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Contemporary geomorphological activity throughout the proglacial area of an alpine catchment

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ABSTRACT

Quantification of contemporary geomorphological activity is a fundamental prerequisite for predicting the effects of future earth surface process and landscape development changes. However, there is a lack of high-resolution spatial and temporal data on geomorphological activity within alpine catchments, which are especially sensitive to climate change, human impacts and which are amongst the most dynamic landscapes on Earth. This study used data from repeated laser scanning to identify and quantify the distribution of contemporary sediment sources and the intensity of geomorphological activity within the lower part of a glaciated alpine catchment; Ödenwinkelkees, central Austria. Spatially, geomorphological activity was discriminated by substrate class. Activity decreased in both areal extent and intensity with distance from the glacier, becoming progressively more restricted to the fluvially-dominated valley floor. Temporally, geomorphological activity was identified on annual, seasonal, weekly and daily timescales. Activity became more extensive with increasing study duration but more intense over shorter timescales, thereby demonstrating the importance of temporary storage of sediment within the catchment. The mean volume of material moved within the proglacial zone was 4400 $m^3.yr^{-1}$, which suggests a net surface lowering of 34 $mm.yr^{-1}$ in this part of the catchment. We extrapolate a minimum of 4.8 $mm.yr^{-1}$ net surface lowering across the whole catchment. These surface lowering values are approximately twice those calculated elsewhere from contemporary measurements of suspended sediment flux, and of rates calculated from the geological record, perhaps because we measure total geomorphological activity within the catchment rather than overall efflux of material. Repeated geomorphological surveying therefore appears to mitigate the problems of hydrological studies underestimating sediment fluxes on decadal–annual time-scales. Further development of the approach outlined in this study will enable the quantification of geomorphological activity, alpine terrain stability and persistence of landforms.

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1. Introduction and rationale

Understanding contemporary sediment fluxes is fundamental to predicting the likely effects of future changes to geomorphological activity and landscape development, whether those changes are induced by climate change or by human activity (c.f. Jones, 2000; Slaymaker, 2010). Catchment-wide denudation is commonly inferred indirectly from rates of fluvial suspended sediment exiting catchments (c.f. Milliman and Syvitski, 1992). However, it is important to recognise that the discharge of suspended sediment *from* catchments effectively considers a catchment as a 'black box'; it does not represent all of the geomorphological activity that occurs *within* that catchment (Caine, 2004), nor does it recognise the spatial and temporal variability of that activity. This problem has been acknowledged for several decades by projects that have examined bedload movements and that have defined sediment production, transfer and storage within a catchment (e.g. Rapp, 1960; Warburton, 1990; Trimble, 1995).

Future changes to geomorphological activity and landscape development will be especially rapid and potentially severe within alpine catchments because they are very sensitive to climate changes and to human impacts. This sensitivity is most evident in water availability (c.f. Barnett et al., 2005), water quality and stream biodiversity (e.g. Brown et al., 2003; 2007), water thermal dynamics (e.g. Carrivick et al., 2012) and sediment fluxes (c.f. Milliman and Syvitski, 1992; Hallet et al., 1996). Understanding contemporary sediment fluxes *from* alpine catchments has to account for the considerable variability in geomorphological activity between adjacent mountain catchments (e.g. Gurnell et al., 1988; Trimble, 1995; Carrivick

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and Rushmer, 2009). However, understanding contemporary sediment fluxes *within* alpine mountain catchments is complicated because mountain glacier responses to regional and local climate are heterogeneous in space and time (e.g. Carrivick and Chase, 2011) and because there is often a significant imbalance between sediment production and sediment transport due to former glacial activity that i) over-steepens topography and promotes paraglacial slope adjustment processes, ii) produces large sediment stores available for erosion, and iii) emplaces moraines that can be both a sediment source and a barrier to meltwater (Beylich and Warburton, 2007). This complexity in the spatial and temporal nature of geomorphological processes hinders the identification and quantification of sediment sources, storages and fluxes (e.g. Dietrich and Dunne, 1978; Jones, 2000; Bertoldi, et al., 2009). For example, it is well known from hydrological measurements of suspended sediment that small mountain catchments have a particularly variable sediment flux that is seldom resolved, partly because large but short-lived events are often missed (Kirchner et al., 2001; Lewis et al., 2005). Consequently, decade-long sediment-yield measurements using conventional (hydrological) methods can greatly underestimate long-term (centennial–millennial) average rates of sediment delivery (Kirchner et al., 2001). Short-term geomorphological activity within parts of a catchment can be determined from repeated topographic measurements and episodic sediment fluxes can be calculated as a volume of material moved between each of these surveys (e.g. Martin and Church, 1995; Ham and Church, 2000; Fuller et al., 2003). However, whilst several European alpine countries are in the process of making systematic country-wide Airborne Laser Scan surveys, use of ALS and Terrestrial Laser Scan (TLS) topographic data (i.e. Light Detection and Ranging; LiDAR data) to determine geomorphological changes within alpine catchments is presently limited. This is perhaps because ALS datasets tend to be acquired on a campaign basis, rather than as part of routine monitoring strategies. It is also undoubtedly because of the problems of processing such voluminous and complex datasets.

The overall aim of this paper is to identify and quantify the contemporary distribution and intensity of activity of sediment sources, storages and fluxes within the proglacial part of a glaciated alpine catchment.

2. Quantifying geomorphological changes within alpine catchments

Long-term (centennial-millennial) sediment storage within alpine catchments has been quantified by combining geophysical surveys, digital topographic analyses and geographic information system (GIS) modelling techniques (e.g. Schrott et al., 2003; Otto et al., 2009). Determination of contemporary sediment sources, storages and fluxes within alpine catchments remains problematic however, not least because existing catchment-wide models (e.g. Caine, 1974; Dietrich and Dunne, 1978) are qualitative. These qualitative conceptual models are relied on heavily for designing contemporary field sampling of water and sediment fluxes. This is a major drawback with sediment budget studies because rigorous definition of sediment storages and fluxes is necessary prior to a field campaign (Warburton, 1990). Furthermore, it is difficult to decide how to focus field campaigns because sediment storages and fluxes vary greatly over the short-term (annual–decadal) (e.g. Trimble, 1995) due to: i) functional activity of geomorphological coupling is dependent on sediment availability and triggering events (Schrott et al., 2006), and; ii) because intermittent valley-floor and braidplain storage is very important (e.g. Warburton, 1990; Orwin and Smart, 2004; Bertoldi, et al., 2009).

The best way to quantify contemporary geomorphological activity within alpine catchments; and specifically to discriminate contemporary sediment storages and fluxes in space and time, is to employ a geomorphological approach (i.e. to re-survey topography; e.g. Martin and Church, 1995; Ham and Church, 2000; Fuller et al., 2003; Bertoldi et al., 2009). Indeed Orwin et al. (2010) recommend resurveying as the most appropriate method for establishing integrated sediment flux studies in cold environments on inter- and intra-annual time-scales. Resurveying using traditional methods is exceptionally time-consuming and financially expensive for anything more than a few fixed cross-sections of valley profiles. Differential Global Positioning Systems (dGPS) have helped to alleviate these problems slightly and Schrott et al. (2006) made excellent use of photogrammetric methods to determine changes in sediment storages over a four year period within a deglaciated valley in Germany. Advancements in surveying technology of LiDAR; primarily in the form of ALS and TLS, for rapid very high-resolution analyses (Abermann et al., 2010) have yet to be exploited for holistically examining multi-scale sediment fluxes within highly dynamic alpine catchments.

3. Laser scanning of alpine geomorphology

High resolution (~1 m) topographic data from photogrammetry (e.g. Schrott et al., 2006) and satellite image datasets from mountainous and alpine catchments have to date been used for i) geomorphological mapping, ii) landform unit-scale analyses of episodic geomorphological changes, and iii) analyses of river reach-scale changes (Smith and Pain, 2009; Wang et al., 2010). ALS and TLS instruments give high resolution (<1 m), high precision (>0.2 m), and rapid acquisition of surface elevation data over a range of spatial scales and are thereby revitalising geomorphological studies.

Alpine catchment-wide use of ALS and TLS datasets is still new and developing, but a notable work to date is that of Van Asselen and Seijmonsbergen (2006) which illustrated that 1 m resolution Digital Elevation Models (DEMs) can be analysed to map mountain hillslope and elevation properties semi-automatically using object-oriented segmentation and classification techniques. Glaciers have received special attention for monitoring and measurement of retreat, down-wasting, and surface character due to the obvious rapid responses to, and consequences of, climate change (Abermann et al., 2010). At a geomorphological unit (i.e. ‘landform’) scale (over tens of metres) and in terms of episodic event-based analyses, Morche et al. (2008) used TLS data to quantify and explain changes on an alpine talus cone within an alpine catchment over a four month period. Dunning et al. (2010) and Abellan et al. (2010) have investigated landslide occurrence and properties. At a river reach scale, repeat surveys using photogrammetric (e.g. Luchi et al., 2007), differential Global Positioning System (dGPS) (Brassington et al., 2000, 2003) and remote sensing data (e.g. Lane et al., 2003) have been used to quantify changes. Hetherington et al. (2005) and Milan et al. (2007) used the same data from a 10 day period in early ablation season (June) to quantify a major episode of avulsion and medial bar erosion as well as transient bank accretion. However, to date no studies have made repeated and multi-scale laser scan surveys within an alpine catchment to identify and quantify the distribution and intensity of contemporary (multi-scale) geomorphological activity and thus sediment sources, storages and fluxes, holistically.

4. Study area description

The Ödenwinkelkees catchment extends from ~47°6′00″ to 47°8′7″N and from 12°37′19.5″ to 12°40′20″E and is partially within the Hohe Tauern National Park, central Austria (Fig. 1). It is well known both for its proximity to the Rudolfshutte Alpinzentrum and for the long-term measurements of the snout position of the Ödenwinkelkees and of the nearby Sonnblickkees (e.g. Slupetzky, 1997; Slupetzky and Aschenbrenner, 1998). The Ödenwinkelkees catchment has an area of 9.2 km^2 and the glacier presently occupies 1.8 km^2 or 19.5% of that area (Fig. 1A). Catchment terrain surface elevations range from 1790 to 3490 m.a.s.l. (Fig. 1B). The Ödenwinkelkees catchment is composed predominantly of granitic gneiss bedrock (Höck and Pestal, 1994) but

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