[AM-04-055] Digital Terrain Models and Terrain Metrics

Abstract

Detailed spatial information on terrain, one of key geographical factors (if not the most crucial), is fundamental for diverse geographic analysis and simulation. Such information includes not only the basic information of elevation but also the derivations for depicting terrain characteristics from diverse perspectives, so called terrain metrics. In GIS, the terrain metrics are recorded in digital terrain models (DTMs, the representative of data models in GIS), being represented as continuous field or discrete objects. They are derived by digital terrain analysis (a representative subdomain of spatial analysis) on the DTM recording elevation (or saying, digital elevation model, short as DEM) and/or other DTMs. Diverse terrain metrics have been proposed, including the topographic attributes typically as contuous field or discrete objects. They could also be classified as those for characterizing terrain at the geometric, structural, or process level, respectively. Corresponding research on DTA has been conducted on how to depict terrain characteristics with higher accuracy, higher efficiency, and/or easier-to-use for diverse applications. This entry introduces these concepts as well as the remarks and issues within research and applications.

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Explanation

1. Introduction and Significance
2. Digital Terrain Models
3. Terrain Metrics
4. Digital Terrain Analysis for Deriving Terrain Metrics
5. Final Remarks

1. Introduction and Significance

Terrain (or topography, or “bathymetry” specifically for those under water) largely controls the movement and distribution of both materials (such as water, and soil) and energy (such as solar and wind) across the planet’s surface. It is one of fundamental (if not the most crucial) geographical factors, which directly or indirectly influences all geographical processes across diverse scales.

Therefore, detailed spatial information on terrain is fundamental for diverse geographic analysis and simulation (such as geomorphologic classification, and hydrological simulation). Such information includes not only the basic information of elevation but also the derivations for depicting terrain characteristics from diverse perspectives, so called

terrain metrics. They are widely used as important spatial variables or spatial constraints within diverse geographic models for spatial analysis, geographic prediction, or geographic process simulation.

Since the very beginning of GIS, both the record and derivation of terrain metrics have been within the core components of GIS (that is, data models and spatial analysis), and been continuously developed.

2. Digital Terrain Models

A Digital Terrain Model (DTM) is a representative of data model in GIS, which is used to record terrain information. When the original or basic terrain information is the elevation of bare-earth surface, the DTA used specifically to record the elevation is named as Digital Elevation Model (DEM). The values recorded in DEM are typically of the orthometric height to Geoid approx

imated by Mean Sea Level (Guth et al., 2021). Sometimes, often because the height observed from aerospace is elevation plus the height of surface attachment (such as tree canopy, and building roof), such observation values need to be recorded for DEM production or other specific applications (like estimation on surface biomass). The DTM recorded such height observations is so called Digital Surface Model.

There are four types of GIS data structure adopted by DEM, i.e., points, contour, Triangulated Irregular Network (TIN), and grid (or raster) (Figure 1). When the former is the more often used during the stage of DEM production, the raster type of geospatial data in GIS has several advantages to being suitable for not only DEM products but also terrain analysis. Some of the advantages include easy to present the spatially continuous field information besides spatially discrete objects, easy to store and analysis in GIS, and naturally compatible with other raster data such as remote sensing images for geocomputation and geographical modeling. Therefore, the gridded DEM is prevailing nowadays. Gridded DEMs can be generated from the elevation points (or point cloud), contours, or TINs, which are basically a kind of spatial interpolation (Hengl and Reuter, 2009; Guth et al., 2021).

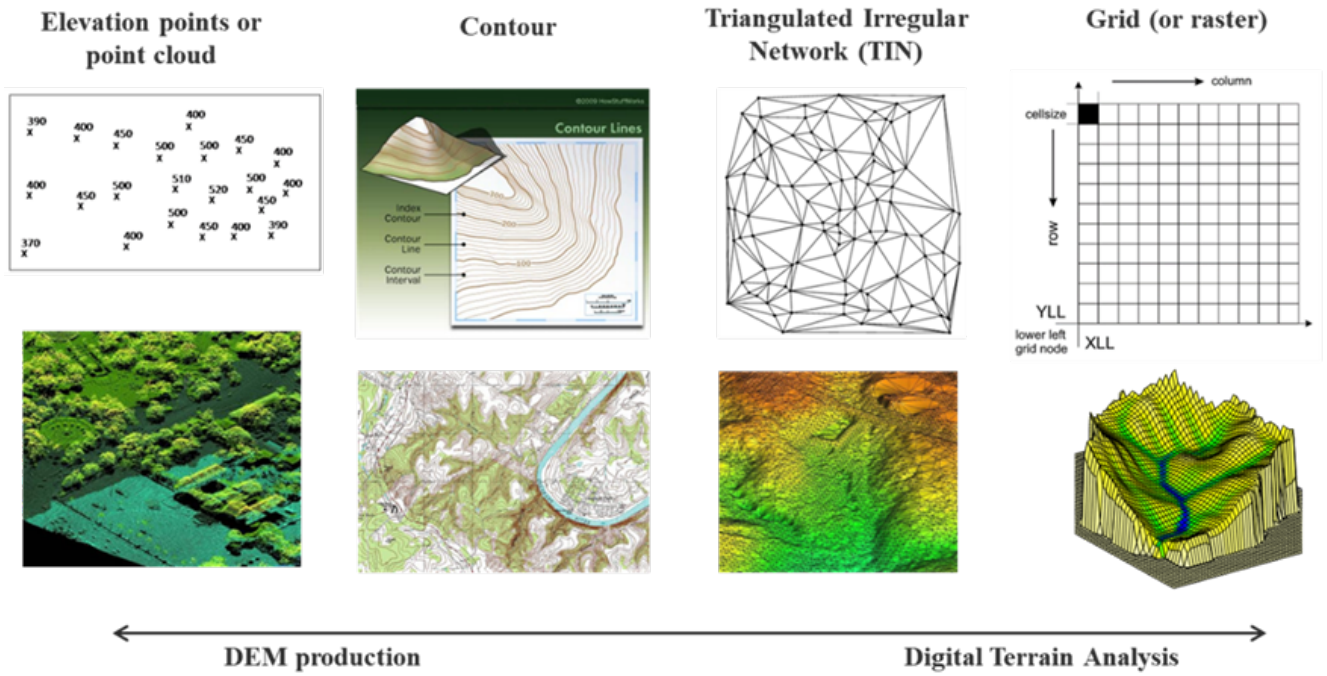


Figure 1. Four types of GIS data structure adopted by DEMs. Source: author.

Currently there are increasingly global-scale, fine-resolution, and high-precision gridded DEM products released to be available, due to the advanced spaceborne observation technologies, global elevation observation missions, and DEM production and data fusion technologies. Those readers interested in DEM are referred to the related entry and references such as Guth et al. (2021).

Correspondingly, DTMs mostly adopt grid (raster structure) for recording diverse terrain information derived from DEM data, that is, terrain metrics (some references may use other terms like terrain attributes, land-surface parameters, etc. See Wilson and Gallant, 2000; Hengl and Reuter, 2009).

3. Terrain Metrics

Diverse terrain metrics have been proposed to characterize terrain information from different perspectives. They span from those for characterizing geometric morphology (such as slope, and curvatures) to those terrain-derived indicators for characterizing other geographic factors or processes (such as topographic wetness index for indicating soil moisture, and insolation for estimating direct irradiation of solar energy) (Hengl and Reuter, 2009; Wilson, 2018). This entry cannot enumerate hundreds of terrain metrics and explain their definitions (or typical calculation algorithms), w hich can be found in textbooks such as Wilson and Gallant (2000), Hengl and Reuter (2009), and Wilson (2018).

3.1 Classification of terrain metrics

There are multiple perspectives for classification of terrain metrics (Table 1). Each of them reflects different comprehensions on terrain metrics, results in corresponding classification of terrain metrics, then may facilitate some kind of knowledge development and application, such as terrain analysis research, program implementation, and end-users' adoption in application domains.

From the perspective of representation model in GIS, terrain metrics recorded in DTMs may be generally classified as two types (the first row of content in Table 1). The first type (or saying, topographic attributes) represents some kind of terrain information (such as slope, and curvatures) typically as continuous field in gridded DTMs often with ratio- or interval-scaled values. The topographic attributes directly depict the spatial variation of terrain in details (cell-by-cell), thus are often used as spatial variables in modeling. The second type (or saying, terrain features) represents those such as peaks, drainage networks, and watershed units to be typically discrete spatial objects, often as vector (points, polylines, polygons, or networks) with nominal or ordinal values in GIS. The terrain features characterize the terrain in a more general manner of taxonomy and spatial discretization, thus are often used as the constraint on individual spatial objects or the spatial relationships between them.

Table 1. Classification of Terrain Metrics

Perspective Towards Classification	Type: Terrain Metrics
Representation model in GIS, towards a field-or-object-based classification	• Topographic attributes (as continuous field): slope gradient, curvatures, specific catchment area (SCA), drainage network density, etc. • Terrain features (as discrete objects): peaks, ridges, drainage networks, slope positions (such as backslope, and footslope), etc
Whether-or-not deriving directly from DEM only, towards a classification being Primary-Secondary topographic attributes (e.g., Moore et al., 1991)	• Primary topographic attributes: slope gradient, aspect, curvatures (such as profile curvature, plan curvature, and total curvature), etc. • Secondary topographic attributes: topographic wetness index (TWI), stream power index, etc.
Character of geocomputation algorithm design for calculating terrain metrics, towards a classification like Local-Focal-Regional-Global terrain metrics (purely following geocomputation) or more groups with other character considered (Wilson, 2018)	• Local: DoE (Difference-of-Elevation), etc. • Focal: slope gradient, aspect, curvatures, moving-window statistics on roughness, etc. • Regional: SCA, TWI, etc. • Global: relative ratio (such as quantile, and Hypsometric Integral) within global area, fuzzy landform classification, etc.
Terrain as a geographical factor influencing geographical processes, towards a classification being Geometric-Structural-Process terrain metrics	• Geometric terrain metrics: slope, aspect, curvatures, etc. • Structural terrain metrics: roughness index, drainage network density, viewshed, relative position index, Geomorphons, fuzzy slope positions, etc. • Process-oriented terrain metrics: SCA, TWI, insolation, etc.

Other widely-considered perspectives for terrain metrics classification include whether-or-not deriving directly from DEM (without other input) for differentiating the primary or secondary terrain metrics, and the perspective of character of geocomputation algorithm design for differentiating the local or regional terrain metrics (Table 1). However, such classifications depend overly on specific algorithm design and implementation of calculating terrain metrics; for example, considering that same topographic wetness index could be calculated by a simple local geocomputation with two inputs (i.e., slope gradient, and specific catchment area) or by a complex regional geocomputation with only DEM as input.

A potential perspective for terrain metrics classification might directly consider terrain as a geographical factor influencing geographical processes. The characterization of terrain at

the geometric, structural, till process level may define the type of terrain metrics correspondingly (the last row of Table 1). When the geometric terrain metrics (such as slope and aspect as the first-order deviations of terrain surface, and curvatures as the second-order deviations of terrain surface; Schmidt et al., 2003) are often with fundamental concepts across all application domains, the structural terrain metrics or process-oriented terrain metrics are often defined based on knowledge in specific geographical disciplines, such as the comprehensive landform classification based on terrain structure (e.g., Jasiewicz and Stepinski, 2013), and SCA and TWI related to hydrological processes.

The perspectives listed in Table 1 are not exhaustive. And such consideration on classification is not just a brain game but could promote our understanding of not only terrain metrics but also spatial analysis.

3.2 Some remarks on using terrain metrics

- Remark 1: Pay attention to the units! For same terrain metrics, the values recorded in DTM could be with different units. For example, slope values could be of degree, percentage, or unitless (for the tangent of slope). SCA should adopt the unit of m2/m according to its definition, however might adopt the unit of cells or even m2 (of catchment area but SCA) in practical implementations.
- Remark 2: Pay attention to the numeric features of terrain metrics! For example, the aspect with the unit of degree is a periodical variable with a value range of 0˚~360˚. Aspect of 0˚ is thesame as the aspect of 360˚. This means the statistics of a simple mean value of aspect is nonsense. Also note that curvature metrics (such as profile curvature, and plan curvature; unit: m-1; Shary et al., 2002) normally have a distribution with very high frequency near 0 and very long bidirectional tails. While the mathematical straight is with s zero value of curvature, and convex (or concave) for positive (or negative) values of curvature, it does not simply mean if the terrain was straight. The straight of terrain should be with a curvature value of 0 or very close to 0 (such as between ±0.0001 m-1, depending on real terrain characteristic as well as specific curvature calculation). Besides, if the curvature grid needs to be transformed such as normalization required during application, it would not be a good practice if simply using a linear transform to new value range such as [-1, 1] or [0,1], because the original zero value of curvature would not be kept to be 0 or the middle of value range after transformation.
- Remark 3: Unlike DEM products, products of most other terrain metrics may be unnecessary and impractical (even improper) to prepare in advance. Each of those terrain metrics can be derived by DTA on DEM, meanwhile there hardly is “standard” product due to the appropriateness of different algorithms with different DEM data in real applications. Therefore, it is more practical to conduct DTA to derive most of terrain metrics. A few possible exceptions include some key terrain features (such as drainage networks, and watershed segmentation), because they are so-widely used as spatial constraints consistently in cross-scale analysis and modeling.

4. Digital Terrain Analysis for Deriving Terrain Metrics

DTA, as a representative subdomain of spatial analysis, is the geospatial analysis for deriving diverse terrain metrics from DEM and/or other DTMs, including those

transformation between different terrain metrics (such as the transformation between topographic attributes and terrain features, as mentioned above in Section 4; Figure 2). In a broader sense, DTA can also include some processes (such as data fusion) of DEM production, as well as some exploratory methods of using terrain metrics in application domains (such as digital soil mapping, and hydrological modeling). Geomorphometry is a disciplinary term as DTA, but proposed later (Pike, 2000; Hengl and Reuter, 2009). Since the beginning of GISys, DTA has been one of key components of spatial analysis in GIS (e.g., O'Callaghan and Mark, 1984), when terrain analysis can be traced far back to the beginning of geomorphology or geodesy.

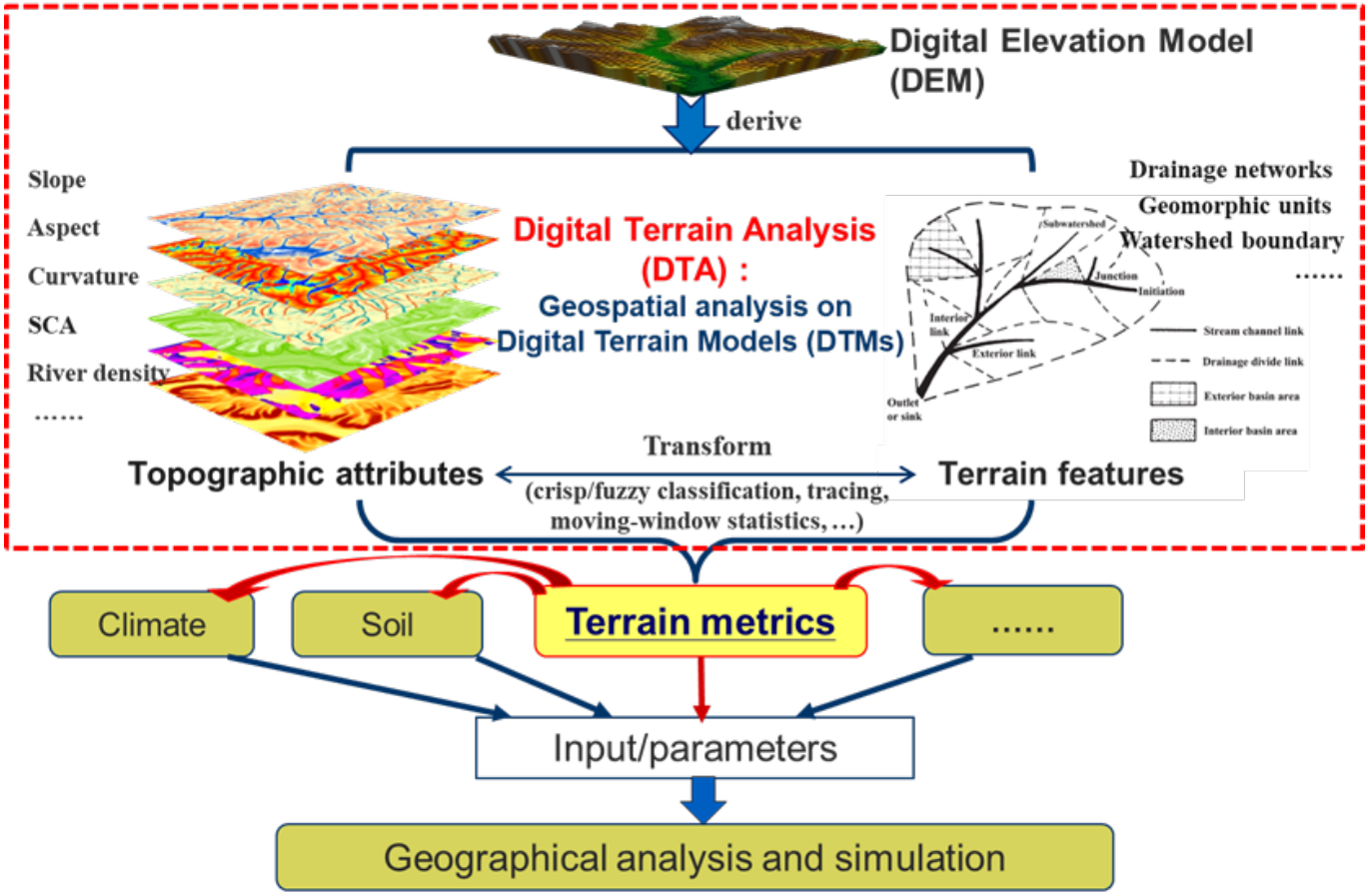


Figure 2. Digital terrain analysis (DTA) is the geospatial analysis on Digital Terrain Models (DTMs) for deriving diverse terrain metrics. Source: author.

4.1 Tools of digital terrain analysis

In general, every GIS software has spatial analysis functionality including DTA. Note that DTA functions in GIS may often implement those classic algorithms and comparatively lag for including those updated DTA algorithms, with reasonable concerns. For example, when multiple flow direction algorithms have been proposed since 1990 and frequently suggested on the improvement by new publications, ArcGIS software started to provide multiple flow direction analysis since its version of 10.6 released in 2018, which implemented the multiple flow direction algorithm published in 2007 (Qin et al., 2007).

Comparatively, those DTA-centered tools such as Whitebox GAT focus on implementing those updated and/or abundant DTA algorithms. They are inclined to be open-source or free with a research community style.

When DTA is widely adopted to support diverse application domains, those tools for specific application domains (such as ArcSWAT for hydrological modeling) often implement the required DTA functionality.

4.2 Some remarks on conducting digital terrain analysis

- Remark 1: Mind the appropriateness of preparing the input data for DTA in real applications. For example, DEM-preprocessing of removing the pits and flats in DEMd is necessary to prepare a hydrologically-correct DEM for flow direction analysis and deriving those related terrain metrics such as SCA, and TWI (Wang et al., 2019). Other examples include local average filtering on DEMd for relieving the unwanted fine-scale roughness, and upscaling/downscaling the original DEM resolution to be appropriate for applications (Hengl and Reuter, 2009).
- Remark 2: DTA results are scale-specific. Even with the same DTA algorithm, the results may vary from the appropriate to completely wrong due to not only the scale of the spatial resolution of DEM, but also the scale of the analysis window size. For example, for deriving the slope gradient for hillslope-scale analysis (such as soil property prediction), slope calculation with an analysis window of 3-by-3 cells on a DEM with a 1-cm resolution may be very precise but cannot be appropriate; however that with a 3-by-3 window on a 10-m DEM or that with a thousand-by-thousand window on the 1-cm DEM can make sense. Similar examples include relief or roughness calculations for geomorphologic analysis.
- Remark 3: Mathematical precision does not mean geographical accuracy or reasonableness. Consider the example of slope calculation presented in the former remark, and that on what value (or value range) of a curvature means a straight slope, as presented in Remark 2 in Section 3.2.
- Remark 4: For each terrain metric (or DTA tasks), there are normally diverse DTA algorithms to choose but there is no single best one fpr all application contexts. This depends on persistent DTA research on both DTA algorithm design and evaluation of DTA performance to derive terrain metrics across different application contexts, as presented in next subsection.

4.3 Research dimensions and main topics in digital terrain analysis

In general, DTA research has been conducted on three dimensions, that is, how to depict terrain characteristics with higher accuracy, higher efficiency, and easier-to-use for diverse applications (Figure 3).

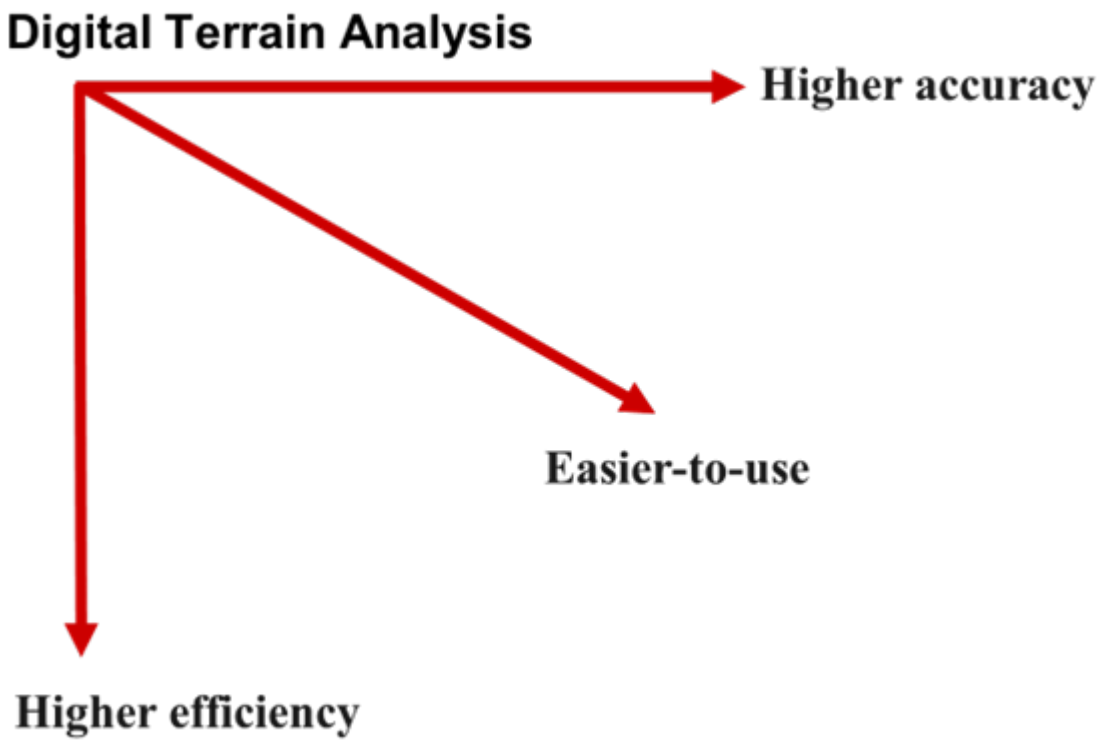


Figure 3. Research dimensions of digital terrain analysis. Source: author.

A first research dimension: higher accuracy

Like all subdomains of spatial analysis, the primary research dimension of DTA is on accuracy. Note that here the accuracy also includes the applicability across wide or specific terrain conditions (or application contexts in a broader sense) with acceptable accuracy, even further including enough information on the errors or uncertainty provided together with the results of terrain metrics under interest.

Research topics on how to depict terrain characteristics with higher accuracy includes two classes. The first is to design more accurate algorithms for deriving terrain metrics. For those existing terrain metrics, existing DTA algorithms could be further improved for higher accuracy, especially adaptive to diverse terrain conditions or application contexts in a broader sense. When existing terrain metrics cannot well meet applications, new types of terrain metrics could be proposed, and then new methods of not only deriving them but also how to apply them successfully within application domains should be explored (e.g., fuzzy slope positions and their innovative application; Zhu et al., 2021). Future research efforts on new terrain metrics might be mainly on new structural terrain metrics like comprehensive and hierarchical landform classification, spatial structural information of hierarchical units, and corresponding information on their spatial transition.

The second class of research topics on higher DTA accuracy is to evaluate the different DTA algorithms for revealing the knowledge on their accuracy, behavior or applicability scope. For those terrain metrics with clear mathematical solutions (mainly geometric terrain metrics, such as slope and curvatures), the precise true values are comparatively available for evaluating the error from the DTA algorithms (e.g., Florinsky, 1998). However, many terrain metrics (mainly those structural terrain metrics or process-oriented terrain metrics; see Table 1) are hard to get the ground true values. Correspondingly, new evaluation

methods should be designed to detailedly evaluate the behavior and performance of different DTA algorithms (Qin et al., 2013). For the evaluation on other aspects such as the uncertainty due to error in DEM, and parameter sensitivity, when mathematical analytical methods could be available for some terrain metrics, the simulation experiment methods (such as Monte Carlo simulation) are universally applicable, especially when advanced geocomputation ability may settle down the accompanying efficiency issue on explosive computation amount.

A second research eimension: higher efficiency

When DTA and the resulted terrain metrics are increasingly applied to wide applications in large areas with higher spatial (and temporal) resolutions, often in a scenario simulation way required plenty of repetitive executions, the computing efficiency issue on DTA is challenging for applicability of DTA. When the fine design on data structures and algorithms for DTA in serial programming has the limit on its applicability, parallel computing with advanced computing architectures is promising for the research dimension on higher efficiency of DTA.

Two types of research have been conducted on this research dimension. The first is specific to individual DTA algorithms, that is, designing the parallel algorithm for an individual DTA algorithm based on a specific kind of parallel programming model for specific parallel computing platform (such as CUDA for general-purpose GPU, or MPI for computer cluster). Such way needs much more engineering efforts instead of DTA research, after some pioneering works were exemplified (Wilson, 2018). It is also hard to meet the increasing requirement when new DTA algorithms will be proposed continuously. A promising and more general solution is to develop parallel computing strategy which may support those serial-computing DTA algorithms to be compatible with different parallel computing platforms. Such a research topic is beyond DTA and towards general geocomputation in GIS (Wang et al., 2022).

A third research dimension: easier-to-use DTA

Note that DTA in real applications is a typical geographical modeling process, that is, to build a DTA workflow (involving the coupling of multiple DTA tasks, the selection of DTA algorithm for each task, and the corresponding parameter-settings) appropriately for specific application context (including such as target task, characteristics of the study area, data availability, etc.). Such a model-building process is highly depended on modeling knowledge on DTA, especially those so-called “application-context” knowledge which is often non-systematical and implicit tacit knowledge (Qin et al., 2016). When existing DTA tools (as well as GIS software) still cannot automatically use such knowledge to assure the built DTA model to be not only executable but also appropriate for resulting in accurate terrain metrics for specific application context, there is a “digital divide” to prevent DTA to be easy-to-use for vast users (especially those DTA novices) in wide applications. Therefore, it is the top of future needs and opportunities to research how to effectively mine the application-context knowledge and use them to achieve easier-to-use DTA (Qin et al., 2016; Wilson, 2018).

Such a research topic is beyond DTA and actually on whole geographical modeling domain with similar characteristics and issue (Qin and Zhu, 2022). Although currently emerging large language models are explored to act as AI agent to couple spatial analysis tasks to be

a workflow for solving different types of geographical (modeling) questions, they would hardly solve this issue alone. The research dimension on easier-to-use DTA (or further, spatial analysis) requires more research efforts based on the legacy of not only the domain-knowledge-based tradition in GIS research but also the models and corresponding modeling knowledge in GIS.

5. Final remarks

Terrain mettrics are terrain information recorded in DTMs, and are derived by digital terrain analyses on DEM and/or other DTM. DTA is a representative subdomain of spatial analysis. These concepts as well as their implementation are core components in GIS. This entry introduces these concepts as well as the remarks and issues within DTA reserach and applications. While presented in this entry with a focus on DTA, the reearch dimensions and some research topics are common for spatial analysis and even GIS.

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