2.05 GIS Applications in Geomorphology

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2.05.1 Introduction

Modern geomorphological research is inextricably linked with geospatial technology and geographic information systems (GIS). Driven by rapid technological advances of remote sensing, geodesy, photogrammetry, computer science, and GIS, the application of analysis tools using digital information on the land surface revolutionized quantitative geomorphological research (Bishop, 2013). In the last three decades, GIS has increasingly influenced various fields of geomorphology. GIS are designed to facilitate spatial investigations, for example, through geostatistical analyses or the mathematical description of surfaces and are hence inherently linked to methodology and concepts in geomorphology. GIS tools support and enable many upfront research fields in geomorphology from the quantitative description of landforms to process modeling, the investigation of form–process interrelations and linkages to climate and environmental conditions, or the assessment of sediment flux. Furthermore, process and form modeling, statistical analysis and regionalization of field data as well as graphical visualization and map creation are key features of GIS applied in geomorphology. A starting point for GIS studies commonly is the digital elevation model (DEM) supplemented with image data of various types (see section "Data sources"). However, GIS tools also allow linking remotely sensed information with field data, for example, land surface features, process rates, or subsurface information, recorded with geopositioning systems.

The roots of the first geomorphographic relief analyses can be identified in early studies of Penck (1894). His pioneering ideas of landforms led to the establishment of taxonomical structures which have been used in many subsequent studies (e.g., Ahnert, 1970; Kugler, 1975; Evans, 1972). A new era in the application of GIS in geomorphological studies, however, started almost 100 years later, in the 1990s. Classic papers by Dikau et al. (1991), Moore et al. (1991), Pike and Dikau (1995), or Wilson and Gallant (2000) focused on digitally derived landform classifications and general geomorphometrical advances using DEMs, respectively. First applications of GIS to traditional geomorphological topics such as landslides, soil erosion, and mountain permafrost distribution were successful on regional or local scales (Chairat and Delleur, 1993; Deroo et al., 1989; Dikau and Jäger, 1995; Moos, 1994; Jäger, 1997; Keller, 1992; van Westen and Terlien, 1996; Koethe and Lehmeier, 1993).

Since the late 1990s, we observe an increasing use of GIS in geomorphological studies (see Fig. 1). This development is strongly related to advances in computer science, remote sensing and photogrammetric techniques, as well as shallow geophysics...
In particular, the availability of global digital terrain datasets has boosted applications and research in GIS for land surface and process analysis. On a global scale, DEMs with resolutions between 1 and 30 m are now available for the entire terrestrial landmass. In addition, laserscanning (LIDAR: light detection and ranging) and structure from motion (SFM) techniques both ground- and air-based provide high-resolution DEMs (< 1 m) on local and regional scales. Additionally, numerous GIS software tools, both commercially and open source, are available today, opening unlimited opportunities for scientists. As a consequence, the use of GIS tools for geomorphological analyses became increasingly popular. Comprehensive reviews on basic elements of remote sensing techniques and application of GIS in geomorphological research are provided by Bishop (2013) and Oguchi and Wasklewicz (2011).

Applications of GIS in geomorphology span from pure visualization approaches, landform classification, land surface and hydrological analysis, process and erosion modeling, topographic change detection to hazard susceptibility modeling. While many applications focusing on land surface analysis, change detection, or hazard modeling are performed within the specific GIS software, some approaches use statistical software (e.g., R software package), or special modeling software (e.g., Matlab, IDL, a.o.) to perform geospatial analysis. For example, modeling of erosional processes and landform evolution often demand requirements that exceed capabilities of GIS software and are produced using other resources (e.g., Chen et al., 2014; Coulthard, 2001; Tucker and Hancock, 2010; also refer to https://csdms.colorado.edu/ for a list of available models).

While GIS software became more powerful and even provided advanced graphical tools, a simultaneous increase in geomorphological mapping cannot be observed. This is somewhat surprising because the overlay of different geomorphological, litho-, and pedological information is one of the most important tools in GIS applications and improves the applicability of maps (Otto and Smith, 2013). However, geomorphological mapping and GIS became a self-evident combination and geomorphological symbol sets are designed for specific purposes and frequently used (Gustavsson et al., 2006; Otto and Dikau, 2004; Schoeneich, 1993). Moreover, geomorphological maps are now serving as an intermediate product for quantitative sediment budget analyses. For this, GIS-based modeling of landforms is combined with subsurface information such as soil or regolith thickness, which is derived from geophysical surveys. The gained knowledge on spatial distribution of sediment storage types plays an important role in quantitative sediment budget studies (Otto et al., 2009; Schrott et al., 2003b; Theler et al., 2008).
Many useful GIS modeling approaches have been developed in the field of natural hazards. Rockfalls, landslides, floods, avalanches, or soil erosion share inherent characteristics of hazards such as magnitude or spatial extension and depend strongly on slope angle, aspect, or other parameters which can be ideally integrated and displayed in GIS environments (e.g., Gruber and Mergili, 2013; Gruber and Bartelt, 2007; Lan et al., 2007; van Westen and Terlien, 1996; Wilford et al., 2004; Wichmann and Becht, 2006). Hazard assessment using GIS often combines geomorphometric analysis with geostatistical analysis of related parameters to generate models of spatial susceptibility (Carrara and Guzzetti, 1995). Comprehensive reviews concerning methodological aspects and GIS-based hazard assessments can be found in Guzzetti et al. (1999), Huabin et al. (2005), and van Westen et al. (2008).

This article gives an overview to various GIS applications in geomorphology. We introduce basic principles of parameters and indices used for landform and process analysis and briefly highlight typical and innovative data sources and references to geomorphological mapping. Instead of reviewing the vast amount of GIS applications in the literature we visualize GIS capabilities for geomorphology by applying a selection of tools and indices in a case study area in alpine terrain (Obersulzbach Valley, Austria, European Alps). The selection touches various fields of geomorphology, however is far from being complete. Applications in the following fields are presented:

(i) Hillslope and gravitational processes.
(ii) Glacial processes.
(iii) Periglacial processes.
(iv) Fluvial processes.
(v) Sediment flux and erosion in mountain areas.

The results of the case study can be accessed online on a WebGIS application (https://tinyurl.com/webgis-book-chapter).

### 2.05.2 Land Surface Parameters and Geomorphological Indices

Quantitative analysis of the land surface is defined by the term geomorphometry, a highly active research field within geomorphology (Hengl and Reuter, 2009). Its focus is on the quantification of land surface parameters (LSPs) and the detection of objects from digital elevation data. In turn geomorphometry as a research area builds a theoretical foundation and serves as a bridge between GIS and geomorphology (Dikau, 1996). Geomorphometric analysis can be separated into general and specific approaches (Evans, 1972; Goodie, 1990). The main distinction between the two approaches is the continuous or discontinuous character of the object in focus. General approaches analyze the continuous land surface without addressing specific landforms or boundaries. Specific geomorphometry aims to identify and describe discrete landforms and their morphological characteristic. One focus of specific approaches is the extraction of these forms from a continuous surface (see what follows), an issue that is at the research frontier of geomorphometry (Evans, 2012).

LSPs are geometrical or statistical attributes of a land surface that can be derived directly from a DEM. They can be quantified locally, or involve a regional analysis approach (Olaya, 2009). While local parameters are quantified for a single location in relation to its immediate surrounding cells, regional parameters include relations to more distant cells. The most common basic LSPs are altitude, aspect, slope, and curvature and represent examples for local parameters. Regional parameters include aspects of flow over the surface, for example, utilized in the modeling of hydrological conditions, calculation of viewsheds, or solar radiation (Gruber and Peckham, 2009; Böchner and Antonić, 2009). Examples for hydrological LSPs are flow direction, flow accumulation, and drainage networks architecture. Relating LSPs to the three fundamental concepts in geomorphology, (i) form, (ii) process, and (iii) material (Gregory and Lewin, 2014), we could identify curvature and slope as principal descriptors of form, altitude, slope, and contributing drainage area as influential factors of process activity (in case of fluvial and gravitational processes) and surface roughness as an indicator of surface material characteristics (Otto et al., 2012).

Based on these basic parameters numerous topographic or geomorphological indices have been developed to study geomorphological form and process configurations (Table 1). Geomorphological indices are combinations of the primary attributes that describe or characterize the spatial variability of specific processes or landforms occurring in the landscape and can be used for landform and process analysis or landscape comparison (Pike and Wilson, 1971; Wilson and Gallant, 2000). These indices are applied in erosional process modeling, hydrological modeling, or digital soil mapping, to name just a few (Matthews et al., 2015; Moore et al., 1991). Many geomorphologic indices have been formulated before the rise of GIS resulting from classical geomorphological works from the early days of quantitative geomorphology (e.g., Leopold et al., 1964; Strahler, 1952, 1957; Bagnold, 1960). GIS tools, however, facilitate the quantification of these parameters and in combination with DEMs enable rapid application of these indices on large areas. It must be acknowledged, however, that some indices are connected to a distinct spatial scale and their application makes sense on large scales only. They serve, for example, for comparing drainage basin characteristics or landform assemblages (e.g., drainage density, hypsometry, elevation relief ratio, a.o.). Other indices can be applied on several scales, for example, terrain or surface roughness.
2.05.3 Data Sources

2.05.3.1 Digital Terrain Models

An abundance of gridded elevation data has been produced from different sources within the last decades. Extent and resolution of such datasets have been growing with computing power and digital storage capacities. Modern geomorphological studies typically employ DEMs with a resolution between 1 and 90 m. Low-resolution DEMs (cell size ≥ 30 m) are widely used for large-scale analyses of landscape evolution. The extensive, often global coverage of low-resolution DEMs allows large-scale analyses and

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<tr>
<th>Index</th>
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<tr>
<td>Channel sinuosity</td>
<td>The Sinuosity index (SI) describes the ratio of the sinuous length (measured down the centerline of the channel) to the straight-line distance of a reach. The sinuous length is divided by the straight-line distance. A sinuosity of 1 describes a completely straight channel. Ratios around 1.5 refer to sinuous channels, while channels with higher ratios are considered meandering channels (Burbank and Anderson, 2011)</td>
<td>( \text{SI} = \frac{L_s}{L_v} ) where ( L_s ) = length of channel, ( L_v ) = length of valley</td>
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<tr>
<td>Drainage density</td>
<td>Drainage density (DD) of a catchment is the total line length of the stream network divided by catchment area. High density values potentially reveal maturity of the channel system, rapid surface runoff and low infiltration rates, or thin vegetation cover (Horton, 1932)</td>
<td>( \text{DD} = \frac{\sum(L)}{A} ) where ( L ) = length of channel, ( A ) = catchment area</td>
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<tr>
<td>Hypsometry, hypsometric index, hypsometric curves</td>
<td>Hypsometry is a measure of the relationship between elevation and area in a catchment. Catchment hypsometry may reveal local flood response and erosional maturity. The hypsometric integral (HI) expresses the elevation/relief ratio and is often used as an estimate of the erosional development of a catchment. Strahler (1952) described HI values of &lt; 0.30 as &quot;tectonically stable&quot; or &quot;mature&quot; basins whereas HI values &gt; 0.60 indicate &quot;actively uplifting&quot; or &quot;young&quot; basins. Intermediate or straight hypsometric curves (HI ~ 0.50) suggest a relatively stable landscape. Please note that complex interplay of climatic, tectonic factors, as well as sedimentation and rock resistance may produce similarly shaped curves. The HI may hence be somewhat ambiguous and needs to be evaluated carefully. Hypsometric curves plot normalized relief against the catchment's normalized cumulative area. The curve’s shape may reveal the dominant geomorphic processes in the catchment (diffusive/fluvial). Convexity indicates a larger portion of the catchment’s area (volume of rock and soil) in the higher elevated areas of the catchment where diffusive hillslope processes dominate. Concavity implies a larger portion of the catchment's area at lower elevation and more channelized, linear, fluvial or alluvial processes. Hypsometric curves and integrals where first introduced by Strahler (1952) and are commonly calculated for catchments. If the HI is calculated using a regular kernel (e.g., a 3 x 3 cell window) it is referred to as the elevation relief ratio (ERR) (Strahler and Knecht, 1988).</td>
<td>( \text{HI} = \frac{(E_{\text{mean}} - E_{\text{min}})(E_{\text{max}} - E_{\text{min}})}{E_{\text{max}} - E_{\text{min}}} ) where ( E_{\text{mean}} ) = elevation integral</td>
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<tr>
<td>Mountain front sinuosity</td>
<td>Mountain front sinuosity is a classic index of tectonic activity, based on the notion that straight mountain fronts tend to lie along active faults (Burbank and Anderson, 2011)</td>
<td>( S_{\text{mf}} = \frac{L_{\text{mf}}}{L_s} ) where ( S_{\text{mf}} ) = mountain front sinuosity, ( L_{\text{mf}} ) = sinuous length measured along a path at the break of mountain slope and alluvial fan, ( L_s ) = length of the mountain front segment (straight line)</td>
</tr>
<tr>
<td>Relief ratio</td>
<td>Catchment relief (km) divided by catchment length (km)</td>
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<tr>
<td>Stream frequency</td>
<td>Stream frequency (F) counts all stream segments per unit area of a catchment to describe the stream network’s texture, strongly governed by bedrock and surficial material properties (strength, fracture density, infiltration, mass wasting tendencies)</td>
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\( A \) = catchment area

Table 1 Frequently used indices in GIS applications in geomorphology (collected from various sources, see references in table, online resource: http://gis4geomorphology.com/)
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<tbody>
<tr>
<td>Terrain or surface roughness (ruggedness)</td>
<td>(A) Relative topographic position (also: topographic position index) estimates terrain ruggedness and serves as an index for local elevation. Topographic position of each pixel is a relative metric based on its local neighborhood. Used to identify landscape patterns corresponding to environmental (geomorphic, vegetational, etc.) factors. Applicable to bathymetric data.</td>
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<td>(B) Standard deviation of elevation is a statistic measure of topographic roughness.</td>
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<td></td>
<td>(C) Slope variability calculates the slope relief based on a slope raster and its local cell neighborhood (e.g., &gt; 100 m)</td>
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<td></td>
<td>(D) Basin-scale ruggedness (Rb) compares the relief of catchments using streamlines and basin boundary polygons</td>
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<td></td>
<td>(E) Standard deviation of residual topography compares ratio of surface height and averaged surface on a local cell neighborhood (Grohmann et al., 2011)</td>
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<td></td>
<td>(F) Standard deviation of slope (Smith, 2014)</td>
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| Valley width-to-height ratio                             | Valley width-to-height ratio (Vf) compares erosional patterns between catchments (one Vf value per catchment) based on values derived from a DEM or aerial photos along a single cross-section per catchment. Vf was originally used to distinguish V-shaped valleys (low Vf values, often close to 0) from U-shaped valleys (higher Vf values) (Burbank and Anderson, 2011) | (A) \( \left( \frac{DE_{\text{smooth}} - DE_{\text{min}}}{DE_{\text{max}} - DE_{\text{min}}} \right) \) where:  
DE_{\text{smooth}} = smoothed elevation raster (10 x 10 pixels)  
DE_{\text{min}} = minimum elevation raster  
DE_{\text{max}} = maximum elevation raster  
(DE) \( \text{Rb} = \frac{\text{ADD}}{A} \) where:  
ADD = catchment ruggedness index  
A = area of the catchment  
(D) \( \text{SV} = \frac{S_{\text{max}} - S_{\text{min}}}{S_{\text{max}} - S_{\text{min}}} \) where:  
SV = slope variability  
S_{\text{max}} = maximum slope value raster  
S_{\text{min}} = minimum slope value raster |
| Glaciality index                                          | The glaciality index (Gl) measures the concavity of a valley flank based on the idea that glacial valleys have a parabolic cross-section. It is defined as the exponent of a power-law fitted to the valley flank, after Svensson (1959) and was calculated automatically by Prasick et al. (2015). A Gl of 1 represents a fluvial valley and progressively higher exponents indicate progressively more U-shaped valleys. |                                                                                   |
| Steepness index (stream power)                           | The steepness index (ks) is the factor of a power-law describing the drainage area—channel slope relation after Flint (1974). Drainage area can be combined with channel slope to derive the stream power or steepness index, a simple metric for the ability of a stream to incise into bedrock (Flint, 1974). It should be emphasized that channel slope represents elevation change over flow path length and hence differs from the topographic gradient as calculated in most GIS. The exponent \( \theta \) depicts the shape of the power-law that describes the relation between channel slope and \( A \). This relation can only be described by a single power-law (i.e., uniform stream power regardless of location) if (i) influencing factors such as climate and rock type are homogenous and (ii) the topography is steady over time (Whipple and Tucker, 1999). If \( \theta \) is known and fixed, \( k_s \) becomes \( k_{\text{norm}} \), the normalized steepness index, and can be used to identify a change in stream power and hence deviations from the spatial and temporal constraints mentioned previously. \( \theta \) generally ranges between 0.25 and 0.7 (Tucker and Whipple, 2002; Whipple, 2004; Whipple et al., 2013), but most studies use a reference value of 0.5 (Hack, 1957) or 0.45 (Whipple et al., 2013) |

(Continued)
comparisons between study areas worldwide. Medium to high resolution datasets (cell size < 30 and ≥ 1 m) are typically national grids with a more limited extent and are a good choice for regional modeling of different LSPs. Submeter resolutions are mostly produced by individual campaigns and spatially limited to single catchments or landscape patches. Such data sets are inevitable for detailed analyses of weathering processes, soil erosion, and rock wall retreat.

Acquisition techniques vary and comprise active (radar, LiDAR) and passive (optical) remote sensing. While terrestrial and airborne LiDAR dominated the acquisition of high-resolution elevation models over the last two decades, photogrammetry has experienced a renaissance due to affordable drone technology and very high-resolution DEMs from SFM techniques.

The most widely used global DTMs with a resolution < 90 m are the elevation data of the shuttle radar topography mission (SRTM) (Farr et al., 2007), available from 60 degree north to 60 degree south with a resolution of 1 arc second (approximately 30 m at the equator) and the ASTER GDEM (Gesch et al., 2012), a global DSM derived from satellite imagery via stereo photogrammetry and available from 83 degree north to 83 degree south with a resolution of 1 arc second. Furthermore, HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales) (Lehner et al., 2008) are derived from different SRTM versions and provide hydrographic information (e.g., imprinted river networks) along with elevation data at a resolution of 3 arc seconds. The radar interferometry-based WorldDEM (http://www.intelligence-airbusds.com/worlddem/) developed by the TanDEM-X Mission by the German Aerospace Center was just completed in October 2016 and for the first time provides a global terrain model with a resolution of 12 m (Zink et al., 2006, 2011).

### 2.05.3.2 Optical Imagery

#### 2.05.3.2.1 Optical satellite imagery

Geomorphologists have been using remotely sensed imagery since it became available during the first half of the 20th century. Carl Troll was one of the first physical geographers who systematically used aerial imagery for the emerging field of geomorphology (Lautensach, 1959).

While conventional aerial photography is still widely applied for local studies, satellite remote sensing has become a useful tool when looking at larger areas. With the start of the first Landsat satellite in 1972, conventional earth observation from space entered a new era. It was now possible to survey large areas continuously from space, revisiting the same locality in only 18 days’ time. Since then, the lower earth orbit (160–2000 km above ground) has become packed with satellites from different agencies. In addition to the large fleet of satellites launched by the US National Aeronautic and Space Administration (NASA) since the 1970s, several other national space agencies and private companies launched their own earth observation missions, for example, the SPOT 1–7 satellites (launched between 1986 and 2014) by CNES (France), the IRS family of satellites (launched between 1988 and 1996) operated by ISRO (India), the World-View 1–4 satellites (Digital Globe) (launched between 2007 and 2016), and Sentinel 1–3 satellites by ESA (launched between 2015 and 2017), to name only a few.

### Table 1

Frequently used indices in GIS applications in geomorphology (collected from various sources, see references in table, online resource: http://gis4geomorphology.com/)

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<tr>
<td>Gradient index</td>
<td>The gradient index (SL) (Hack, 1973) allows the identification of breaks in channel geometry based on the assumption that channel length L is related to channel slope (Hack, 1957)</td>
<td>( SL = \frac{\Delta H}{\Delta L} )</td>
</tr>
<tr>
<td>Topographic Wetness index (TWI)</td>
<td>A parameter describing the tendency of a location to accumulate water. TWI was developed within the hydrological runoff model TOPMODEL (Beven and Kirkby, 1979) and applied in studies on soil moisture, soil chemistry or species distribution analysis (Matthews et al., 2015)</td>
<td>( TWI = \log_{10} \left( \frac{A_{up}}{A_{dn}} \right) )</td>
</tr>
<tr>
<td>Connectivity index (IC)</td>
<td>The connectivity index (IC) focuses on the influence of topography on sediment flux. It is intended to represent the linkage between different parts of the catchment and aims, in particular, at evaluating the potential connection between hillslopes and features of interest like channels, sinks and sediment storage landforms. (Cavalli et al., 2013)</td>
<td>( IC = \log_{10} \left( \frac{D_{up}}{D_{dn}} \right) )</td>
</tr>
</tbody>
</table>
With the ongoing development of new sensors (and the launch of new satellites), spatial ground resolution of optical imagery has been enhanced very quickly. While the first Landsat satellites had a maximum ground resolution of 60 m (resampled), the WorldView-3 satellite's panchromatic channel is collecting images with a ground resolution of 31 cm, a level of detail that only aerial surveys could achieve before. Services like GoogleEarth or BingMaps make these high-resolution images available for visual interpretation and comparison of different time steps.

For geomorphological applications, the temporal resolution of satellite images might be at least as important as the ever-increasing spatial resolution of newly launched missions. For the detection of geomorphological changes, both long time series of satellite imagery and short revisit times of the same locality are of vital importance. Increasing computational power but also political decisions during the past decade have boosted the use of satellite remote sensing products in geosciences (Wulder and Coops, 2014). Since a change in data policy in 2008, millions of images acquired by the Landsat family of satellites between 1972 and today have become available at no cost. The Landsat 8 satellite, launched in 2013 to ensure data continuity with nearly the same specifications as before, collects several hundred images each day, revisiting the same location every 16 days. The free distribution of these images via the USGS EarthExplorer (https://earthexplorer.usgs.gov) has spurred the use of satellite products in geomorphological research, enabling the detection of geomorphological change from space over more than four decades. Shortly after 2008, geoscientific studies making use of freely available Landsat imagery sharply increased (Fig. 2). Landsat imagery is not the only high-resolution imagery available at no cost. In 2016, data recorded by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a sensor onboard the Terra satellite (sensor resolution: 15–90 m), became freely available as well (https://asterweb.jpl.nasa.gov/). Since 2014, the Sentinel satellite imagery from the European Space Agency (ESA) has been distributed via the ESA Science Hub (https://scihub.copernicus.eu) at no cost. Launched in 2015, the Sentinel-2A satellite already collects optical imagery at 10 m ground resolution with a revisit interval of 10 days at the equator, delivering comparable ground resolution and spectral specifications as Landsat and ASTER imagery. Together with the Sentinel-2B satellite (launched in early 2017; phased at 180 degree with Sentinel-2A), the Sentinel-2 mission will deliver optical imagery with a revisit time of 5 days at the equator (2–3 days in mid-latitudes). Alongside with the remote sensing products, ESA offers a stand-alone desktop Sentinel-2 Toolbox that features a set of processing and visualization tools for Sentinel-2 imagery, but also for other ESA and third-party remote sensing data.

The potential for geomorphological research to gain knowledge through the enormous amount of remote sensing products is huge. One of the most prominent applications in geomorphology is the detection of glacial changes from space (Kääb et al., 2016; Paul et al., 2015), but multitemporal satellite imagery has also been applied to landslide studies (Scaioni et al., 2014; Stumpf et al., 2017), fluvial geomorphology (Legleiter and Fonstad, 2012; Rowland et al., 2016), and coastal erosion (Hara et al., 2015; Li and Damen, 2010). It is beyond the scope of this article to give a full overview of potential applications; the following example shall merely highlight the potential of satellite imagery to (a) pinpoint geomorphological change in remote regions and (b) to determine rates of certain processes from space.

Despite potential distortion by intensive cloud cover, the high spatio-temporal resolution of Sentinel-2A makes it possible to detect geomorphological change in remote areas. In early 2016, a rock avalanche detached from the northeastern flank of the Cerro...
Alto San Juan, situated on the border between Argentina and Chile (Fig. 3). The mass detached at around 5200 m and dropped onto the large glacier descending from the massif. The rock avalanche deposit covers an area of roughly 1 km² (> 2000 m length; 500 m width). Repeated Sentinel-2A imagery narrows the detachment down to the time span between 22 January 2016 and 04 February 2016. Comparison with an image obtained on 26 January 2017 shows how the debris is transported 50–100 m on top of the moving glacier.

2.05.3.2.2 Unmanned aerial vehicles and structure from motion

Regarding the ground resolution, conventional aerial photography still outperforms satellite imagery by far. The major downside of conventional aerial photography, however, is the cost-intensive data acquisition from small planes or helicopters. Technological advances during the past decade revitalized the use of aerial photography in geosciences. Unmanned aerial vehicles (UAVs), also referred to as drones or multicopters, are available at low cost and make data acquisition cheap and relatively easy. Especially in remote areas and in steep and rugged terrain, where shadowing effects limit the use of conventional aerial photography, the acquisition of high-resolution aerial photography from UAV platforms offers new possibilities. Furthermore, repeated surveys make geomorphological change detection also feasible on small scales that remote sensing data from satellites cannot resolve in comparable detail.

Along with the advances in data acquisition, newly developed image processing software and algorithms offer new opportunities for geoscientific research. Digital photogrammetry, grounding on the same principles as classical photogrammetry, is a powerful method for extracting digital topography from overlapping images (Baltsavias et al., 2001; Keutterling and Thomas, 2006; Lane et al., 2000). In the last couple of years, SFM, a new low-budget photogrammetric method to create DEMs from overlapping images,
has caught the attention of the geoscience community (Fig. 1). As opposed to classical photogrammetry, picture geometry, orientation, and position of the cameras toward the object of interest are not a prerequisite. SFM software calculates these parameters by matching common features in a set of overlapping digital images (Snavely et al., 2008). For a comprehensive summary of SFM tools and their applications in geosciences, see Westoby et al. (2012).

### 2.05.3.3 Other Data Sources

GIS offers numerous possibilities to combine data sets of different sources for analysis and visualization. Besides DEM and image data, all kinds of field and lab data can be imported into GIS for analysis. Data on surface material characteristics produced by sampling, coring, or near-surface geophysics, mapping data, as well as measurements of process rates and lab data, for example, sediment analysis or dating information, can be combined with digital land surface data. A prerequisite for the combination of field/lab and digital data is correct georeferencing. Global positioning systems (GPSs) have become a standard requisite for field work. Modern GPS receivers combined with correction signals transferred via mobile communications deliver high-accuracy positioning data. Additionally, low-resolution positioning is available in every smartphone, which appears almost ubiquitous today. Great potential lies in the combination of surface and subsurface information. Especially with the commonly applied techniques of near-surface geophysics, landforms can be studied in three dimensions. The most frequently used techniques in geomorphology are ground penetrating radar, seismic methods, resistivity and EM methods, and gravity methods (Kruse, 2013; Schrott and Sass, 2008). Since most geophysical systems have a distinct data format and many methods deliver data along a survey line, transfer of subsurface information often requires a conversion of, for example, depth information into point or line data, before further processing in GIS software is possible.

### 2.05.4 Digital Geomorphological Mapping

#### 2.05.4.1 Map Creation

Geomorphological mapping is a fundamental tool for geomorphologists. Geomorphological maps are highly complex thematic maps that contain various different layers of geomorphological information. Digital map creation requires good map design and sophisticated graphical tools to produce a readable and understandable map. The developments of graphical and analytical functions in GIS software provide numerous valuable tools that facilitate map creation and distribution. Compared to analog methods of map creation, the application of GIS software tools represents a significant simplification of the production process and an important reduction of creation time and production costs.

Within GIS software, manipulation and analysis of various types of geomorphological information, for example, delineation, measurement, mathematical operations and others, and the design and production of the map are possible. Furthermore, the logical storage structure of geomorphological data enables rapid production of derivative maps with special thematic focus, like process domains, surface processes, surface material, or other. Geomorphological maps are created using either data gathered during field campaigns and/or data extracted from digital data sources like aerial photography, satellite imagery, and DEMs. Field mapping is significantly enhanced using mobile devices like tablets or handheld computers connected with GPS. Field mapping software, usually a GIS-type software, enables direct collection of observations into a georeferenced database system that can later be transferred to the desktop GIS used for map creation (Gustavsson et al., 2008; Minar et al., 2005). The mapping process can be performed manually, automated, or semiautomated. Manual mapping relies on the experience and competence of the mapper using visual heuristics to identify landforms of interest. The method is simple and rapid to deploy, and accuracy is generally high. Automated or semiautomated mapping allows generation of more objective and repeatable information but usually falls behind in accuracy compared to manual approaches. Corresponding methods rely on feature extraction techniques applied to satellite/aerial imagery or different types of DEMs and their derivatives (see section “Automated land surface classification”). The representation of a landform on an image is dependent upon (i) the landform itself, (ii) the data source, and (iii) the visualization method (Otto and Smith, 2013; Smith, 2011). Smith and Wise (2007) identified three main controls on the representation of landforms on images: (i) relative size: the size of the landform relative to the spatial resolution, (ii) azimuth biasing: the orientation of the landform with respect to solar azimuth, and (iii) landform signal strength: the tonal/textural differentiation of the landform. Consequently, the relative reflectance of the landform in relation to surrounding features determines the detectability of a landform. DEMs are applied using derivatives of elevation that provide various forms of visualization of inherent information including relief shading, gradient (slope angle), or curvature classification.

The complex content of geomorphological maps is depicted using compound and often illustrative symbols (Otto et al., 2011). GIS software provides tools for the creation of custom symbols representing geomorphological features and functions for cartographic design and map production. Digitally produced maps are easily distributed in various formats ranging from print maps to online web services, making full use of the data organization structure and the georeferencing of the data (Smith et al., 2013). Additionally, the standard PDF (Portable Document Format) has been extended into a GeoPDF for display and dissemination of referenced map data. Geospatial functionality of a GeoPDF includes scalable map display, layer visibility control, access to attribute data, coordinate queries, and spatial measurements (www.terragotech.com).
2.05.4.2 Automated Land Surface Classification

2.05.4.2.1 General land surface classification
The extraction of discrete entities from a continuous digital image has been a main research field within geomorphometry for decades. Evans (2012) stresses the need to distinguish between landform and land surface form. The difference between the two arises from the discontinuity or continuity of the feature, respectively (referring to the concept of general and specific geomorphometry, see the previous discussion). Tasks related to the description of the continuous land surface are here addressed as general land surface classification, while discontinuous landforms will be treated in the following chapter on specific land surface classification. Theoretical frameworks for general land surface classification have been developed by several authors, mostly addressing basic LSPs, such as elevation, slope, aspect or curvature. Based on these characteristics the continuous land surface is split into discrete parts termed land surface elements. Their main characteristic is geometric homogeneity (Minár and Evans, 2008). Dikau (1989), for example, proposed nine landform elements, defined by their profile and plan curvature, to represent the building blocks of the land surface (Fig. 4). MacMillan et al. (2000) and Schmidt and Hewitt (2004) both used plan curvature to classify landforms into different classes.

**Fig. 4** (A) Relief classification using the approach by Dikau (1989). (B) Basic landform elements based on curvature conditions in two directions. Based on Dikau, R. 1989. The application of a digital relief model to landform analysis in geomorphology. In: Raper, J. F. (ed.) *Three dimensional applications in geographical information systems*. London: Taylor & Francis.
and profile curvature, slope and slope position for automated segmentation of landforms into landform elements based on DEMs, heuristic rules and fuzzy logic. They extend the model of Dikau (1989) by nine elements with classes for ridges, peaks, valleys, spurs, terraces, hollows, plains, saddles, and slope position. Shary et al. (2005) presented 12 slope types, while Minár and Evans (2008) even distinguished between 25 elementary landforms. The main function of these elementary forms lies in their relation with process dynamics rather than the delineation of discrete real landforms. Curvature changes evoke an acceleration or deceleration of gravity flow and result in dispersion or concentration of transported matter (Minár and Evans, 2008). However, general land surface classification can be used as starting point for specific classification approaches (Drăguţ and Blaschke, 2006).

### 2.05.4.2.2 Specific land surface classification

Specific landform classification ambitiously aims at combining single pixels or landform elements to landforms as perceived by experts and hence is somewhat more subjective and adds a lot of additional complexity (Hengl and Reuter, 2009). Attempts to classify entire scenes or at least specific landform types have only partially been successful. This is mostly owed to the exceptional complexity immanent in Earth’s landscapes. The surface of real-world landscapes or even small parts of it can never be exactly matched by mathematical representations of landforms. As a consequence, variations in the appearance of landforms have to be considered and measures for similarity have to be applied. Beyond these technical issues, different geomorphological processes may produce similar landforms, a mechanism that is known as “equifinality” and considerably hampers the interpretation of landscape shape.

Analysis of remote sensing data including DEMs as well as aerial and satellite imagery is mainly performed in a pixel-based manner. Each pixel is treated separately and only a few attributes are at hand for characterization and classification. The adoption of image segmentation and object classification techniques from computer science to GIS applications (Blaschke and Strobl, 2001) allowed overcoming these limitations which can be particularly useful for the automated interpretation of complex landforms. Image segments are regions which are automatically merged from pixels referring to one or more criteria of homogeneity in one or more dimensions of feature space (e.g., spectral reflectance). The resulting objects can be described and classified using additional spectral (e.g., mean, median, variance), geometrical (e.g., circularity), textural, and hierarchical information (Blaschke, 2010). Schneevoigt et al. (2008) combined ASTER satellite imagery with DEM data to detect 20 different alpine landform types. They report an overall accuracy of 92% with good results for talus slopes, free rock faces and cirque walls but detection problems for fluval, glacial, and debris flow deposits. Among the most successful approaches for a gapless classification of a landscape into individual landforms, Anders et al. (2011) employed an object-based approach to extract karst, glacial, fluval, and denudation landforms from a high-resolution DTM and reached an overall accuracy of about 70%. Focusing on specific landforms only, d’Oleire-Olmmanns et al. (2013) and Eisank et al. (2014) reached accuracies around 60% when attempting to automatically map gullies and drumlins. Object-based image analysis is a promising technique for landform classification but clearly further research is needed to handle the exceptional complexity of real-world landscapes in automated routines of landform mapping.

### 2.05.5 Application of Various Geomorphological Indices for Process and Landform Analysis—Case Study Obersulzbach valley, Eastern Alps, Austria

Instead of reviewing the vast number of studies that apply GIS in geomorphological research, we now present the application of selected topographic indices and geomorphological analyses for a local test site in the Eastern European Alps. The Obersulzbach valley is located north of the main divide in the Hohe Tauern range in Austria and represents a southern tributary of the Salzach river (Fig. 5). It covers an area of 81 km² of complex high alpine relief between 850 and 3657 m. Glacial imprint dominates surface morphology and is manifested by numerous cirques in the upper reaches and pronounced U-shaped sections along the main channel of the valley. The longitudinal profile of the main valley shows two pronounced steps, one located about 4 km into the valley and the other located 6 km from the valley head (Fig. 6). The first step separates the deeply incised, rather V-shaped lower level that connects to the Salzach valley from a U-shaped upper level. The upper step separates the U-shaped section from the cirque-like valley head area. Glaciers are still present in some of the cirques and cover large parts of the valley head, summing up to 17% of glacier coverage in total. The Obersulzbachkees glacier at the valley head covered an area of 15 km² in the Little Ice Age and is now split into several glacier parts of 9 km² area in total (last glacier extent from 2009, data by: Fischer et al., 2015). A large proglacial lake has formed in the valley (second pronounced step) since the late 1990s.

The calculation of the geomorphological indices is based on a DEM with cell size of 10 m (provided by data.gv.at under the INSPIRE framework). We used ArcGIS, SAGA GIS, and TAUDEM for the analysis and ArcGIS for visualization. The results of the case study can be accessed online on a WebGIS application (https://tinyurl.com/webgis-book-chapter).

### 2.05.5.1 Hillslopes and Gravitational Processes

Process dynamics are governed by surface topography, impacting on energy potentials, for example, by intensification of attenuation of friction or diffusion, or concentration of flow. In absence of convergent flow and moving ice, hillslope processes are mostly controlled by surface slope and curvature. Erosion is most commonly modeled by hillslope diffusion where sediment transport depends only on slope and a diffusivity constant (Montgomery and Foufoula-Georgiou, 1993; Dadson and Church, 2005;
Fig. 5  (A) Location of the study area. (B) Aerial image of the Obersulzbach valley, Eastern European Alps, Austria. Free orthofoto data from basemap.at.

Fig. 6  Longitudinal profile of the Sulzbach Creek draining the Obersulzbach Valley. Note the changes in channel slope along the path and the distinct steps along the profile (cf. text for details).
Egholm et al., 2012; Tucker and Bras, 1998; Kirkby, 1987). This makes basic LSPs such as slope and curvature very valuable for evaluating hillslope processes.

Surface slope controls how gravitational acceleration is split into retentive and detaching forces and profile curvature holds information on how this relation changes. Convexity indicates areas of increasing slope, increased sediment transport capacity and hence erosion, while concavity represents reduced transport capacity which leads to deposition of material.

The length and relief of the hillslopes holds information on forcing at a range of scales (e.g., Grieve et al., 2016) and plays an important role in the universal soil loss equation for estimating soil erosion (e.g., Hickey et al., 1994; Moore and Burch, 1986; Liu et al., 2000) and in slope susceptibility for shallow landslides (e.g., Carrara, 1983; Gómez and Kavzoglu, 2005). Furthermore, following Salcher et al. (2014), glacial landscapes tend to show longer hillslopes and greater hillslope relief than fluvial ones. For our study area, we calculated both hillslope length and relief with TauDEM (Tarboton et al., 1991) and observe this trend only in distinct cirques on the western valley flank. However, less dissected terrain can generally be expected to have longer hillslopes (Fig. 7).

Another example for assessing the impact of surface characteristics on hillslope processes is the surface roughness index. Roughness, also termed ruggedness or microtopography, describes the local variability of elevation on a given scale. On a large scale, roughness of a land surface is controlled by the number, size and distribution of landforms and is expressed by landform and landform elements or breaklines. On small scales, roughness of a single landform results from material properties, processes acting upon it, and the time since formation (Grohmann et al., 2011). In this case it signifies grain size of surficial deposits, or surface smoothing due to erosion. The parameter is applied, for example, in fluvial geomorphology to characterize bed morphologies and fluvial erosion, in hydrological modelling, in weathering studies, for landslide detection and for relative age dating (Smith, 2014). In permafrost studies surface roughness controls energy transmission into the ground and fosters permafrost formation (Otto et al., 2012). Numerous approaches exist to quantify surface roughness (see Table 1; Grohmann et al., 2011; Smith, 2014). We have applied two ways to calculate roughness in the study site: (1) standard deviation (STD) of slope (Fig. 8A) and (2) STD of residual topography (Fig. 8B). Both calculations use a focal statistics tool with a 3 × 3 cell analysis window. Residual topography results from the difference between the surface height and a low pass filtered height. STD of slope describes sensitivity to changes in curvature, while STD of residual topography represents changes in altitude and hence gradient. Both approaches are sensitive to major breaklines and steps, especially at the cirque-main valley boundary (Fig. 8). They allow for a delineation of linear landforms, like ridges, lateral moraines, or steep walls. They also depict differences in roughness between bedrock slope, for example, cirque walls, and sediment covered cirque floors (see eastern valley flanks).

2.05.5.2 Glacier Environments

GIS play an important role in analyzing and visualizing glaciers and glacially sculpted landscapes (compare chapter on GIS for Glaciers). GIS are used by glacial geomorphologists to integrate multisource data, manage multiscale studies, identify spatial
and temporal relationships and patterns in geomorphological data, and to link landform data with numerical models as part of model calibration and verification (Napieralski et al., 2007).

When looking at the ice itself, mass balance constraints are inevitable to understand glacier development and GIS are ideal to process and visualize related data. For example, GIS can be used to visualize manually mapped glacier extent or to even apply automated mapping routines based on DEM and spectral data (Racoviteanu et al., 2008). If glacier extent is known, the altitude of the equilibrium line (ELA), the virtual border between accumulation and ablation area that is central for mass balance assessment, can be calculated by applying different methods such as the accumulation area ratio (AAR).

Fig. 8 Surface roughness calculated using the standard deviation of local slope (A) and the residual topography approach (B) in the study area (extract). See text for explanations.
The ELAs for the glaciers of our study area range between 2400 and 3300 m (Fig. 9). The distribution of the glaciers in the Obersulzbach valley already indicates the importance of climatic influences. While glaciers still exist on the slopes facing towards east and north, western slopes only show remnants of past ice cover. The climatic influence is further indicated by the relation between ELA and exposition. While northeast-facing glaciers feature the lowest ELAs, south-facing glaciers have the highest ELAs. When applying the AAR method for ELA calculation, the mass balance of the reference glaciers needs to be considered. If these glaciers were not fully adapted to the climatic conditions during ELA measurements, any deviation in mass balance is transferred to the ELAs calculated with the AAR method.

Once the ELA is known, be it from field campaigns or GIS-based models, the glacier surface can be split into accumulation and ablation area. Shear stress models can be used to derive ice thickness estimations and hence calculate ice volume and water equivalent (Huss and Farinotti, 2012; Frey et al., 2013). Mass balance-based models can be applied to calculate ice flux and to retrieve similar results. We applied the model GlabTOP2 developed by (Frey et al., 2013) to the current glacier extend of our study site. The model calculated ice thickness from slope and shear stress relationships based on a simplified term presented by Haeberti and Höflzle (1995). Ice thickness modeled ranged from less than 25 m for many small cirque glaciers to maximum values of more than 200 m for the larger glaciers at the valley head (Fig. 10).

Glacially sculpted landscapes are also frequently analyzed using GIS, be it the morphometric characterization of moraines or cirques, or automated mapping of glacial landscapes and glacial imprint based on estimations of cross-sectional valley shape.

**Fig. 9** Equilibrium line altitudes of the glaciers of the Obersulzbach Valley.
or hypsometric indices (e.g., Prasicek et al., 2015; Smith et al., 2006). Furthermore, a variety of GIS-based models has been applied to assess the volume of glacial valley fill (e.g., Mey et al., 2016; Jaboyedoff and Derren, 2005a). The hypsometry of glaciated landscapes has been used to predict the state of glacial landscape evolution and to distinguish between glacial and fluvial terrain (Brocklehurst and Whipple, 2004; Sternai et al., 2011).

In our example, we quantify the U-shapedness of the valleys in our study area based on the glaciality index (GI), derived from parabolas fitted to valley flanks for all flow path cells (Prasicek et al., 2014, 2015). To analyze the glaciers themselves we use outlines mapped by Abermann et al. (2009). We calculate the approximate ELA of all glaciers in the study area employing an AAR of 0.6, which is in the center of the range of reported values (e.g., Porter, 1975; Benn and Lehmkohl, 2000; Gross et al., 1977).

For calculating U-shapedness as a proxy for the degree of glacial imprint, we automatically determine valley width using a multi-scale curvature approach (Prasicek et al., 2014) and subsequently fit power-laws to the valley flanks (Prasicek et al., 2015). These calculations are performed for flow path cells only and then averaged for a spatially continuous result. Results show that deeply incised and dissected parts of the study area have a fluvial GI and hence rather straight valley flanks while the main trough and distinct cirques show increased glacial imprint. However, the effect of valley fill producing flat valley floors as well as other deposits on valley cross-sectional shape needs to be considered for interpretation (Fig. 11).

**Fig. 10** Ice thickness modeling using the model GlabTOP2 applied to the glaciers in the study area (Frey et al., 2013).
2.05.5.3 Periglacial Environments

Land surface is strongly interrelated with climate on a regional and local scale. The spatial differentiation of near-ground atmospheric processes and climate variables is dominantly controlled by topography. This impact of topography on climate is expressed by the term topoclimate or topoclimatology (Böhner and Antonić, 2009). In geomorphology, topoclimatic effects are related to the spatial distribution and variable morphological characteristics of landforms. Especially landforms of process domains sensitive to climatic influences such as glacial, periglacial and fluvial processes show interrelations with topoclimatic parameters, such as aspect, altitude or slope angle (Olyphant, 1977; Allen, 1998; Humlum, 1998; Sattler et al., 2016). Within periglacial geomorphology GIS have been used to model and visualize permafrost distribution since the early 1990s (Riseborough et al., 2008). Two classic models originally applied in the Swiss Alps, namely PERMAKART (Keller, 1992) and PERMAMAP (Funk and Hoelzle, 1992), can be considered as a starting point of GIS applications in permafrost research. The model PERMAKART is based on empirical geomorphological evidence concerning permafrost occurrence (e.g., lower limit of active rock glacier, basal temperature of snow) and integrates besides perennial snow avalanche deposits (protecting the ground surface from radiation) classic topoclimatic parameters such as altitude and aspect. These LSPs are used as proxy information for air temperature and solar radiation, respectively, two influential factors on the formation of mountain permafrost. Additionally, slope position and slope

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**Fig. 11** Glaciality index of U-shapedness in the study area.
angle are used representing the influence of snow cover on permafrost. The distribution modeling thus consists of a regionalization approach based on these LSPs using a DEM and the empirical data on permafrost occurrence classified by altitude and aspect, the so-called topoclimatic key. Over the years the original model structure has been modified and improved several times. One of the latest GIS-based empirical permafrost models comprises a topoclimatic key of 24 different relief classes subdivided in eight classes of aspect, each of them divided into three slope categories (rock, steep slopes and slope foot-positions, see Fig. 12) (Schrott et al., 2013). The empirical model PERMAKART 3.0 has an index-based permafrost probability ranging from 1 (very unlikely) to 100 (very likely). This allows a more transient and realistic visualization, also because the relief class “rock” displays more realistically lower permafrost probabilities even in higher altitudes (Fig. 13)

![Fig. 12](image)

**Fig. 12** Topoclimatic key used in the GIS-based permafrost distribution model PERMAKART 3.0 (Schrott et al., 2013).

![Fig. 13](image)

**Fig. 13** Map of permafrost index in the Obersulzbach valley (extract). Note the varying index values in similar aspect situations (e.g., on the eastern cirque walls) that result from differences in the topoclimatic key between rock slopes, steep slopes, and foot slopes.
2.05.5.4 Fluvial Environments

The investigation of fluvial environments is a key task in GIS applications, not only in the field of geomorphology but also hydrology and ecology. This is mainly because river networks constitute the backbone of most humid and also semi-arid landscape types worldwide. Even the course of present-day glacial valleys is determined by pre-glacial fluvial topography. Consequently, the structure of river networks manifested in basins and watersheds is commonly used to partition the land surface and the fluvial catchment is the standard unit for geomorphological and environmental analyses. In our example we provide an overview over the standard tools to extract the river network and subsequently calculate a number of indices to further characterize the drainage system.

First, sinks in the DEM should be filled, if a continuous drainage network is desired. The pit-filled DEM can then be used to calculate flow direction and flow accumulation. Drainage area is one of the most important LSPs and it is typically derived from gridded elevation data via standardized GIS routines. It is used as a simple and easily determined proxy for discharge. Thus, drainage area is a major factor for assessing the erosive power of convergent flow and reveals the architecture of the drainage network, the backbone of many landscape types worldwide.

A wealth of methods exists to determine drainage area from DEMs. The integration of drainage area in the direction of flow is central to all of them but they differ in the way flow directions are determined. It is beyond the scope of this book section to discuss the details of these approaches and the interested reader is referred to the work of, for example, Jenson and Domingue (1988), Fairfield and Leymarie (1991), Freeman (1991), Tarboton et al. (1991), Costa-Cabral and Burges (1994), or Seibert and McGlynn (2007). While in the classic procedure of Jenson and Domingue (1988) all flow is assumed to descend via the steepest path, cell area is partitioned between two or more flow directions in most other approaches—a difference that needs consideration for geomorphological applications. In single flow direction algorithms, drainage area cannot decrease downstream, which leads to the formation of distinct flow paths. In contrast, multiple flow direction algorithms allow flow dispersion. Differences between the two types of algorithms are most pronounced in divergent areas such as ridges, hillslopes and planar valley fills (Erskine et al., 2006). Consequently, algorithms capable of flow dispersion should be used for detailed analyses of ridges and hillslopes, while single flow direction algorithms are designed for the extraction of drainage networks, Strahler orders and other derivatives such as flow length and river longitudinal profiles.

Once the per-cell upstream drainage area has been computed, drainage area–slope relations can be used to identify the drainage area threshold between divergent and convergent flow, that is, the extent of the valley network, on a regional basis. Montgomery and Foufoula-Georgiou (1993) showed that the extent of topographically divergent hillslopes, and thus the extent of the valley network, corresponds to a change in sign of the relation between local slope and contributing drainage area. They further demonstrated that debris flow-dominated channels can be determined from an inflection in the drainage area–slope relation. In practice, a regional drainage area threshold for valley network initiation can be determined by establishing drainage area bins and plotting mean slope against drainage area.

For our study area, such a plot is shown in Fig. 14. In our example, the slope–area relation shows a change in sign around $10^{-4}\text{km}^2$, at a scale where convergent terrain starts to establish and colluvial processes come into play. Further breaks are evident around $10^{-2}$ and $10^{-1}\text{km}^2$ and we interpret the latter one to indicate the transition from colluvial to fluvial processes. We thus

![Fig. 14](image_url)

**Fig. 14** Slope-area plot of the Obersulzbach Valley. Note the pronounced kink at a drainage area of approximately 0.1 km².
chose this drainage area cutoff for river network extraction. The extracted drainage network acts as basis for the calculation of stream orders (Horton, 1945; Strahler, 1952), subcatchments and drainage density. We calculated drainage density per square kilometer (i) for the entire study area using a kernel with a size of 1 km² (Fig. 15A), and (ii) for catchments of Strahler order 2 by dividing the summarized length of all drainage lines in each catchment by catchment size (Fig. 15B). Results show that elevated and cirque-shaped parts of the study area have a lower drainage density, probably due to more recent and/or more intensive activity of ice.

In addition to identifying the transition between divergent and convergent flow, drainage area–slope relations and flow length–slope relations can be used to identify breaks in channel geometry and catchment evolution. Steepness index ($k_s$) and gradient index ($SL$) hold information on deviations from fundamental relations between drainage area and slope and flow length and slope in a fluvial landscape, respectively. On glacially sculpted terrain deviations from fluvial topography can of course be expected to be ubiquitous. Nevertheless, both indices clearly indicate disturbances in narrow valley sections where knickpoints with comparatively steep channel sloped are located (Figs. 5 and 16).

Horton-Strahler orders (Horton, 1945; Strahler, 1957) can also be calculated from the extracted drainage network. Subsequently, subcatchments can be delineated for each Strahler order which allows the comparison of landscape patches with similar drainage topology.

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**Fig. 15** (A) Drainage density calculated for the entire Obersulzbach Valley using a kernel of 1 km². (B) Drainage density calculated for catchments of Strahler order 2.
Hypsometry has been used to describe and interpret the topography of both fluvial and glacial landscapes (e.g., Brocklehurst and Whipple, 2004; Strahler, 1952). The hypsometric integral (HI) can be used in both cases to assess landscape maturity. However, if landscapes are influenced by both process domains, the interpretation of the HI gets difficult. We nevertheless calculate the HI in our study area (Fig. 17A), once for Strahler order 2 catchments and once applying a kernel-based approach on the entire Obersulzbach valley (elevation relief ratio—ERR). The size of the kernel is 1 km². The ERR is high for convex landscape patches and becomes lower with increasing concavity (Fig. 17B). The HI calculated for the irregularly shaped catchments of Strahler order 2 show a similar pattern with high HI values for hillslope-dominated catchments and low HI values for catchments that include a considerable amount of valley floor (Fig. 17A). Both the steepness index and the gradient index can be applied to identify spatial and/or temporal distortions of the drainage system and are hence very valuable tools for GIS-based geomorphological studies.

**2.05.5.5 Sediment Flux and Erosion in Mountain Areas**

GIS tools are also applied for the analysis and quantification of sediment flux. One focus in GIS-based sediment flux analysis is the issue of connectivity. Coupling of geomorphological processes and catchment connectivity are central to the efficiency of sediment flux and represent a significant impact on the sensitivity of geomorphological systems towards changes.
Fig. 16 (A) Normalized steepness index (calculated a concavity index of 0.5) for the Obersulzbach Valley. (B) Gradient index for the Obersulzbach Valley.
Fig. 17  (A) ERR for the lower part of the Obersulzbach Valley. (B) HI for the lower part of the Obersulzbach Valley.
Various approaches exist to visualize and quantify catchment connectivity using GIS tools. Indices of hydrological connectivity are presented by Borselli et al. (2008) and modified by Cavalli et al. (2013). They are based on parameters like slope gradient, flow length, surface roughness and contributing area. The tools have been applied in various environments and locations and used to discuss landform distribution and sediment flux (Gay et al., 2016; Lane et al., 2017; Messenzehl et al., 2014). Heckmann and Schwanghart (2013) apply a different approach using network analysis and graph theory to identify sediment cascades and delineate subcatchments of sediment flux. We have applied the connectivity index (IC) by Cavalli et al. (2013) to our study area (Fig. 18). The IC index depicts highly variable connectivity conditions, a generic characteristic of high mountain topography. Low connectivity areas (blue) are located in the floodplain and at footslopes. Zones of high connectivity represent flowlines mainly in channels and gullies. The index visualizes, for example, how sediment production and storage in cirques on the eastern valley side are connected, or disconnected, from the main valley and the dominant fluvial transport system of the main river.

Several approaches have been applied for sediment flux quantification in GIS. Quantification of deposits is achieved by combining surface and subsurface data on sediment depth, for example, from logging or geophysical surveying. In this approach, sediment volumes result from the difference between the landform surface and the level of various sedimentary units or the bedrock boundary. Since data from geophysical surveying or from logging often represents local information of single points or along transects, interpolation of subsurface information is required and performed using GIS tools. The density of subsurface data, the interpolation method applied as well as the resolution of the surface and subsurface data determines the accuracy of the quantification result and needs to be considered. Due to the often-limited availability of detailed subsurface data due to high efforts in both time and costs of field campaigns, these approaches usually generate information on a limited number of single landforms. Examples for single landform quantification with GIS and subsequent calculation of sediment flux or erosion rates include glacial valley fills, talus slopes, rock glaciers, or moraine deposits (Sass, 2007; Schrott and Adams, 2002). Sediment budgets of entire catchments or valley fill deposits have been generated based on interpolation of dated sedimentary layers from cores (Tunnicliffe et al., 2012), on geophysical data (Otto et al., 2009; Hinderer, 2001), or a combination of both (Götz et al., 2013).

An alternative solution to quantify sediment volumes is achieved by approximating the three-dimensional shape of the deposit or the bedrock boundary using geometric models or mathematical functions. Simple geometric shapes or power-law functions are applied for the representation of the volumetric body of landforms or the bedrock boundary, respectively (Hoffmann and Schrott, 2002; Schrott et al., 2003a). For single landforms sediment volumes of deposits or erosional features, for example, gullies, fans or talus slopes, are approximated using geometrical shapes, for example, cone sectors or prisms, that represent the landform. Volumes are quantified using the outline dimensions of the landform (height, length, width, depth) and the respective mathematical term corresponding to the geometry type (Campbell and Church, 2003; Curry, 1999; Shroder et al., 1999). Valley cross-sections and valley fill deposits of formerly glaciated terrain have been quantified using power law or polynomial functions based on the assumption that bedrock topography sculpted by glaciers can be described mathematically (Harbor and Wheeler, 1992; James, 1996). These mathematical approximations are applied to cross-sections and the results are interpolated in order to quantify entire valley sections (Schrott et al., 2003a; Jaboyedoff and Derron, 2005b).

Finally, GIS tools are applied to quantify erosion and deposition using DEM data of different points in time. Calculating DEM of differences between two surfaces results in volumetric surface changes that can be associated with geomorphologic process activity. This approach is mostly applied for rock fall processes using high-resolution LIDAR or SFM data (Rabatel et al., 2008; Rosser et al., 2005; Warrick et al., 2017; Bremer and Sass, 2012). Even though spatial resolution of the data used in the presented cases is high, the temporal resolution depends on the frequency of measurements. The resulting erosion rates thus only represent current developments. A look into past erosion and more long-term rates can be established using DEM from historical aerial imagery (Fischer et al., 2011). Micheletti et al. (2015) use seven different scenes of aerial images between 1967 and 2005 to quantify surface changes in a high mountain environment and relate their observations to decadal climate changes in their study site. Within this environment, glacial and periglacial landforms show the greatest changes in the time period. They relate phases of warming with increasing surface displacement and downwasting and identify most dynamic changes in periods of observed increased precipitation and high temperatures. Bennett et al. (2013) quantified hillslope and channel erosion using a similar approach in the Illgraben catchment (Switzerland). Here, also periods of temperature increase and pronounced frequency and magnitude of intense rainfall events are associated with the observed changes. It is important to acknowledge that the resolution of the aerial images used, as well as the accuracy of the ground control points and the software used for DEM generation, significantly determine the observable surface changes. The studies presented generated DEMs at average resolution between 0.3–0.5 m (Micheletti et al., 2015) and 2–4 m (Bennett et al., 2012).

An alternative way to quantify erosion is the approach of geophysical relief (Champagnac et al., 2007; Small and Anderson, 1998). Geophysical relief describes the eroded volume of valleys or entire mountain ranges derived from the difference between the actual surface heights and an interpolated surface connecting the highest points. The approach is used to analyze long-term landform evolution on mountain ranges and to differentiate between impacts of tectonic uplift, erosion and isostatic rebound on relief. We have applied the geophysical relief index on the study area (Fig. 19). The pattern of geophysical relief distribution in the Obersulzbach valley reveals the greatest removal in the central part above the lower step. Relief values exceed 1000 m compared to 700–900 at the lower valley level. This could hint at increased glacial erosion in this location that may be due to a longer time of glacier presence, for example, in late glacial times.
Fig. 18  (A) Connectivity index (IC) for the Obersulzbach Valley (part). The index displays distinct variation between valley floor locations and cirques. The largest changes applying are present between channels and flats (based on IC tool by: Cavalli et al., 2013). (B) Ortho image of the same area. Data from: basemap at, http://maps.wien.gv.at/basemap/1.0.0/WMTSCapabilities-arcmap.xml.
Modern quantitative geomorphological research can be regarded inextricably linked with GIS analysis. The availability of both high-resolution and global data on the land surface contributed significantly to recent fundamental advances in the discipline and opened new fields of research. Applications of GIS in geomorphology span from pure visualization approaches, landform
classification, land surface and hydrological analysis (usually derived from DEMs), process and erosion modeling, and topographic change detection to hazard zonation or susceptibility modeling. Herein, statistical analysis and spatial interpolation of field data as well as graphical visualization and map creation represent key features of GIS applied in geomorphology. Numerous topographic and geomorphological indices have been developed to study geomorphological form and process configurations using GIS techniques.

In our paper we presented a selection of GIS-based tools and indices in some classic fields of geomorphology such as fluvial, gravitational, glacial, and periglacial environments. A promising approach which has become more popular in recent years focuses on quantifying sediment fluxes and deposits using digital data. The latter can be achieved by combining surface and subsurface data on sediment depth or by comparing surface data from various points in time.

Increasing resolution of both DEM and image data, free availability of local and global data sets, and low-cost technology to generate high-resolution surface information will foster the possibilities of geomorphological analysis using GIS. Challenges, however, exist with respect to scale and the applicability of tools and parameters originally developed using data of lower resolution. High level of detail can contribute to scientific insights but may also represent noise that prevents clarity (Drăguț and Blaschke, 2006). Scale-dependency of LSPs and objects needs to be carefully considered when performing quantitative landform analysis.

References


GIS Applications in Geomorphology


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