Investigating sediment budgets and pathways using LiDAR DEMs of difference and a geomorphological map

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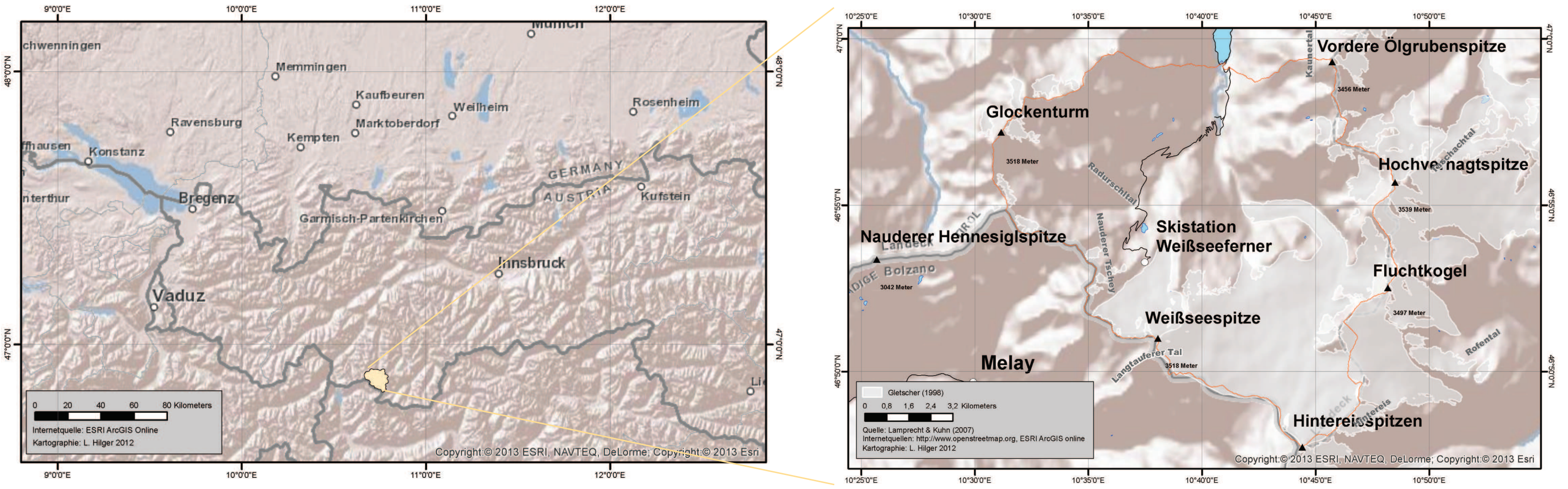
1. Introduction

In alpine catchments sediment is moved from one landform to another as long as they are coupled by the activity of geomorphic processes. The spatial and functional interaction of these processes forms sediment cascades reaching from sediment sources or stores to sediment sinks, and ultimately to the catchment outlet. In study presented here, multitemporal high-resolution LiDAR datasets are used to establish a morphological sediment budget. These can easily be calculated on the raster cell scale, i.e. by differencing digital elevation models (DEM), and on the landform scale, by establishing the net balance of eroded and accumulated material within spatial units like polygons on geomorphological maps.
The flow of mobilised sediment can be estimated on a DEM using flow routing algorithms, and the net balance (sediment eroded – sediment deposited) is accumulated along correspondent pathways.
Graph theory is used to store and investigate resulting sediment pathways on different aggregation levels. The incorporation of the geomorphological map highlights potential advantages of object-based over pixel-based approaches to generating graph nodes and analysing sediment cascades. The methodology enlarges the possibilities of the flow accumulation algorithms by the possibility to trace and analyse sediment pathways.
A very similar approach involving debris flow, rockfall and slope wash simulation models was used by Heckmann & Schwanghardt (2013) to analyse sediment cascades in the Zwieselbach valley, Central Alps, Austria.

2. Study Area

The method of analysing and visualizing sediment pathways derived from flow routing algorithms using graph theory is examplified on a small spatial subset of the upper Kaunertal valley in the Ötztal Alps (Austrian Central Alps). The valley is a tributary of the Upper Inn river system and is drained by the Fagge brook. Its upper part, where the investigated slope section is located, is underlain by crystalline rocks (siliceous para- and orthogneiss). The landscape is dominated by glacial landforms and the two main glaciers in the area are rapidly shrinking (Abermann et al. 2009). In fact, the study area for this poster is a large section of the true right LIA lateral moraine of the Gepatschferner glacier, the larger of the two. The 120 m high moraine section is interspersed with bedrock sections and the moraine deposits have been reworked considerably by since their deposition, the most important processes being fluvial transport and debris flows. These processes have transported material from the upper to the lower parts of the slope and partly into the fluvial system of the Fagge brook.



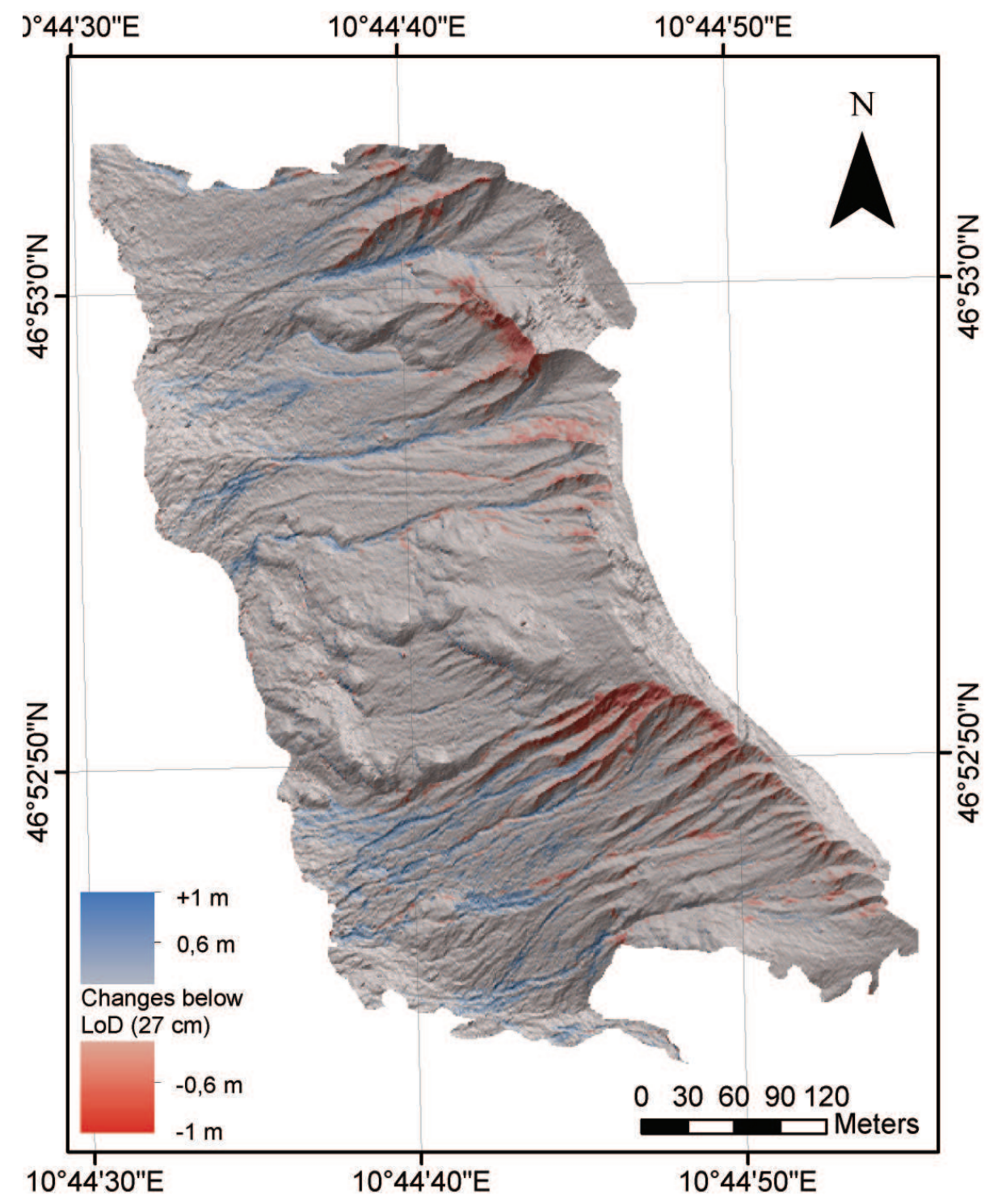


Figure 1: DoD over the period Sept. 2006 to Sept. 20122012

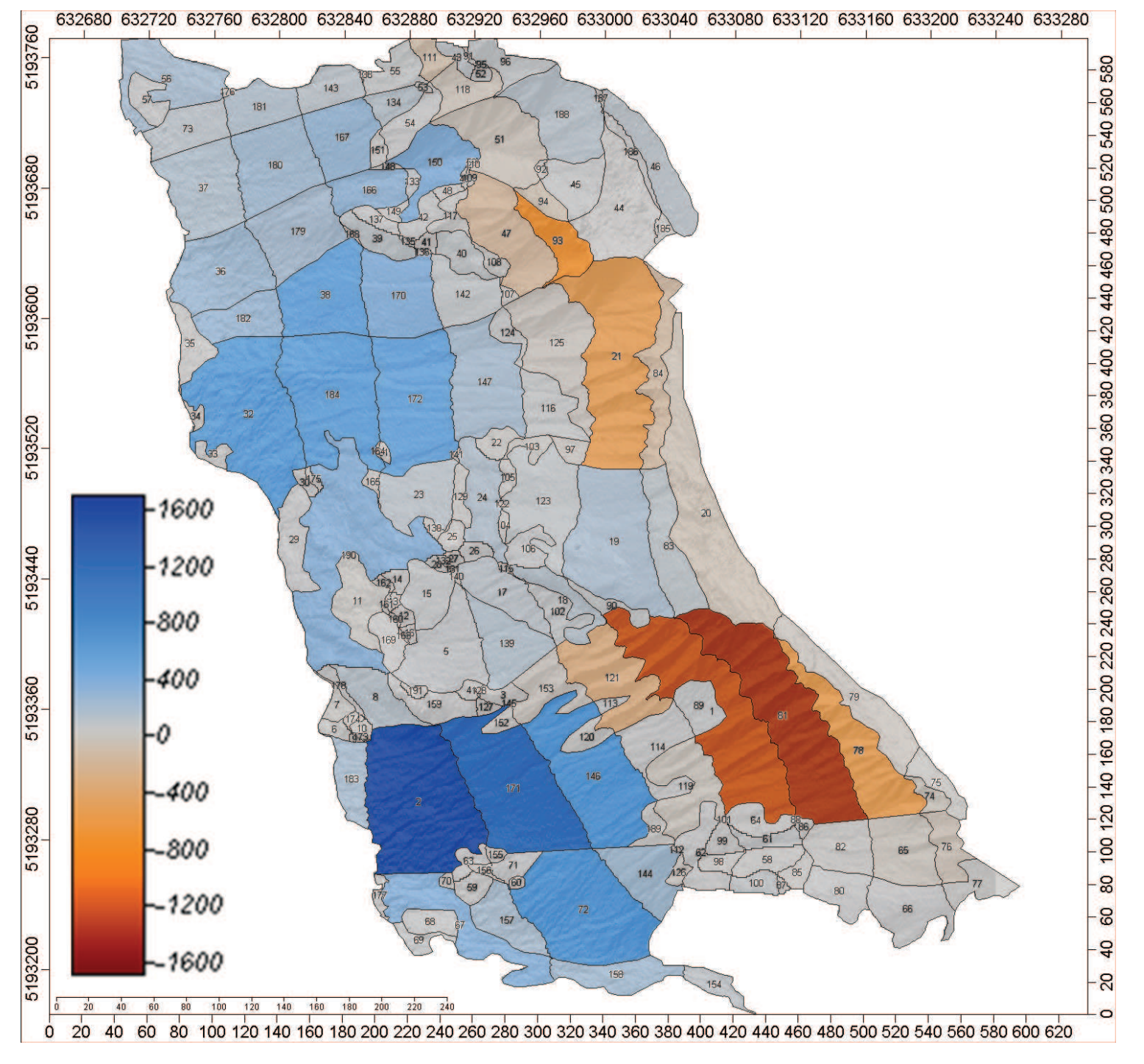


Figure 2: Aggregated net balances (m^3) for the different Polygons used as spatial units

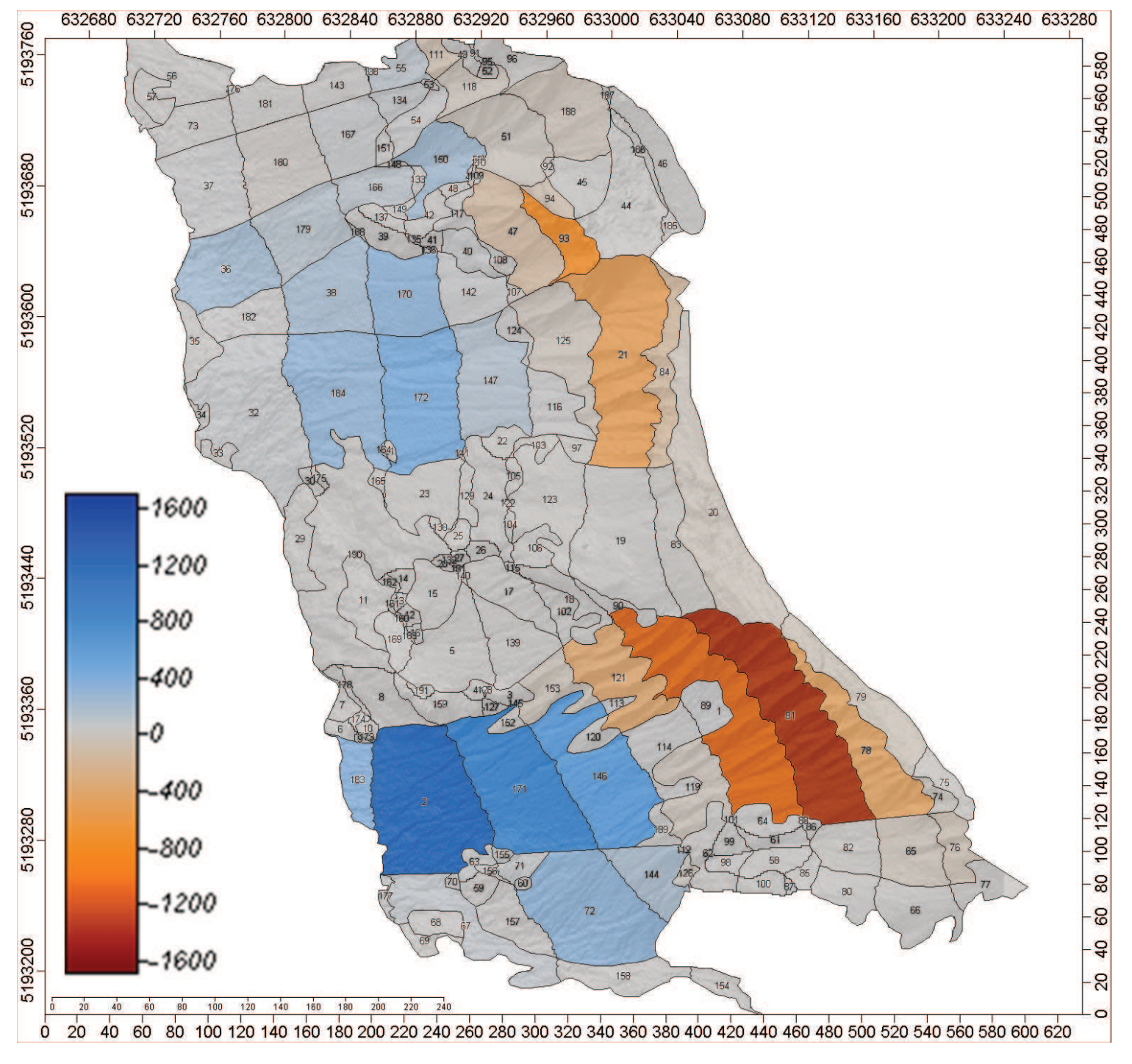


Figure 3: Net balances (m^3) for the different Polygons used as spatial units calculated from the polygon-level graph

3. LiDAR survey, DEM and DoD generation

The topographic data used in this study were acquired in two ALS flight campaigns. The first campaign was conducted in September 2006, the second in September 2012. While the first mission yielded a point density of ~ 2 pt / m^2, the second resulted in ~ 10 pt / m^2. The first campaign was conducted by the Tyrolean State and the second was flown specificly for the PROSA project using the Riegl LMS-Q680i (= 1550 nm) sensor. 72 fight strips were adjusted and georeferenced using mountain hut roofs as tie surfaces (Kager, 2004). In the following, only measurements corresponding to last returns of a laser pulse were used. Flying points and measurement errors were removed by applying algorithms based on point neighbourhood statistics. Then DEM1s taking the height of the measurement point being closest to the grid cell center as the cell value. Very few and isolated no-data cells due to low point density for the 2006 timestep were interpolated. The threefold standard deviation of an area that had been stable between the two timesteps was used as a simple Level of Detection during DoD (see Fig. 1) generation.
All processing steps on the point level were accomplished using dierent ready-made algorithms available in the software package LIS (http://www.laserdata.at). All processing steps on the grid level were accomplished using a combination of SAGA GIS (Conrad, 2006) and R‘s spatial extentsion packages (Brenning, 2009; Hijmans, 2013; Pebesma et al., 2014).

4. Geomorphological Mapping

A geomorphological map of the study area, corresponding to the state of September 2009, was prepared at a scale of 1:6000. Field data, literature consideration, orthorectifed aerial images of different temporal volumes and multiple DEM-derived land surface parameters like slope, aspect, height above channel network or local percentile and a moving-window based delineation of rock wall sections were used facilitate the mapping process.
The map has been conceptionalised from the very beginning of the project to serve the aim of model-based connectivity analysis. While helpful in creating informative geomorphological maps for the field using the standard symbolology set forth by Kneisel et al. (1998), such representation does not lend itself to GIS-based analysis (areal proportion of landform types, analysis of landform topology etc). Hence, the digital geomorphological map was constructed entirely of non-overlapping polygon objects representing, in most cases, sediment storage landforms, but also areas of geomorphic process activity (Vehling et al. 2013).
As the slope selected for this case study compromises comparatively few geomorphological units, the number of the polygons was artificially enlarged by cutting landforms along 20 m contours. Aggregated net balances for each spatial unit were then calculated by summing detected morphological changes within each polygon.

5. Investigation of sediment pathways using graph theory

SAGA GIS‘s flow accumulation module was modified in a way that the each flowing step from cell to cell was recorded in an edgelist. Both the accumulated material volume and the information which spatial polygon units served as origin and target were stored as an edge attribute.
All edges that recorded sediment movement within polygons were deleted and sediment flux between cells belonging to different polygons were summed and aggregated to edges on the polygon level. The sediment balance for each polygon was calculated by offsetting the sediment entering the polygon along all incoming edges against the flux along outgoing edges. Graphs were constructed for 80 different MFD Exponents between 1.1 and 9 and the RMSE over the spatial polygons was calculated in an attempt to find the best setting.
All graph-related based analyses were performed using R‘s igraph (Csardi, 2014) and sqldf (Grothendieck, 2014) packages.

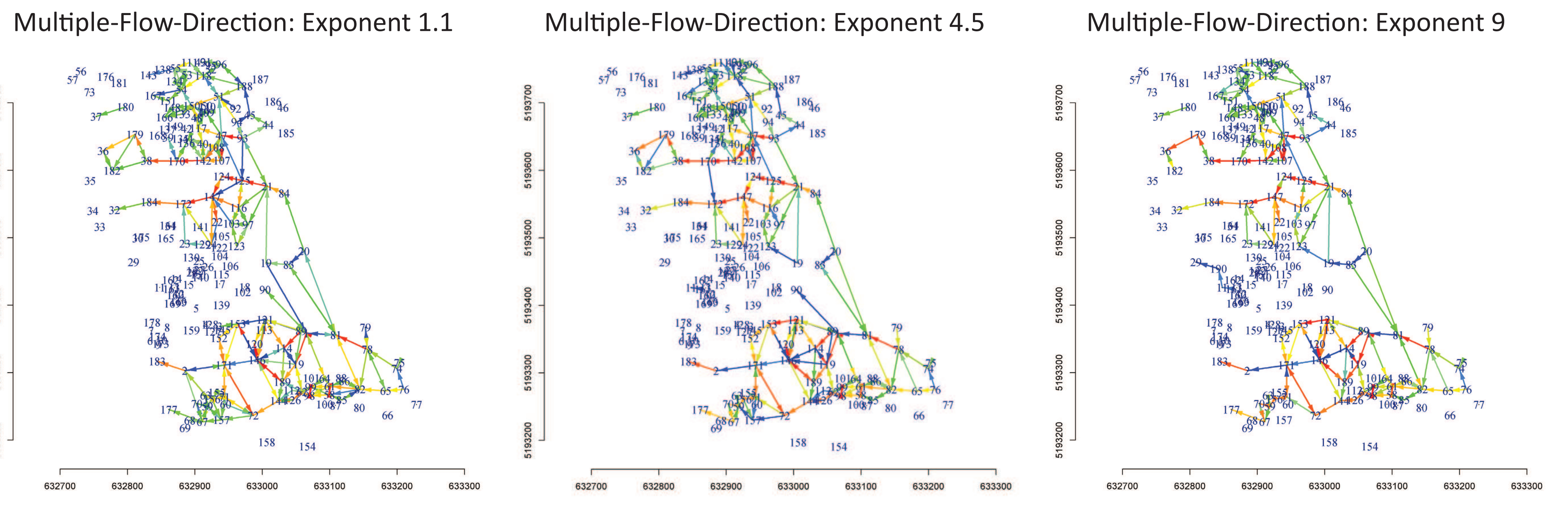


Figure 4: Resulting graphs of sediment flux between different spatial polygons (numbers are IDs) for three different MFD-Exponent settings. Only Fluxes > 2 m^3 are represented by an edge.

6. Results

- due to some systematic time synchronisation error in the ALS data (meanwhile solved), only a simple LoD of 9 cm could be achieved, which resulted in measured changes between +/- ~27 cm were not accounted for in the analysis (see Fig. 4).
- about 4400 m^3 were mobilised on the slope between 2006 and 2012
- with the modified algorithm it is possible to to trace sediment movement by fluvial processes from erosional zones to depositional zones
- net balancing the polygons offsetting the flows along the in- against out-going edges resulted in a good representation of the net balances acquired using the actual DoD
- the RMSE of the net balances shows only minor increase with increasing MFD-exponent settings while the number of edges between spatial polygons decreases with increasing MFD-exponent, but the sediment fluxes along the edges do not increase strongly. This is probably a consequence of the structuring of the slope in small subcatchments represented by gullies, resp. many polygons running parallel to countour lines and covering multiple sediment routing gullies. It would be of great interest to test the procedure with spatial units running more or less parallel to the flow direction and on a surface with less pronounced subcatchments.

7. Discussion

- The multiple-flow direction algorithm is typically used to simulate sediment movement by flowing water. The main sediment redistributing process on the slope investigated, however, is debris flow. It is therefore questionable if the algorithm
- As the density of accumulated material is generally lower than the material eroded, there is the possibility that “negative sediment” is routed along the edges as soon as the all material accumulated in erosion zones of the DoD is depleted with the simulated flow crossing measured depositional zones. These fluxes of “negative sediment” have deleted for the study presented here and more research in how to solve this problem is needed.
- The raw graph results in several low-volume sediment fluxes between polygons / landforms that are separated by watersheds. This is a consequence of an inaccurate mapping of the original landform units with their borders crossing watersheds slightly. The problem could be mitigated by using either DEM-based, automated landform classification methods (e.g. van Asselen & Seijmonsbergen, 2006) or watershed boundary detection tools that could be used during the mapping process (e.g. Hardin et al., 2012).

Acknowledgements:
We would like to thank Philipp Glira from the TU Vienna for his work in adjusting and georeferencing the airborne LiDAR data and repated valuable advice concerning 3D point data handling.

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