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Sediment storage in Alpine sedimentary systems – quantification and scaling issues

J.-C. OTTO, J. GOETZ & L. SCHROTT
Department of Geography and Geology, University of Salzburg, Hellbrunner Strasse 34, A-5020 Salzburg, Austria
jan-christoph.otto@sbg.ac.at

Abstract The role of sediment storage is considered to be crucial for the construction of sediment budgets, and for linking sediment dynamics to landform evolution. In Alpine sedimentary systems, dynamic and highly-complex system behaviour, combined with changing climate and process regimes, lead to the formation of numerous types and generations of storage landforms. The strong impact of Quaternary glaciation on the sediment flux is very often still observable in the reworking of glacial sediments, as described by the concept of paraglacial sedimentation. Controlled by changing process rates and variable coupling conditions through time, storage landforms strongly affect sediment output from Alpine catchments. Sedimentary deposits may be temporarily decoupled or preserved, from erosion by climatic (e.g. permafrost), vegetation, or topographic (hanging valleys, cirques) conditions leading to a complex distribution of sediment storages and cascades. Changing climate or sediment availability may also result in a remobilisation of these deposits modifying the sediment flux dynamics. Various approaches to quantify storage volumes have been applied, with changing efficiency and accuracy at different spatial scales. Whereas at small scales (<10 km^2) higher accuracies can be reached, the assessment of storage volumes on large scales is still problematic and often based on rough estimations. Methods of quantification range from high resolution techniques using field geophysics, to less accurate techniques applying simple geometries and DEM analysis. However, few approaches tackle the gap between scales and provide ways to integrate between them. Paying special attention to Alpine sedimentary systems, we review the most frequently applied methods of storage quantification at various scales, in order to evaluate their usability and accuracy in sediment budget studies. To initiate a discussion on the quantification of sediment storage in large Alpine drainage basins, we present a simple approach to approximate the storage volume of the Upper Rhone catchment, Swiss Alps.

Key words sediment budget; sediment storage; scaling issues; large Alpine drainage basins

INTRODUCTION

The role of sediment storage is considered to be crucial for the construction of sediment budgets, and for linking sediment dynamics to landform evolution. However, the exact quantification of the volume of sediment stored in a catchment is problematic, especially with increasing catchment sizes (Slaymaker, 1991; Slaymaker & Spencer, 1998). Alpine sedimentary systems show dynamic and highly complex sediment fluxes. Combined with changing climate and process regimes, they produce a highly variable land surface that contains numerous types and generations of storage landforms at various scales. The strong impact of Quaternary glaciations on the sediment flux is very often observable in the landscape by the reworking of glacial sediments. These deposits are important sources of sediment, as described in the concept of paraglacial sedimentation by Church & Ryder (1972). Controlled by changing process rates and variable coupling conditions through time, storage landforms strongly affect sediment output from Alpine catchments. What we observe today is a landform assemblage of relict, overlapping and replaced landforms that reflects the influence of past processes on today's environment (Hewitt, 2002). On the one hand, land surface variations and landforms created by past processes serve as a grounding, boundary condition and regulator for current processes. On the other hand, deposits from past processes are sediment stores that may become sources for subsequent processes.

Sediment flux is considered to operate in a cascading system that is primarily driven by gravitational forces and height differences (Slaymaker, 1991). Alpine sedimentary systems can be described on various spatial scales ranging most commonly from assemblages of single landforms in a hanging valley, to the investigation of large basin sediment flux including several subsystems (Otto & Dikau, 2004).

Problems of scale crossing and linkage are critically discussed in various fields of geosciences (Schumm, 1991; Phillips, 1999; De Boer, 2001). Perspectives have changed from simple cumulative effects of scale linkages, with propagation of properties from lower to upper scales, towards more complex, nonlinear behaviour with emerging properties that cannot be explained or predicted by the simple interaction of the systems individual components (Wasson, 1996; Spedding, 1997; Phillips, 1999). However, the crossing of scales, up- and downscaling, still remains an unresolved issue (Slaymaker, 2006).

With respect to sediment budget studies, different landform parameters have to be considered according to the scale (Fig 1). Consequently, the methodology on each scale needs to be adapted. Crossover relationships may exist between plot and hillslope studies, or between small and large basin; however, very few studies try to bridge across scales. Moreover, it seems that different scientific communities work at different scales (geomorphologists, geologists, ecologists). This often is reflected in the little communication between these groups.

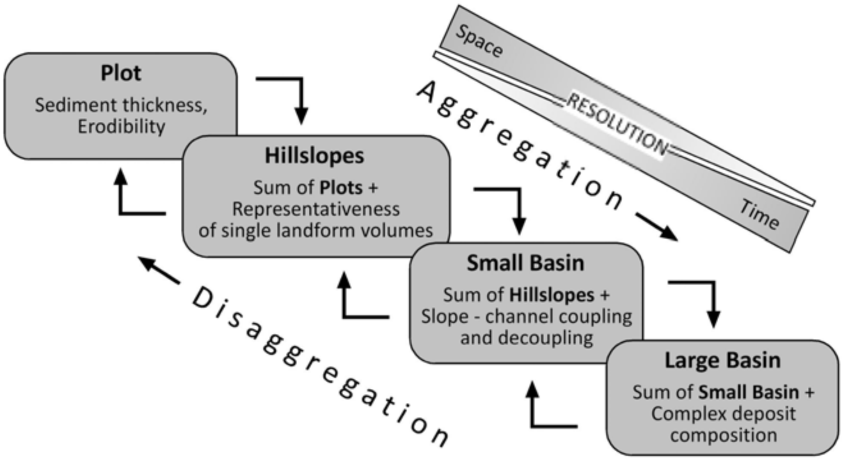

Fig. 1 Scaling relationships in sediment budget studies focusing on sediment storage (modified from Phillips, 1999).

Different approaches have been applied to determine the volume of stored debris in a drainage basin with variable accuracy. While in small catchments (<20 km^2) geophysical surveying and GIS modelling deliver the most accurate sediment volume, storage in large catchments is often roughly estimated and seldom verified. Thus, in larger basins sediment budget investigations often concentrate on denudation rates and sediment delivery, while paying less attention to the role of sediment storage. However, problems of the sediment delivery approach and its relationship to the role of storage have already been recognised (de Vente *et al*., 2007). So far, few attempts have been made to investigate the role of storage in larger catchments.

We present an overview here of the currently applied approaches towards sediment storage volumes and critically discuss their accuracy and reliability. In order to bridge the gap between more accurate small-scale quantification and large-scale volume estimation, we discuss scaling issues in storage quantification, and highlight possibilities and pitfalls of scaling relationships with respect to sediment storage. To initiate a discussion on the quantification of sediment storage in large Alpine drainage basins, we present a very simple approach to approximate the storage volume of the Upper Rhone catchment in the Swiss Alps.

METHODS OF SEDIMENT STORAGE QUANTIFICATION

Fundamental geomorphic methods like mapping, topographic survey and image interpretation are the most basic methods for analysing storage distribution. Geomorphic maps often form the data base for the quantification of sediment deposits. However, the exact position and shape of the bedrock–debris boundary cannot be derived from the surface data. Quite a number of studies on sediment budgets consider storage volumes; however, volume data are frequently derived from estimations only (Jäckli, 1957; Jordan & Slaymaker, 1991; Watanabe *et al.*, 1998; Curry, 1999). For single landforms, a more reproducible approach is the application of geometric forms to represent the shape of the storage body and thus approximate its volume (Curry, 1999; Shroder *et al.*, 1999; Campbell & Church, 2003). Geometric forms, like prisms or sectors of cones and others are used in order to represent single landforms, for example talus slopes, talus cones, debris cones, fans or fluvial terraces (Fig. 2). Parameters used for the volume calculation are usually extracted from maps, aerial photos or DEM data. This approach only approximates the real landform volume because landforms almost never have the ideal symmetrical shape of the geometric form used. Apart from approximations to the surface area, the shape and location of the bedrock surface can only be guessed and relies on assumption. As exemplified in Fig. 2(a) and (b), the bedrock surface below the storage landform is assumed to have the same inclination as the rock wall above (Campbell & Church, 2003). In Alpine environments with intense glacial scouring, this surface will be more concave representing the glacial trough and the steeper slope of the underlying bedrock. In this case, the approximation results in an underestimation with a missing volume generated by the degree of concavity compared to the straight rock wall above. The use of geometric forms for the approximation of the sediment volume is a very tedious method in larger study areas, and introduces large uncertainties.

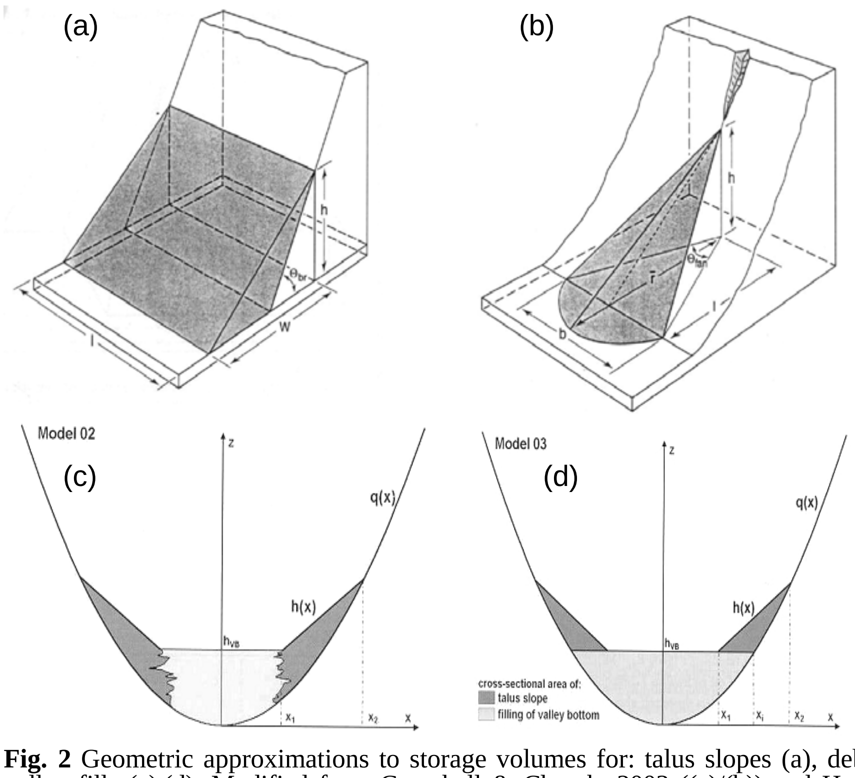

Fig. 2 Geometric approximations to storage volumes for: talus slopes (a), debris cones (b) or trough valley fills (c),(d). Modified from Campbell & Church, 2003 ((a)/(b)) and Hoffmann & Schrott, 2003 ((c)/(d)).

Following the ideas of Harbour & Wheeler (1992), Li *et al.* (2001) and others, glacial valleys can be described using simple power-law equations. This principle has been used to quantify the deposits in Alpine trough valleys (Hoffmann & Schrott, 2002; Schrott & Adams, 2002; Schrott *et al.*, 2003; Jaboyedoff & Derron, 2005). Subsurface bedrock topography is assumed to have a mathematically-describable shape. As Schrott *et al.* (2003) have demonstrated, this assumption leads to uncertainties and overestimation of storage volumes. The study showed that in narrow

Alpine valleys, higher order polynomial functions accurately represent the adjacent rock walls, but tend to model a pronounced trough leading to an overestimation of sediment volumes. Though, this approach approximates the sediment thickness of a valley cross-section, the composition of this deposit cannot be differentiated. Glacial valley bottoms are often filled with a composition of different sediments, ranging from till and glacio-fluvial sediments, to alluvial and debris flow sediment deposited in fans and debris cones. Depending on the onset, duration and cessation of the deposition process activity, these sediments can either be stacked on top of each other, or interfinger, when two processes work at the same time (Fig. 2 (c), (d)). Studies intending to differentiate processes within a sediment budget need to consider the subsurface composition in the storage quantification. However, geophysical surveying techniques, like ground penetrating radar or refraction seismology, are able to resolve the internal composition of these landforms (Sass, 2007).

Due to technical difficulties posed by the often remote locations and coarse materials, sediment coring has been applied only occasionally to determine sediment volumes (Schrott & Adams, 2002; Schrott *et al*., 2003). Consequently, coring is restricted to very few landforms in mountain environments, like flood plains or alluvial deposits. The accuracy of sediment volumes derived from sediment cores strongly relies on the density of data points and the interpolation algorithm used. Nevertheless, this technique has been used to validate data derived from field geophysics.

The use of shallow geophysical survey techniques, such as refraction seismic, ground penetrating radar, electric resistivity tomography and others generate the most accurate subsurface information, which can be used to quantify sediment volumes. Differences in geophysical properties between debris and bedrock are used to detect the bedrock–debris boundary. In mountain environments, geophysical techniques require a greater effort due to rough terrain conditions, heavy equipment and remote locations. Consequently, shallow field geophysics is most commonly applied in most small scale studies on single landforms, in hanging valleys, or first to second order basins (Hoffmann & Schrott, 2002; Otto, 2006). However, a few large Alpine basins, such as the Rhone and Rhine rivers, have been analysed using geophysics and the bedrock topography of the main troughs has been determined the (Finckh & Frei, 1991; Pfiffner *et al.*, 1997). It needs to be stressed that geophysical surveying only produces a model of the subsurface conditions based on the geophysical material properties. Thus, verification by coring, or the application of complementary geophysical methods, is needed to minimize potential interpretation errors (Schrott & Sass, 2008).

SCALING ISSUES IN SEDIMENT STORAGE QUANTIFICATION

In Alpine environments, sediment deposits are located at different positions along an altitudinal gradient. Their vertical distribution can be depicted in a simple way by a toposequence. A toposequence is a topographic succession of landforms passed by a virtual particle following gravitational forces (Speight, 1974; Rasemann, 2004). Along a toposequence, sediment may be transferred from one landform to another creating a sediment cascade. We can identify several altitudinal levels of sediment storage that represent the sediment cascade structure of a catchment (Fig. 3). These levels can be associated with different subsystems of the sediment flux system. Storage distribution differs on each level/subsystem, with some landforms being more ubiquitous than others, depending on the process regimes and their dependence on altitude. The depositional age of storage increases from ridges to valley bottoms, as many large valleys were free of ice much earlier than the upper locations. However, due to remobilisation processes, younger landforms may also be found in valley floors, e.g. fluvial fans or debris cones. This implies that the complexity of the deposits increases downwards. While in hanging valleys single landforms dominate and little intersection of deposits can be observed, many large valleys are composed of highly complex mixtures of deposits originating from different processes that interfinger with each other. Both the geometry and size of the sediment deposits vary within a drainage basin along a gravitational gradient, which has implications for the quantification of storage within a large catchment. The hierarchical structure of drainage basins, with many lower order subsystems, like

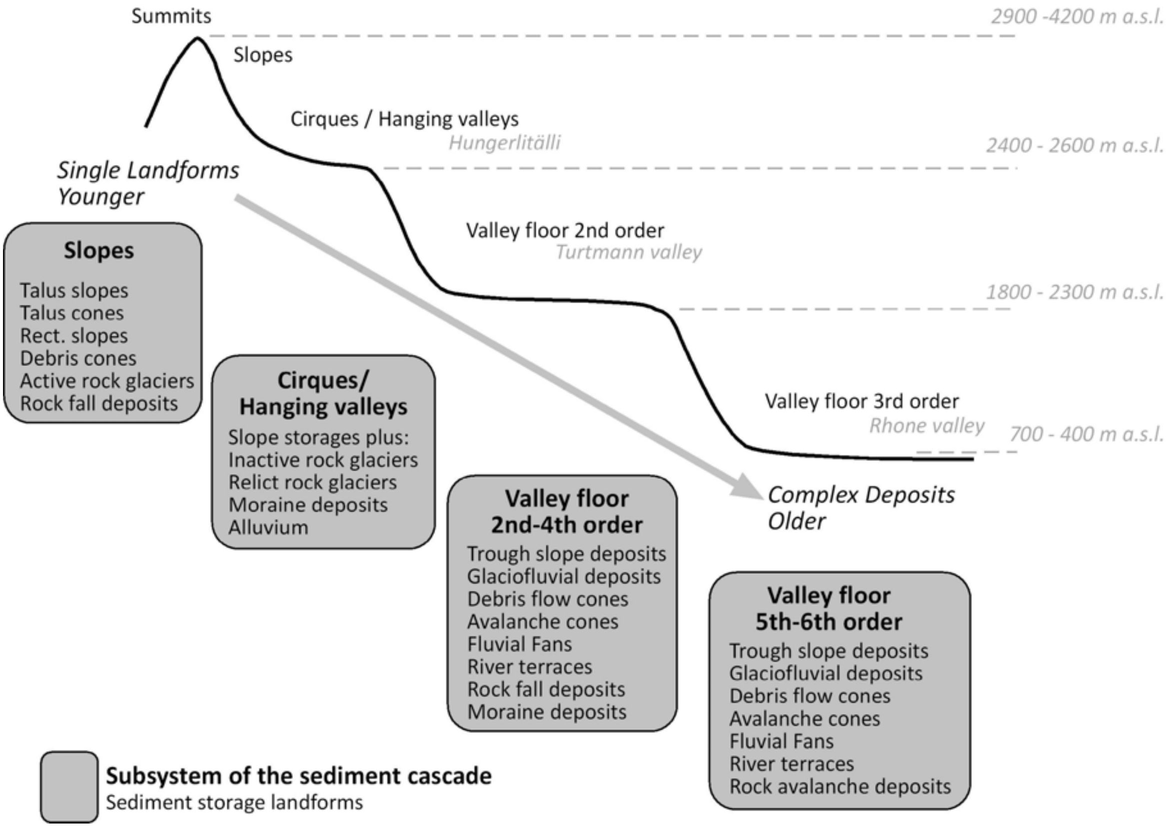

Fig. 3 Toposequence of sediment storage location, exemplified in the Turtmann valley (grey annotations) a subcatchment of the Upper Rhone valley, Swiss Alps.

hanging valleys and cirques, and a small number of large valleys, imply that the number of deposits per landform type differs as well.

Thus, Alpine environments contain a very complex pattern of sediment storage. To handle this complexity of deposits, a drainage basin should be divided into different sedimentary subsystems and process/landform units before storage volume is quantified. This enables use of a combination of quantification techniques adjusted to the location, size and composition of sediment deposits. More accurate methods, like geophysical sounding, should be applied on single landforms. However, as geophysical surveys are often time consuming, characteristic sediment depth should be derived for different deposit types or process/landform units to assess the volume of a large number of single landforms (Otto *et al*., 2008). For larger, more complex deposits, morphometric and topographic proxy information could help to assess the depositional volumes. For example, if two valleys have experienced the same glacial impact and lithology, similar valley morphologies could indicate similar sediment volumes. Then the relationship between the inclination of the valley trough slopes and the valley width could be used. Jaboyedoff & Derron (2005) introduced a simple algorithm that takes this approach for the estimation of sediment volumes in the upper Rhone valley. A comparison with the geophysical data used by Hinderer (2001) revealed promising results. To differentiate between steep V-shaped valleys and wider glacial troughs, the width to height ratio can be applied (Burbank & Anderson, 2005). Smoothed glacial troughs, or U-shaped valley are represented by a ratio greater than 1, while narrow, steep V-shaped valleys have a width-to-height ratio of less than 1. Sediment deposition in U-shaped valleys is expected to be larger than in V-shaped valleys, where erosion and sediment transport dominate. However, these methods deliver the entire valley fill only, and do not resolve the composition structure of the deposit.

The largest uncertainties in large-scale storage quantification will be introduced by the numerous cirques and hanging valleys that contain a complex pattern of single storage landforms.

This implies that precise mapping of these landforms is a prerequisite for volume determination. As geomorphic mapping is time consuming, besides field work, automatic image interpretation and classification techniques should be used to map larger basins. A successful first approach is presented by Schneevoigt *et al.* (2008) in the Reintal, German Alps, who detected typical landforms in a basin of 17-km^2 size. The widespread availability of high resolution terrain and imagery data provides a solid base for the mapping of deposits.

TOWARDS A SEDIMENT STORAGE MODEL OF THE UPPER RHONE VALLEY, SWISS ALPS

We applied a very simple approach to estimate sediment storage in the Upper Rhone Valley, Swiss Alps, aiming at the quantification of the storage volume in large Alpine drainage basins. Several geophysical surveys delivered information on sediment depth in the Upper Rhone Valley (Besson *et al.*, 1991; Finckh & Frei, 1991; Pfiffner *et al*., 1997; Rosselli & Olivier, 2003). Based on this data, Hinderer (2001) calculated the main trough volume between Brig and Lake Geneva to have a total volume of 106 000 $\times$ 10^6 m^3. Otto *et al*. (2008) and Otto (2006) quantified the storage volume of a southern Rhone tributary, the Turtmann Valley. In this subcatchment, around 1005 $\times$ 10^6 m^3 of sediment are stored in several subsystems and different landforms. We will use this data to estimate the total storage volume of the entire upper Rhone basin.

The Rhone Valley upslope of Lake Geneva drains an area of 5220 km^2 at altitudes between 400 and 4600 m a.s.l. The drainage basin structure of the Upper Rhone Valley (Fig. 4) is dominated by the large main valley that runs almost straight from east to west until Martigny, before the valley turns northwest towards Lake Geneva. The basin has an asymmetric shape with more tributaries to the south than to the north of the main valley.

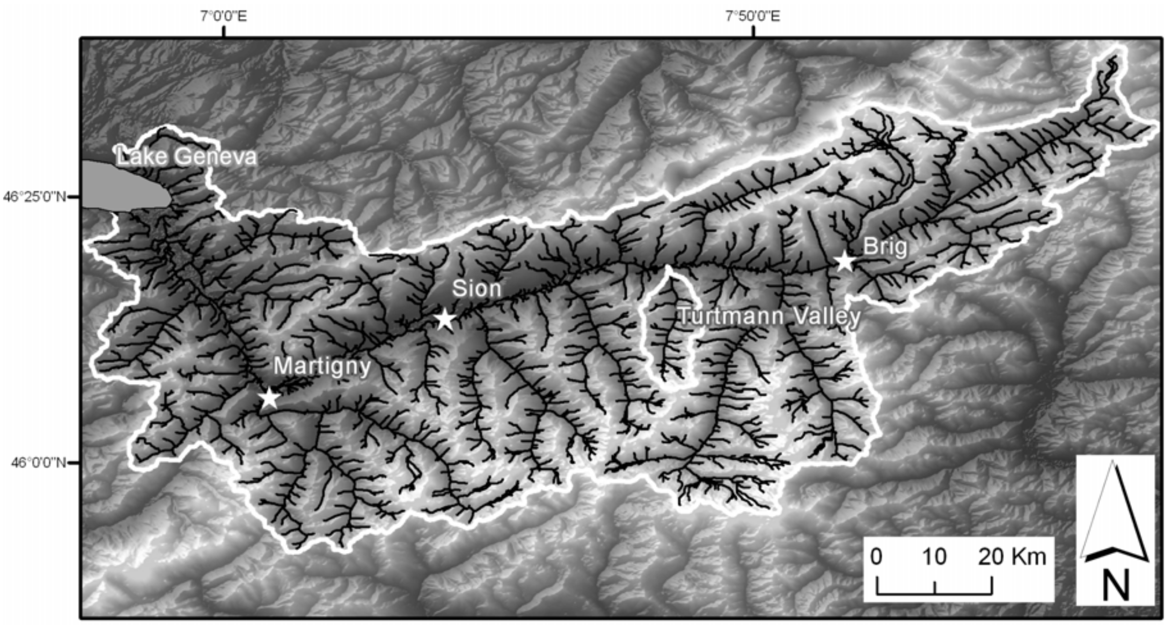

Fig. 4 Drainage network of the upper Rhone basin. Base data – SRTM (NASA).

By combining channel order and topographic surface characteristics, we can derive the subsystem type of the sediment cascade. Using the highest source point of the channels, we identify 526 channels of stream order class 1 above a given threshold of 2000 m. These are assumed to represent cirques or hanging valleys (cf. Fig. 3). By comparing valley floor width and altitudinal position, about 30 channels of stream order classes 2–4 can be classified as main tributary rivers to the Rhone River. These tributaries include the uppermost part of the Rhone valley (above Brig, cf. Fig. 4) and the main valleys to the north and the south. They are characterised by having valley floor width less than 2 km, representing a less wide, but steeper glacial trough compared to the Rhone Valley with hanging valleys and cirques above. In most cases, they contain a large valley glacier in the uppermost locations and terminate in a narrow gorge towards the Rhone.

In the Turtmann Valley, 593 storage landforms have been mapped in the 13 hanging valleys, containing a total volume of 750×10^6 m^3 of sediment. The glacial trough of the Turtmann Valley, including its valley slopes and the adjacent glacier forefield of the Turtmann Glacier, contains around 300×10^6 m^3 of deposits. Assuming the Turtmann valley as representative for the Rhone tributaries, a simple upscaling approach could be to multiply these values by the number of subsystems derived from the morphometric analysis of the hydrological network. This produces a volume of roughly $30\,000 \times 10^6$ m^3 of deposits in the hanging valleys and around 9000×10^6 m^3 deposits in the tributary troughs and slopes. Combined with the volume for the main trough of the Rhone Valley, $106\,000 \times 10^6$ m^3 (Hinderer, 2001), we come up with a total sediment volume for the upper Rhone basins of about $145\,000 \times 10^6$ m^3. Sediment storage distribution reveals a basin structure with a large number of hanging valleys that contain significant amounts of debris. This quantity can be explained by a decoupled system state of these upper locations due to current topographic conditions and process activity. Only fine sediment leaves these hanging valleys, while most of the coarse material is stored due to the lack of removal processes. The tributary valleys to the Rhone contain fewer deposits due to their better coupling to the hydrological network. Here, glaciofluvial and fluvial transfer processes dominate and provide sediment passage towards the Rhone valley. High water discharge, produced by the terminal glaciers, combined with narrow valley floors and steep valley gradients cause a reduction in temporary storage. The Rhone main valley is a major sink for the eroded sediment from the tributaries that has been filled since the Pleistocene and consequently contains the largest amount of material.

CONCLUSIONS

The quantification of storage volumes in large Alpine basins is still an unresolved issue. Although, accurate techniques to quantify sediment volumes exist, data acquisition and analysis is time consuming and requires experience and intense collaboration (e.g. with geophysicists). In rough and inaccessible Alpine terrain, use of these techniques is restricted to small areas. More simple approximations tend to introduce large uncertainties due to the assumptions made. The larger number of storage landforms in the hanging valleys of large basins require more time consuming and tedious work, especially if geometric approximations are applied. This might be the reason why previous studies have been limited to smaller drainage basins or valley floor deposits.

We propose to apply a combination of different quantification techniques in order to consider the scaling relationships between sediment deposits over large areas. A subdivision of the sediment flux system into subsystems of sediment cascades and process/landform units will help to identify different deposit types and storage locations. Quantification methods can then be adjusted to the different subsystem characteristics, combining more accurate approaches on smaller scales with less accurate methods on larger scales.

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