Geomorphology 290 (2017) 222–235

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Predictive modeling of slope deposits and comparisons of two small areas in Northern Germany

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ARTICLE INFO

Keywords:
Geomorphometry
Catchment area
Light Detection and Ranging (LiDAR)
Multiple regression models
Exponential models

ABSTRACT

Methods for correct quantitative comparison of several terrains are important in the development and use of quantitative landscape evolution models, and they need to introduce specific modeling parameters. We introduce such parameters and compare two small terrains with respect to the link slope-valley for the description of slope deposits (colluvium) in them. We show that colluvium accumulation in small areas cannot be described by linear models and thus introduce non-linear models. Two small areas, Perdoel (0.29 ha) and Bornhöved (3.2 ha), are studied. Slope deposits in the both are mainly in dry valleys, with a total thickness M_{total} up to 2.0 m in Perdoel and up to 1.2 m in Bornhöved. Parent materials are mainly Pleistocene sands aged ~ 30 kyr BP. Exponential models of multiple regression that use a 1-m LiDAR DEM (digital elevation model) explained 70–93% of spatial variability in M_{total}. Parameters DH_{12} and DV_{12} of horizontal and vertical distances are introduced that permit to characterize and compare conditions of colluvium formation for various terrains. The study areas differ 3.7 times by the parameter DH_{12} that describes a horizontal distance from thalwegs at which M_{total} diminishes 2.72 times. DH_{12} is greater in Bornhöved (29.7 m) than in Perdoel (8.12 m). We relate this difference in DH_{12} to the distinction between types of the link slope-valley: a regional type if catchment area of a region outside a given small area plays an important role, and a local type when accumulation of colluvium from valley banks within a small area is of more importance. We argue that the link slope-valley is regional in Perdoel and local in Bornhöved. Peaks of colluvium thickness were found on thalwegs of three studied valleys by both direct measurements in a trench, and model surfaces of M_{total}. A hypothesis on the formation mechanism of such peaks is discussed. The parameter DV_{12} describes a vertical distance from a peak of colluvium thickness along valley bottom at which M_{total} diminishes 2.72 times; values of this parameter differ 1.4 times for the study areas. DV_{12} is greater in Perdoel (3.0 m) than in Bornhöved (2.1 m) thus indicating more sharp peaks of M_{total} in Bornhöved. Exponential models allow construction of predictive maps of buried Pleistocene surfaces for both the terrains and calculate colluvium volumes with an error 4.2% for Perdoel and 7.1% for Bornhöved. Comparisons of buried and present surfaces showed that the latter are more smoothed, more strongly in valleys where flow branching is increased.

1. Introduction

Remobilization and transport of sediments on timescales of thousands years occurs in watersheds on an event-to-event basis (e.g. Walling, 1983; Fryirs, 2013). During this time a portion of sediments appears washed out as indicated by remaining fragments of slope deposit (colluvial) layers. Some proportion is deposited at various basin locations such as gullies, gentle slopes or near various barriers like bogs. The practical importance of erosion and attempts to solve the problem of sediment delivery (Walling, 1983) have led in geomorphology to more careful studies on locations and causes of the sediment accumulation in catchments for long-term erosion processes as well as regularities in spatial distributions of buried sediments. Basins often demonstrate dis-connectivity in sediment flows (Otto et al., 2009; Jain and Tandon, 2010; Fryirs, 2013) although some basin portions, especially small ones, may behave as connective (Messenzehl et al., 2014; Zimmermann et al., 2014). Dis-connectivity partly depends on 'effective timescales' (Harvey, 2002) because large events (such as storms) occur infrequently. Nevertheless, essential portions of buried sediments stay inside basins for most timescales (e.g. Fryirs, 2013).

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http://dx.doi.org/10.1016/j.geomorph.2017.04.018
Received 11 November 2015; Received in revised form 6 April 2017; Accepted 11 April 2017

Some models are based on a concept of discrete "compartments" such as gullies, fans, landslides, subdivided and linked by discrete blockages: buffers (e.g. swamps), barriers (e.g. dams) and blankets (e.g. floodplain sediment sheets) (Fryirs, 2013). Such discrete models (e.g. Harvey, 2002; Fryirs et al., 2007; Jain and Tandon, 2010) evaluate sediment flows in a whole basin and are based on the assumption that discrete blockages play dominant role within basin, thus forming cascades of compartments.

When this is not so (i.e. blockages are absent or not essential), continuous approaches are used instead, in which topography plays an important role (Wilkinson et al., 2005; Dymond, 2010; Lebedeva and Brantley, 2013). Although continuous approaches are of great interest for so-called landscape evolution models, LEMs (Tucker and Hancock, 2010; Kirkby, 2015; Minasny et al., 2015), LEM developers do not sufficiently use geomorphometry, the science of quantitative land surface analysis (e.g. Bishop et al., 2012). Process-based LEMs that simulate thousands of years include CAESAR, CHILD, GOLEM, SIBERIA etc., usually generate poor empirical confirmations (Coulthard and Van De Wiel, 2012) and unknown errors (Van De Wiel et al., 2011).

Some interesting experiments in landscape evolution use long-lived cosmogenic isotopes (e.g. ^{10}Be, ^{21}Ne, ^{26}Al, ^{36}Cl) to measure rates of very slow processes like long-term denudation, ≥ 10 mm kyr^{-1} (Wilkinson et al., 2005) or soil production. However, this technique assumes steady rates of long-term erosion processes (Brown et al., 2009) although the rates may change in time (e.g. Tunnicliffe et al., 2012).

An alternative approach tries to simulate landscape evolution and colluviation in small study areas (not an entire basin) documented with trenches and dense boreholes. Topographic data of high resolution reflect both terrain depositional sequence and sub-surface stratigraphy (Dreibrodt et al., 2010; Coulthard and Van De Wiel, 2012; Tarolli, 2014). High-resolution Digital Elevation Models (DEMs) available from airborne Light Detection and Ranging (LiDAR) provide typically 1 m resolution with a vertical accuracy estimated to be 10 to 15 cm (Brown et al., 2009). LiDAR allows high precision mapping of cultural (field boundaries, banks etc.) and geomorphic features to form historical geo-archives. Despite time-consuming and expensive dense augering and trench excavations, this approach using detailed subsurface data coupled with LiDAR could provide sediment delivery budget estimates (Brown et al., 2009). Small areas so far studied are usually 0.3–10 ha and surveyed at high spatial resolutions of 1–5 m. The number of such excavated small areas exceeds 100 only in Germany (Dreibrodt et al., 2010).

Each system or process has its own characteristic size. One example is the distance from which sediments are transported to a given place (for thousands of years). Neither LEMs nor discrete models can estimate this distance accurately when a large basin is considered because the distance changes over time along main stream. Advantages to use small study areas, LiDAR and inventory-based models is that they allow us to characterize this distance. In turn, this distance allows comparison of qualitatively different terrains. This opportunity is difficult for LEMs or discrete models. Coulthard and Van De Wiel (2012) noted that some LEMs may perform well on the basis of the data from which they were developed, but in different circumstances they may tell us little about how a system may operate.

We define here the link slope-valley (slope-channel coupling) with respect to slope sediment as the supply of sediment to a given place, usually a grid cell, in a dry valley from either (i) valley banks or (ii) distant up-slope parts of the basin; sediment delivery pathways within and outside the valley are not distinguished in this definition. Average sediment delivery pathways are relatively short for (i) and long for (ii). Many authors used the concept of the link slope-valley (e.g. Brunsden and Thornes, 1979; Caine and Swanson, 1989; Lang et al., 2003; Fryirs et al., 2007; Fuchs et al., 2010; Cavalli et al., 2013; Zimmermann et al., 2014), but with various definitions that may include, for example, rivers. Messenzehl et al. (2014) suggested to restrict this concept to lateral (not within valley) pathways. Lang et al. (2003) considered changes in sediment delivery pathways due to rainfall events. Clearly, the link slope-valley is related to two characteristic distances of sediment delivery pathways: horizontal and vertical.

A horizontal distance, *DH*, from various objects is often used in geomorphology because it is an important driver or indicator of many processes. Such objects may be thalwegs (Nandi and Shakoor, 2009), water divides (Brenning, 2009), hedgerows (Follain et al., 2006), roads (Schicker and Moon, 2012), faults (Ozdemir and Altural, 2013), and so on. A vertical distance, *DV*, is used infrequently. Möller and Volk (2015) used it from thalwegs to study modern soil erosion.

Mitusov et al. (2013) found significant pairwise correlations between thicknesses of several colluvial layers and some topographic attributes. However, more informative are approaches when a given geomorphic feature is compared with a set of environmental variables. Such approaches are known in ecology (Guisan and Zimmermann, 2000), soil science (Scull et al., 2003) and geomorphology (Bishop et al., 2012) as predictive modeling.

This study is restricted by the total colluvium thickness, M_{total}. We use statistical comparisons of M_{total} to topography, *DH* and *DV*, with no process-based modeling. For very sharp spatial changes in M_{total} (several times in few meters), usual regression models may be not suitable, in which case special models are necessary.

The purposes of this paper are: (i) to develop multiple regression models that correctly describe links between M_{total} and independent variables, verify them, and calculate maps, (ii) to introduce and evaluate characteristic horizontal (*DH*) and vertical (*DV*) distances, (iii) to compare two small terrains using *DH* and *DV*, and to classify links slope-valley, (iv) to reconstruct the surface of underlying materials and evaluate sediment volumes, and (v) to study regularities in spatial distributions of sediment in terms of M_{total} along valley bottoms.

2. Study areas

We investigate two small study areas, Perdoel (0.285 ha) and Bornhöved (3.24 ha), located 4.5 km apart in Northern Germany (Fig. 1). Perdoel (54°6′31″ N, 10°15′2″ E) is in the bottom part of a dry valley in the lake Belay basin (~16 ha). Perdoel is approximately 35 km south of Kiel. This site has been a permanent pasture for 50 years. The distance between the western bank of the lake Belau and the most eastern observation point is 23 m. Dated colluvial layers (Dreibrodt and Wiethold, 2015) indicate several periods of increased erosion partly due to intensified agricultural land use in the middle Neolithic (*c.* 7.0–6.4 kyr BP), late Bronze Age and Pre-Roman Iron Age (*c.* 3.3–2.0 kyr BP) and some Medieval Times around 1342 CE possibly due to a catastrophic rainfall event known from historical documents (e.g. Dreibrodt et al., 2010). Aeolian input from a distant source was observed between 4.0 and 2.5 kyr BP, replaced later by water erosion, but the loess belt is in central and southern Germany (Larsen et al., 2016) and this input was considered as negligible (Dreibrodt and Wiethold, 2015). Mitusov et al. (2014) report results of pairwise links between thickness of colluvial layers and topographic attributes in Perdoel at LiDAR DEM resolution of 1 m. Dreibrodt and Wiethold (2015) provide a detailed description of colluvial layers in trenches and results of radiocarbon dating for this (watershed II in their paper) and several other sites within the basin of Belau. Radiocarbon dating was primarily based on charcoal pieces, 2–3 for each layer.

Bornhöved (54°4′ N, 10°15′ E) includes two main dry valleys (catchment area ~8 ha) of the lake Bornhöveder. It is approximately 40 km south from Kiel. This site is used as an agricultural field. The above description of general situation in Perdoel may be applied to Bornhöved because it is only 4.5 km apart from Perdoel. Dreibrodt et al. (2009) provide a detailed description of colluval layers and radiocarbon dating for trenches of this site. Mitusov et al. (2013) describe results of pairwise links between thickness of colluvial layers and topographic attributes based on a differential GPS survey at resolution of 5 m.