

GIS-based modelling of glacial sediment balance

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with 8 figures and 2 tables

Summary. In view of ongoing atmospheric warming, there is concern as to whether retreating glaciers uncover a rocky or sedimentary bed. Sedimentary beds are abundant in high-mountain areas and represent, if exposed, a severe hazard potential for outbursts of periglacial lakes or debris flows. Furthermore, knowledge about glacier sediment balance is needed when dealing with climate sensitivity of recent and historical glaciers.

The main factors influencing sediment balance of a glacierised mountain catchment have been organised into an *index* (I_{es}) of *glacier erosion and sedimentation*, which distinguishes between glaciers eroding into bedrock and those building up thick sedimentary beds. GIS-based methods were developed to extract the needed I_{es} -parameters from Digital Elevation Models (DEM), digitised glacier outlines and central flowlines. These methods were automated and tested on 84 Swiss Alpine glaciers. The results were validated through comparisons with forefield classifications and manually derived index results.

The comparison with classified forefields confirms that the index allows for a rough assessment of the glacial sediment balance. In order to improve the predictability of glacier-bed characteristics, a better understanding of the periglacial debris production is necessary. However, the high overall accuracy of the comparison with the manual glacier-by-glacier investigation shows the potential of using GIS-based modelling with DEM in geomorphodynamics.

Zusammenfassung. GIS-basierte Modellierung der glazialen Sedimentbilanz. Mit der fortschreitenden Erwärmung der Erdatmosphäre ziehen sich Gletscher weiter zurück und legen ihre Fels- oder Sedimentbetten frei. Sedimentbetten sind in hochalpinen Gebieten weit verbreitet und beinhalten in exponierten Lagen ein Gefahrenpotential für Ausbrüche von periglazialen Seen oder Murgängen. Darüber hinaus ist das Wissen um die glaziale Sedimentbilanz notwendig im Zusammenhang mit der Klimasensitivität von heutigen und historischen Gletschern.

Die Hauptfaktoren der Sedimentbilanz von vergletscherten Einzugsgebieten im Hochgebirge wurden in einem *Erosions-/Sedimentationsindex* (I_{es}) zusammengefasst, der zwischen Gletschern unterscheidet, die ihr Bett erodieren und jenen, die dicke Sedimentbetten aufbauen. Es wurden GIS-basierte Methoden zur Extraktion der notwendigen I_{es} -Parametern aus digitalen Höhenmodellen (DHM), digitalen Gletscherumrissen und zentralen Fliesslinien entwickelt. Diese Methoden wurden automatisiert und an 84 Alpengletschern in der Schweiz getestet. Die Resultate wurden durch Vergleiche mit Gletschervorfeldklassifikationen und manuell berechneten Indexresultaten validiert.

Der Vergleich mit den klassierten Vorfeldern bestätigt, dass sich der Index für eine grobe Beurteilung der glazialen Sedimentbilanz eignet und dass zur Verbesserung der Vorhersagbarkeit der Gletscherbettcharakteristik ein besseres Verständnis der periglazialen Schuttproduktion notwendig ist. Dennoch zeigt die gute Übereinstimmung des GIS-basierten Ansatzes mit den Resultaten des manuell berechneten Indizes das Potential von GIS-basierten Modellierungen mit digitalen Höhenmodellen für Anwendungen in der Geomorphodynamik.

Résumé. Modélisation du bilan des sédiments glaciaires basée sur un SIG. Avec le réchauffement progressif de l'atmosphère, les glaciers se retirent et laissent apparaître des rochers ou lits de sédiment. Dans le domaine alpin, les lits de sédiment sont abondants et représentent dans des situations exposées, un danger potentiel et aléatoire de rupture des lacs périglaciaires ou des coulées boueuses. De plus, la connaissance du bilan des sédiments est nécessaire en liaison avec la sensibilité climatique des glaciers d'aujourd'hui et du passé.

Les facteurs principaux du bilan de sédimentation des bassins glaciaires ont été résumés en un indice *érosion-sédimentation* (I_{es}), qui différencie les glaciers dont le lit s'érode à ceux consolidant leur épais sédiment en lit. Des méthodes SIG ont été développées pour extraire les paramètres I_{es} nécessaires d'après des modèles numériques d'altitude (MNA), de contours de glaciers et de lignes centrales d'écoulement. Ces méthodes ont été automatisées et testées sur 84 glaciers alpins de Suisse. Les résultats SIG ont été validés d'une part par comparaison de classification des zones périglaciaires sur le terrain et d'autre part d'indices calculés manuellement.

La comparaison de classification des zones périglaciaires confirme que l'indice permet un jugement grossier du bilan de sédiments glaciaires et que pour améliorer la prédiction des caractéristiques d'un lit glaciaire, une meilleure compréhension de la production du débris périglaciaire est nécessaire. Cependant, la bonne estimation des indices calculés manuellement montre le potentiel de la modélisation basée sur un SIG avec un MNA dans le domaine de la géomorphologie dynamique.

1 Introduction

As a consequence of ongoing atmospheric warming, most Alpine glaciers are retreating. Swiss Alpine glaciers lost about 27% of surface area and about 30% of ice volume from 1850 to 1973 (MAISCH et al. 2000), and another 20% of surface area from 1973 to 2000 (PAUL 2003). Thereby, increasing areas of former glacier beds become exposed. Characteristics of such newly exposed glacier beds greatly influence sediment flux in melt water streams, the formation of potentially dangerous periglacial lakes and debris flow activity on steep morainic slopes (HAEBERLI et al. 1997, HUGGEL et al. 2002, KÄÄB et al. in press).

Knowledge about glacier sediment balance becomes important when dealing with climate sensitivity of recent and historical glaciers. Growing sedimentary beds may lead to a surface height - mass balance feedback. Moraine bastions with dimensions of several decametres influence a glacier's mass balance in dependence of its mass balance gradient, which is for Alpine glaciers typically between 0.1 m and 1 m water equivalent per 100 m. In addition, sediment beds influence glacier dynamics (HAEBERLI 1996). Debris on glacier surface affects substantially glacier's energy fluxes and therefore terminus behaviour (e.g. NAKAWO et al., eds., 2000: 25-132).

The question whether glaciers erode into bedrock or build up thick sedimentary beds leads to the subject of the processes of glacial erosion and sedimentation, and of glacial sediment balance. These processes are complex and, since taking place at the glacier bed, are difficult and expensive to be measured (HOOKE 1989, FISCHER et al. 2001). Direct erosion measurements (QUERVAIN 1919, LÜTSCHG 1926, BOULTON 1974) and measurements of sediment flux in melt water streams from different sources as collected and published in DREWRY (1986: 84-87) show that the sediment balance of alpine glaciers with surrounding rock walls is dominated by the periglacial debris input, whereas glacial erosion is less important (HAEBERLI 1996).

This paper presents an erosion-sedimentation index to estimate the glacial sediment balance of alpine glaciers. An index for manual glacier-by-glacier investigations is thereby integrated into a fully automated, GIS-based approach and tested on glaciers in south-western

Switzerland. The automatically computed results are validated against a manual-derived indexation and a glacier forefield classification. We discuss the methods of the GIS-based approach, its validation against the manual index and the forefield classification as well as an outlook in the light of other literature.

2 Erosion-sedimentation index I_{es}

The sediment balance of a glacierised mountain catchment, i.e. the ratio between debris input from the surrounding rock walls and debris evacuation by the melt water stream, can hardly be measured directly. Therefore, the main factors influencing the governing processes have been organised by HAEBERLI (1986) into an index (I_{es}) of glacier erosion and sedimentation (Fig. 1), which distinguishes between glaciers eroding into bedrock and those building up sedimentary beds:

$$I_{es} = \frac{a \cdot C}{(P - b) \cdot S \cdot J^k \cdot L} \quad (1)$$

where $a \cdot C$ represents debris production in which a is a factor indicating whether debris is furnished to the ablation area (1.0) or to the accumulation area (0.5). C is the mean height of debris-providing cliffs (100 m units). $(P - b) \cdot S \cdot J^k$ reflects the transport capacity of the melt water stream where P is the annual precipitation (m), b is the annual glacier mass balance (m), S is the total surface area of the glacier (km^2), J is the inclination of the sub-/proglacial melt water stream ($\tan(\alpha)$) and k is a constant from river hydraulics (1.6). L is the glacier length (km). The units in this ratio of factors are chosen so that dimension-less index values around 1 result. The numerator of equation (1) represents debris input, whereas the denominator stands for the debris output from the system. If the input is greater than the output, i.e. $I_{es} \gg 1$, the glacier tends to have a sedimentary bed. If the input is lower than the output, i.e. $I_{es} \ll 1$, the glacier tends to have a rocky bed.

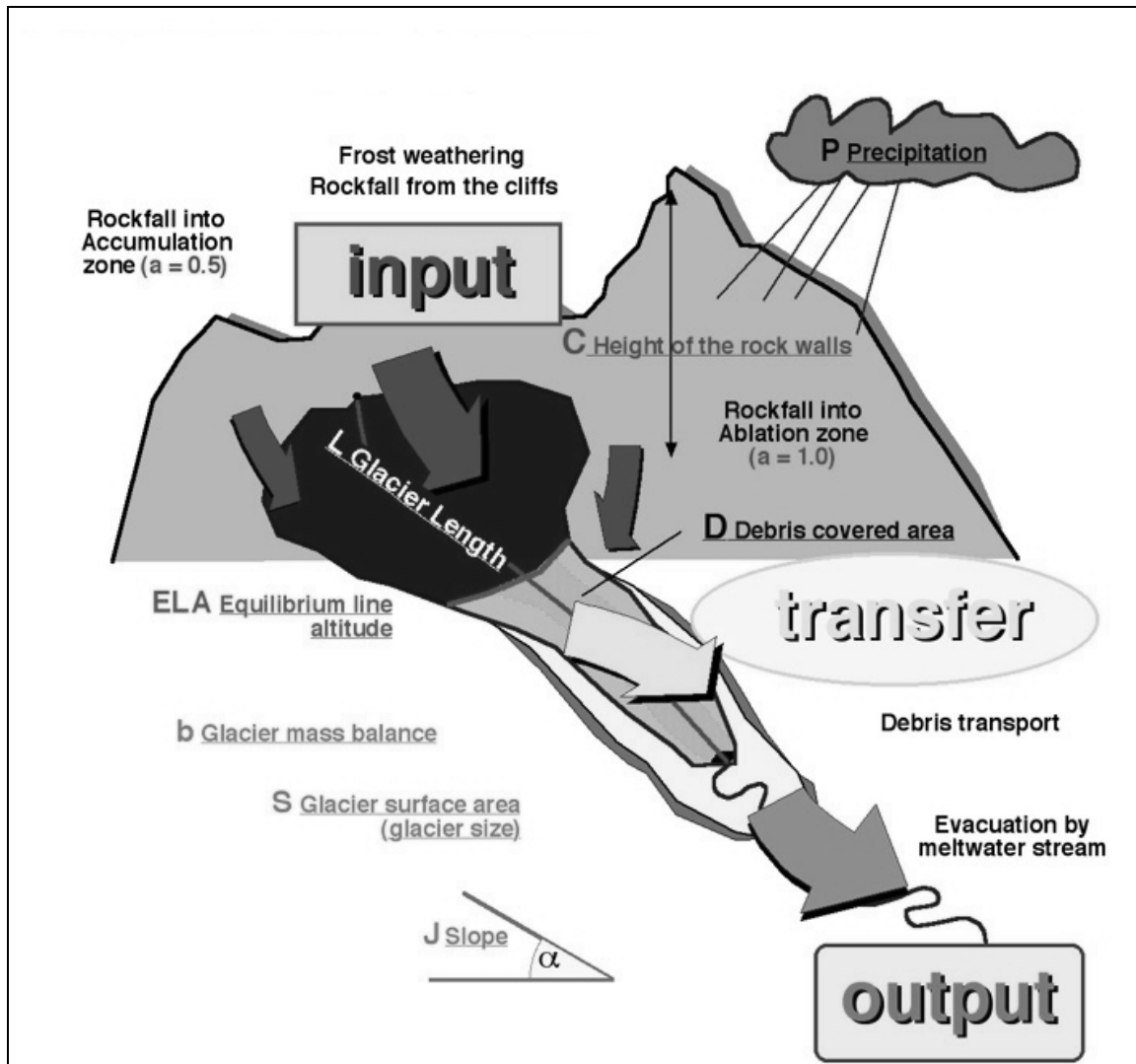


Fig. 1. Scheme explaining the erosion-sedimentation index (I_{es}), the processes and parameters involved. Figure from MAISCH et al. (1999).

The I_{es} has been developed as a “rule of thumb” and allows a rough assessment of glacial sediment balance. WENZEL (1992) applied this approach in an unpublished investigation of glaciers in the Valais Alps, Switzerland. He used glacier inventory data, maps, aerial photographs and field observations to derive the needed I_{es} -parameters for each glacier. To validate his approach he compared his results to the debris characteristics found in the glacier forefields. MAISCH et al. (1999) tested the index with systematically classified glacier forefields from the revised Swiss Glacier Inventory. They showed that the I_{es} allows for a rough assessment of glacier bed characteristics and that the entire system of debris input, transfer and output should be considered in order to understand glacier sediment balance.

3 Parameter extraction

For an integration of the I_{es} into a GIS-based approach, methods to extract the needed I_{es} -parameters from DEM have been developed. The methods are based on a hierarchical system for the extraction of geomorphometric parameters and objects presented by SCHMIDT & DIKAU (1999) (Fig. 2). The system is based on the extraction of primary geomorphometric

parameters. In a second step these parameters are analysed to derive geomorphometric objects. These objects are the basis of a hierarchical system consisting of object analysis and object aggregation leading to representative geomorphometric parameters and geomorphometric objects of a higher scale.

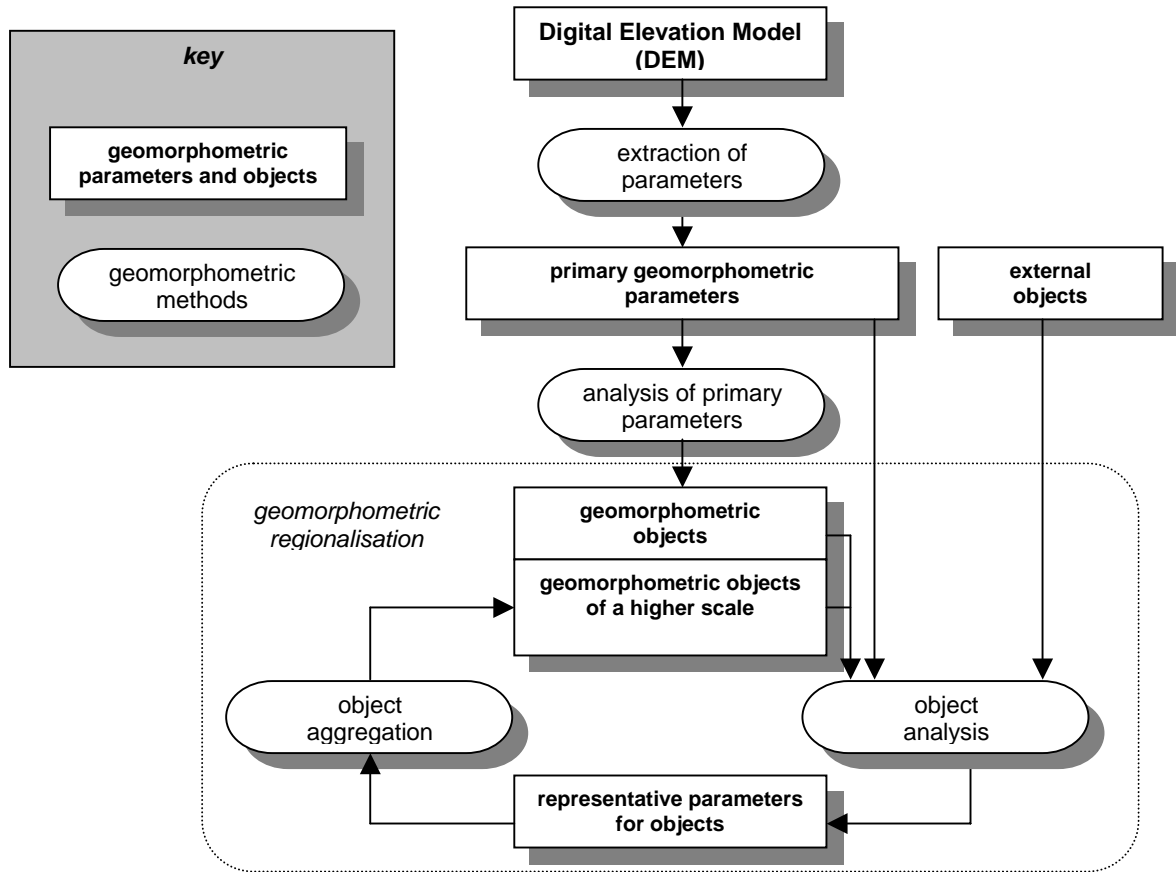


Fig. 2. System of methods for the extraction of geomorphometric parameters and objects (slightly modified after SCHMIDT & DIKAU 1999).

For the I_{es} -parameter extraction, a digital elevation model (DEM25) with a resolution of 25 meters, digital Alpine precipitation climatology 1971-1990 (FREI & SCHÄR 1998, SCHWARB et al. 2001), digitised glacier outlines from 1973 (GLACIER1973) and central flowlines from 1850 (CFL1850) from the new Swiss glacier inventory SGI2000 (KÄÄB et al. 2002, PAUL et al. 2002) were used. The methods were developed in ArcGIS 8.x Desktop and Workstation.

In the following paragraphs a description of the I_{es} -parameter extraction is given.

Glacier surface area and glacier length

Glacier surface areas S and glacier length L can be derived from the shape of GLACIER1973 and CFL1850. Both were digitised (see PAUL et al. 2002 for details) from original topographic maps (scale 1:25'000) of the Swiss Glacier Inventory 1973 (MÜLLER et al. 1976) and reconstructions of the 1850 outlines (MAISCH et al. 2000). Glacier length and the length of the glacier forefield results from clipping GLACIER1973 with CFL1850.

Slope of the melt water stream

The slope of the melt water stream J can be extracted from the DEM25. Therefore the mean slope is computed over the length of the glacier forefield and the same distance within the GLACIER1973 along the CFL1850.

Mean height of debris-providing cliffs

For the extraction of rock walls, slopes derived from DEM25 were compared to the rock wall signature in topographic maps, scale 1:25'000 (from the Swiss Federal Office of Topography). Rock wall classifications with different slope angle thresholds were validated with digitised rock wall signatures within a high Alpine test area. Thereby, glacierised areas were considered as non-rock wall cells independent of their slope. Fig. 3 shows the results for slope angle thresholds between 20° and 62°. Cells with a slope angle greater than the threshold are classified as rock wall. Correct classification, i.e. rock wall cells within and non-rock wall cells outside digitised rock wall signatures, reaches its maximum at a threshold of 36°. The percentage of classified rock wall cells outside rock wall signatures (i.e. the error of commission) decreases and the percentage of classified non-rock wall cells inside rock wall signatures (i.e. error of omission) increases with steeper slope angle thresholds. The point of intersection of the two errors is around 34°. Therefore, we classified slopes equal or steeper than 34° as rock walls.

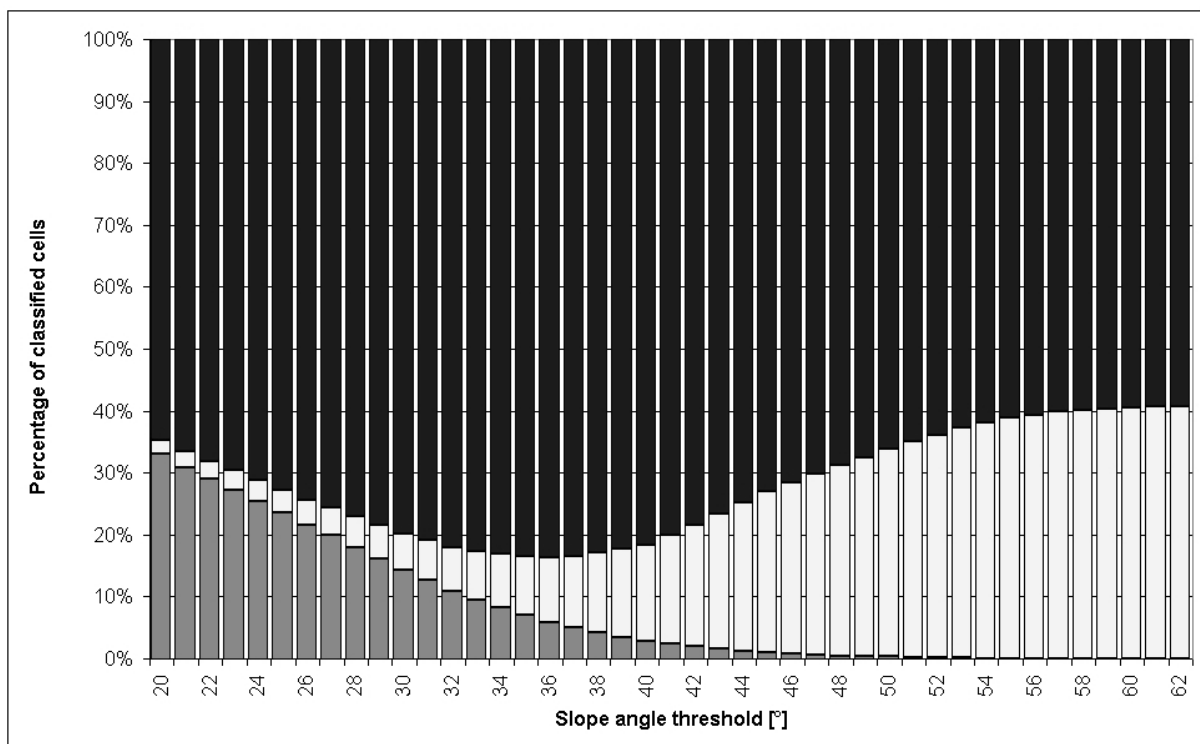


Fig. 3. Percentage of correctly and wrongly classified rock wall cells in dependence of the slope angle threshold. Correctly classified cells (i.e. rock wall cells within and non-rock wall cells outside rock wall signatures) in black, error of commission (i.e. rock wall cells outside rock wall signatures) in grey and error of omission (i.e. non-rock wall cells inside rock wall signatures) in light grey.

Within each glacier's hydrological basin a rock-fall model allows the selection of all the rock walls that are responsible for the debris input onto the glacier. Therefore, we applied the shadow angle model from EVANS & HUNGR (1993), which uses a critical angle between lowermost rockfall starting point and lowermost point of the deposition zone. We combined this model with a cell-based hydrological flowpath-model to calculate for each cell the horizontal distance Δh and vertical distance Δv to its closest rock wall cell along the flowpath. The minimum shadow angle β (i.e. the estimation of the maximum travel distance of the rockfall) can then be computed as:

$$\tan(\beta) = \frac{\Delta v}{\Delta h} \quad (2)$$

From 21 investigated rockfall events in Germany and Austria, MEISSL (1998: 57-65) found a range of shadow angles between 21° and 40° with a mean of 30.5° . Thus, we used a minimum shadow angle of 30° to determine the maximum travel distance of potential rockfall. Fig. 4 shows an example of the modelled potential rockfall within the investigated area.

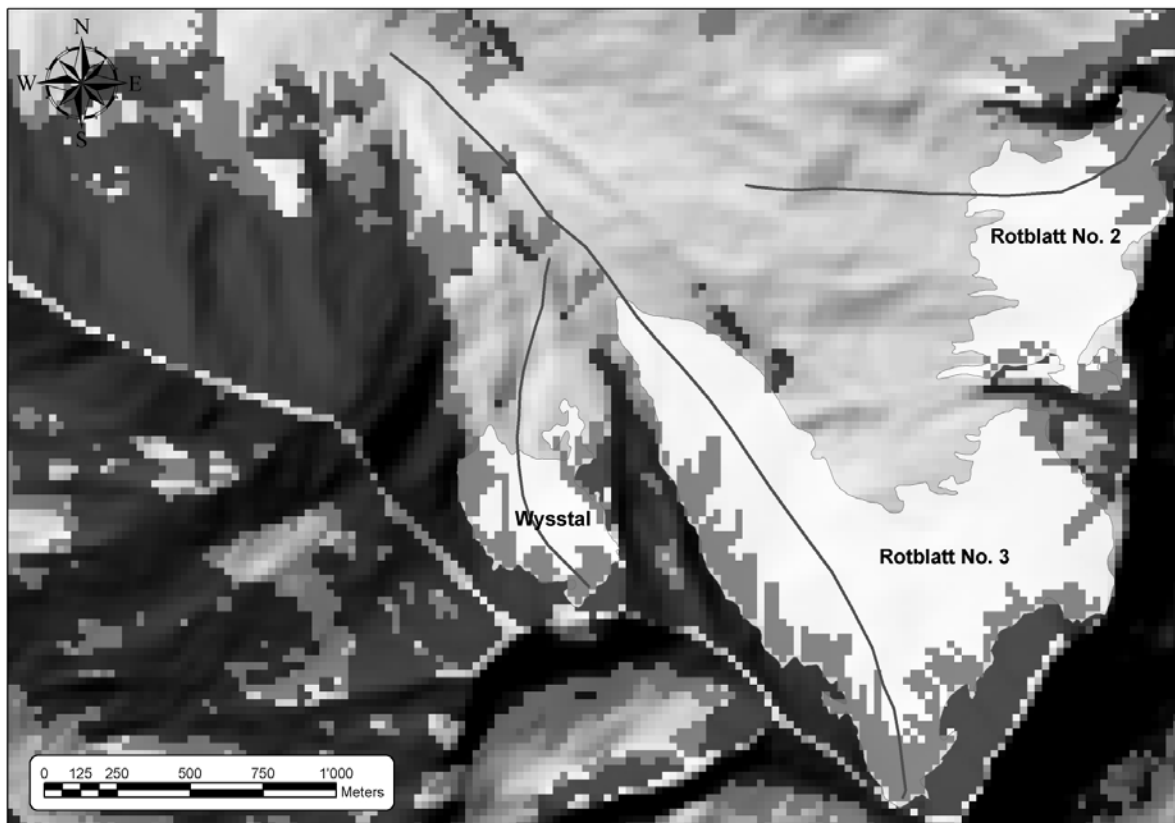


Fig. 4: Modelled rockfall within the area of Wysstal, Rotblatt No. 3 and Rotblatt No. 2. glaciers from 1973 (white polygons), central flowlines from 1850 (black lines), rock walls in dark grey and potential rockfall cells in grey. Hillshading derived from the DEM25 © 2003 swisstopo (BA035816).

The potential rockfall cells within the glacier allow to determine the corresponding rockfall sections. Hence, the area-weighted mean height of debris-providing rockfall sections, corresponding to the index parameter C , can then be calculated. Fig. 5 summarises the extraction of the parameter C from a DEM.

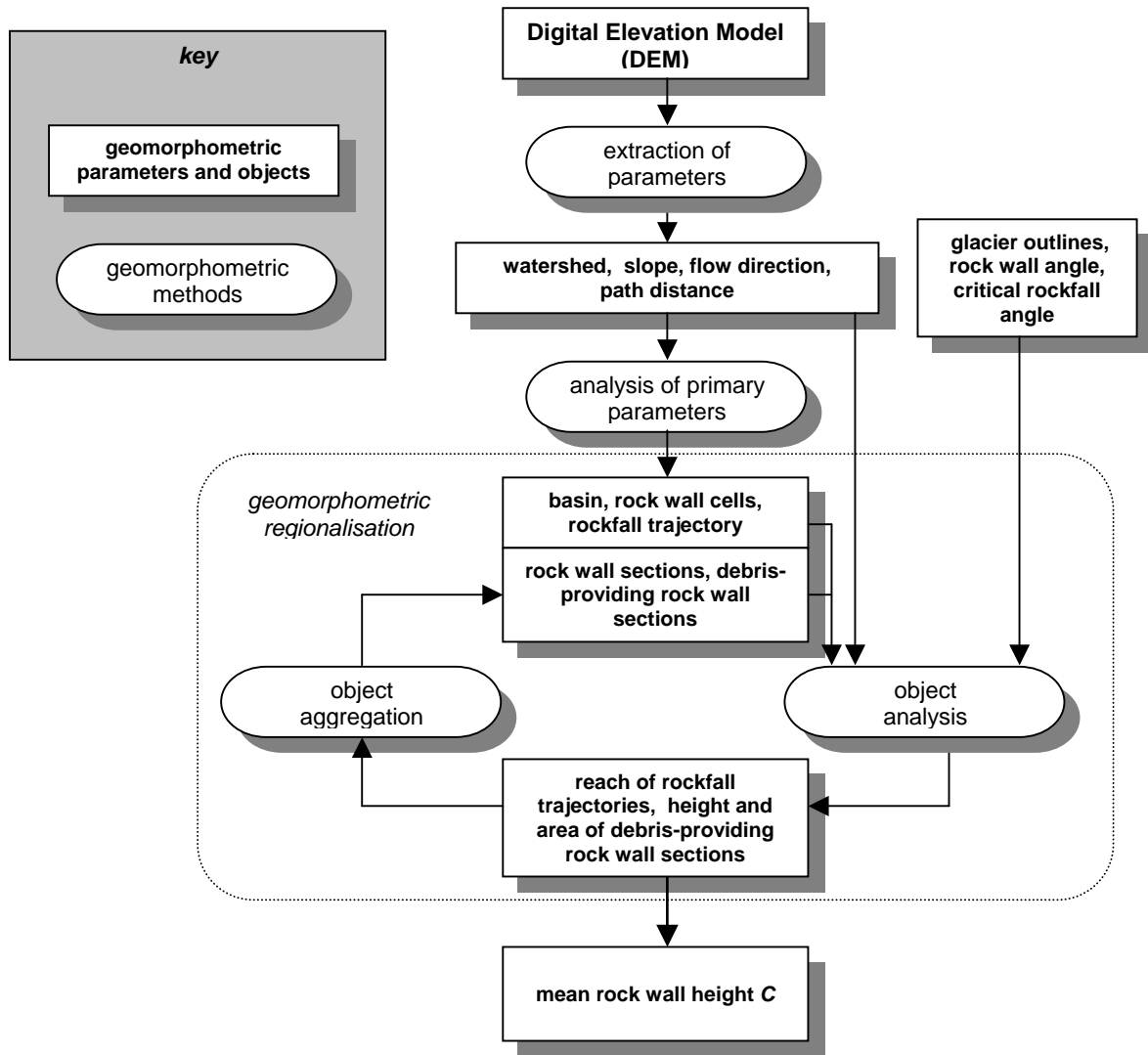


Fig. 5. Scheme explaining the extraction of the mean height of a glacier's debris-providing cliffs, corresponding to the I_{es} -parameter C . The extraction is based on the hierarchical system for the extraction of geomorphometric parameters and objects presented by SCHMIDT & DIKAU (1999), illustrated in Fig. 2.

Factor a

To extract factor a , the equilibrium line altitude (ELA) is used. The ELA is often estimated by an accumulation area ration (AAR) of 0.67 (e.g. MAISCH et al. 2000), i.e. for a steady-state Alpine glacier the accumulation area can be roughly approximated to be twice as large as the ablation area. Thus, the ELA can be computed by extracting the glacier hypsography from GLACIER1973 and DEM25.

Once having determined the glacier's ELA, factor a is set by analysing rockfall cells within accumulation and ablation area. Rockfall cells weighted with the area of the corresponding rock wall section are counted. If this sum within the accumulation area is larger than the corresponding one within the ablation area, a is set to 0.5, otherwise a is set to 1.

Annual precipitation

Mean annual precipitation P was derived from the Alpine precipitation climatology (1971-1990) by FREI & SCHÄR (1998) and SCHWARB et al. (2001) with a resolution of 2 kilometres. For each glacier the zonal mean of the annual precipitation was calculated from this digital dataset and GLACIER1973.

Annual glacier mass balance

Steady-state conditions for glaciers were considered. Therefore, annual glacier mass balance b was set to zero.

4 Results

Automation

The GIS-based parameter extraction was automated as AML-routine for ArcInfo 8 and tested on 84 glaciers in the investigation area in the Valais Alps, Switzerland. Using the DEM25, the digital precipitation dataset, GLACIER1973 and CFL1850 as input data, the AML-routine calculates the I_{es} -parameters. The used AML-routine was developed with ArcInfo Workstation 8.0.1 and was successfully tested with ArcInfo Workstation versions 8.0.2, 8.1, 8.2 and 8.3. Fig. 6 shows the resulting indexation of the 84 glaciers, classified from rocky beds towards sedimentary beds.

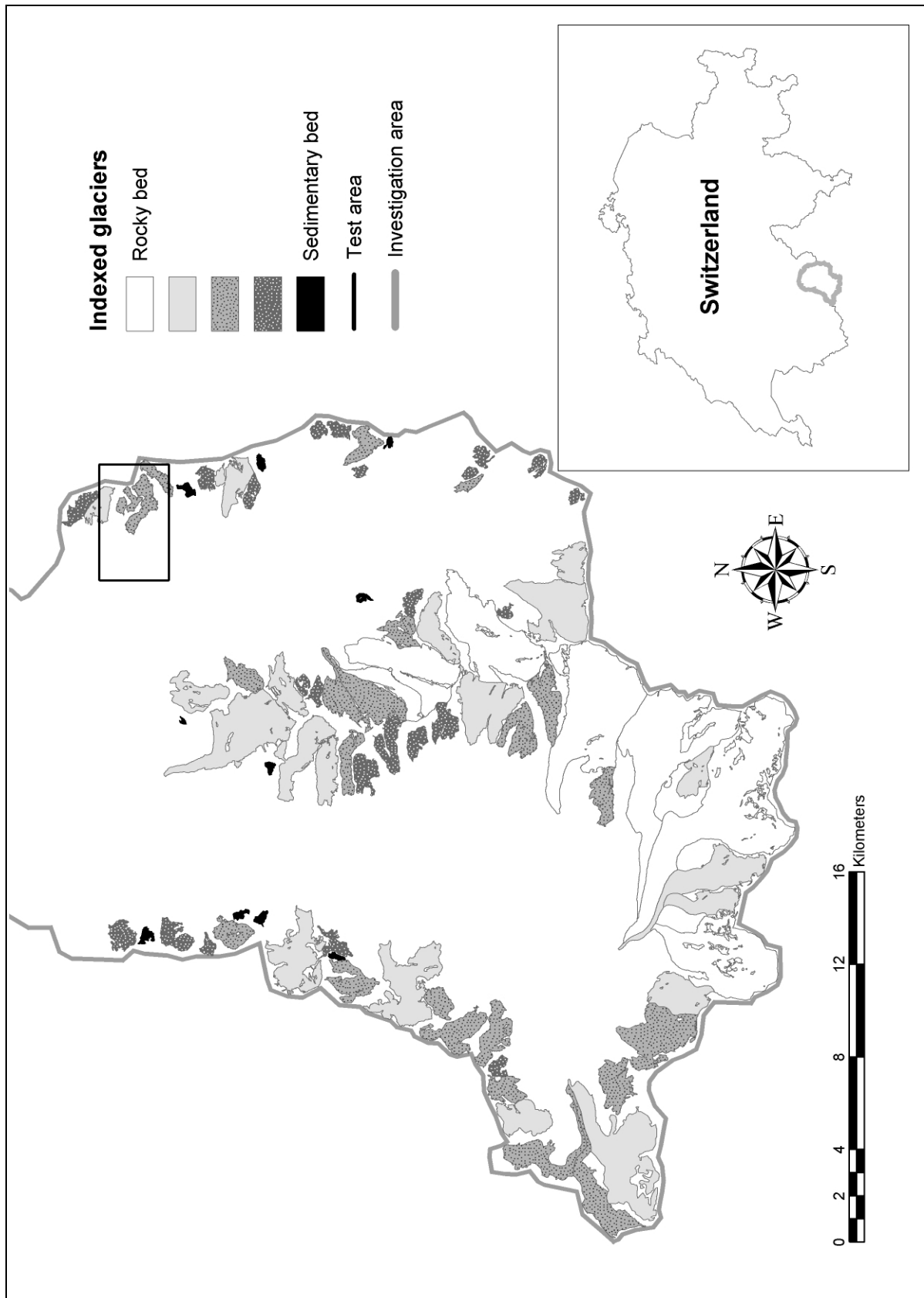


Fig. 6. Indexed glaciers in the Valais Alps, Switzerland. Indexed glaciers are shown in five classes going from rocky beds (white) towards sedimentary beds (black). The grey polygon marks the investigation area within Switzerland, the black square shows the test area where the rock wall modelling has been calibrated.

Validation

In the investigation area (Fig. 6) unpublished, manual glacier-by-glacier analyses were carried out by WENZEL (1992). He derived the index parameters from glacier inventory data, maps, aerial photography and field observations. In addition to these index calculations, he used aerial photography and field observations to assign glacier forefields to classes of rocky, mixed or sedimentary forefields. The results from this analysis served as ground truth. From the 84 investigated glaciers, 64 glaciers could directly be compared with the ones investigated by WENZEL (1992). For 20 glaciers WENZEL (1992) did not use the same glacier outlines, so the corresponding glaciers could not directly be compared. The results from the GIS-based approach were compared with the forefield classification (Fig. 7 and Table 1) and the manual index calculation by WENZEL (1992) (Fig. 8 and Table 2). For these comparisons the glaciers were classified into rocky, mixed and sedimentary beds, based on the GIS-based indexation.

A classification error matrix (LILLESAND & KIEFER, eds., 1994: 612-618) was used to validate the predicted glacier bed characteristics of the GIS-based approach. An error matrix compares, on a category-by-category basis, the relationship between known reference data (i.e. ground truth) and the corresponding results of an automated classification.

GIS-based approach versus forefield classification

The comparison of the results from the GIS-based approach with the forefield classification (Table 1) shows an overall accuracy of 61%, i.e. for 39 glaciers there is a total agreement between index and forefield classification. For 31% of the investigated glaciers there is a difference of 1 class. For 8% of the glaciers the GIS-based approach predicts the opposite of what can be found in the glacier forefield. Predicted rocky beds do have the highest user's accuracy with 82%, which means that 82% of the glaciers with a predicted rocky bed also have a rocky forefield. However, producer's accuracy of rocky forefields is only 41%, signifying that only 41% of glaciers with a rocky forefield are classified as having a rocky bed. Sedimentary forefields have the highest producer's accuracy (75%). WENZEL (1992) found for the comparison of his manually indexed glaciers with the classified forefields an overall accuracy of 59%.

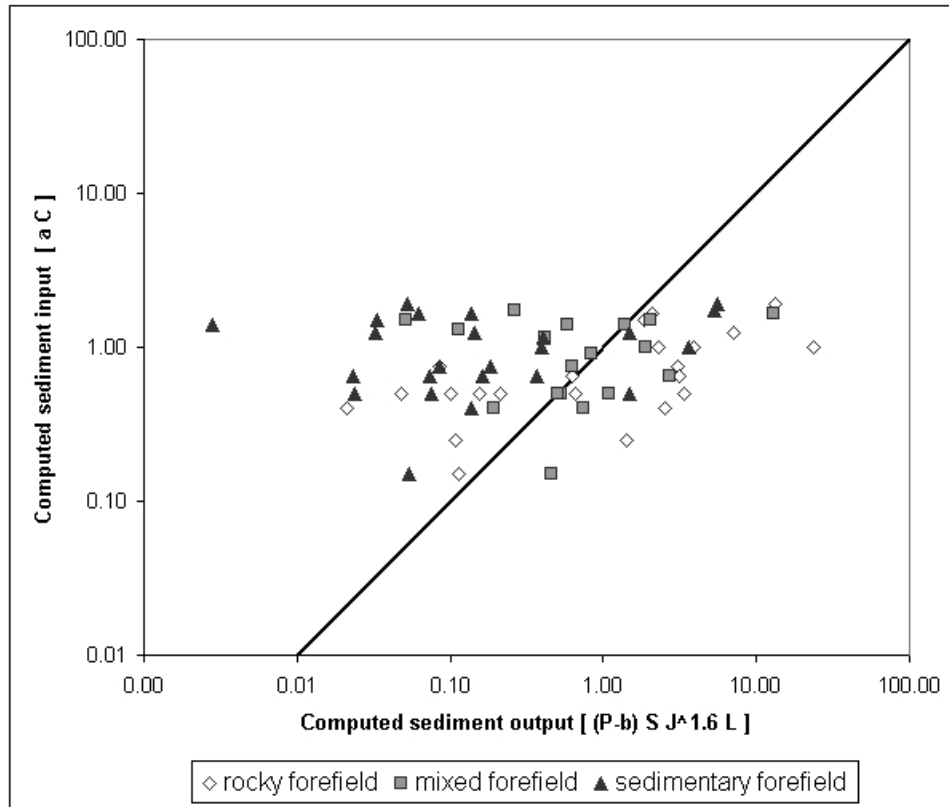


Fig. 7. GIS-based index from this study compared to the forefield classification by WENZEL (1992) from in-situ and aerial photo interpretation. The investigated glaciers are coloured depending on their forefield classification. The units on the axes correspond to the computed index numerator and denominator from the GIS-based approach, in logarithmic scale. The line of equal sediment input as output is drawn in black.

Table 1. Comparison of the GIS-based approach with the forefield classification by WENZEL (1992). r = rocky bed, m = mixed bed, s = sedimentary bed. Bold numbers represent the number of glaciers of the corresponding classes.

		Forefield (WENZEL 1992)			Total	User's accuracy [%]
		r	m	s		
Predicted bed (GIS-based approach)	r	9	2	0	11	
	m	8	12	6	26	46
	s	5	4	18	27	67
Total		22	18	24	64	
Correct [%]		41	67	75	61	
Difference of 1 class [%]		36	33	25	31	
Differences of 2 classes [%]		23	0	0	8	

GIS-based approach versus manual index calculation

Comparing the indexed glaciers from the GIS-based approach with the ones from the manual approach by WENZEL (1992) (Table 2) an overall accuracy of 86% was found; there is a difference of one class for 14% of the glaciers and no glacier where the two approaches came to a contradictory result. All classes show high user's and producer's accuracies. For the rocky bed there is even a total agreement between the two approaches.

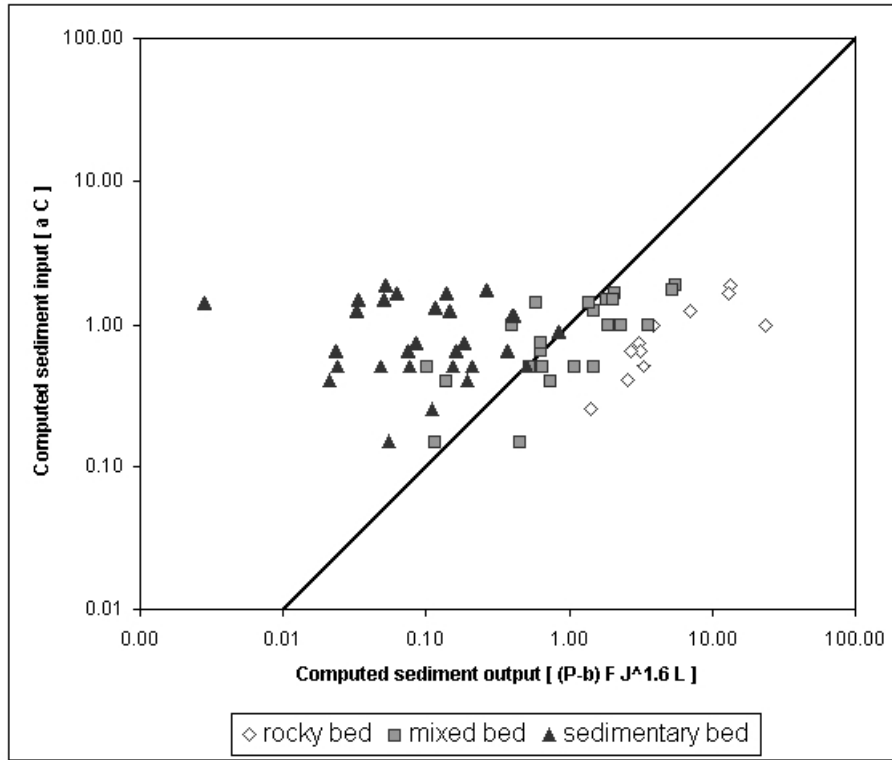


Fig. 8. GIS-based index from this study compared to the manually calculated index by WENZEL (1992). The investigated glaciers are coloured depending on their indexation by WENZEL (1992). The units on the axes correspond to the computed index numerator and denominator from the GIS-based approach, in logarithmic scale. The line of equal sediment input as output is drawn in black.

Table 2. Comparison of the GIS-based approach with the manual approach by WENZEL (1992). r = rocky bed, m = mixed bed, s = sedimentary bed. Bold numbers represent the number of glaciers of the corresponding classes.

		Predicted bed (WENZEL 1992)			Total	User's accuracy [%]	
		r	m	s			
Predicted bed (GIS-based approach)	r	11	0	0	11		100
	m	0	20	6	26		77
	s	0	3	24	27	89	
Total		11	23	30	64		
Correct [%]		100	87	80	86		
Difference of 1 class [%]		0	13	20	14		
Differences of 2 classes [%]		0	0	0	0		

5 Discussion

Methods

A qualitative analysis of the classified rock walls in the investigation area showed that the slope angle threshold of 34° achieved good results in high mountain areas, finding all important rock walls without introducing large, non-existing ones. At lower altitudes some steep areas with vegetation signature were wrongly classified as rock wall. A combination of the applied slope-based approach with a remote sensing vegetation classification (e.g. PAUL et al. 2004) should improve the results in those areas. However, the slope threshold depends on scale and quality of the used DEM and maps, and on the scope of the application. Thus, the used slope angle threshold of 34° may have to be re-evaluated when using other data or applying to other applications.

The implementation of the shadow angle approach for rockfall modelling allows, in spite of some simplifications, the determination of rock walls providing debris to the glacier. For rockfall modelling that focuses on precise run-out trajectories or hazard zones more sophisticated models might be needed (e.g. ZINGGELER et al. 1991, MEISSL 1998, or DORREN & SEIJMONSBERGEN 2003).

The use of mean cliff height C is appropriate for in-situ assessments but may be problematic when dealing with glacier parts. Comparing the index of a compound glacier with the indices of its individual tributaries, mean cliff height C may remain equal while glacier surface area S is divided into parts. This means that the indices of the glacier parts are artificially shifted towards sedimentary beds. The GIS-based approach allows a replacement of *mean cliff height C* by *rock wall area*, solving the problem of compound glaciers. Furthermore, debris-providing rock wall area is the basis for quantification of debris production. This becomes important when the index is extended to consider different rock wall lithologies with specific erosion rates.

Validation

The distribution of the forefield types and the overall accuracy of 61% (Fig. 7 and Table 1) show that the three classes of the forefield classification by WENZEL (1992) are not well represented by the computed I_{es} . Besides the fact that the I_{es} only roughly represents the forefield characteristics, there are some arguments why the comparison of the indexed glaciers from 1973 with the forefields from 1850 may not be appropriate:

- The erosion-sedimentation characteristics may have changed during glacier retreat.
- The assignment of a glacier to only one of the three classes may not be adequate, i.e. glaciers forefields often show diverse sediment characteristics.
- The same problem appears when dealing with glacier confluences.
- Glacierets and glaciers with a steep forefield may have a mixed or sedimentary bed according to the index while showing a rocky forefield in reality, because slope is too steep for debris to hold.
- Some glaciers have rocky forefields surrounded by moraines. In such cases it depends on the spatiotemporal scale if moraines should also be taken into account.

A closer analysis of the five glaciers, where the computed I_{es} predicts the opposite of what can be found in the forfields, showed that those glaciers had an area smaller than 0.4 km². Glacier size is represented twice in the index (surface area S and length L) and is the parameter with the largest range. This leads to the assumption that the I_{es} may assign very small glaciers rather to sedimentary beds and big glaciers too easily to rocky beds.

The high accuracy between the two approaches shown in Fig. 8 and Table 2 proves that the I_{es} had successfully been integrated from a manual glacier-by-glacier investigation into a fully automated GIS-based approach. The manual approach has its advantages in the interpretation and explanation of processes in the field without the need of many additional information. Experience and further background knowledge may thereby influence the setting of the parameters. The GIS-based approach forces a clear definition of each parameter which is then equally applied to all of the investigated glaciers by the AML routine. This provides an objective basis for a further scientific analysis of the results.

Besides the above mentioned correlation between the I_{es} and glacier size (surface area S and length L), the weakest point of the index is the representation of the debris-providing processes only through cliff height C . Debris input into the system does not only depend on rock wall size but also on its weathering characteristics. In high mountains the latter is governed by

- temperature (freeze-thaw frequency, freezing intensity, freeze rate),
- moisture (saturation, height of water table),
- rock characteristics (tensile strength, specific surface area, porosity, hydraulic conductivity)
- and permafrost occurrence and condition

(e.g. SASS 1998, HALL et al. 2002, MATSUOKA et al. 2003, NOETZLI et al. 2003). However, the processes of frost weathering are complex and thus not easy representable by single index parameters.

The index does not take into account subglacial processes and thermal boundary conditions at the ice-bedrock interface (e.g. DREWRY 1986: 14-17.). These become important when the glacial sediment balance is not mainly governed by the periglacial debris production.

Outlook

The erosion-sedimentation index is a first step to introduce glacial sediment balance to a quantification of sedimentation storage in alpine basins (e.g. HALLET et al. 1996, SCHROTT & ADAMS 2002). Thereby, the replacement of the parameter *mean cliff height C* by *rock wall area* and the introduction of frost weathering, permafrost occurrence and thermal regime of the glacier might improve the index. Furthermore, estimations of glacial sediment balance can contribute to the finding of historical, recent or future glaciers where debris has a substantial impact on mass balance (e.g. NAKAWO et al., eds., 2000: 25-132), to automated mapping of debris-covered glaciers (e.g. PAUL et al. 2004) and to the early detection of newly exposed sediment beds in context of hazard assessment of glacier lake outbursts (e.g. HUGGEL et al. 2002).

6 Conclusions

GIS-based methods to extract the needed I_{es} -parameters from DEM have been developed and successfully automated. We propose a replacement of the *mean height* of debris-providing rock walls by its *area*, which is the more representative parameter for debris production and provides a necessary basis for a quantification of debris input. The I_{es} allows for a rough assessment of the glacial sediment balance. In order to improve the predictability of glacier-bed characteristics, a better understanding of the periglacial debris production is necessary. However, the high overall accuracy of the comparison with the manual glacier-by-glacier investigation shows the potential of using GIS-based modelling with DEM in geomorphodynamics.

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