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Gustavsson, M.; Seijmonsbergen, A.C.; Kolstrup, E.

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Structure and contents of a new geomorphological GIS database linked to a geomorphological map — With an example from Liden, central Sweden

Marcus Gustavsson [a,*], Arie C. Seijmonsbergen [b], Else Kolstrup [a]

[a] Department of Earth Sciences, Physical Geography, Uppsala University, Villavägen 16, 752 36 Sweden
[b] IBED-Physical Geography, Universiteit van Amsterdam, Nieuwe Achtergracht 166, 1018 WV, Amsterdam, The Netherlands

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Abstract

This paper presents the structure and contents of a standardised geomorphological GIS database that stores comprehensive scientific geomorphological data and constitutes the basis for processing and extracting spatial thematic data. The geodatabase contains spatial information on morphography/morphometry, hydrography, lithology, genesis, processes and age. A unique characteristic of the GIS geodatabase is that it is constructed in parallel with a new comprehensive geomorphological mapping system designed with GIS applications in mind. This close coupling enables easy digitalisation of the information from the geomorphological map into the GIS database for use in both scientific and practical applications. The selected platform, in which the geomorphological vector, raster and tabular data are stored, is the ESRI Personal geodatabase. Additional data such as an image of the original geomorphological map, DEMs or aerial orthographic images are also included in the database. The structure of the geomorphological database presented in this paper is exemplified for a study site around Liden, central Sweden.

Keywords: GIS; Geomorphological mapping; Geodatabase; Sweden

1. Introduction

For more than a hundred years geomorphological maps have been used to illustrate the spatial distribution of landforms and geomorphological processes. The first attempts only depicted selected features or processes, but starting with Gehne (in 1912) and Passarge (in 1914) geomorphological mapping continued to develop and reached its maximum attraction in the 1970s (Klimaszewski, 1990). Before the introduction of Geographical Information Systems (GIS) to geomorphology, some manual landscape analyses were complicated, time consuming and difficult to perform if many landscape elements were included. Therefore, the maps, especially applied maps, became largely based on selected expert criteria (e.g. Brunsden et al., 1975; Kienholz, 1978). In the late 1980s the use of GIS became widespread in geomorphology as the GIS-software provided a tool for handling the large spatial datasets that are needed for a full and scientifically sound representation and analysis of the landscape. In line with a geomorphological map a comprehensive GIS database should include descriptive

* Corresponding author.
E-mail address: marcus.gustavsson.72@telia.com (M. Gustavsson).

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raw-data and be designed to be used in multiple applications. Nevertheless, the development of geomorphological studies with the aid of GIS has to a large extent been towards maps or databases that focus on specific thematic and/or applied studies. In other words, the added holistic scientific potential of GIS has not been fully explored. Meanwhile, the traditional geomorphological paper maps with their scientific understanding of the landscape have hardly developed over the last decades. Instead, the use of GIS has to some extent replaced such maps with thematic digital maps that highlight a specific theme or application. The focus has thus shifted from general overviews and contexts to specific themes or problems to be solved. The use of GIS as a tool in geomorphology, however, broadens the opportunities for both research and practical applications (cf. Butler and Walsh, 1998).

At present major fields of investigation that make use of GIS in geomorphology include: 1) GIS used to construct inventories of landforms (e.g. Jakobsen, 2003; Clark et al., 2004); 2) GIS used in slope analysis and (natural) hazard zonation and management (e.g. Dai and Lee, 2002; Zerger, 2002; Pike et al., 2003; van Westen et al., 2003; Gaspar et al., 2004; Otto and Dikau, 2004; Seijmonsbergen and de Graaff, 2006); and 3) automated or supervised landscape classification from remote sensing data often in combination with Digital Elevation Models (DEMs) (Brown et al., 1998; Giles and Franklin, 1998; Bocco et al., 2001; Bartsch et al., 2002; Plaza et al., 2004; van Asselen and Seijmonsbergen, 2006). Even though some attempts to construct applied or thematic GIS databases have incorporated a wide variety of data (e.g. Gaspar et al., 2004), a general design of a geomorphological GIS database that contains structured informative data on comprehensive scientific aspects of the landscape has still not been proposed. Such a GIS database could form the basis for the extraction of thematic maps, geomorphological analyses and exchange with external databases.

Although advances have recently been made in the interpretation of remotely sensed (hyperspectral) data and high resolution elevation models (Plaza et al., 2004; van Asselen and Seijmonsbergen, 2006), a detailed assessment of landform genesis and material distribution remains complex. Therefore, remotely sensed data needs to be incorporated with field observations which remain necessary for validation of interpretations and classifications in case landforms of similar morphography consist of different materials and thus have different origin. Van Den Eeckhaut et al. (2004) illustrate the advantages of field investigations over the interpretation of aerial photographs and shaded DEMs for interpretation of geomorphological features in densely vegetated areas, and Smith et al. (2006) conclude that field-mapping using a LIDAR base map potentially provides the best mapping results.

Some geomorphological field experts still have difficulties in formulating their knowledge into decision rules that are needed in GIS based modelling. Consequently, GIS based methods are often applied by GIS-experts rather than geomorphological experts. The importance of this gap is emphasized by van Westen et al. (2003), who increased the accuracy of natural hazard susceptibility maps from 52% to 76% by adding information from a detailed geomorphological map to the GIS analysis. van Westen et al. (2003) also noticed that many symbol-based geomorphological mapping systems such as those developed by Brunsden et al. (1975), Kienholz (1978), Cantuni et al. (1987) and de Graaff et al. (1987) cannot be easily used in a GIS because these maps need to be transformed into classified polygon maps before digitalisation. Yet, if expert-based conversion rules could be formulated, the information in these classic geomorphological maps could be transferred into functional geomorphological GIS databases, which can then form the basis for further GIS-based analyses.

In this paper we present a standardised geomorphological GIS database developed in parallel with a new "traditional" geomorphological mapping system (Gustavsson et al., 2006), which is designed to be suitable for digitalisation. Therefore the transformation from the "analogue" information presented in the geomorphological map to useful digital geomorphological GIS datasets is easily performed. In this way a direct relation between geomorphological expert knowledge and new GIS tools is enabled.

In the following the system is presented and exemplified by a standardised geomorphological GIS database that is suitable for both scientific and practical applications. A detailed geomorphological inventory of the Liden area in central Sweden (Fig. 1) exemplifies how the information of a classic geomorphological map (morphography/morphometry, hydrography, lithology, genesis, processes and age) can be transferred and organized into an ESRI Personal geodatabase.

2. Design, structure and content of the geomorphological GIS database

For the new geomorphological GIS database, the ESRI ArcGIS® desktop environment (Arctur and Zeiler, 2004) was selected. The desktop database (ArcGIS®, Personal geodatabase) presented in this paper, can easily

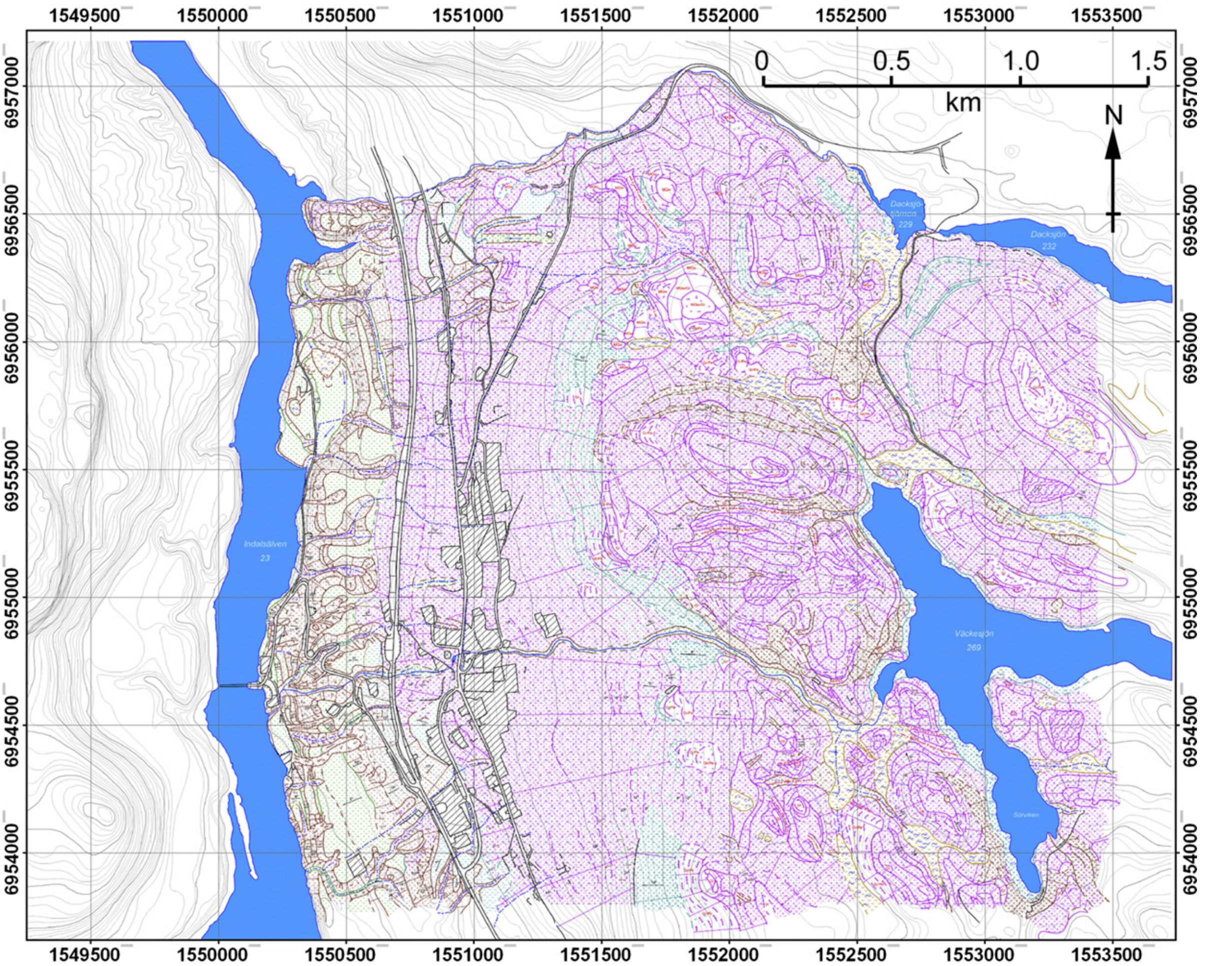

Fig. 1. The geomorphological map Liden E (east) mapped at 1:5,000 scale. The grid is the Swedish RT90 2.5 W in which the coordinates are presented in meters (distances from Equator and relation to a mean median respectively). The village Liden can be seen as the shaded area near the centre of the map (c. 62°43′N, 16°48′E). A brief description of the mapped area is given in Section 3.1. The 5 m interval contour lines are reproduced with permission I 2006/1599, © Lantmäteriverket Gävle. For a complete legend see Gustavsson et al., 2006.

be converted into a server geodatabase (e.g. ArcSDE®, Multiuser geodatabase) that can store a larger amount of data and be available for use and editing by an entire workgroup (Longley et al., 2005).

The first step in the construction of a geomorphological database is implementing a geodatabase design scheme. Such a scheme will contain different types of information. In the present case they are grouped into five main datasets: 1) a geomorphological feature dataset derived from the geomorphological map; 2) a hydrographical feature dataset also derived from the geomorphological map; 3) a geological feature dataset; 4) other feature classes and non-spatial tables inside the geodatabase; and 5) additional data connected to the geodatabase. These datasets are stored in different data formats, inside the geodatabase or connected to it. An overview scheme is presented in Fig. 2a, which will be referred to when further outlining individual methodological steps and in discussions on feature classes.

2.1. Transfer of the basic geomorphological map into a GIS geodatabase

The decision on how to transfer the information of the analogue geomorphological map into the digital geodatabase is a crucial step. Since most landscapes record long histories of changing climates, processes and land use, it is likely that they contain inherited, relict landforms in addition to presently active geomorphological systems (Cammeraat, 2002). Therefore a definition of uniform landscape units with comparable present and inherited internal properties is essential to facilitate structured storage and processing of the geomorphological data. Three steps are followed here: 1) element

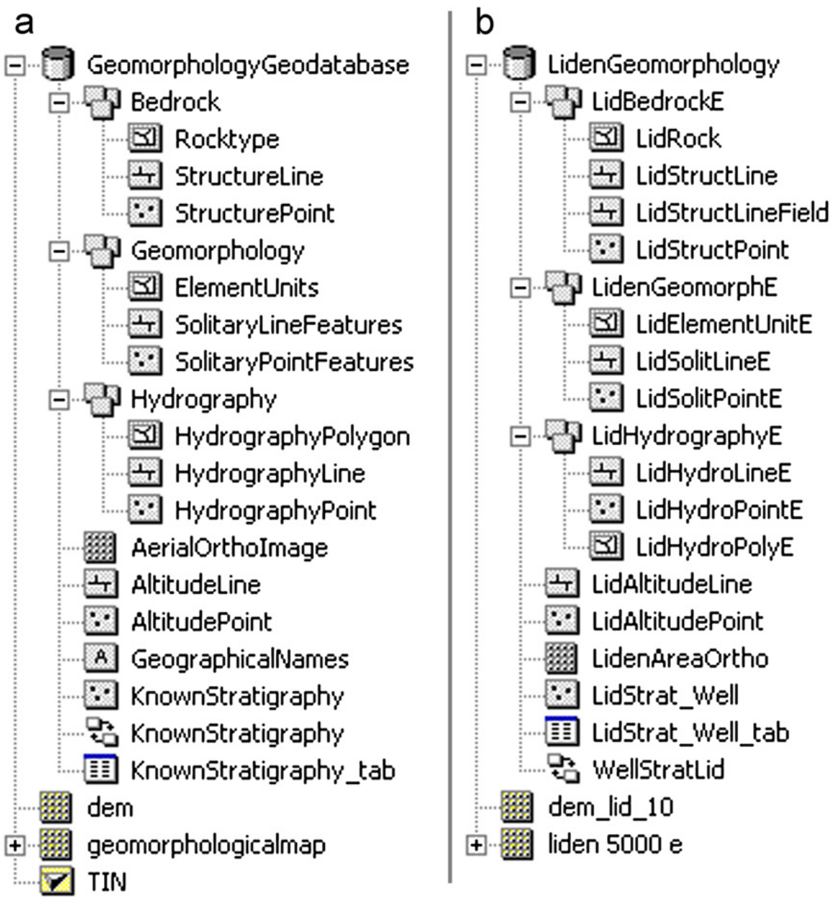

Fig. 2. Structure of the geomorphological GIS geodatabase. a) A hypothetical geomorphological geodatabase, b) structure of the geomorphological geodatabase LidenGeomorphology exemplified in this paper.

unit definition; 2) addition of attribute data; and 3) data base structuring and expansion.

In step 1, the information in the original geomorphological map is transferred into digital objects (points, lines and polygons) based on qualitative and quantitative geomorphological characteristics (i.e. morphography, lithology, genesis, processes and age). Here, the open structure and data separation of the new mapping system reveals its advantage because geomorphological characteristics can be studied individually (see also Gustavsson et al., 2006). Since the mapping system is partly based on the Landform Element Model defined by Speight (1974), coherent units formed in this way are named element units. An important decision with this step is to decide whether the geomorphological data is stored in raster or vector format, or both. For detailed discussions on the use of data format see e.g. Batten (2001), Arrell (2002), Heywood et al. (2002), Clarke (2003) and Gaspar et al. (2004). In step 2 the qualitative and quantitative geomorphological characteristics of the units are added as tabular attribute information linked to the vector information as attribute data. Step 3 involves the addition of external information including metadata (describing source, scale, errors, and other qualities) and organisation of data in the geomorphological GIS database (Fig. 3).

In the original geomorphological map of Gustavsson et al. (2006) the information is based on elementary characteristics (morphography/morphometry, lithology, hydrography, processes/genesis and age) that are presented separately, which eases the construction of element units. The units can then be digitalised into vector data which are stored in datasets that can be handled in the GIS. The reason for choosing vector data is the better representation of morphography and the advantage of relating several attribute data to the same vector object. The main geomorphological information in the database is thus stored as codes in attribute data tables related to the vector objects. The codes used in the attribute tables are presented in Appendix A. The procedure of transferring the traditional map into a geodatabase is outlined in Fig. 3.

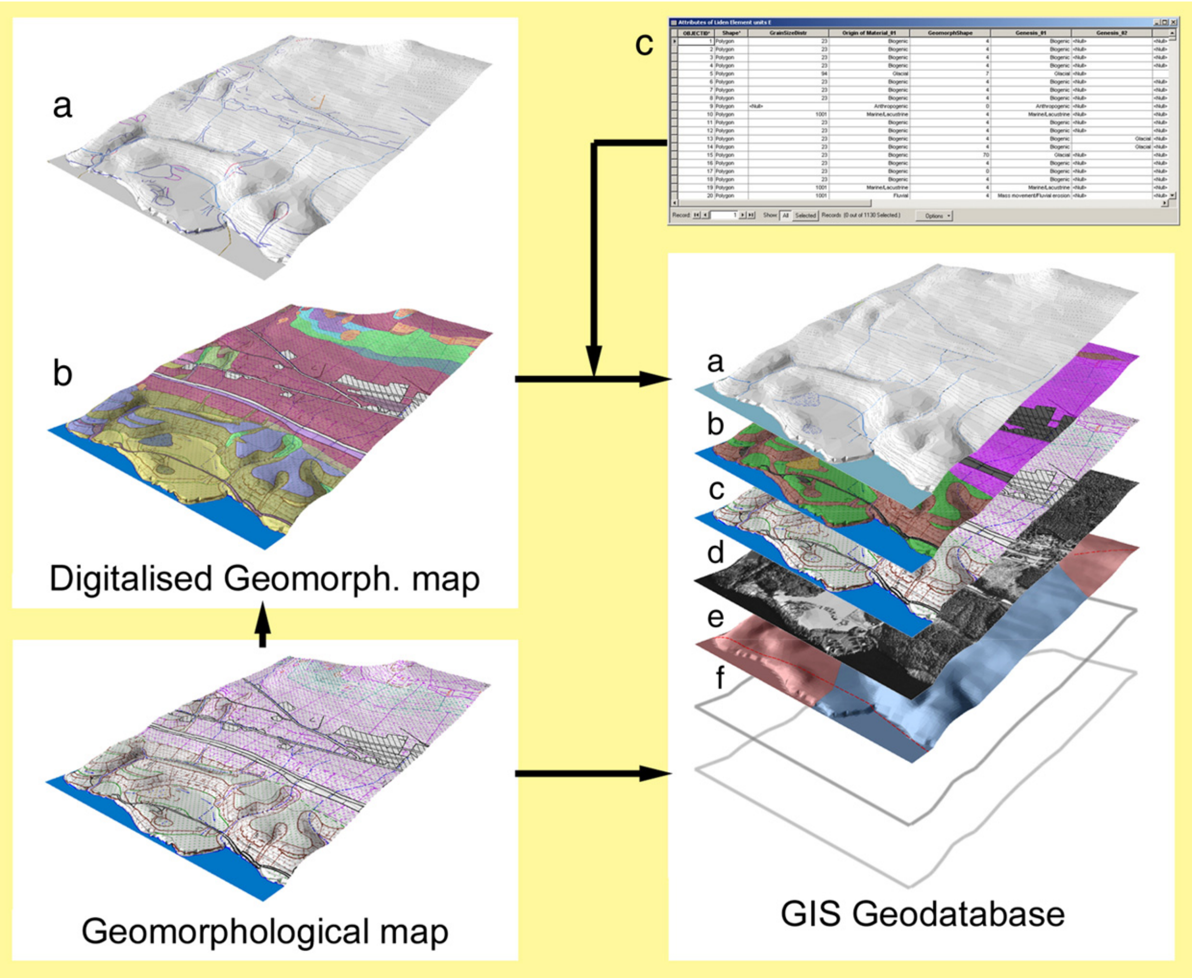

Fig. 3. Transfer process of the traditional geomorphological map (lower left) into the object based digital version of points and lines (a) and polygons (b). Tabular data (c) are related to the vector objects, and they are integrated into the geodatabase. In the GIS geodatabase the geomorphological vector datasets (a and b) can easily be combined with other spatial data such as the scanned geomorphological map (c), an aerial orthographic image (d), bedrock information (e) and can be supplemented with any other additional data (f). The 5 m interval contour lines and orthographic image are reproduced with permission I 2006/1599, © Lantmäteriverket Gävle.

2.2. The geodatabase structure

The geomorphological GIS database is composed of two basic types of components: 1) feature classes that store spatially related data; and 2) non-spatial tables in which tabular data is stored. Feature classes can be stored into thematically based feature datasets. This has the advantage that topological relations can be constructed between the incorporated feature classes and management of the data is more efficient. Most of the digitalised information of the traditional geomorphological map is stored in the two feature datasets Geomorphology and Hydrography (given alphabetically in Fig. 2a). A feature dataset Bedrock that holds information on rock types and structure is also added. When relevant, other stand-alone feature classes can be added, for example contour lines and place names. Non-spatial tables related to feature classes in the geodatabase can be used to store more data, for example, known stratigraphy (cf. Gustavsson et al., 2006).

Most basic information in the geomorphological GIS database is transferred from the original geomorphological map, but data from other sources can also be imported. In this way the mapped area can be completely described. Owing to the possibility that imported data might have been collected at different spatial/temporal scales and for different purposes it is important to keep these separated from the "original data" derived from the geomorphological map. The following sections will explain the structure of data incorporated in the geodatabase in more detail. Obviously, the structure will differ in details depending on the available data (see Fig. 2).

2.2.1. Geomorphology feature dataset

Owing to the fact that most of the digitalised information of the traditional geomorphological map is stored in the two feature datasets Geomorphology and Hydrography in Fig. 2a, these are dealt with first below. The feature dataset Geomorphology contains three feature classes (ElementUnits, SolitaryLineFeatures, and SolitaryPointFeatures) that store digitalised information from the original map legend (cf. Gustavsson et al., 2006). The polygon feature class ElementUnits stores converted information on morphography, lithology, processes and genesis. The polygons in this feature class are hierarchally defined by: 1) geomorphological boundaries in the original legend (Gustavsson et al., 2006); 2) lithology; 3) morphography/morphometry (including gradient and aspect of slope); 4) processes; and 5) forms too small to map at scale (for further description of these terms see Gustavsson et al., 2006). Features without enclosing outlines, such as niches and river channels, in the original map are “closed” to become polygons and were digitalised as separate element units. Symbols describing processes are integrated in the element units that surround them. Exceptions to this include small slides that can be digitalised as separate element units. Also clusters or rows of symbols like V-shaped grooves and undulations on slopes in the original legend can form separate element units. An example of how the digitalisation of element units is applied is given in Section 3.2 and Fig. 4.

The geomorphological characteristics of the digitalised element units are stored as coded information in the attribute table (Table 1a) connected to the feature class Element units. For the description of unconsolidated materials a special coding system is used. This code is based on grain size distribution presented by products of prime numbers where each prime number expresses a specific grain size (based on SGF81: Karlsson and Hansbo, 1992) (Appendix A). To keep the products relatively low, prime numbers have been added to express commonly found diamictons, for example to distinguish tills with different surface boulder frequencies (Karlsson and Hansbo, 1992). For example, a normal till (code: 47) covered by a thin layer (<0.5 m) of peat (code: 23), can be described by a unique product (1081). Unfortunately, the stratification succession cannot be given in this way, but it can instead be given as known stratigraphy (see Section 2.2.4).

In some erosional landforms and in some landforms influenced by human activity, the form and the materials are not always the result of the same single genesis. In the traditional geomorphological map (Gustavsson et al., 2006) this is shown by one process/genesis colour for the outline of the landform, and another colour for the origin of the sediment. In the geodatabase this genetic

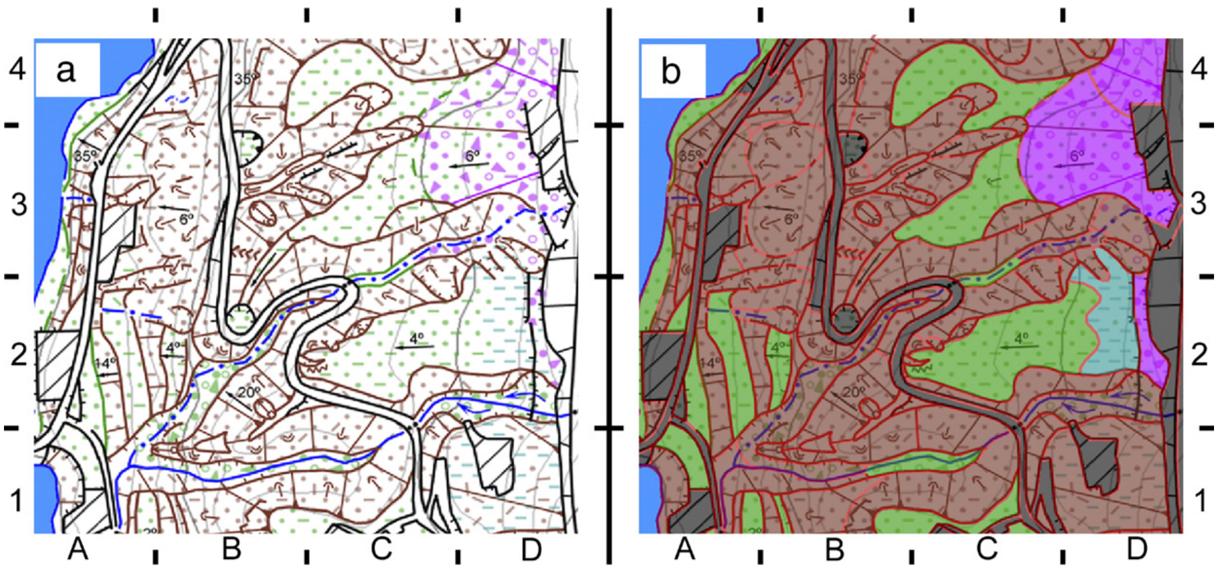

Fig. 4. A comparison between the original geomorphological map (a) and the converted polygons (element units) of the combined feature classes LidElementUnitE and LidHydroPolyE (b). The polygons are delineated with red lines and the colour fill representing the attribute data Genesis has been made transparent to enable the view of the backdrop geomorphological map. The 5 m interval contour lines are reproduced with permission I 2006/1599, © Lantmäteriverket Gävle.

Table 1
Schematic attribute tables to the feature classes: a) element units; b) solitary line features; and c) solitary point features

a) Element units

Grain size distribution	Origin of material 1, 2, *n*…	Genesis 1, 2, *n*…	GeomorphShape	Process 1, 2, *n*…	Name	Remarks	…
Grain size code	Genesis code	Genesis code	GeomorphShape code	Process code			

b) Solitary line features

Type	Genesis	…
Type code	Genesis code	

c) Solitary point features

Type	Direction	Length	Width	Depth	…
Type code	1–360°	m	m	m	

In relation to this the length and area (when possible) of the objects are automatically calculated and stored in the attribute table.
Codes are presented in Appendix A.

information on form and sediment has been stored separately. The term "Genesis" has been kept to express the origin of the landform, while the term "Origin of material" has been chosen to express the origin of the sediment (see Table 1a). To enable description of materials of polygenetic origin and polygenetic morphology, the attribute table can contain several columns on Origin of material and Genesis. In this case the first column describes the dominant origin/genesis, while the later columns describe origin/genesis of secondary importance. The attribute data on both Origin of material and Genesis uses the same coding (Appendix A).

Morphographical differences between element units are recognized in the attribute data GeomorphShape, which contains a simple qualitative description of the shape (Table 1a). The attribute data Process expresses the modifying process that acts upon the geomorphological element. The attribute table contains several process values (columns), of which the first expresses the most dominant process and the last expresses the least dominant one (Table 1a).

Apart from the data outlined above, which is presented as polygons, some information such as descriptive information on escarpments, narrow ridges and tensional fissures, needs to be stored as line objects in the feature class Solitary line features (Table 1b). Point data on for example known transport direction, potholes, and glacial striae is stored in Solitary point features (Table 1c). In the case of Solitary line features, we did not find a technical solution to provide these objects with information that is usable in the GIS environment so they form part of an inventory.

Information on slope breaks and morphometry were not digitalised from the traditional geomorphological map because it is still too difficult to give this any useful meaning in the GIS. Alternatively, such geometrical information might be calculated from the available digital terrain data in the geodatabase.

2.2.2. Hydrography feature dataset

The feature dataset Hydrography (Fig. 2a) has been separated into three feature classes. Data on lakes, large rivers, waterlogged areas, etc. are stored as polygons in the feature class HydrographyPolygon (Table 2a), while the line data on smaller streams are stored in HydrographyLine (Table 2b). Springs, dams and waterfalls are stored as point objects in the feature class HydrographyPoints (Table 2c). To enable the construction of a Hydro network, the digitalised streams need to be connected through lakes and other hydrographical polygon features. In a Hydro

Table 2
Schematic attribute tables to the feature classes: a) hydrography polygon; b) hydrography line; and c) hydrography point

a) Hydrography polygon

Type	Altitude	Name	…
Type code	m a.s.l. for lake surfaces		

b) Hydrography line

Stream type	Name	…
Type code		

c) Hydrography point

Type	Name	…
Type code		

In relation to this the length and area (when possible) of the objects are automatically calculated and stored in the attribute table. Type codes are presented in Appendix A.

network additional parameters such as flow direction and capacity can be stored.

2.2.3. Bedrock feature dataset

The Bedrock feature dataset illustrates one of the advantages of the GIS database. Based on available bedrock maps and geophysical data, the three feature classes, Rocktype (polygons), StructureLine and StructurePoint, stored in this feature dataset, contain more information on bedrock lithology, structure and geological age than the original geomorphological map (Fig. 2a). The attribute tables are not shown since these feature datasets often depend on the availability of external data. Examples of attribute codes are presented in Appendix A.

2.2.4. Other feature classes and non-spatial tables in the geodatabase

Some information in the original geomorphological map was digitalised as separate feature classes that are stored directly in the geodatabase proper (Fig. 2a). Attribute tables are not shown for any of these feature classes but codes can be found in Appendix A. The feature class AltitudeLine contains digitalised contour lines while the feature class AltitudePoint contains information on known point altitudes, such as summits and triangulation benchmarks. The feature class KnownStratigraphy stores locations of drill holes, exposures, field observations, etc. This feature class is related to a non-spatial table (KnownStratigraphy_tab) which stores detailed information on known stratigraphy at specific localities. The properties of their relationship are described in the Known stratigraphy relationship class (Fig. 2a). Other similar feature classes can also be linked to "pop up" features showing photographs, figures and descriptions of the stratigraphy of the locality.

Finally, annotation feature classes that store text (e.g. geographical names) or measurements that are spatially related to the features in the mapped area can be added for location purpose (see GeographicalNames in Fig. 2a).

Included in the database is the original geomorphological map. It is stored as a georectified.tif-image (geomorphologicalmap in Fig. 2a) and is connected to the geodatabase for use as a backdrop image to enhance the geomorphological understanding of the data.

2.3. Additional data connected to the geodatabase

To further broaden the use of the geomorphological GIS database, other vector and raster data sets can be added or stored outside the geodatabase. The geodatabase should preferably be connected to elevation data from which surface models can be built. In Fig. 2a, a DEM has been connected and from this a Triangular Irregular Network (TIN) has been constructed and included. Since a DEM or TIN can be constructed from digitalised contour lines and vice versa, the geodatabase only needs to include one form of altitude data, preferably the available data with the best quality.

Outside the geodatabase it is also preferable to store additional data such as aerial orthographic images, data on infrastructure and vegetation. However, a raster dataset (AerialOrthoImage) was created inside the geodatabase for easier access of the aerial orthographic images (Fig. 2a). Table 3 presents examples of data that can be connected to the geomorphological GIS database for use in various applications.

3. Scientific application of the geomorphological GIS database — the example of Liden

3.1. Field situation

The village of Liden (62°43′N, 16°48′E) is located in the Indalsälven (älv=river) valley in central Sweden (Fig. 1). From Liden to the Baltic coast to the east, the

Table 3
Examples of datasets in or connected to the geomorphological geodatabase

Vector data	Raster data	External databases
Geomorphological elements	**Geomorphological basemap**	Stratigraphy
Hydrography	DEM/DTM*	Precipitation
Bedrock data	Aerial orthographic images	Ground water
Contour lines+point altitudes*	Satellite images	Snow cover
Names		Temperature
Infrastructure		Geophysical data
		Vegetation

The datasets in bold letters form suggestions to sets that should be included as "minimum" information in a comprehensive geodatabase. Data on elevation (*) can be included either as digitalised contour lines or as a grid DEM/DTM.

valley follows a straight tectonic fracture zone, but within the Liden area, the river comes from the north where it has a course outside this tectonic zone. Geologically, the area can be divided into two lithological domains: the valley area consists of metagreywackes with dikes and small massive intrusions of granite, aplite and pegmatite. In the higher areas pegmatite, aplite and aplite granite (Härnö-granit) with dikes of pegmatite and aplite dominate. All rocks in the area belong to the late stage of the Svekofennian orogeny (1820–1850 Ma) and their bedding planes dip vertically (Lundqvist et al., 1990).

In the Late Weichselian the area was covered by the Fennoscandian ice sheet. During the deglaciation, at approximately 9800 BP (calculated from Borell and Offerberg, 1955) till and large quantities of glaciofluvial and lacustrine sediments were deposited. Along the valley floor glaciofluvial sediments formed a sub-aquatic esker that progressively became buried by a complex sequence of lacustrine silts/clays and later by silty/sandy fluvial and deltaic sediments. The deglaciation of the valley caused pressure relief along the valley slopes, which triggered intense mass movement in the steeper parts. Due to the Holocene isostatic uplift of the area, the highest former coastline today is situated at 260–270 m a.s.l., which is halfway up the valley slopes. As a consequence, the slopes in the lower part of the valley have been exposed to wave action and locally shoreline erosion features and beach deposits occur (Lundqvist, 1987). The isostatic uplift also forced the Indalsälven to incise into the thick complex sediment fills in the valley floor. This resulted in the deposition of deltaic sediments and a series of terrace remnants at different altitudes that record older and higher river plains. At the same time, mass movements, locally with bank collapse, occurred along the steep river banks. The presence of silty/sandy valley fills in combination with the continued uplift has resulted in the formation of incised channels, which locally reach the underlying till. In 1955, a water power plant was constructed further downstream with the consequence that the water level of the Indalsälven was raised and the reservoir has now a rather stable water level at 23 m a.s.l. (Blomqvist, 1970). The Liden area is a challenging case area to test the geomorphological GIS database structure and content, because it is characterized by a variety of processes, landforms, (both relict and active) and a wide variety of unconsolidated deposits as well as bedrock.

3.2. Building the Liden geomorphological GIS database

The Liden area was mapped in the field at a scale of 1:5,000 using enlarged 1:10,000 topographical maps as base maps and with additional help of a GPS device. During the final map drawing, orthographic aerial images were used in combination with contour lines in a digital drawing environment. The final geomorphological map was imported into the GIS software as a georectified.tif-image, for on screen digitalisation of polygons. The 1:5,000 geomorphological map of Liden E is displayed in Fig. 1.

To exemplify the element unit definition, Fig. 4 illustrates both the original 1:5,000 scale geomorphological map of Liden (left) and corresponding polygon feature classes LidElementUnitE and LidHydroPolyE (right) in which the original geomorphological map is displayed as a backdrop image. Most element units follow geomorphological boundaries according to the legend in the traditional geomorphological map (Gustavsson et al., 2006), but there are some principal exceptions. Uncertain boundaries are digitalised as certain (e.g. in A-B/3-4 of Fig. 4), and "open" features (e.g. gullies in C-D/3) have been closed. In D/2 and D/3-4, element units were delineated according to changes in lithology, and in B/4 and B/1, they were delineated to conform to changes in slope gradient. A change of dominant process along the slope in B-C/1-2 is indicated by delineation into separate element units. Slides too small to be mapped at scale (e.g. in C/2) were digitalised as separate units. A V-shaped groove, in the map described by a row of V-shaped symbols, has been enclosed as an element unit (B/3). Two polygons digitalised as part of the hydrographical information are also presented in Fig. 4. In A/3-4 a segment of a river can be seen and in A-B/4 a periodically waterlogged area has been digitalised.

In the Liden geomorphological GIS database, bedrock structure and lithological data were digitalised from the 1:200,000 bedrock map of Lundqvist et al. (1990) and stored as three feature classes in the LidBedrockE feature dataset (Fig. 2b). Information on bedrock structure derived from the traditional geomorphological map has been stored in the feature class LidStructLineField (Fig. 2b). The reason to introduce different feature classes for the data is that they originate from two different sources and were collected at different scales.

For the Liden geomorphological GIS database, the best elevation data available were the contour lines of the digital 1:10,000 topographical map downloaded from Digitala kartbiblioteket, Lantmäteriet (https://geoimager.lantmateriet.se/digibib/index_s.html). These data were imported into the GIS database in .shp-format. The contourlines were then given attribute data on altitude and modified to fit field observations for use as a source on elevation. The resulting feature class LidAltitudeLine is stored directly under the geodatabase proper

(Fig. 2b). The altitude point data (stored in LidAltitudePoint) were digitalised from two topographical maps (Ekonomisk karta över Sverige, 18G0j and 18G1j).

In the Liden geodatabase, data on Known stratigraphy have been imported from external datasets derived from the water well data archive of the Swedish Geological Survey. The locations for these point data are imported into the point feature class LidStrat_Well, which in turn is related to the table LidStrat_Well_tab that stores information on stratigraphy recorded during the drilling/digging of the wells. The properties of this relationship are stored in the WellStratLid relationship class (Fig. 2b). Since each well-ID in the feature class is related to several lines in the table, a "one to many" relationship has been chosen.

A DEM (dem_lid_10) was constructed by interpolation of the LidAltitudeLine and LidAltitudePoint data described above. To facilitate orientation and interpretation in the Liden geodatabase, two 1 m spatial resolution orthographic aerial images were downloaded from Digitala kartbiblioteket, Lantmäteriet (https://geoimager.lantmateriet.se/digibib/index_s.html). The images were imported into the database as a raster dataset (LidenAreaOrtho in Fig. 2b).

3.3. Using the Liden geomorphological GIS database

Fig. 5 shows a view of the interface of the Liden geodatabase as presented in the ESRI ArcMap™ environment. All data from the geodatabase are added, but to present a clear picture, only five data sources are "switched on" (squares checked under Layers) in the example. The attribute data table for LidenElementUnitE is open and the attribute parameters can be seen as columns, while the objects (in this case polygons) are shown as rows. The material of the selected object (484)

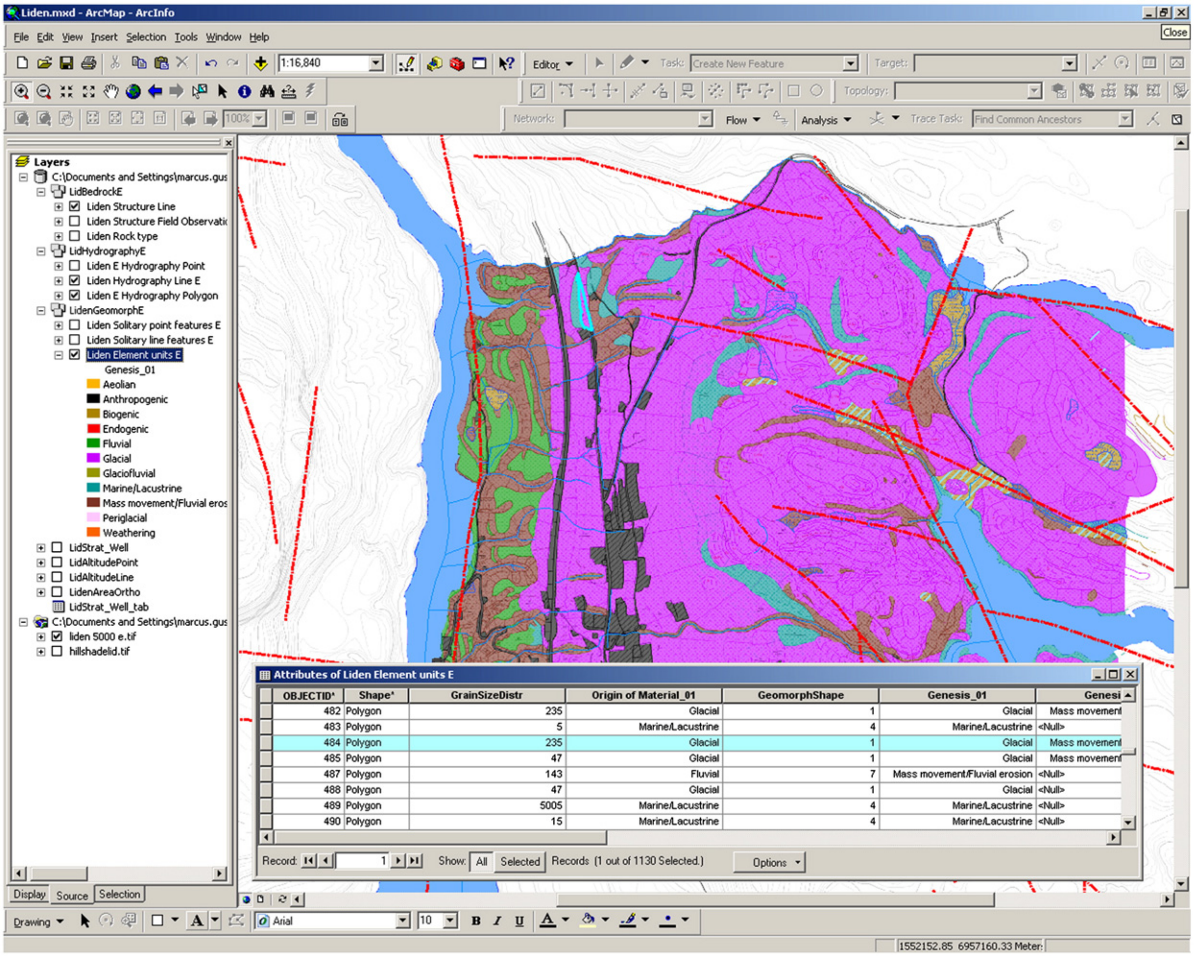

Fig. 5. A screenshot of the Liden geodatabase in the ArcMap^{TM} interface. The 5 m interval contour lines are reproduced with permission I 2006/1599, © Lantmäteriverket Gävle.

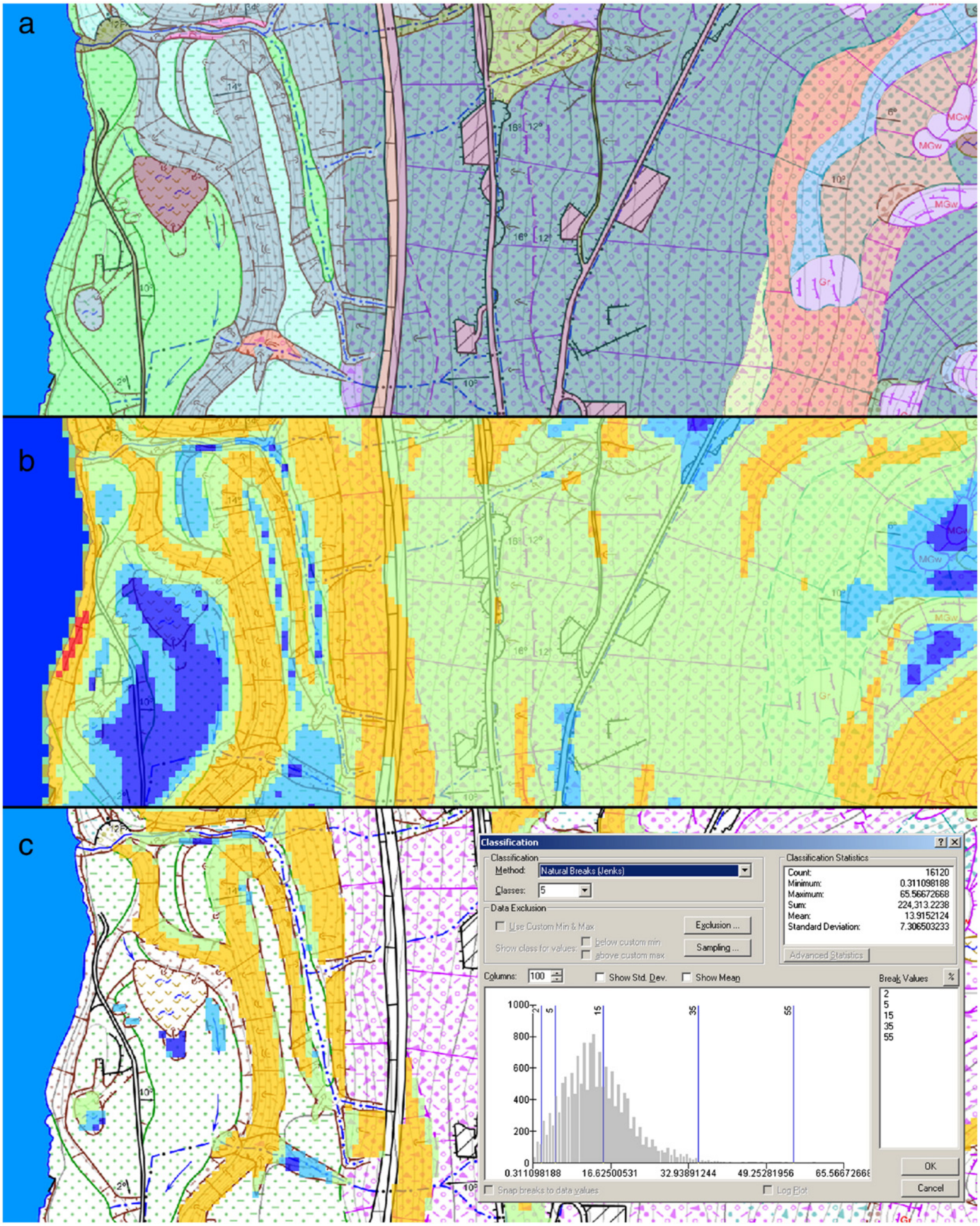

Fig. 6. Three different visualisations of the same area using the geodatabase LidenGeomorphology. a): LidElementUnitE presenting the attribute data GrainSizeDistr (i.e. grain size distributions); b): Slope gradient derived from the DEM (dem_lid_10). The pixel size is 10 m. Dark blue 0–2°, Blue 2–5°, Green 5–15°, Yellow 15–35° and Red 35–55° (the slope classification follows Demek et al., 1972); c) Slope gradient (same classification as above) in areas of presently active mass movement. The open table presents the slope statistics for the affected areas. The original geomorphological map can be seen as a backdrop image. The 5 m interval contour lines are reproduced with permission I 2006/1599, © Lantmäteriverket Gävle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

presents the grain size distribution (GrainSizeDistr) 235 (i.e. 5×47, sand×(till) normal; interpreted as a thin cover of sand over till), mainly originating from glacial activity (Origin of Material_01). The surface is a slope (GeomorphShape, 1) formed by glacial action and modified by mass movement/fluvial erosion (Genesis_01 and Genesis_02). Under Layers to the left in the open view (Fig. 5) it is shown that the information for the LidenElementUnitE currently viewed is based on the Genesis_01 attribute data. This view can easily be changed to another attribute parameter or to combinations of attribute parameters. This is the simplest way of visualising and combining the data for a feature class but more advanced processing that includes single or several datasets and external data can be performed with the toolbox incorporated in the ESRI software and by the construction of queries or models.

Fig. 6 presents examples of both basic data views (Fig. 6a) and results of easily performed analyses. An automated morphometric analysis of the DEM was performed and Fig. 6b presents the resulting slope gradients as pixels at 10×10 m. The slope raster dataset was subsequently used to analyse the effect of slope on mass movement processes indicated in the geomorphological map (Fig. 6c). The open table in Fig. 6c presents the slope statistics for the areas affected by mass movement. Notable here is the distribution of mass movement at slope gradients around 15° (Mean: 13.9°) and the sparse process activity at steeper angles. This pattern reflects the difference in material stability between silty sediments (at the valley bottom terraces) and tills (which generally make up a thin cover on bedrock in the higher, steeper parts).

4. Discussion and conclusion

The new geomorphological mapping system of Gustavsson et al. (2006) and the geomorphological GIS database that is presented in this paper have been developed in parallel. Therefore, the mapping system enables easy transition from the traditional geomorphological map into the comprehensive geomorphological GIS database. This is mainly because the basic legend separates the individual descriptive data which form the building blocks of the landscape element units used in the geomorphological GIS database.

We believe that a digital construction of landscape units can also be developed in relation to already existing traditional paper mapping systems (e.g. Kienholz, 1978; Barsch and Liedtke, 1980; de Graaff et al., 1987). As a consequence, the GIS database that is presented in this paper can be more widely applied, although the above mentioned mapping systems do not always incorporate a sufficiently detailed separation of their geomorphological legends. This means that the resulting landform units will include combined attribute data, for example, material described through genesis (e.g. a till deposit) or morphography described through genesis (e.g. an esker). This will reduce the geomorphological attributes available for analysis, and demands more complicated classifications. Another drawback is that geomorphological presentation is often based on landscape patterns instead of combinations of landscape elements (e.g. ridges vs. slopes and crests) (cf. Speight, 1974). This also limits data separation and thus the possibilities of digital landscape analysis and manipulation.

In the transformation process from the traditional map to the GIS, it turned out that some generalization was demanded and that some geomorphological information is easier to convert than other. Information on morphological elements, lithology and processes are easily transferred with the exception that uncertain borders need to be drawn as certain. The conversion of information given by, for example, escarpment lines and narrow ridges (Section 2.2.1) however turned out to be difficult, because we were not able to find a technical solution that would allow us to add useful morphographic information to these digital components.

A major advantage is the possibility to display the original geomorphological map as a backdrop image connected to the geodatabase. This helps with the orientation and the overview because it uses a legend, which enables a legible presentation of various geomorphological data at the same time, an ability that is not yet easily achieved by the GIS software. The base map also gives the advantage that uncertain borders can still be seen, an information which is useful in further analysis. The connection with a DEM in the database has many merits, e.g. it allows for the validation of slope gradients, it can offer a bird's eye view of the study area in combination with orthographic air photo's and it helps select land unit boundaries more accurately.

In summary, it can be concluded that the geomorphological geodatabase structure presented here can be successfully applied to a geomorphologically complex area. The geomorphological GIS database contains structured scientific information and allows flexible incorporation of additional thematic datasets from external databases. At the same time it is a flexible environment for management, analysis and visualisation of the geomorphological as well as the added data.

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Appendix A

Codes used in attribute tables. The codes have been chosen to make digitalization easy. As mentioned in Section 2.2.1. the Grain size codes are combined to form products describing the grain size distribution. The process codes have been based on the genesis codes following the same hundreds. For example, processes related to mass movement (genesis code 100) are spaced between 100 and 199, and weathering processes between 200 and 299 (genesis code 200). Space has also been left to extend the attribute codes to fit the purpose of any specific survey.

Gain size	
(Polygons)	
Consolidated material	0
Clay/silt	2
Clay/silt — layered	3
Sand	5
Gravel	7
Cobbles	11
Boulders	13
Large boulders	17
Blocks	19
Peat	23
Gyttja	29
Shell deposit	31
Permafrost	37
Glacier/perennial snow	41
Diamictons	
(Till), few boulders	43
(Till), normal	47
(Till), high freq. boulders	53
(Till), large boulders	59
(Till), surface washed	61

Genesis	
(Polygons)	
Endogenic	0
Mass movement/fluvial erosion	100
Weathering	200
Fluvial	300
Glaciofluvial	400
Glacial	500

Appendix A (*continued*)

Gain size	
(Polygons)	
Periglacial	600
Marine/Lacustrine	700
Aeolian	800
Biogenic	900
Anthropogenic	1000

Shape	
(Polygons)	
Modified area	0
Slope	1
Slope — undulating	2
Patterned ground	3
Even surface	4
Undulating terrain	5
V-shaped groove	6
Depression/channel	7
Crest	8
Undulating surface, level terrain	9

Solitary line feature	
(Lines)	
Escarpment (<10 m, less distinct)	10
Escarpment (<10 m, distinct)	11
Escarpment (>10 m, less distinct)	20
Escarpment (>10 m distinct)	21
Small ridge	80
Tensional fissure	90

Solitary point features	
(Points)	
Striae	10
Groove	11
Chattermark	12
Cresentic gouge	13
Whaleback	20
Roche moutonnée	21
Crag and tail	22
Pothole	30
Muschelbruch	40
Sichelwanne	41
Comma form	42
Known transport direction	100

Processes

(Polygons)

Anthropogenic		*Glacio-fluvial*		*Aeolian*	
			400	Deflation	800
	1		410	Abrasion	810
	2		420		820
	3		430		830
	4		440		840

(*continued on next page*)

Appendix A (*continued*)

Processes					
(Polygons)					
Anthropogenic		*Glacio-fluvial*		*Aeolian*	
	5		450		850
	6		460		860
	7		470		870
	8		480		880
	9		490		890
Mass movement/fluvial erosion		*Glacial*		*Biogenic*	
Creep	100		500		900
Dry flow/scree	110		510		910
Solifluction/gelifluction	120		520		920
Mass flow (Mud/Earth/debris)	130		530		930
Debris avalanches	140		540		940
Slide	150		550		950
	160		560		960
Heave	170		570		970
Fall/toppling	180		580		980
Subsidence	190		590	Reef	990
Weathering		*Periglacial*		*Endogenic*	
	200	Nivation	600	Uplift	1000
	210	Circles	610	Subsidence	1010
	220	Polygons	620		1020
	230	Nets	630		1030
	240	Steps	640		1040
	250	Stripes	650		1050
	260	Pingo	660		1060
	270	Palsa	670		1070
	280	Thermokarst	680		1080
	290		690		1090
Fluvial		*Marine/lacustrine*			
	300		700		
	310		710		
	320		720		
	330		730		
	340		740		
	350		750		
	360		760		
	370		770		
	380		780		
	390		790		

Hydrography lines	
(Lines)	
Wet area, periodically	10
Wet area, permanent	11
Lake	12
Sea	13
River	14

Hydrography lines	
(Lines)	
Stream, ephemeral	100

Appendix A (*continued*)

Hydrography lines	
(Lines)	
Stream, permanent	101
Stream, subsurface	102
Stream, ephemeral, man made	103
Stream, permanent, man made	104
Stream, subsurface, man made	105
Abandoned channel	110
Rapid	300
Waterbody connection	900

Hydrography points	
(Points)	
Spring	1
Sinkhole	2
Waterfall	3
Dam	4

Bedrock structure	
(Points)	
Bedding	10
Bedding, horizontal	11
Bedding, vertical	12
Bedding, overturned	13

Bedrock structure	
(Lines)	
Fault/joint	10

Known stratigraphy	
(Points)	
Well	10
Exposure	20
Coring	30

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