DOI: 10.23784/HN110-01

Mass wasting in Lake Constance

A GIS-based geo-morphometric reconnaissance

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New high-resolution hydroacoustic data from the »Tiefenschärfe« project in Lake Constance (central Europe) reveals a large amount of mass wasting events occurring on all slopes and influencing large parts of the lake floor. Within a GIS-supported geomorphologic investigation, a manual picking of mass transport deposits, as well as a digital reconnaissance were carried out, based on the visual appearance of mass transport deposits and on elevation-derived morphometric parameters, respectively. Subjective manual and objective (semi-)automatic detection strategies show the usability of the latter to be a new, easy-to-use assistive tool for identifying mass transport deposits in large bathymetric data sets and quantifying the morphological imprint of events on the lake floor. The iteratively determined algorithm divides mass wasting occurrences into the sub-features break-off edge, transport channel and depositional lobe and suggests morphometric dependencies for each sub-feature. Because Lake Constance consists of three mutually independent sub-basins the algorithm success differs somewhat, which we credit to locally changing hydrodynamic and sedimentologic patterns.

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Lake Constance | bathymetry | mass wasting | morphometry | GIS

1 Introduction

Mass wasting (MW) is a geologic process and commonly described as the downslope movement of material under the direct influence of gravity. With the recent advent of hydroacoustic techniques accompanied by qualitatively improving bathymetrical maps, subaqueous mass transport deposits (MTD) can be (manually) detected with the help of relief-dependent hillshade maps. Depending on the size of the event and adjacent anthropogenic life and infrastructure, mass wasting events can pose a significant threat, especially in highly populated areas, for example in the Central European, Pre-Alpine area. Here, regional MW inventories (e.g. Chapron et al. 2004; Hilbe et al. 2008; Hilbe et al. 2011; Brückner 2016) highlight unstable areas and assess different MW mechanisms. However, manually detecting all MW events remains a subjective and tedious undertaking, especially for high-resolution bathymetry and large lakes. Because MW causes well-known morphological impacts (Fig. 1) these types of elevational changes can be param-

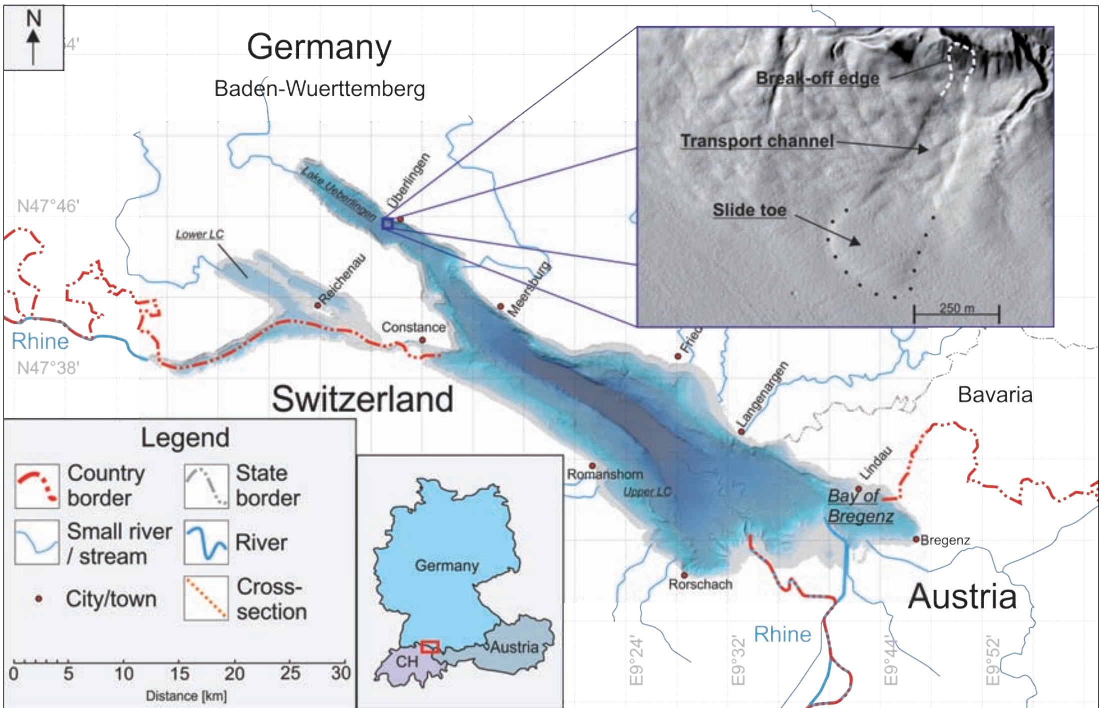

Fig. 1: Geographic setting of Lake Constance. Separated into different basins (»Lower Lake« and »Upper Lake«) and the Upper Lake extension »Lake Überlingen«, the lake borders Germany (Baden-Württemberg and Bavaria), Austria (Vorarlberg) and Switzerland (Thurgau and St. Gallen). The river Rhine is its main inflow, entering the lake in the south-eastern area. An example for mass wasting depiction with characteristic sub-features is shown, as well

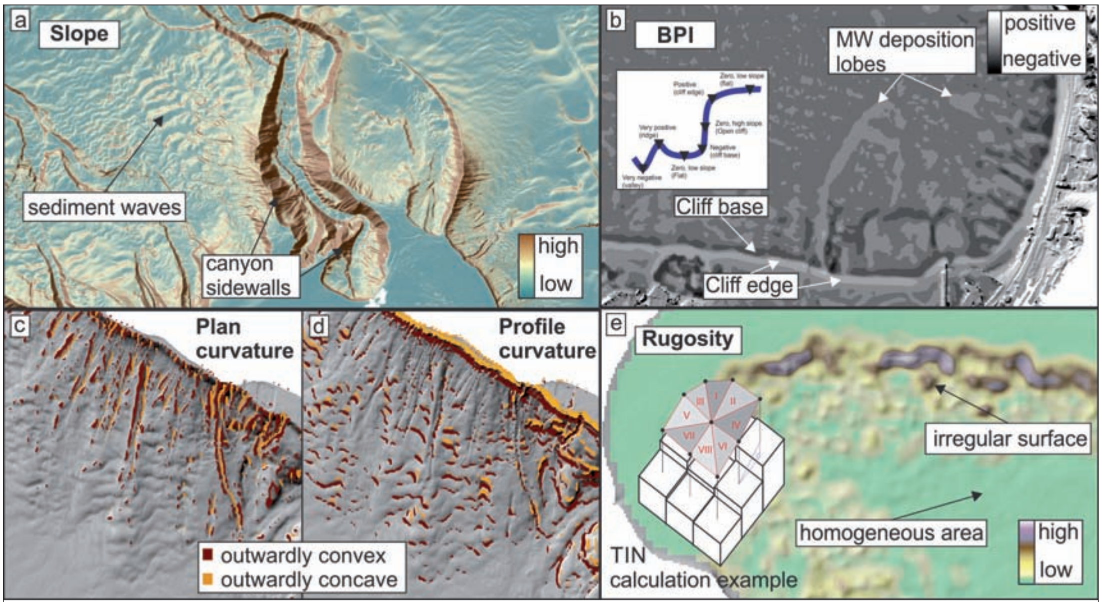

Fig. 2: Morphometric parameters used in the algorithm. **a:** Slope parameter, the 1st order derivative of the surface: maximum steepness. **b:** Bathymetric Positioning Index (BPI): relation of mean elevation to the surrounding cells. **c:** 2nd order derived slope-perpendicular changes in the elevation (plan curvature). **d:** 2nd order derived slope-parallel changes in the elevation (profile curvature). **e:** Rugosity determination by triangulated irregular networks (TIN) approximation

eterised to help understand transport mechanisms and testify morphological changes with subjective quantification. By using morphometric attributes (see Fig. 2) derived from multidimensional, bathymetric surfaces, a possible ArcGIS-supported digital reconnaissance strategy will be executed, where several sub-features of MTD will be identified and compared to the outcome of a »classic« manual detection.

2 Geographical/geological setting

The freshwater, pre-alpine Lake Constance is in many ways a remarkable area. With approximately 536 km^2, it is the third largest Central European water mass trailing Lake Geneva (Switzerland/France) and Lake Balaton (Hungary). Lake Constance has a maximum water depth of 251 m while exhibiting a surface elevation of 395 m above sea level. Due to Lake Constance's usage as the largest reservoir for drinking water in Europe and its location at the tri-border region between Austria, Germany and Switzerland (Fig. 1), the lake and its surroundings are the main place of residence for approximately 600,000 inhabitants. Therefore, it is a valuable resource which needs to be monitored in terms of maintaining excellent drinking water quality despite a high anthropogenic pressure on the lake and its shorelines.

Lake Constance is the product of extensive movement, formation and erosional excavation by water and ice activity during the last Quaternary glaciation period 20 to 18 thousand years ago, which created the elongated shape of Lake Constance (Schreiner 1979; Wessels 1998). The morphology of the lake floor is shaped by Rhine river turbidity currents along its pathway from the delta towards the deepest part in the Lakes' centre. However, the underflow potential of the Rhine is significantly smaller since the International Rhine Regulation (Brückner 2016). The lake floor is highly influenced by mass movement, especially in the north western Lake Überlingen, where thin-channelled events dominate, the Rhine Delta and its erosive canyon landscape and the Bay of Bregenz, where large-scale sediment creep is reported (Schröder et al. 1998; Brückner 2016).

3 Methods

3.1 Data acquisition

A combined digital terrain model (DTM) acquired from a Kongsberg EM2040 multibeam echo sounder and a LiDAR RIEGL system (VQ-820G) was used. Bathymetric multibeam echo sounder data were acquired on board RV *Kormoran* (LUBW-ISF, Langenargen) during two campaigns in spring/summer of 2013 and February 2014. LiDAR green laser acquisition was carried out by the company Airborne Mapping GmbH in March of 2014, before both data sets were blended together to create a joint topo-bathymetric DTM with resolution up to 0.5 m (IGKB 2016). The investigation carried out in this contribution is based on a DTM resolution of 3 m grid cell size projected in UTM32 and ETRS89. More details in Wessels et al. (2015).

3.2 Morphometry

The morphologic appearance of mass transport deposits is divided into smaller sub-features, each showing characteristic depictions, as shown in Fig. 1. The beginning of a MW event is the break-off edge, where the slope is discontinued by a steep surface. This rupture generally appears in a slope parallel setting. Oppose to the break-off edge, the downslope movement of material is perpendicular to the slope and undertaken by a

Parameter	Calculation	Description	MW-usability	Reference
Slope (Fig. 2a)	1st order derivative of the surface	Maximum steepness of an elevational surface	Recreating break-off edges and slide toes	Horn (1981)
BPI (Fig. 2b)	2nd order derivative, relation of each cell's elevation to the mean elevation of the surrounding cells	Scale-dependent morphological variation, statistical approach of how data points in a cell are varying	Non-directional erosion and depositional areas	Weiss (2001)
Plan curvature (Fig. 2c)	2nd order derived changes in the elevation, primarily in slope perpendicular changes	Small-scale steepness variations with regards to a given direction. Alternation of convex and concave areas	Transport channels and convex/concave alterations	Zevenbergen and Thorne (1987)
Profile curvature (Fig. 2d)	2nd order derived changes in the elevation, primarily in slope parallel changes	Small-scale steepness variations with regards to a given direction. Alternation of convex and concave areas	Break-off edges and creeping structures. Non-curved slide toes	Zevenbergen and Thorne (1987)
Rugosity (Fig. 2e)	Relation of the surface area and the planar area using triangulated irregular networks (TIN) approximation	indicator of the predominant microtopography and the intensity of small-scale elevation changes	Slide toe microtopography; depositional areas of coarse material (rockfalls)	Jenness (2004)

transport channel. However, a channel-like concave incision can only be found, when transport is well directed. Noticeably, transport channels often depict the smallest width of the event and follow the aspect direction where the slope exhibits its steepest values. The end of the deposition consists of a slide toe (or »slide lobe«) marked by a funnel-like shape. This toe acts as a convex, depositional rim and features microtopography that exhibits higher rugosity than adjacent areas.

A hillshaded surface was used to evaluate the lake floor in terms of mass movement appearances. When such an event was found, a polygon was drawn around the influenced area and the depositions' geometry was attained. In order to be classified as a mass wasting event the abrasional location must be visibly linked with the depositional area at the end of the event. By manually digitising MW events a large amount of morphological information was compiled in a geomorphometric database, where parameters like initiation and deposition depth, length, width, area and others are collected.

The most important aspect for the digital reconnaissance is the detection of sub-features associated with mass movement. By a unified query, composed of a multitude of morphometric parameter increments listed in the table and shown in Fig. 2, sub-features were defined. The morphometric parameters were iteratively combined in a joint query (Fig. 3) to reflect the morphological imprint of each MW sub-feature.

4 Results

4.1 Mass wasting in Lake Constance

The (manual) detection of MTDs in Lake Constance revealed a total of 860 discrete events, which are distributed in every sub-region of the lake. Generally, it can be said the lake floor is highly influenced by mass movement. However, even though mass wasting can be found in on all associated slopes, the overall distribution of such events is incoherent and tied to local geology (Wessels 1995; Brückner 2016; Brückner et al., in prep.).

4.2 Digital reconnaissance

4.2.1 Parametrisation

Fig. 3 shows the proposed algorithm and its chosen values and increments, which were iteratively determined and proven to be most resilient. Using Esri ArcGIS Model Builder a step-by-step algorithm was created, which defines the sub-features, where the value increment queries are carried out using the Map Algebra tool. The algorithm starts by traversing the bathymetric data set with a 3-by-3 pixel high pass to enhance the edges of target features in the raster surface data set. This filtered bathymetry is then used to create several raster data sets featuring the proposed morphometric parameters. Therefore, the analysis is pixel-based and allows for pixel-specific assignments.

For each sub-feature a joint inquiry was elaborated that relied on morphometry. For instance, a pixel which exhibits a slope value larger or equal 10 degree, a profile curvature between –2 and –6 and a BPI (5 m annulus) larger than 0 is potentially part of a break-off edge. To be assigned to this sub-feature however, every criterion must be met. All pixels that pass through this query are labelled »YES« and are put through ultimate artefact low pass smoothing filtering. As the analysis is done on a 3-by-3 pixel wireframe, the central pixel and its adjacent cells are investigated in terms of the aforementioned criteria. To be ultimately classified as part of a break-off edge, 60 % of all adjacent cells need to be labelled »YES«, as well, for the middle pixel to pass.

4.2.2 Sub-feature detection

The break-off edge sub-feature has an impact on the parameters slope, profile curvature and BPI. The algorithm includes an initial, edge-enhancing,

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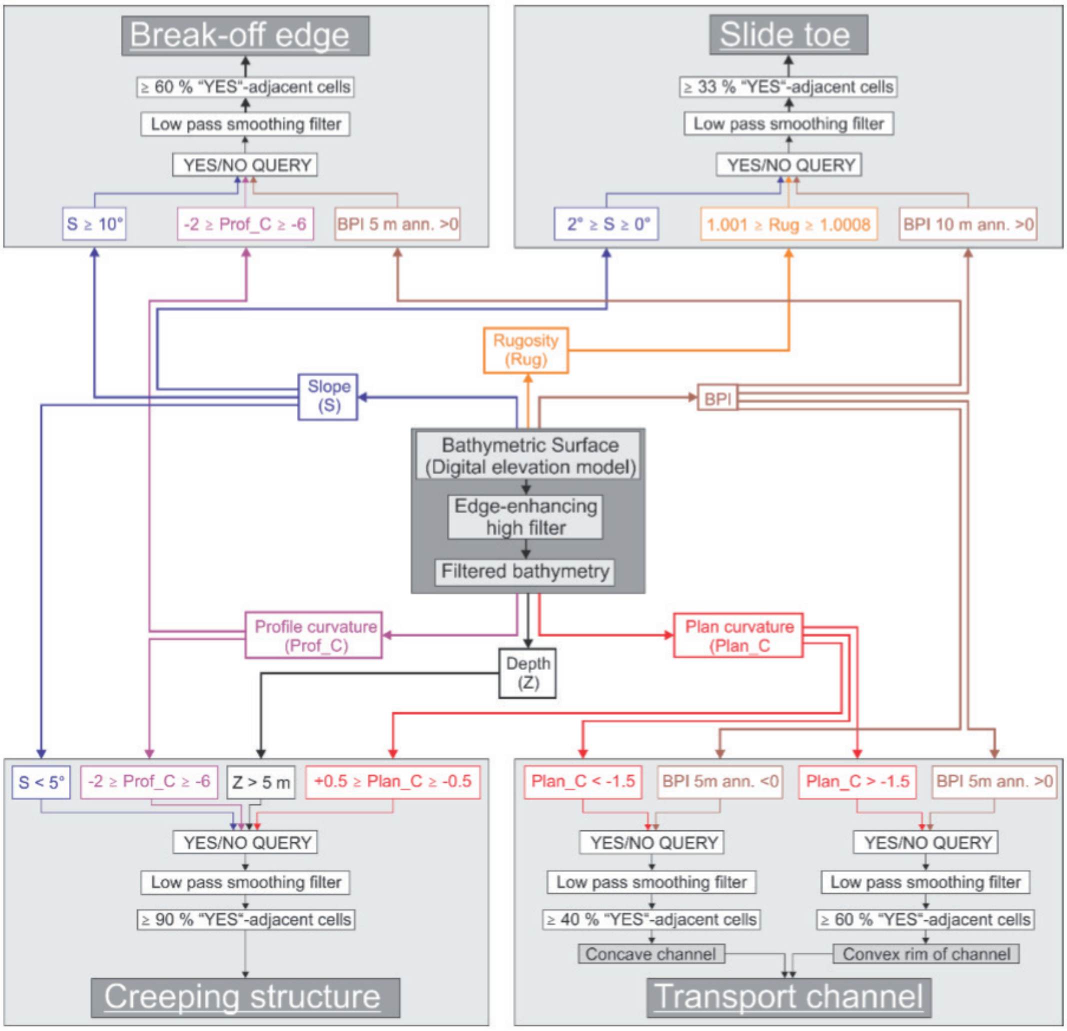

Fig. 3: Digital reconnaissance algorithm. The bathymetric surface (middle) is filtered and used to create the morphometric parameters. These are the basis for a joint inquiry to recreate the presented MW sub-features (break-off edges, transport channels and slide toes, creeping structures)

high-pass filtering of data to eliminate outer beam bending errors. The proposed algorithm was not only able to detect break-off edges but also canyon sidewalls, which exhibit a level of steepness forcing the algorithm to misjudge these features.

The detected break-off edge pixels of the digital reconnaissance strategy were compared to the manually picked initiation depth distribution of landslide events. As revealed by Fig. 4, this distribution produces a correlation coefficient of 0.86 between the two detection methods. The digital reconnaissance testifies the existence of a dominant break-off edge depth level, which was first seen in the polygons' statistics.

Transport channels of MW events have an impact on the parameters plan curvature and BPI. The algorithm for transport channels is split into two different parts (Fig. 5) to detect concave (blue) and convex (red) impacts individually, where the value increments are inverted for the two shape types. The algorithm for this sub-feature was very well suited to depict rounded narrow structures but struggled to detect broad channels. The convex outer rim of structures was best detected in shallower parts and higher slope positions, whereas the concave incisions could be traced into deeper settings.

In the proposed algorithm the slide toe detection was attempted using a moderate 0 to 2 degree slope angle increment, a positive broad scale BPI and highly specific rugosity values. A

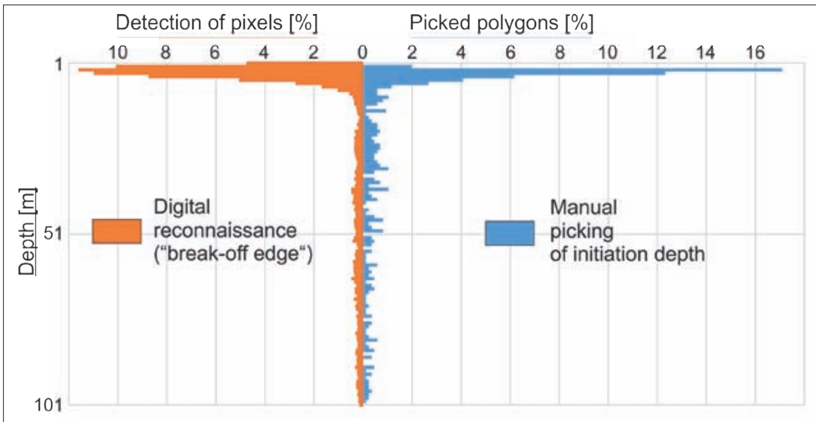

Fig. 4: Break-off edge depth distribution and method comparison in the first 100 m. The outcome of the digital reconnaissance strategy is plotted in orange colour, while the manual picking events is displayed in blue. The distribution is very similar with a dominant portion in the first 5 m depth. In deeper settings, both methods produced subordinate values, which are more evenly spread for the digital reconnaissance

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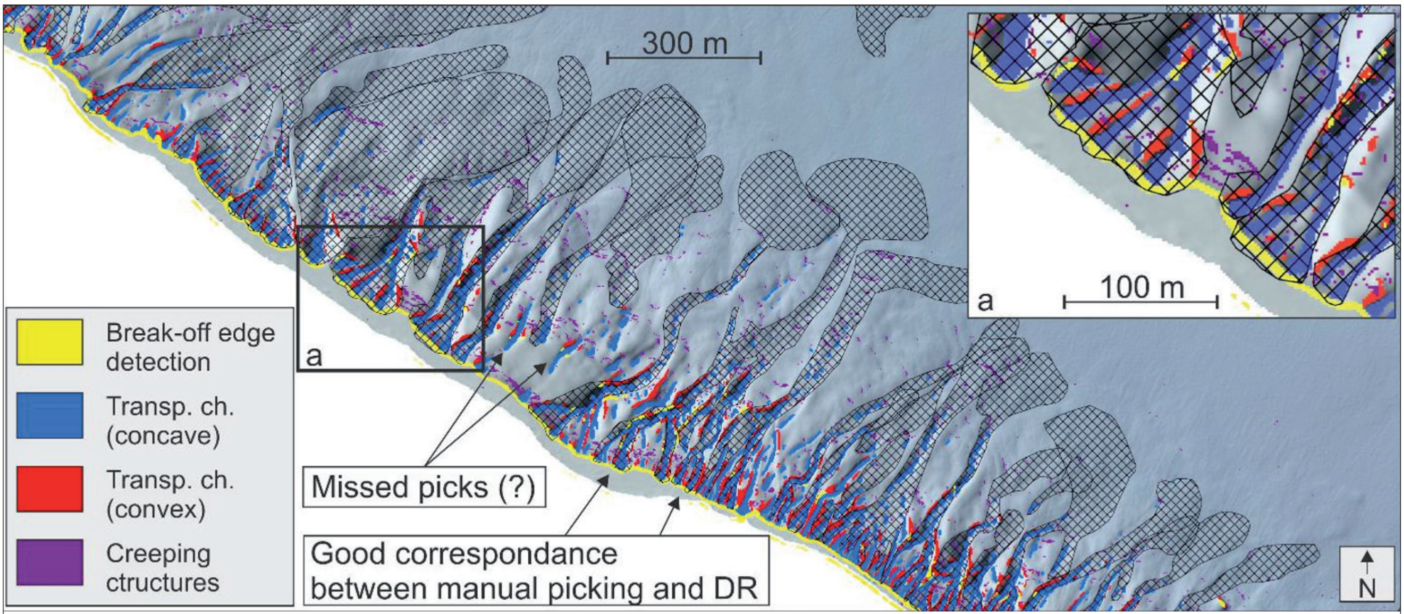

Fig. 5: Comparison of picked polygons and digital reconnaissance sub-feature detection. The manually detected MW events (cross-hatched polygons) are well resembled by sub-feature detection in Lake Überlingen. a: Detailed zoom showing resemblance

Acknowledgments
This contribution is an outcome of a master thesis of the »Tiefenschärfe« project, which was funded by the European fonds for regional development (Interreg). The project is organised by the environmental agency of Baden-Württemberg (LUBW) and the International Commission for water protection of Lake Constance (IGKB).
We thank the supervisors of the thesis Prof. Dr. Christian Winter (Christian-Albrechts-Universität, Kiel) and Prof. Dr. Gerhard Bohrmann (University of Bremen/MARUM). We also thank the acquisition team on board the RV *Kormoran* for data collecting and the »Tiefenschärfe«-bathymetry editing team of the University of Bremen/MARUM for their effort in data processing.

surface area/planar area ratio of 1.0008 (difference of 0.08 %) produced the best results. The »detectional window« for slide toes is small, so that only the largest slide toes could be detected. However, the found rugosity difference is able to depict the slope/basin transition, while anomalies in the basin testify the uncertainty of the algorithm.

5 Discussion

The digital reconnaissance carried out in this contribution is not able to detect mass wasting itself, yet depicts elevational changes caused by mass wasting – a seemingly trivial but essential difference. It proved to be a versatile strategy to put emphasis on these elevational changes caused by mass movement, while pixel-based highlighting is able to assist the manual detection strategy immensely by providing structural information and is able to underline and assist manual interpretations by pointing out MW occurrences which were overseen. By calculating the presented morphometric parameters and plotting them together with hillshade surfaces, the manual detection approach will be more resilient as it potentially yields better results. Especially the curvature parameters with their directional inquiries are useful to highlight certain sub-features and can be calculated quickly before manual detection. Because all sub-features (except the slide toe) exhibit a clear direction, they can be assessed with the morphometric equations presented. The slope parameter is useful to detect events associated with a certain angle and works well for creeping structures (moderate slopes) and break-off edges (high slopes). BPI information is used to generate an extra obstacle inside the inquiry, but is not the dominant factor, as it only provides general structural information. The rugosity parameter proved to be inefficient as rugosity differences were very small, making the algorithm for slide toes difficult. Using even higher resolutions (up to 0.5 m for the Lake Constance) rugosity differences would potentially increase, yielding better results.

Furthermore, the used algorithms exhibited varying success for the different sub-basins. For Lake Überlingen and the Lower Lake, the algorithm produced the best reconnaissance of MW events, especially for break-off edges and transport channels. The Upper Lake proved to be more challenging and the detection of these sub-features were difficult especially in the deep, central basin and near the Rhine delta. This is very likely due to increased sedimentation rates especially in the more turbulent, hydrodynamic setting of the eastern Upper Lake. Another factor of provided structural information is that the manifestation of sub-features can possibly be presented using confidence levels of recognition. As the parametrisation involves a distinct percentage-barrier for adjacent cells to pass through the query, differences in percentage values imply varying levels for the manifestation of sub-features. For instance, stronger, well-exposed break-off edges depict a larger value than rounded equivalents. Comparing values potentially leads to a prioritisation highlighting the most prominent shapes.

The analysed Lake Constance mass wasting inventory and the inherent mass transport deposit statistics help determining mass wasting prone areas. The statement of Schröder et al. (1998) that »slope areas of Lake Constance are quite stable (with a few exceptions)« needs reevaluation, at least in some areas. Especially Lake Überlingen and the slope around Meersburg represent high mass transport deposit-densities and are largely influenced by mass wasting occurrences, which was already described by Wessels (1995).