24h) Continuous recording	Hellmann rain gauge	
Intensity of precipitation	mm h^{-1}	1	Continuous recording (IV/V - IX/X)	Recording rain gauge	
Thickness of snow cover	Cm	0 or 1	1/day (dt-24h)	Probe	
Water content in snow (snow density)	%	1	1/day (dt-24h)	Gravimetric method	
Groundwater stage	cm p.p.t.	0 or 1	1/day (dt-24h) Continuous recording	Piezometer	
Water stage H in stream	Cm	0 or 2	1/day (dt-24h) 2/day (dt=12h) 24/day (dt=1h) Continuous recording	Staff gauge with analogue recording gauge or hydrometric sensor	Staff gauge + digital recording gauge, wide-crested weir
Specific runoff	ls^{-1} km^{-2}	1	1/day (dt-24h) 2/day (dt=12h) 24/day (dt=1h) Continuous recording	Calculated	
Discharge Q_H [Q for H from Q=f(H)], depth of river channel, measurement of velocity in stream	M^3s^{-1}, m^3s^{-1}	1, 2 or 3	1/day (dt-24h) 24/day (dt=1h) 1-2/week	Sounding of stable cross-section, hydrometric current meter, hydrometric sensor	
Water temperature T	°C	1	1/day (dt-24h) 2/day (dt=12h) 24/day (dt=1h)	Water temperature sensor with conductometer/pH	Recording mercurial thermometer,

Parameter	Unit	Accuracy (Decimal places)	Frequency of measurement	Basic method	Alternative method
				meter	thermograph
Analytical methods					
Specific electric conductivity SEC	µS m^{-1}	1	1/day (dt-24h) 2/day (dt=12h) 24/day (dt=1h)	Conductometrically at reference temp. of 25ºC	Oscillometrically
Suspension Cs	Mg l^{-1}	1	1/day (dt-24h) 2/day (dt=12h) 24/day (dt=1h)	Gravimetric method	Nephelometer
Reaction (pH)	pH	2	1/day (dt-24h) 24/day (dt=1h)	Potentiometrically at reference temp. of 25ºC	
Alkalinity	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Titrimetrically in the presence of phenolphthalein or methyl orange	
Sodium Na	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Atomic absorption spectrometry	Flame photometry
Potassium K	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Atomic absorption spectrometry	Flame photometry
Calcium Ca	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Atomic absorption spectrometry	Titrimetrically with versenate
Magnesium Mg	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Atomic absorption spectrometry	Titrimetrically with versenate
Sulphate sulphur S-SO_4	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Ion chromatography	Gravimetrically in the presence of barium chloride, nephelometric method
Bicarbonates HCO_3	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Titrimetrically; *see* alkalinity	
Chlorides Cl	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Ion chromatography	Potentiometrically with chloride electrode, titrimetrically - Mohr's method
Silica SiO_2	mg dm^{-3}	2	1/day (dt-24h) 24/day (dt=1h)	Colorimetrically with ammonium molybdate	

3.3 SLOPE WASH

The quantification of slope aquatic sediment fluxes (e.g. in alpine environments) includes high demands on the methods chosen. Frequently, logistical problems (limited accessibility) have to be considered as well as a high variability of meteorological conditions and sediment fluxes.

In general, the amount of denudation caused by slope wash can be determined by measuring

a) The change in topography (measurement on the plot scale or along profiles), or
b) The sediment yield of small catchments where slope wash takes place.

Other techniques suitable for various scales (e.g. ^{137}Cs dating of sediment profiles, photogrammetry, splash cups etc.) are reviewed by Collins & Walling (2004) and Stroosnijder (2005).

a) Quantifying slope wash by measuring changes in topography

In order to quantify topographic changes on surfaces subject to slope wash, denudation gauges (also referred to as 'erosion pins', see Haigh, 1977) can be installed (Fig. 3.1). Rods made of construction steel should be driven deep into the slope substrate (e.g. 40 cm deep with 50 cm long rods) and perpendicular to the slope surface (in order to measure normal distances). Preferably, gauges should be positioned on the slope in a way that longitudinal and cross sections (1-D) can be constructed. Readings from multiple gauges can also be interpolated (2-D) in order to detect the spatial distribution of denudation and deposition.

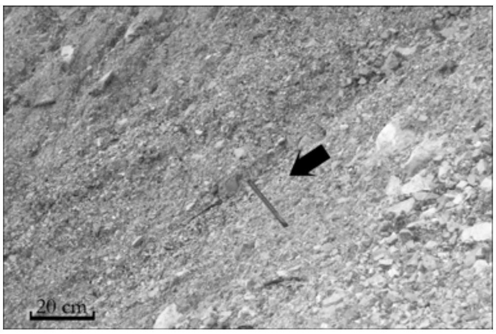
Preferably, readings should be made regularly (e.g. twice a year, in autumn and in spring) from the top of the gauges to the slope surface. If the surface is highly uneven (high roughness), multiple readings (maximum-minimum) are necessary at each gauge; it has been suggested to slide a cardboard disk with a central hole down the rod to determine the reading (Wetzel, 1992).

Depending on the frequency of the readings, the temporal resolution of this method is rather low. Therefore, in most cases, reasonable event-based results cannot be expected. The accuracy of denudation gauge readings may be questionable, e.g. because the steel rods are susceptible to frost-heave

(Evans & Warburton, 2005). A major drawback is that slope processes may be subject to a considerable bias when the researcher has to climb the slope to read the gauges (Haigh, 1977) and because of mechanical effects of the gauges themselves. In spite of these problems, we consider the method to be highly suitable for medium- and long-term quantification of slope aquatic sediment flux.

Contactless surveys of hillslope surfaces can be achieved using laser scanners and laser tachymeters. With the former, a large quantity of points can be surveyed in a very short time, and the resulting representation of the surface, e.g. a digital elevation model, is very accurate. The latter takes more time, but is not less accurate; we suggest the following procedure (Fig. 3.2): Three points are fixed on the slope, which serve as anchor points for a virtual reference plane, which is orientated parallel to the slope. Predefined grid points (‘virtual denudation gauges’) on the reference plane can be surveyed again and again without affecting the surface.

With both alternatives, high-resolution digital elevation models can be generated and compared with each other in order to calculate a spatially distributed sediment budget and to delineate zones of erosion and deposition (cut-and-fill analysis; see e.g. Morche et al., 2007). The application of terrestrial digital stereophotogrammetry is a conceivable alternative (see e.g. lab experiments by Rieke-Zapp & Nearing, 2005), but further experience is needed before a recommendation can be made without restriction.



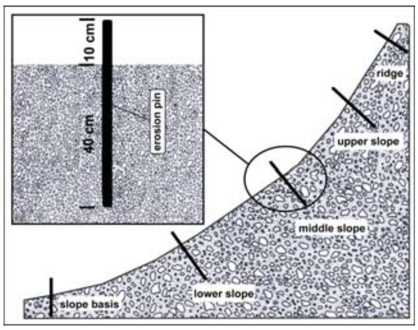


Fig. 3.1. *Denudation gauge (arrow) at a test site (left) and schematic slope profile with recommended positions of erosion pins.*
Figure taken from Haas (unpubl.)

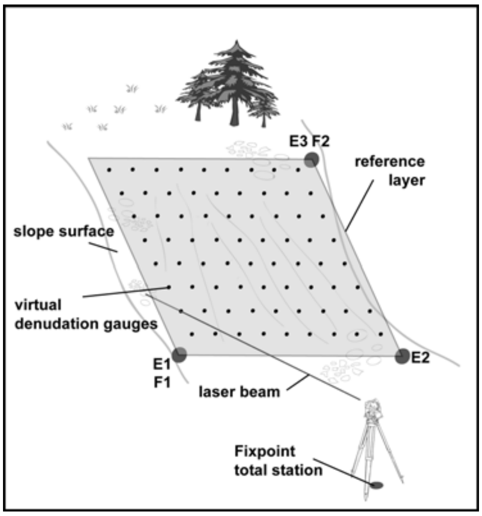


Fig. 3.2. *Assembly of a test plot with 'virtual denudation gauges'. The points E1-E3 define the reference plane. Figure taken from* HAAS *(unpubl.)*

b) Measurement of sediment yield

Sediment traps can be installed in small channels draining sub-basins in which slope wash occurs, or on test plots. For the former, inexpensive plastic troughs ('Gerlach troughs') with a capacity of 65-95 litres (Becht, 1995; Rieger, 1999) can be used as sediment traps, metal gutters have been used on test plots (Morgan, 1979; Hudson, 1993). In order to ensure that discharge and sediment load are completely collected by the sediment trap, the channel bed or hillslope surface at the inflow should be covered with a rugged, impermeable foil. In the ideal case, the complete bed load or the sediment washed from the slope, respectively, is stored in the sediment trap and can be sampled at regular intervals (e.g. weekly).

The installation of Gerlach troughs is only appropriate in small channels (mean discharge smaller than 10 ls^{-1}), and during high discharge events (e.g. a storm), the capacity of the troughs is quickly exceeded. In this case, only a minimum sediment flux can be indicated. To mitigate this problem, the installation of multiple troughs in a row has been suggested (Oostwoud Wijdenes & Ergenzinger, 1998). In catchments with high sediment loads, the sampling frequency of the sediment traps has to be kept very high. In addition, it must be considered that the installation and maintenance of sediment traps in channels exerts some influence on the channel itself; in particular, the first readings have a high probability of overestimating the sediment flux. In the presence of coarse substrate (talus, moraine) or permafrost, the installation itself is problematic.

For the interpretation of the results, it has to be stated that the sediment sampled from traps includes both material derived from slope wash (plus other slope processes) and from channel erosion. As such, it is the product of multiple processes rather than of slope wash alone. For this reason, the importance of slope wash in the sub-basin should be evaluated before sediment traps are installed.

3.4 SOLIFLUCTION

Solifluction is a slow mass movement process associated with freeze-thaw cycles and frost heave. The Encyclopedia of Geomorphology (Goudie, 2004), refers to solifluction as consisting oft the two processes frost creep and gelifluction. Solifluction processes induce formation of features, such as lobes, terraces, sheets and sorted stripes.

Matsuoka (2001) has listed different methods to evaluate solifluction rates. Surface velocity of the landforms can easily be determined and compared using low-cost methods, such as painted lines and marked stones for movement of uppermost particles and tilting rods and pegs for movement of the uppermost soil layer. Subsurface velocity can be obtained using marker columns, aluminium foil strips and plastic tubes, but they need re-excavation. The Circumpolar Active Layer Monitoring network (CALM) has also recommended the use of vertically inserted strings with a wooden disc on the surface, which allows heave measurements. Marker columns have the advantage that they allow the detection of shear surfaces. The disadvantage of using foil strips and tubes is that they are limited in deformation and cannot provide fully accurate displacement profiles. Electric sensorss such as the inclinometer, the solifluction meter and strain probes can also be used and permit year-round automatic recording using data loggers. Important environmental parameters (e.g. temperature, soil moisture, pore pressure) can be measured simultaneously. Electric systems are sensitive for technical problems such as damage or malfunctioning, cost more and are less easy to use. These methods are applicable on a local scale (plot or slope scale). Remote sensing can be used for a larger scale assessment (Walsh et al., 2003).

The length of the monitoring period is also important. Climatic variations during the year cause movement variability and the sensor installation produces soil disturbance, which affect solifluction rates during the first few years (Matsuoka, 2001).

If an understanding of environmental conditions influencing solifluction rates is required these should also be monitored. Environmental parameters should include monitoring of *ground temperatures* (e.g Smith, 1988; Price, 1990), *soil moisture conditions* (e.g Smith, 1988; Price, 1990; Jaesche et al., 2003), *slope gradient* (Åkerman, 1996), *duration and thickness of snowcover* (e.g Hugenholtz and Lewkowicz, 2002; Jaesche et al., 2003), *soil texture* (e.g Hugenholtz and Lewkowicz, 2002) and *vegetation.* Ground temperatures give information on the ground frost regime, including freeze and thaw depths and frequency of frost cycles. Duration and thickness of snow cover is important to understand since it is one factor that controls the soil moisture conditions and thermal regimes, such as rate of the autumn freeze-up.

Suggestions for monitoring methods for the quantification of solifluction rates

For local scale measurements two low cost and easy to use methods are proposed. Painted stones are proposed to use for surface movement assessment in areas with high stone abundance and/or intensive frost heave. In areas where frost heave is less intense and/or stoniness on the surface less abundant (for example where turf-banked lobes dominate) wooden markers of 20 cm length and 1 cm^2 width are suitable. If possible a total station or a differential GPS (DGPS) is used to measure the position of the stones or the markers. If a total station or a DGPS cannot be used, a reference line is used. This should be carefully anchored to the ground, preferably by drilling a hook into the bedrock or to a large boulder. The measurement lines should not exceed 30 m, as the accuracy of the measurement decrease with the length of the line. The length of monitoring periods should be at least 5 years.

3.5 AEOLIAN PROCESSES

Aeolian processes refer to sediment movement by air-flow. Due to the often suppressed vegetation cover in cold environments, as well as abundance of fine sediments related to e.g., glacial and periglacial processes, wind may play a significant role as a geomorphological agent in these environments. With respect to catchment scale studies, the operation of aeolian processes differs from fluvial or slope processes in that it does not fully obey topographic barriers such as water divides. Hence, wind is capable of blowing material across catchment borders, causing potential “leakage” to standard flux calculations.

There is no single standard design for aeolian sediment flux monitoring in the field. This is due to the fact that many aspects of aeolian transport process are still inadequately understood and field campaigns are continuously developed and adjusted accordingly. The physics of the aeolian sediment transport is outside the scope of this paper, but it may be useful to familiarise oneself with Bagnold’s (1941) classic work and many recent updates and summaries (e.g., Sørensen, 2003; Raupach & Liu, 2004).
Furthermore, large variation in the field circumstances (sediment properties, topography, wind speed, vegetation, moisture content, etc.) and rationale of the study (process study, flux measurement, net changes, etc.) call for site-specific field campaign. Nonetheless, a minimum set up of aeolian flux research typically consists of a device to monitor aeolian sediment transport. Transport data are typically supported by wind information either with *in situ* wind observations or data from a suitable (nearby) weather station.

Aeolian material

The key characteristic of aeolian processes is the restricted maximum grain size of the sediment suitable for transportation. This is due to the comparably low density (approx. 1/1000 of water density) and low viscosity of air as a transporting fluid. Most common particle sizes subject to aeolian transport vary from fine–medium sand to silt. The lowest threshold velocities correspond to the size fraction of ca. 0.2 mm. Smaller particles than this require higher initial flow velocities due to the aerodynamically smooth surface and strong cohesion (often related to moisture or bonding salts), whereas larger particles are simply heavy enough to restrain the shear. In flux studies, it is advisable to do at least basic analyses on sediment textural parameters, e.g. mean grain size, sorting, skewness and kurtosis, plus possibly mineralogy (for density) and grain form. Care has to be taken when sampling the sediment as due to winnowing effect (lag formation) and moisture gradients the immediate grain surface may show characteristics different from the bulk sediment.

In cold environments, sediment surface may be seasonally frozen or snow covered, which hamper the aeolian process but do not necessarily stop it completely (McKenna Neuman, 1989; 1990; Lewkowicz & Young, 1991; Law & van Dijk, 1994; van Dijk & Law, 1995; 2003).

Transport processes

Aeolian sediment transport takes place in three processes: creep (reptation), saltation and suspension (see e.g., Leenders et al., 2005). *Creep* denotes to rolling or sliding of particles over neighbouring grains by the impacts of other moving grains. *Saltation* is bouncing or jumping of grains, whereby wind shear lifts grains from the surface at steep (55°) initial ascent angle. Grains fly in the airflow gaining momentum and return back to surface at low angle (10°) and high speed, causing dislodgement of further particles. Saltation typically represents the largest proportion of the total sediment transport. *Suspension* refers to the movement of small particles (dust) in turbulent air without frequent rebounds on the surface and is therefore challenging to monitor. Suspension is often initiated by larger saltating grains disturbing the fine sediment surface sealed by salts or moisture.

Flux monitoring

Traps

Aeolian sediment flux can be investigated with various methods. The flux is normally given as kilograms through a one-metre wide “gate” in a second (kg $m^{-1}s^{-1}$). Instantaneous sediment flux is most commonly accomplished with sediment traps of various designs. There are two main types of sand traps commonly used by researchers: horizontal traps, which do not rise above the sand surface and measure the falling sand mass flux, and a vertical trap, which rises some tens of cm above the sediment surface and measures the horizontal sand mass flux (see e.g., Li & Ni, 2003). Horizontal traps have generally higher sampling efficiency but are rather large to operate. A common problem with sediment traps is their aerodynamic robustness: they interfere with the airflow and instigate scour in the surrounding sediment surface resulting in deteriorating effectiveness in time. Many vertical traps are made of nylon or metal mesh to allow airflow escape through the porous screening whilst stopping the grains.

Impact responders

In many studies, sediment traps are replaced with various flux impact responders (often referred to as saltiphones), which count impacts of grains hitting a specially designed microphone (see e.g., Baas, 2004). This method does not, however, resolve the mass flux due to the fact that the observation is based only on the momentum of the saltating grains. It is therefore difficult to relate the sensor response to a mass flux, unless traditional sand traps are deployed alongside the impact sensors to determine site-specific relationships between mass transport and signal response. Saltiphones are useful, for example, in determining threshold wind speeds when used in combination with high frequency wind data (Stout, 2006).

Long-term fluxes

Instantaneous flux approach helps understanding the sedimentary processes but may not reveal long-term sediment balance due to the highly variable nature of wind as compared to, say, fluvial environment. Therefore, more representative results of sediment budgets may be gained by long-term monitoring of the sediment surface. This is typically monitored with erosion pins or high-accuracy levelling (see e.g., Käyhkö, 2007).

Landscape level changes

Landscape level flux estimates may be done using remote sensing techniques. Multi-temporal high resolution optical data (air photos, Ikonos, SPOT etc.) may reveal dynamics between vegetated and barren sediment surfaces, whereas vertical changes in sediment surfaces may be disclosed with synthetic aperture radar data with interferometric (InSAR) techniques.

Wind measurements

Should one be interested in spatio-temporal extrapolation of the aeolian flux results, there is a need to find a locally valid correlation between wind speed and sediment flux. Therefore, it is of crucial importance that the monitored air-flow (and the resolved shear stress) represents the monitored flux. This requires carefully designed monitoring campaign. In the field, wind velocity is typically measured with a vertical series of cup anemometers or, should one prefer monitoring at micro-scale (i.e. very low elevation above sediment surface and/or very high frequency) with hot wires, sonic anemometers or other miniature device. Selection of monitoring frequency and period depends on the specific question to be addressed, but the highly fluctuating nature of airflow requires monitoring frequency from sub-seconds to minutes, still easily accomplished with modern data loggers. Long-term wind data are often available from weather stations, but one should use wind data from distant stations with caution, as their regional representativeness is rather limited.

3.6 MASS MOVEMENT PROCESSES

3.6.1 DEBRIS FLOWS

Debris flows are rapid mass movements involving a mixture of water and heterogeneous debris, occurring on steep mountain-slopes. Descriptions of the process progressing downslope can be found in Larsson (1982), Johnson & Rodine (1984) and Decaulne *et al.* (2005).

The study of debris flows in cold environments has to highlight five main issues, mainly raised through field investigation and air photo interpretation:

- The characteristics of the source-area reveal the initiation of the debris movement: the destabilisation of the debris mass can be caused by a rotational slide on unconsolidated material (associated with large amounts of inherited material, Prior *et al*., 1970; Statham, 1976; Addison, 1987; Decaulne *et al.,* 2005), or by a fire-hose effect (mostly debris supplied by present-day freeze-thaw, Neboit-Guilhot *et al.,* 1989; Glade, 2004). The origin of material has essential implication on the recurrence of the process, as it requires permanent debris availability or, in contrary, the necessity of the reconstitution of the stock of material in between two events.
- The transfer of debris downslope builds a typical landform assemblage succession along a track, which is commonly fixed upslope but migrates laterally downslope (Sharp, 1942; Rapp, 1960; Brunsden, 1979). The upper section is characterised by a deep incision more or less filled with material from the debris flow. The mid section shows both incision and accumulation between debris levées. The levées are more developed in the lower section, bordering a non-incised channel, leading to the debris lobes. The parallel levées, often uneven and asymmetrical, show an inverse vertical sedimentary architecture, the largest boulders being at the surface; the observation of those levées is the main indicator of a debris flow activity.
- The geomorphological impact of the debris flow is dependent on its scale or magnitude, i.e. on the volume of material transferred (Innes, 1983a) and the creation of specific features. Most of the time, only coarse material volume is estimated. Debris-flow volume estimates are therefore derived from morphometric properties of the deposits (Fig. 3.3), i.e. on terrain profiling and measuring using tape and inclinometer (Rapp, 1960; Innes, 1983a; Costa, 1984; Nyberg & Rapp, 1998; Decaulne & Sæmundsson, 2006). The calculation of denudation rates can be obtained for each event by dividing the sediment yield by a denudation area; it is expressed in mm/km². The sediment yield analysis can be completed with a survey of suspended material in the

stream just after the debris flow pulse, underlining the high concentration of fine sediment through the debris-flow channel (Decaulne *et al*., 2005). Samples are obtained by plunging a bottle in the flow at different moments before, during and after the event according to the aim of the study; the water is later evaporated from the bottle in a drying oven and the sediment is weighed, and the results expressed preferentially in mg/l. As this latter sampling requires crossing the unstable material forming the levées, minimal precautions have to be taken by the researcher to insure safety.

- Debris-flow frequency in a specific area is derived from absolute-age and relative-age sources. The historical documents are the most accurate archives (Sæmundsson & Pétursson, 1999; Glade, 2001), and have to be completed by natural evidences to fit the gap of unwitnessed events. Especially, vegetation cover is a useful geomorphic indicator (Broscoe & Thomson, 1969; Sauchyn *et al.,* 1983; Decaulne, 2007), as well as lichenometry (Rapp & Nyberg, 1981; Innes, 1983b; 1985; Jonasson *et al*., 1993; Decaulne & Sæmundsson, 2003; Decaulne *et al.,* 2005) if measurements can be calibrated to a local lichen growth curve. In suitable areas, dendrochronology datings are a significant helping tool (Strunk, 1991; Bollschweiler et al., in press). For older events, rock weathering and rock hardness investigations using a Schmidt hammer and weathering rinds measurements are appropriate methods (Boelhouwers *et al.,* 2001).
- Debris-flow triggering factors can be related to external or internal causes. Even if seismic activity can release this process, most of the events are due to an excess of water within the debris masses. Intense rainfall, long-lasting rainfall, rapid snowmelt and melt of permafrost are the main triggers (Jahn, 1976; Kotarba, 1992; Luckman, 1992; Harris & Gustafson, 1993; Sandersen *et al.,* 1996; Starkel, 1996; Sæmundsson *et al.,* 2003). Investigating the meteorological data is therefore essential, to highlight the origin of the water supply within the debris masses. When available, one hour or ten minutes rain intensity should be preferred to 24 h data; snowmelt modelling could also be necessary for nival releases.

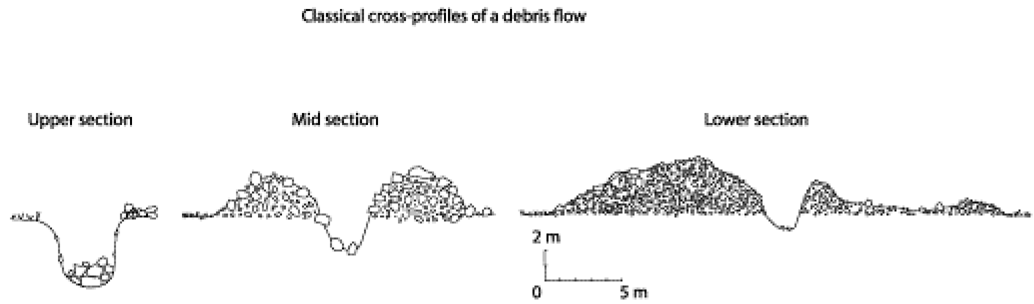


Fig. 3.3. *Terrain profiling highlighting the slope incision, material accumulation, and levées architecture related to debris flow activity and geomorphic impact (modified from Decaulne et al., 2005)*

3.6.2 SNOW AVALANCHES

The snow deposits of avalanches that have been in contact with snow-free surfaces during their descent (above all: full-depth avalanches) can contain considerable amounts of rock, soil and organic debris, which concentrate on their surface during snowmelt. In order to quantify sediment yield, the snow deposits should be mapped (e.g. on large-scale aerial photos) and sampled at a late stage of snowmelt, when the process of debris melt-out has advanced. In many cases, the avalanche snow deposits can be subdivided into sections with homogeneous debris cover that should be mapped and sampled separately.

A prerequisite for this procedure is that dirty avalanche deposits must be clearly distinguishable from unaffected areas. Therefore, it is not always possible to do the fieldwork when snowmelt is over. On talus slopes, for example, avalanche deposits cannot be distinguished from the talus substrate once the avalanche snow has disappeared. Mapping and sampling of the debris cover can be done on vegetated (Ackroyd, 1986) or glacier surfaces (André, 1990), large blocks cleaned before the avalanche season (Luckman, 1978) or artificial plates fixed to slopes (Luckman, 1978; Gardner, 1983). Frequently, thin dirty avalanche deposits cover clean snow (either undisturbed snow cover or snow deposits of previous avalanches) and can be easily mapped and sampled (Becht, 1995; Jomelli & Bertran, 2001; Heckmann, 2006). In order to keep the sample weight to be carried in a reasonable range, sampling areas of 0,25-1 m² are suggested for fine debris. Coarse debris should be collected and weighed directly in the field.

In a GIS, the sample weight or volume per unit area and the surface area (preferable to planimetric area, as the latter is too small on steep slopes) of the respective deposits are used to calculate the total sediment yield of the avalanche. Multiple sampling of avalanche deposits which were homogeneously covered by debris showed the accuracy of the calculation of sediment yield to be in the range of +/- 30% (Heckmann et al., 2005; Heckmann, 2006). The calculation of denudation rates (by dividing the sediment yield by a denudation area) is more difficult: As different areas (study area, catchment area, rockwall area, process area etc…) have been used in previous studies, their results are not comparable. It is suggested that the area affected by the respective avalanche (i.e. the complete process domain) should be determined as exactly as possible in order to get a more realistic estimate of denudation. This can be done by mapping the starting and transit zones shortly after the event, or by spatial modelling (Heckmann, 2006).

3.6.3 ROCKFALLS

A *rockfall* is defined as a free movement of rock material away from steep slopes such as a cliff (Flageollet & Weber, 1996). Small rockfalls originate from rock blocks that are freshly detached from the rock face (primary rockfall) or alternatively from material that has been resting in situ, on ledges or in gullies on the rock wall (secondary rockfall) (Matznetter, 1956). Larger rockfalls occur due to sliding of a rock mass often on a pre-existing discontinuity or due to toppling of a rock tower (Whalley, 1974; Petley & Petley, 2005). The most common classification for rockfalls is the volumetric classification introduced by Whalley (1974; 1984) that divides up debris falls

(<10 m³), boulder falls (10-10^2 m³), block falls (10^2-10^4 m³), cliff falls (10^4-10^6 m³) and falls of bergsturz size (> 10^6 m³).

The sediment transfer can be evaluated *directly* by measuring the quantity of rockfall over a short span of time or *indirectly* by estimating historical rockfall deposits that were accumulated over time. Indirect methods are preferably applied to high-magnitude rockfall deposits, scree slopes and rock glaciers, with the latter representing an integral value of rockfall deposition over a Holocene to Lateglacial time-scale (Barsch & Jakob 1998; Schrott et al., 2002). Direct methods include acoustic observations, lichenometric and dendrogeomorphological dating, measurement of height differences of quartz veins, measurements of accumulations on snow patches and on rockfall collectors, evaluation of removal rates on painted rock walls, laser scanning and road inventories (overview see Krautblatter & Dikau, 2007). Due to their high spatial and temporal resolution, rockfall collector measurements provide the most accurate results for primary (Sass, 1998; Sass, 2005) and secondary rockfalls (Krautblatter & Moser, 2005b) in restricted catchment areas. Repeated high-resolution laser scanning is about to become the most sophisticated method for extended rock faces (Rosser et al., 2005). Target values of rockfall studies are rockwall retreat (mm/y), sediment transfer from the rockface on the deposition area (t/a) and, where information on fall heights is available, released geomorphic work (J). Rates of primary rockfall can be attributed to pre-weathering factors (geological properties, topography) and weathering factors (climate, hydrology, biological conditions) while secondary rockfalls mostly respond to internal and external triggers.

Measurement and interpretation of rockfall studies is connected with a number of problems: The impact of pre-weathering factors, weathering factors, external and internal triggers is poorly understood and their properties are often not reported (Matsuoka, 2001). Only certain rockfall magnitudes are measured and no reliable relations exist for the proportion of different magnitudes (Rapp, 1960; Hungr , et al. 1999; Guthrie & Evans, in press; Krautblatter et al., in press). Proportions of primary and secondary rockfalls are often not mentioned (Sass, 1998). The attenuation of debris fall intensity with distance from the rock face is not considered (Statham, 1976; Krautblatter et al., in press). To standardise rockfall measurements we recommend to (i) classify *promoting conditions* (permanent) in the catchment area according to Selby’s rock mass strength classification (Selby, 1980). (ii) *Triggering factors* (transitional) that are prone to influence rockfall intensity (obligatory: freeze-thaw, rainfall intensity; facultative: seismic tremors, rock moisture, ice contents, etc) should be recorded permanently. If extreme events are included in the study period, their magnitude and frequency should be referred to an “average” return period of such conditions (Krautblatter & Moser, 2006). (iii) The *attenuation* of debris fall intensity *with distance* from the rock face must be assessed or modelled. (iv) Different *rockfall magnitudes* should be evaluated combining direct and indirect methods to create complete values of rockfall sediment yield.

When comparing these data to other sediment yield or sediment transfer data it must be considered that the unit mm/y refers to horizontal rock wall retreat while it is applied to vertical rates of denudation for other processes. A comparison of both, sediment yield and geomorphic work with other processes may result in contrary relations due to the considerable transport height of rockfalls that is only included in the concept of geomorphic work (Krautblatter et al., in press). The large discrepancy of rockwall retreat values reported from different studies (0.005-4.5 mma^{-1}) (Glade, 2005) emphasizes the importance of further quantitative studies that are well referenced with environmental conditions. Only a combination of direct laboratory and field studies (Viles, 2000) that deliberately focuses on nonlinear behaviour (Krautblatter & Moser, 2005a; Petley & Petley, 2005; Viles, 2005) with indirect sediment studies that decipher the information gathered in rockfall storages (Van Steijn et al., 1995; McCaroll et al., 2001; Sass & Krautblatter, in press) is prone to reveal the complex behaviour of rockfall over time.

3.7 EXTREME EVENTS

The terminology related to “extreme events” is quite widespread in cold environment literature, and always describes a major episode triggered during excessive conditions. The extreme event is therefore unusual, either because of its cause, or because of its consequences. Speaking about an extreme debris-flow event supposes that the “usual” debris-flow events are well known in the investigated area, at least during the previous 100 years. Hence, it will be an event of low frequency and high magnitude (*cf.* specific frequency/magnitude paragraph). The event might not be extreme by itself, but in comparison with others. Thus, it is not systematically relevant to compare the character extreme of a single process in different cold environments. A discussion related to normal/extreme event can be found in Starkel (1976, pp. 205-207).

The term extreme event can have various meanings:

- It can refer to unusual weather conditions that induced abnormal water input from high rainfall intensity, long-lasting rainfall or rapid snowmelt, triggering the debris flows (Rapp, 1974; 1987; Starkel, 1976; 1996; Decaulne *et al.,* 2005). Meteorological data have to be examined carefully, knowing that the frequency of extreme rainfall/snowmelt conditions is not a valuable basis from which the debris-flow frequency can be extrapolated.
- It could also reveal a spectacular geomorphic impact (both erosive and accumulative), transferring a large volume of material downslope, reaching an exceptionally further point, i.e. having a singular magnitude, intensity and / or duration (Rapp & Strömquist, 1976; Nyberg, 1985; Nyberg & Rapp, 1998; Decaulne & Sæmundsson, 2006).
- The last aspect of an extreme debris-flow event concerns its human impact: the damages, the catastrophic dimension induced by debris flows on communities could transform a “normal” event into an extreme one after impacting human infrastructures in areas where population have not been endangered since their settlement (Larsson, 1982; Nyberg & Rapp, 1998; Decaulne, 2005).

3.8 MAGNITUDE AND FREQUENCY

The evaluation of short- and medium-term measurements of water or sediment fluxes is severely hampered by the fact that the time scale within which they are conducted will not cover the full range of process magnitudes. This fact has consequences for various research objectives, such as to determine the range of potential sediment flux rates or to estimate long-term average, total flux, and the relative effectiveness of particular events in terms of geomorphic work. Therefore, it is important to consider the frequency of events of a given size, the so-called magnitude-frequency-relationship (MFR). Obtaining data for both magnitude and frequency is not a straight-forward procedure, which differs for the individual geomorphic processes.

In general, the determination of the *magnitude* of sediment fluxes

- Depends on the type of process (episodic or continuous activity),
- Uses various methods (estimation, ground/aerial photo survey, measurement), and
- Is possible using data obtained by direct measurement (discharge, sediment concentration, particle sizes, mass or volume of deposit) or data, which allow the indirect estimation ('proxy' data: depth or length of failure or scarp, area of deposit)

Depending on the units of measurement, the magnitude of sediment fluxes may already include temporal aspects, e.g. if rates are given (m^3/s, t/a etc…). The determination of event magnitude (e.g. mass movements) from deposits in the field is complicated by the fact that deposits of smaller events are easily destroyed or covered by erosion and larger events so that small events may be overlooked. Therefore, among other reasons, inventories made from aerial photos or mapping in the field are often incomplete (see Malamud et al., 2004). In addition, different methods and/or observers produce different inventories (Ardizzone et al., 2002; van Westen et al., 2004).

The *frequency* of hydro-meteorological and geomorphic events (e.g. annual maximum flood, storms, landslides etc…) can be obtained in various ways (see below). With respect to processes with continuous activity, frequency mostly refers to the exceedance of a threshold (e.g. discharge, sediment concentration etc…); for these processes, frequency can be calculated from continuous or threshold-triggered measurements.

If there is an empirical correlation of governing variables and flux rates, the results obtained from measurements can be tentatively extended on the basis of long-term records (e.g. MFR of discharge). For example, sediment rating curves relating sediment concentration to discharge can be used to estimate sediment loads for the length of available discharge records and to quantify the contribution of different discharge magnitudes to the total sediment load (cumulated sediment transport curves on the basis of flow-duration curves). The same may apply to the MFR of hydro-meteorological triggers where there is a sound statistical correlation with the occurrence of mass movements (see e.g. Jakob & Weatherly, 2003).

The investigation of less frequent events (e.g. mass movements) requires mapping their traces, e.g. deposits (caveat: small events, see above), and dating them (radiometric and luminescence dating, dendrogeomorphology, lichenometry, tephrochronology, multitemporal aerial surveys, historical data etc., see e.g. Lang et al., 1999). If no absolute dating can be achieved (e.g. undated landslide or debris flow inventories), at least the relative frequency of different magnitudes can be determined. A return period for a given event magnitude can only be estimated where at least a tentative time scale is available for the inventory. Sedimentary archives such as colluvial (e.g. Blikra & Nemec, 1998) or lake sediments (e.g. Irmler et al., 2004) can be used to establish event chronologies, but the magnitude of formative events is not readily deduced from stratigraphy.

Magnitude-frequency-relationships (MFR) are investigated on different spatial scales, from single hillslopes to large catchments. A theoretical probability function (e.g. power-law, inverse gamma function, see Malamud et al., 2004) can be adapted to the empirical data in order to define the MFR for visualisation and further analysis. The probability of exceeding a threshold can be modelled by fitting extreme value probability functions (e.g. Gumbel or Pareto distributions, see Katz et al. (2002) for hydrological examples).

As recent papers have shown, some processes relevant to sediment transport exhibit a MFR described by a power-law, at least for a certain range of scales. The parameters of the power-law function often appear to be very specific for a process, i.e. the same parameters apply, for example, for landslide magnitude-frequency-distributions in different study areas and for events with totally different triggering factors (see e.g. Hergarten, 2002; Guzzetti et al., 2002; Malamud et al., 2004).

Working with MFR is very common in meteorological, hydrological and natural hazards research, especially in the field of risk assessment. Geomorphological papers often still rely on averaged short- or medium-term measurements regardless of their distribution. Based on MFRs, it can be estimated which part of the magnitude-frequency-spectrum contributes most to the long-term sediment budget or to landform development (e.g. the classic paper by Wolman & Miller (1960), see also Eaton et al. (2003), Nash (1994), Vogel et al. (2003)).

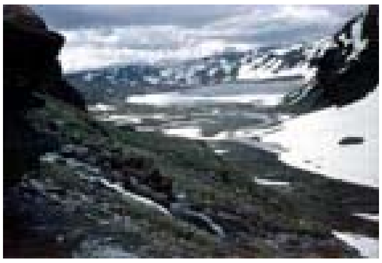
Under certain assumptions, MFR can be used to estimate long-term process rates from short- or medium-term measurements. The greater the record length, the more significant is the observed MFR and the smaller is the confidence interval for the estimation of long-term averages; but longer times of observation decrease the validity of the assumption that environmental conditions, above all climatic variables, have remained and will remain constant over time (a very important constraint for extrapolation). This is especially problematic considering the fact that cold environments are particularly sensitive to environmental change, and even small changes of governing variables may result in significant changes of geomorphic processes.

3.9 CONCLUSIONS

The methods and techniques outlined and recommended in this Chapter 3 should be considered when trying to quantify present-day sediment fluxes in cold environment small catchment geosystems.
The adequate selection of methods and techniques depends on the environmental and logistic conditions at the selected key test site.
For detailed sediment budget work longer-term investigations and field monitoring (at least 5 -10 years) are required to generate reliable data sets.

Part B

Recording and Documenting Field Measurements



SEDIBUD Key Test Site:

Latnjavagge (Swedisch Lapland)

(Photo by A.A. Beylich)

SEDIBUD Key Test Site:

Tana River (Finnish Lapland)

(Photo by A.A. Beylich)

Chapter 4

Selection of critical key test catchments

4.0 INTRODUCTION

The major aim of the SEDIFLUX/SEDIBUD programme is to perform the quantitative analysis of impact of climate change on sediment transfers and sediment budgets in cold environments. Such an analysis clearly depends on the magnitude of climate change. However the major focus of SEDIFLUX/SEDIBUD is the impact of climate change on the sediment flux processes that link source to sink. To provide an integrated study of source-to-sink sediment fluxes and sediment budgets in cold environments, the key processes of weathering, chemical and mechanical denudation and erosion, mass movements, fluvial transport, glacial processes, and sedimentation in lakes, fjords and coastal areas need to be considered (Beylich et al., 2005; 2006). This requires researchers to collect and to compare data from a wide range of different high-latitude and high-altitude cold environments worldwide and to apply standardized methods, techniques and approaches to characterise sediment fluxes, sediment budgets and relationships between climate and sedimentary transfer processes.

Long-term investigations (10+ years) of sediment transfers and budgets, including the analysis of storage elements as well as long-term and year-round monitoring of meteorological parameters, snow cover, ground frost and denudative geomorphic processes will be carried out in 30 – 40 selected *SEDIFLUX/SEDIBUD Key Test Sites* (critical catchments of ca 10-30 km^2) worldwide using the methods, techniques and protocols as recommended in this manual. Scaling issues will be addressed through upscaling at selected target areas where the key test site is a nested catchment within a larger (ca. 100 km^2 +) drainage basin system. The comparable data sets generated in the different cold environments will be used for the development of the *SEDIBUD Metadata Database*. This database will be used to identify and model the effects of climate change on sediment transfers and sediment budgets in cold environments.

4.1 SELECTION OF CRITICAL KEY TEST SITES

Based on the proposals received, we will select globally distributed SEDIFLUX/SEDIBUD Key Test Sites where long-term investigations/ monitoring will be carried out under the SEDIBUD umbrella, following guidelines and protocols contained in the SEDIFLUX Manual. Selected Key Test Sites may fulfil all or some of the requirements listed in the *List of Requirements for Proposed SEDIFLUX/SEDIBUD Key Test Sites* below. Key Test Sites with different levels and degrees of complexity of the investigations/monitoring will be included in the SEDIBUD program. Additional Key Test Sites can be added during the next few years.

The comparable data sets generated at these different Key Test Sites will be available for the SEDIBUD Metadata Database. The Responsible Contact Person for each selected Key Test Sites will be asked to sign an agreement letter (contract) including details on data management, data sharing and ownership of data.

4.2 LIST OF REQUIREMENTS FOR PROPOSED SEDIFLUX/SEDIBUD KEY TEST SITES

Requirement for the proposed Target Region Cold Environment
Requirements for the proposed SEDIFLUX/SEDIBUD Key Test Catchment within this Target Region: Test Catchment is a representative landscape unit within the target region YES ___ NO ___ Type: ______ Catchment Size of ca. 10 – 30 km^2 YES ___ NO ___ Critical Test Catchment of ca. 10-30 km^2 is a nested Catchment within a larger drainage basin system (of ca. 100 km^2 ++) YES ___ NO ___ Critical Test Catchment with a well delimited catchment area of ca 10-30 km^2 and with a well-defined outlet YES ___ NO ___

Range of denudative geomorphic processes is given YES ___ NO ___ Different storage elements are given YES ___ NO ___ Only minimal (or no) human influence is present in the catchment YES ___ NO ___
Further Requirements for the proposed SEDIFLUX/SEDIBUD Key Test Catchment: Given research accessibility and infrastructure YES ___ NO ___ Key Test Catchment is a key site within another existing program (ITEX, CALM, IPY, etc.) YES ___ NO ___ If YES: Program(s) ___________ Ongoing scientific activities at site YES ___ NO ___ Existing datasets and existing other material (aerial photographs, etc.) available YES ___ NO ___ Funding available and/or given potential to generate funding for long-term investigations/monitoring YES ___ NO ___ Existing Commitment of responsible scientists to contribute actively to the SEDIFLUX/SEDIBUD program YES ___ NO ___ Responsible Contact Person available YES ___ NO ___

4.3 INFORMATION ON THE PROPOSED SEDIFLUX/SEDIBUD KEY TEST SITE

Name of the proposed SEDIFLUX/SEDIBUD Key Test Site:
Name and email address of the Responsible Contact Person for the proposed site:
Title of ongoing or recently completed project(s) at this site: Duration of project(s) (start and (expected) end dates) at this site:

Description of the proposed SEDIFLUX/SEDIBUD Key Test Site / Catchment

Country:

Region:

Geographical coordinates (Lat/Long):

Elevation a.s.l.:

Size of critical test catchment (km^2):

If the proposed key test site is a nested catchment within a larger drainage basin system: Size of this larger drainage basin system:

Climate:

Vegetation cover:

Topography:

Lithology:

Relevant denudative geomorphic processes active in this area:

Relevant storage elements / sinks given in this area:

Human influence in the area:

Research accessibility and infrastructure:

Available funding and potential to generate funding for long-term investigations/monitoring (ca. 10 years +):

Other descriptions:

Short description of data sets already available from this site (meteorological data, data on snow cover and ground frost, data on storage elements, data sets from longer-term geomorphic process monitoring, etc.):

Short description of other material which is available from this site (aerial photographs, DEM, maps, etc.):

Short description of instrumentation and methods already used at this proposed site:
Other comments:

4.4 INFORMATION ON ONGOING AND RECENTLY COMPLETED PROJECTS AT THE PROPOSED SEDIFLUX/SEDIBUD KEY TEST SITE

Project title(s):
Principal investigator(s) Name(s):
Title: Postal address: Phone number: Fax number: Email:
Scientific personnel within the project(s):
Collaborators:
Start date of project(s): (Expected) completion date of project(s):
Funding agency/agencies:
Short summary, project description(s):
Main goals of the project(s):
Key words (5 – 10):
Other comments:

4.5 INFORMATION ON SEDIFLUX/SEDIBUD MEMBER AND MAIN CONTACT PERSON RESPONSIBLE FOR THE PROPOSED SEDIFLUX/SEDIBUD KEY TEST SITE

Name of Responsible Main Contact Person:
Title:
Position:
Postal address: Phone number: Fax number: Email:
Webpage:
Scientific field:
Research interests:
Research areas/study sites:
Five key publications of the last 5 years:
Are you willing to send photo(s) of your proposed key test site: Yes: _ No: _ If yes: Please send photo(s) (one or two) in digital form.

Chapter 5 -

Integration and synthesis of cold environment sediment flux data

5.1 INTRODUCTION

Sediment budgets generally refer to a conceptual simplification of the interaction of geomorphologic transfer processes acting upon a given area and time interval. They provide a conceptual framework for the quantification and identification of storage elements and linkages within a predefined spatial and temporal context. Sediment budgets and the methods used to compile them are almost as numerous as the number of locations they attempt to describe. Moreover, constructing and representing a sediment budget can prove to be a truly challenging task, if the purpose is to make it interpretable by the broader research community. The aim of this Chapter 5 is to propose a set of unified data tools and parameters for the characterisation of sediment and nutrient fluxes from cold environment small catchment geosystems. These parameters are designed as minimum requirements for the compilation of a database on cold environment small catchment geosystems with varying levels of detail. They build on the set of practices described in the previous Chapters and on international standards associated with modelling and geospatial information.

These recommendations are articulated in three points:

1) The definition of a basic metadata implementation protocol (catchment summary information),

2) Basic quantifiable parameters common to watersheds (data table) and

3) The representation of sediment budgets in Tables and Diagrams.

The purpose of the Tables provided below is to facilitate the growth of a cold environment catchments database to document and monitor contemporary sediment fluxes. This database shall also serve to explore and estimate the impact of a variety of climate change scenarios on sediment transfer processes. The method is principally based on a “static” table (Table 5.1), consisting of a series of elements characterizing the catchment and used subsequently to query the database, and a “data” table inventorying sediment- and nutrient-related yearly data for the catchment.

5.2 CATCHMENT SUMMARY INFORMATION

In an effort to promote unified metadata compilation among test sites across the globe, a set of basic identifying characteristics should be provided for each catchment. These include basic geographic information, in compliance with geographic information standards (ISO 19100 series), physiographic and climatic features of the study area. This summary forms the basis for the identification of the catchment and its most primary characterization. A template is provided to the reader in Table 5.1. The summary information in Table 5.1 is crucial and should be addressed first as it will form the main identification of the study area.

5.2.1 SEDIFLUX-ID

The SEDIFLUX-ID is the unique identifier used to identify and retrieve the catchment in the database. It is assigned to the catchment by the database administrator after the sheets are submitted for the first time. This section shall therefore not be filled by the principal investigator the first time the sheets are submitted.

5.2.2 Metadata

- Catchment name:

Refers to the common name of the catchment, if possible taken after the toponymy defined by the national mapping agency.

- Country:

Refers to the country in which the catchment is located.

- Principal Investigator:

Refers to the contact person for the catchment, *a fortiori*, the person who filled the sheets.

- Coordinates (outlet):

These coordinates shall be expressed in decimal degrees, with at least three decimals. Longitudes shall be labelled by appending the “E” or “W” sign, depending on the hemisphere they refer to. The outlet refers to the point through which sediments are flowing out of the catchment. In case the catchment ends in a lake or pond, the coordinates should be taken after the outlet of the water body.

- Closest field station or settlement

Self-explanatory. This section shall be filled only if field work undertaken in the catchment can be directly operated from the field station or settlement.

5.2.3 Climate

- Mean Annual Air Temperature

The mean annual air temperature (MAT) shall be expressed in °C

- Mean annual precipitation

Mean annual precipitation shall be expressed in mm. It refers to total precipitation, including combined snow and rainfall.

- Mean annual snow precipitation

Mean annual snow precipitation refers to annual snow precipitation in mm equivalent water.

- Mean annual rainfall

Mean annual rainfall is measured in mm. It refers to total rainfall precipitation.

- Melting degree-days

Cumulative number of annual degree-days above 0 degrees.

5.2.4 Physiography

- Catchment area

The catchment area is expressed in squared kilometers. An equal-area projection is recommended for area computation in a GIS. The Lambert azimuthal equal-area and Albers equal-area conic projections are good examples.

- Maximum altitude

Altitude is measured in metres above sea level. The maximum altitude refers to the point with the highest elevation within or at the border of the catchment.

- Outlet altitude

Altitude is measured in metres above sea level. The outlet location is defined in the aforementioned “coordinates (outlet)” category.

5.2.5 Vegetation

- Vegetation zone

The vegetation zone shall be defined after the CAFF’s, 'Arctic vegetation zones', (UNEP/GRID-Arendal Maps and Graphics Library, 2001, <http://maps.grida.no/go/graphic/arctic_vegetation_zones>). One of the five following zones shall be used to characterize the catchment.

- o Arctic Desert
- o Mountain Tundra
- o Lowland Tundra
- o Middle Boreal
- o Northern Boreal

These categories are defined in the CAFF habitat report n.5. (CAFF, 2001)

5.2.6 Hydrology

- Glaciers

Boolean field

Refers to the presence of glaciers in the catchment.

- Gauging station

Boolean field

Refers to the presence of a gauging station at the outlet of the catchment

5.2.7 Permafrost

- Permafrost type

This section refers to the type of permafrost (if any) underlying the major part of the catchment. Permafrost types are divided in absent (a), sporadic (s), discontinuous (d) and continuous (c). The definition of these terms follows the recommendations from the International Permafrost Association (IPA) (van Everdingen, 1998).

- o Continuous permafrost: Permafrost occurring everywhere beneath the exposed land surface throughout a geographic region with the exception of widely scattered sites, such as newly deposited unconsolidated sediments, where the climate has just begun to impose its influence on the thermal regime of the ground, causing the development of continuous permafrost.

- Discontinuous permafrost: Permafrost occurring in some areas beneath the exposed land surface throughout a geographic region where other areas are free of permafrost.
- Sporadic permafrost: Permafrost underlying 10 to 35 percent of the exposed land surface.
- Absent permafrost: Absence of permafrost.

5.2.8 Literature and comments

- Available literature

In this section is listed the body of relevant literature. A primary reference, listed first in the table shall be emphasized by the contributor.

- Comments

Additional comments related to Catchment summary information table only can be added in this section.

5.3 DATA TABLE

The data table (Table 5.2) is a collection of data related to sediment yield and corollary parameters in cold environment small catchment geosystems. It forms the basis for the collection and comparison of data across all network catchments. The numbers to be reported refer to the quantities at the catchment outlet.

The data table is two-fold. A few parameters are expressed as "*primary*" parameters, while some others are expressed as "*secondary*" parameters. The primary parameters are intended to be the common data product for all catchments. The secondary parameters are parameters, which, if recorded, would provide a valuable addition to the primary parameters.

The data table is expandable. The list of parameters is not exhaustive and other parameters will be included in the table in the future. Likewise, Parameters presently listed as secondary parameters could become primary in the future, although it is expected that primary parameters will remain primary.

The data table is linked to a specific timeframe (e.g., a year or field season), and, as such, can be filled as many times as different timeframes are collected. Similarly, it can be used for overlapping, yet different timeframes (i.e. 20th Century, Holocene, etc.). The Catchment Summary Information table will however remain the same.

The first focus of SEDIFLUX/SEDIBUD is the quantification and evolution of contemporary fluxes. Contributors should therefore focus on contemporary fluxes (i.e. yearly rates). The timeframe of the measurements shall be indicated in the table as well as the measurement method. Measurement methods and techniques are indicated in Chapters 2 and 3.

5.3.1 Environmental forcing

- <u>MAT</u>

Primary parameter
The mean annual air temperature (MAT) shall be expressed in °C

- <u>Mean Annual precipitation</u>

Primary parameter
Mean annual precipitation shall be expressed in mm. It refers to total precipitation, including combined snow and rainfall.

- <u>Mean annual snow precipitation</u>

Primary parameter

Mean annual snow precipitation refers to annual snow precipitation in mm equivalent water.

- Mean annual water precipitation

Primary parameter

Mean annual rainfall is measured in mm. It refers to total rainfall precipitation.

5.3.2 Hydrology

- Annual discharge

Primary parameter

Annual discharge is the total annual amount of water flowing out at the catchment outlet. It is expressed in km^3.

- Total sediment yield

Primary parameter

Total sediment yield shall be expressed in Mg (1 Mg = 1000 kg).

- Suspended sediment

Secondary parameter

Suspended sediment (i.e. soil particles that remain in suspension in water without contact with the bottom) shall be expressed in Mg.

- Bedload transport

Secondary parameter

Bedload transport (portion of the total sediment in transport that is carried by intermittent contact with the streambed by rolling, sliding, and bouncing) shall be expressed in Mg.

- Date of first flow

Secondary parameter

The date of first flow is the earliest day in the investigated year at which waters start to flow at the catchment outlet. It is labelled as ddmmyyyy in the data table.

- Date of last flow

Secondary parameter

The date of late flow is the latest day in the investigated year at which waters start to flow at the catchment outlet. It is labelled as ddmmyyyy in the data table.

5.3.3 Sediment budget – contribution of slope processes to the overall sediment yield

The goal of this subsection of Table 5.2 is to quantify the respective contribution of different denudative slope processes in the annual sediment yield at the outlet. A series of generic slope processes are listed in this subsection and must be labelled with a percentage corresponding to their contribution to the sediment yield.

If a slope process or a category of slope processes is thought not to have contributed to the sediment yield at the catchment outlet during the recorded period, the field should be left blank.
The following definitions are mostly taken taken after the Terrain classification system for British Columbia (1976) and the multi-language permafrost glossary (van Everdingen, 1998).

- Weathering (mechanical and chemical)

Secondary parameter

Weathering is the physical disintegration and chemical decomposition of rocks, minerals, and immature soils at or near the Earth's surface. Physical, chemical, and biological processes induced or modified by wind, water, and climate cause the changes. The contribution of sediment by weathering to the total sediment yield is expressed in Table 5.2 in %.

- <u>Creep, slopewash, rill erosion and solifluction</u>

Secondary parameter

Creep is the imperceptibly slow, more or less continuous, downward and outward movement of soil or rock on slopes. Slopewash is the action of water from rain or melted snow carrying (washing) soil down a slope. Rill erosion is the removal of soil by concentrated water running through little streamlets, or headcuts. Solifluction is s slow downslope flow of saturated unfrozen earth materials (one component of solifluction can be the creep of frozen ground). The contribution of sediment by these processes to the total sediment yield is expressed in Table 5.2 in %.

- <u>Mud- and debris-flows</u>

Secondary parameter

Mud-flows are a form of mass movement where fine textured sediments and soil mix with water to create a liquid flow Debris-flows are a type of mass movement where there is a downslope flow of a saturated mass of soil, sediment, and rock debris.
The contribution of sediment by mud- and debris-flows to the total sediment yield is expressed in Table 5.2 in %.

- <u>Slides and slumps</u>

Secondary parameter

A slide is a mass of sediment/rock that sticks together as a coherent block and travels down slope along a tilted plane or surface of weakness. Slumps are types of slides wherein downward rotation of rock or regolith occurs along a concave-upward curved surface (rotational slides).
The contribution of sediment by slides and slumps to the total sediment yield is expressed in Table 5.2 in %.

- <u>Rock- and boulder-fall</u>

Secondary parameter

Rock-falls or boulder-falls occur when a piece of rock on a steep slope

becomes dislodged and falls down the slope.
The contribution of sediment by rock- and boulder-fall to the total sediment yield is expressed in Table 5.2 in %.

- Streambank erosion

Secondary parameter
Streambank erosion is a loss of ground in the banks of a stream due to mechanical erosion (and thermoerosion in the presence of permafrost and/or ice).
The contribution of sediment by streambank erosion to the total sediment yield is expressed in Table 5.2 in %.

- Snow avalanches, slush flows

Secondary parameter
A snow avalanche is a massive slide of snow down a slope. Slush flows refer to the movement of water saturated snow downhill.
The contribution of sediment by snow avalanches and slush flows to the total sediment yield is expressed in Table 5.2 in %.

- Eolian erosion (deflation)

Secondary parameter
Eolian erosion is erosion due to wind activity.
The contribution of sediment by eolian erosion to the total sediment yield is expressed in Table 5.2 in %.

5.3.4 Solutes

- Annual solute yield

Primary parameter
The annual solute yield refers to the total amount of solute released annually at the catchment outlet. Solutes refer to the substance present in a solution in

the smaller amount. Water is here considered the solvent even in concentrated solutions with water molecules in the minority. The annual solute yield is expressed in Table 5.2 in g/year.

- Annual atmospheric solute input

Secondary parameter

The annual atmospheric solute input refers to the total amount of solutes from atmospheric origin captured annually by the catchment. For a definition of solute, see “Annual solute yield”. The annual atmospheric solute input is expressed in Table 5.2 in g/year.

5.3.5 Organic and inorganic matter

- Dissolved Organic Carbon (DOC)

Secondary parameter

DOC is organic material based on Carbon broken down to a size at which it is “dissolved” into water. DOC is the difference between Total Dissolved Carbon and DIC. It is expressed in Table 5.2 in kg.

- Dissolved Inorganic Carbon (DIC)

Secondary parameter

DIC is the sum of quantities of carbon dioxide, carbonic acid, bicarbonate anion, and carbonate anion. It is expressed in Table 5.2 in kg.

- Dissolved Organic Nitrogen (DON)

Secondary parameter

DON is the difference between Total Dissolved Nitrogen (TDN) and DIN. It is expressed in Table 5.2 in kg.

- Dissolved Inorganic Nitrogen (DIN)

Secondary parameter

DIN is the sum of quantities of nitrate and ammonia. It is expressed in Table 5.2 in kg.

5.4 DATA QUALITY

In order to facilitate the correction, verification and validation of the datasets generated using Tables 5.1 and 5.2, a data quality field was added to Table 5.2.

Data quality is expressed using the denominators “low”, “medium” and “high”. Those are determined using the range of uncertainty around the value input into the table

”low” refers to a range of uncertainty greater than 20%

”medium” refers to a range of uncertainty between 5 and 20%

”high” refers to a range of uncertainty below or equal to 5%

“low”, “medium” and “high” shall be expressed as “l”, “m”, and “h” in the data table.

5.5 REPRESENTATION OF OUTPUTS IN TABLES AND DIAGRAMS

The combination of the data elements used to characterise the catchments can be used to derive an important number of sub-products. The reader can use the templates to compare sediment budgets and/or create diagrams to represent sediment fluxes for selected or all catchments. The key identifiers used in the table can be used to organize the templates into a relational database.

Table 5.1 – Catchment summary information

SEDIFLUX ID		
Metadata		
Catchment name		
Country		
Principal investigator		
Coordinates (outlet), (decimal degrees)		
Closest field station or settlement		
ITEX site ☐	CALM site ☐	IPY observatory ☐
Climate (climatic norms)		
MAT (°C)		
Mean Annual precipitation (mm)		
Mean annual snow precipitation (mm)		
Mean annual water precipitation (mm)		
Melting degree-days:		
Physiography		
Catchment area (km²)		
Maximum altitude (masl)		
Outlet altitude (masl)		
Vegetation		
Vegetation zone		
Hydrology		
Glaciers (yes=y, no=n)		
Gauging station (yes=y, no=n)		
Permafrost		
Permafrost type continuous=c, discontinuous=d sporadic=s, absent=a		
Literature and comments		
Available literature Please acknowledge one primary reference		
Comments		

Table 5.2 – Data table

Only one timeframe can be used when filling a data table.
Primary parameters are mandatory fields.

Primary requirement: ●; Secondary requirement: ○

SEDIFLUX-ID					
	Parameter	**Value**	**Measurement timeframe (ddmmyyyy-ddmmyyyy)**	**Measurement method**	**Data quality (l, m, h)**
Environmental forcing					
●	**MAT (°C)**				
●	**Mean Annual precipitation (mm)**				
●	**Mean annual snow precipitation (mm)**				
●	**Mean annual water precipitation (mm)**				
●	**Bedload transport (Mg)**				
Hydrology (outlet)					
●	**Annual discharge (km^3)**				
●	**Annual sediment yield (Mg)**				
○	Suspended sediment (Mg)				
○	Bedload transport (Mg)				
○	Date of first flow (ddmmyyyy)				
○	Date of last flow (ddmmyyyy)				
Sediment budget					
○	Weathering (mechanical and chemical) (%)				

○	Creep, slopewash, rill erosion, solifluction (%)				
○	Mud- and debris-flows (%)				
○	Slides and slumps (%)				
○	Rock- and boulder-fall (%)				
○	Streambank erosion (%)				
○	Snow avalanches, slush flows (%)				
○	Eolian erosion (%)				
Solutes					
●	Annual solute yield (g/yr)				
○	Annual atmospheric solute inputs (g/yr)				
Nutrients					
○	Dissolved Organic Carbon (Mg)				
○	Dissolved Inorganic Carbon (Mg)				
○	Dissolved Organic Nitrogen (Mg)				
○	Dissolved Inorganic Nitrogen (Mg)				
○	Total dissolved materials (Mg)				

Primary requirement: ●; Secondary requirement: ○

Prospect

This *First Edition* of the *SEDIFLUX Manual* will serve as a basis for discussing and realising quantitative long-term investigations on solute and sediment fluxes and sediment budgets in selected cold environment catchment geosystems by applying unified methods and techniques.

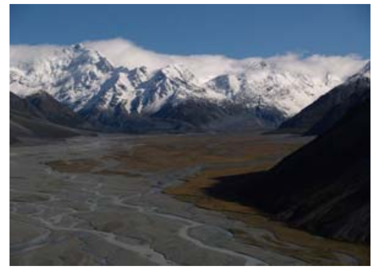
Comparable data sets generated in different cold environment key test catchments in polar and alpine cold environments that follow the recommendations, guidelines and protocols provided in this *SEDIFLUX Manual* allow intersite comparisons and will be added to the *Metadata Database* developed within the global *I.A.G./A.I.G. SEDIBUD programme* (http://www.geomorph.org/wg/wgsb.html).

The *SEDIBUD Metadata Database* will be used to investigate effects of projected climate change on solute fluxes, sediment fluxes and sediment budgets in sensitive and changing present-day cold environments worldwide.

PRELIMINARY SELECTION OF SEDIBUD KEY TEST SITES

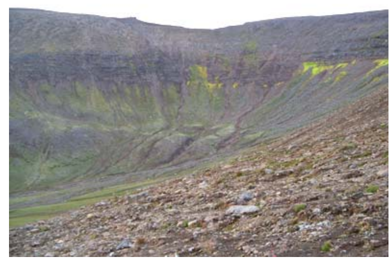

Kärkevagge *field site, Sweden (Photo: John Dixon)*


Moore House *field site, UK (Photo: Jeff Warburton)*


Godley Valley *field site, New Zealand (Photo: John F. Orwin)*


Musala *field site, Bulgaria (Photo: Emil Gachev)*


Kaffiøyra *field site, Svalbard (Photo: Michal Krol)*


Tindastöll *field site, Iceland (Photo: Helgi Páll Jónsson)*

Antarctica

Joyce and Garwood Glacier, Garwood Valley*, proposed by John F. Orwin, New Zealand (jfo@geography.otago.ac.nz)*

Argentina

Laguna Potrok Aike*, proposed by Bernd Zolitschka, Germany (zoli@uni-bremen.de)*

Austria

Pasterze*, proposed by Andreas Kellerer- Pirklbauer, Austria (andreas.kellerer@uni-graz.at)*

Bulgaria

Musala area, *proposed by Emil M. Gachev, Bulgaria (e_gachev@yahoo.co.uk)*

Canada

Cape Bounty, *proposed by Scott F. Lamoureux, Canada (Scott.Lamoureux@queensu.ca)*

Finland

Kidisjoki, *proposed by Achim A. Beylich, Norway (achim.beylich@ngu.no)*

Germany

Reintal, *proposed by Karl-Heinz Schmidt, Germany (karl-heinz.schmidt@geo.uni-halle.de)*

Greenland

Kangerlussuaq-Strømfjord
Mittivakkat glacier catchment
Zackenberg, *proposed by Bent Hasholt, Denmark (bh@geogr.ku.dk)*

Iceland

Botn í Dýrafirði
Reykjarströnd
Tindastöll
Fnjóskadalur-Bleiksmýrardalur, *proposed by Armelle Decaulne, France (armelle@nnv.is)*
Hofsjøkull, northern forefield
Austdalur
Hrafndalur, *proposed by Achim A. Beylich, Norway (achim.beylich@ngu.no)*
Örravatnrústir, *proposed by Þorsteinn Sæmundsson, Iceland (nnv@nnv.is)*

New Zealand

Douglas Glacier
Godley Valley
Unnamed Valley, *proposed by John F. Orwin, New Zealand (jfo@geography.otago.ac.nz)*

Norway

Erdalen
Bødalen
Vinstradalen, *proposed by Achim A. Beylich, Norway (achim.beylich@ngu.no)*
Tana catchment, *proposed by Jukka Käykhö, Finland (jukka.kayhko@utu.fi)*

Russia

Mezen, *proposed by Achim A. Beylich, Norway (achim.beylich@ngu.no)*

Svalbard

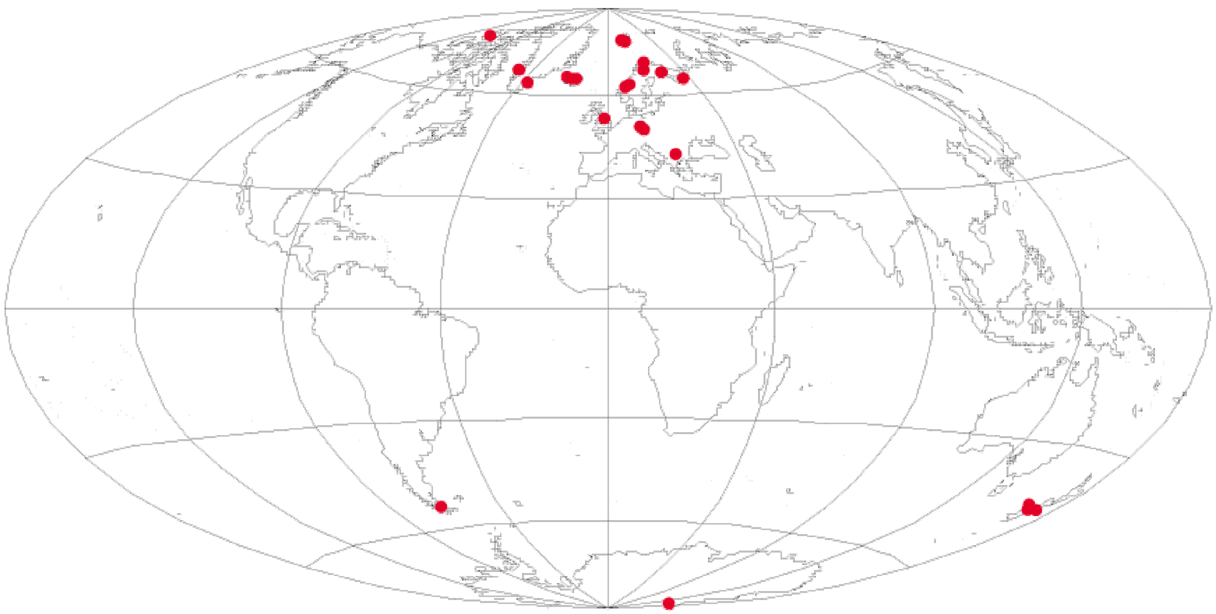
Catchment at Nordaustlandet, *suggested by Achim A. Beylich, Norway (achim.beylich@ngu.no)*
Dynamiskbekken
Ebbaelva
Hørbyeelva, *proposed by Grzegorz Rachlewicz, Poland (grzera@amu.edu.pl)*
Kaffiøyra, *proposed by Michal Krol (supervised by Marek Grzes), Poland (gmark@geo.uni.torun.pl)*
Scottelva, *proposed by Josef Superson, Poland (superson@biotop.umcs.lubin.pl)*

Sweden

Latnjavagge, *proposed by Uf Molau, Sweden (ulf.molau@dpes.gu.se) and Achim A. Beylich, Norway (achim.beylich@ngu.no)*
Kärkevagge
Kårsavagge
Låktavagge, *suggested by Achim A. Beylich, Norway (achim.beylich@ngu.no)*

United Kingdom

Moor House, *proposed by Jeff Warburton, UK (jeff.warburton@durham.ac.uk)*



Spatial distribution of proposed SEDIBUD Key Test Sites

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