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Revealing Caine's energy concept to characterise sediment flux in alpine geosystems: problems and perspectives reanalysed by a one-decade record of rockfalls, soil slips, earthflows and soil creep in two highly active catchments (Reintal and Lahnenwiesgraben, German Alps)

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Quantification of sediment flux by mass-movements in Alpine geosystems is a key requirement for both, applied questions in relation to geotechnical measures and scientific questions relating landform generation to present-day processes. In 1976 Nel Caine proposed a concept to refer subaerial erosion to released potential energy ("geomorphic work" in Joule) and to power (Joule per second = Watt). This is done by including the vertical height difference effected by a certain sediment transport (geomorphic work) and by referring the effected geomorphic work to a certain span of time (power).

Based on a one-decade dataset of sediment flux in two alpine geosystems, we argue that the traditional quantification of sediment flux in t/year or m^3/year is often not meaningful. In our case studies, the sediment flux value of 125,000 t characterises both, a rockfall that was falling down 500 m from a cliff (geomorphic work: 610 GJ within a few minutes), and an earthflow lobe that is travelling at a speed ranging from 1.5 to 2261 mm/year (geomorphic work: ca. 0.06 GJ within one year). Both have totally different impacts in terms of transport efficiency and geomorphic effects on

the catchment. Thus we argue that the energy concept is more appropriate as soon as (i) internal transport in the subsystems of a sediment cascade is reflected and (ii) continuous and discontinuous sediment fluxes are compared.

We compare two adjacent alpine valley catchments exhibiting similar climatic characteristics but differing with respect to geology, resulting valley shape and geomorphological processes. In the U-shaped Reintal valley (1050-2744 m a.s.l.), compact Triassic limestones crop out as 400-1200 m high rockwalls and result in a high importance of rockfalls as sediment transport process. In the V-shaped Lahnenwiesgraben valley (705-1985 m a.s.l.), which was deeply incised and oversteepened by fluvial processes in the Lateglacial, clayey and marly layers intercalate with competent carbonate rocks and result in a high abundance of soils slips, earthflows and soil creep phenomena, while rockfalls are less important.

Small-magnitude rockfalls were measured by means of rockfall nets from 1999-2004, mid-magnitude rockfalls were recorded volumetrically over several years and high-magnitude rockfalls were dated based on landscape, geophysical evidence, historical documents and C14 dating. In the Lahnenwiesgraben valley, the speed of earthflows and soil creep was measured on 23 test sites from 2000-2006, 218 embankment failures and 182 slope failures were recorded continuously in the field from 1993-2002, in terms of volumes and movement vectors.

In the Reintal valley, high-magnitude rockfalls ($>$1 mio. m^3) and small-magnitude rockfalls ($<$10 m^3) already contribute 35.0 ($\pm$3.1) GJ/year and 9.2 ($\pm$4.1) GJ/year to the overall rockfall budget of 54.6 ($\pm$7.8) GJ/year. In the Lahnenwiesgraben valley, soil slope failures (1 GJ/year), small-magnitude rockfalls ($<$ 10 m^3; 0.4 GJ/year), high-magnitude rockfalls ($>$ 10.000 m^3; 0.2 GJ/year) and earthflows (0.2 GJ/year) dominate the overall hillslope denudation of 2 GJ/year, while soil embankment failures (0.1 GJ/year), mid-magnitude rockfalls (10-10.000 m^3; 0.1 GJ/year) as well as soil creep (0.02 GJ/year) are less important.

In mountain environments, the energy approach to sediment flux may reflect the activity of geomorphic processes and their efficiency much better than a pure volumetric approach. We argue that it makes different processes, time scales and catchments comparable and is a key approach to link the short-term process scale to a long-term landscape evolution scale.