

Chinese progress in geomorphometry

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Abstract: Geomorphometry, the science of digital terrain analysis (DTA), is an important focus of research in both geomorphology and geographical information science (GIS). Given that 70% of China is mountainous, geomorphological research is popular among Chinese scholars, and the development of GIS over the last 30 years has led to significant advances in geomorphometric research. In this paper, we review Chinese progress in geomorphometry based on the published literature. There are three major areas of progress: digital terrain modelling methods, DTA methods, and applications of digital terrain models (DTMs). First, traditional vector- and raster-based terrain modelling methods, including the assessment of uncertainty, have received widespread attention. New terrain modelling methods such as unified raster and vector, high-fidelity, and real-time dynamic geographical scene modelling have also attracted research attention and are now a major focus of digital terrain modelling research. Second, in addition to the popular DTA methods based on topographical derivatives, geomorphological features, and hydrological factors extracted from DTMs, DTA methods have been extended to include analyses of the structure of underlying strata, ocean surface features and even socioeconomic spatial structures. Third, DTMs have been applied to fields including global climate change, analysis of various typical regions, lunar surface and other related fields. Clearly, Chinese scholars have made significant progress in geomorphometry. Chinese scholars have had the greatest international impact in areas including high-fidelity digital terrain modelling and DTM-based regional geomorphological analysis, particularly in the Loess Plateau and the Tibetan Plateau regions.

Keywords: geomorphometry; digital terrain model; digital terrain analysis; progress; China

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1 Introduction

Terrain is considered one of the most important natural geographical factors. Explicit analysis of terrain is the core focus of geographical research, and it is important in geomatics, cartography and geomorphology. With the development of geographical information science (GIS), terrain research has undergone a revolution from qualitative surface description to quantitative terrain modelling and analysis. Terrain research now relies on digital terrain models (DTMs), which combine the digital expression of surface morphology with digital information on terrain for geo-analysis and have been used to simulate the earth's surface (Tang *et al.*, 2005).

Geomorphometry is the science of digital terrain modelling, analysis and quantitative land surface analysis (Hengl and Reuter, 2008). It is considered a digital information processing technology for calculating terrain derivatives, extracting terrain features and conducting geo-analysis based on DTMs (Zhou and Liu, 2006). Many studies in earth information science have focused on the basic theory, methodology and applications of geomorphometry. After several decades of research, many of the basic theoretical problems of geomorphometry (including digital terrain modelling, DTA methods, and the accuracy and scale of DTA) have been addressed, and DTM-based DTA theory and methodology have gradually matured. At the same time, the advantages of DTMs (such as their simple data organization, direct expression of terrain, easy and effective extraction of terrain derivatives, and diversity of data sources) have led to the application of DTA methods in many domains of geoscience, including geomorphology, hydrology, and soil science. These DTA methods also have societal uses such as surveying and mapping, water and soil conservation, the monitoring and control of hydrogeological disasters, and land use planning and management (Tang, 2014).

In recent years, Chinese scholars have made significant progress in geomorphometry research with the support of various funding agencies, especially the National Natural Science Foundation of China. In this paper, we systematically summarize and analyse research achievements and progress in the field of geomorphometry in China. First, we summarize DTM methods, including both traditional and more recent terrain modelling approaches. Second, we discuss various DTA methods to achieve a comprehensive understanding of geomorphometry. These methods are not confined to traditional DTA methods of extracting terrain derivatives and geomorphological and hydrological features; they also include methods for analysing strata structure, ocean dynamics and even socioeconomic spatial structures. Third, we review the applications of geomorphometry to demonstrate the capabilities of DTA. Based on these achievements and progress, we also discuss the future direction of geomorphometry.

2 Methods of digital terrain modelling

2.1 Traditional data models and structure

2.1.1 Vector-based digital terrain modelling

DTMs have been defined as the digital simulation of land surfaces using limited surface elevation data; they are also called digital elevation models (DEMs) (Tang *et al.*, 2005). Wang *et al.* (2004) summarized the data models used in DEMs and classified them into six

different types: discrete point-based, contour-based, triangular irregular network (TIN)-based, profile-based, grid-based, and hybrid DEMs. The first four types are vector-based DTMs, the latter two are raster-based DTMs.

Among the vector-based DTMs, discrete point DEMs involve a terrain model in which the surface is expressed as discrete points; each point is stored and organized based on its x, y and z coordinates. Contour DEMs are mainly digitized from existing topographical maps in which the elevation is recorded by contour lines. TIN DEMs are a type of model in which elevation is recorded using a triangular irregular network composed of nodes, arcs and polygons. TIN DEMs rely heavily on the use of triangulation algorithms. Many triangulation algorithms and methods of rapidly updating them have been proposed for the construction of TIN DEMs in China. These include the mathematical morphology-based approach (Li and Chen, 1990) and the constrained data set-based approach (Liu and Gong, 2001). Finally, profile-based DTMs record the coordinates of points on the profile using either varying distance intervals or the same time intervals.

Currently, TIN-based DEMs appear to be the most appropriate vector-based DTM method for describing the true surface of a terrain because they can preserve detailed terrain information by using both hard and soft lines. However, the complex data structure and calculations required by this method, as well as the difficulty in integrating the method with remote-sensing (RS) imagery, means that vector-based DTMs are always converted or interpolated to raster-based DTMs.

2.1.2 Raster-based digital terrain modelling

Raster-based digital terrain modelling involves organizing an area into a series of cells that are distributed in space. These cells are generally regular grid cells or spheroidal equiangular cells (Florinsky, 2017). Regular grid-based DTMs are now the most popular type of DTM. This variety of model records the elevation (z) as the attribute of the cell and stores the x and y coordinates as the row and column numbers of a matrix. The data structure of regular grid-based DEMs has been widely accepted because of its simplicity, ease of storage and easy integration with RS imagery.

Most regular grid-based DTMs are constructed using interpolation and digital photogrammetry approaches. Chinese scholars have contributed significantly to both approaches. Interpolation can be divided into global interpolation, local interpolation and point-by-point interpolation (Tang *et al.*, 2005). The global interpolation method is rarely used in constructing DTMs because it is concerned with large-scale terrain features and ignores local terrain characteristics. However, many local interpolation methods have been proposed by Chinese scholars, including the dual spline function (Wang *et al.*, 2000), the Coons surface (Chen *et al.*, 2012; Wang *et al.*, 2008), and the polyhedral function (Lv, 1981). Research on point-by-point interpolation has mainly focused on the selection of interpolation functions and the determination of input parameters and weights (Dong *et al.*, 2013).

In addition to the traditional interpolation approaches described above, other interpolation approaches for constructing DEMs have been proposed, including Map Algebra DEM (MADEM) (Hu *et al.*, 2007a, 2007b) and High Accuracy Surface Modelling (HASM) (Yue *et al.*, 2007). MADEM is a linear interpolation on a horizontal projection along the line of steepest descent. The method can fully utilize all sampled elevation data and therefore its

accuracy exceeds that of traditional methods such as TIN, kriging, and inverse distance weighted (IDW) (Hu *et al.*, 2007a). The HASM method constructs a DEM by using discrete points and contours based on the fundamental theorem of surfaces (SMTS) (Yue *et al.*, 2007). The HASM method significantly increases DEM accuracy compared to traditional TIN methods (Chen and Yue, 2010; Yue *et al.*, 2007). In addition, the HASM method can also be applied to real-time dynamic simulations (Yue, 2011).

Digital photogrammetry is another popular method of constructing DTMs. The photogrammetric method involves processing overlaid digital images to produce DTMs from orthophotographic maps (Zhang and Zhang, 1996). The specific process includes calculation of directed parameters, automatic aerial triangulation, epipolar image resampling, image matching, and final DTM production. The development of RS imagery has led to greater use of the digital photogrammetric method to produce DTMs because the RS data acquisition process is more efficient than traditional field survey methods. The VirtuoZo digital photogrammetry system, which was created by Chinese scholars, is famous worldwide (Zhang *et al.*, 2000). Chinese scholars have also discussed the selection of features for image matching (Wang, 2005), quality controls for producing DTMs (Du, 2009; Long *et al.*, 2011), and determining the resolution for expressing DTMs (Wang, 2013) during the DTM construction process.

2.2 High fidelity-based digital terrain modelling

Among traditional vector- and raster-based DTM types, regular grid-, contour- and TIN-based DTMs are often used in geological research. These models meet the basic requirements of geo-applications in expressing surface morphology. However, many geographical objects have complicated surface morphologies. One example is a complex landscape that includes both areas of gradual and rapid topographic change. While vector-contour DTMs can only provide general information about topography, the vector TIN method can describe areas with gradual and rapid changes. However, the TIN data structure and calculations process are complex and cannot be accurately extended over large areas. Interpolated regular-grid DEMs are restricted by the similarity presupposition of the First Law of Geography. That is, interpolated DEMs are more suitable for expressing surfaces characterized by gradual change, and areas with sudden changes in relief (including specific geomorphological features) are often ignored. Photogrammetric regular-grid DEMs are constructed from overlaid orthophotographic images, and many types of surface information cannot be acquired by orthophotographic cameras. In addition, photogrammetric DEMs often do not reproduce geomorphological features such as ridge lines and gully networks, even though these features are sampled during the image-matching process used to produce the DTM. To compensate for this issue, algorithms should be proposed to extract geomorphological features from photogrammetric DTMs during the digital terrain analysis process.

2.2.1 Point-by-point high fidelity modelling based on TINs

The problems with the traditional DTM types described above demonstrate that current DTM data models cannot meet the need for high-fidelity terrain modelling and terrain analysis. Instead, high-accuracy applications in complex areas require a high-fidelity-based digital terrain modelling method. To resolve the inability of regular-grid DTMs to express

terrain features, many Chinese scholars have developed high-fidelity DTMs using the TIN method, which includes all points and topographical features. Such DTMs include feature-preserved DTMs (FP-DTM, Wang *et al.*, 2009), plain river network area-oriented DTMs (Gao, 2010), and terraced DTMs (Zhu *et al.*, 2011; Zhao *et al.*, 2013). These hybrid DTMs combine or overlay high-accuracy vector DTM data with grid DTM data, resulting in higher fidelity terrain expression. Similarly, a unified raster- and vector-based digital terrain modelling method has been developed, retaining the advantages of both raster and vector data structures and preserving the terrain features (Gong, 1992). This concept has been explored using different data structures (Chang and Liu, 1998; Wang and Teng, 2010). However, due to its complex data structure, more development is needed before this novel DTM data model can be applied in practice.

2.2.2 Point-by-point high-fidelity modelling based on point cloud

LIDAR point clouds are another data source for high-fidelity digital terrain modelling. These point clouds, which represent a surface, are acquired using an on-board, truck-mounted, or ground-based laser scanner. The points are then connected to construct high-fidelity DTMs using approaches such as propinquity rules (Cheng *et al.*, 2013; Wang and Guo, 2012; Wang and Hu, 2012; Zhang *et al.*, 2009). The resulting DTMs have highly detailed geometric structures due to the high density of points in the LIDAR point cloud.

With the development of photogrammetry, new photogrammetric methods for constructing high-fidelity DTMs have become available in China. These include oblique photogrammetry, close-range photogrammetry, and LIDAR point clouds measured by 3-D laser scanners. Oblique photogrammetry, which differs from vertical aerial photogrammetry, is an oblique photographic technology in which images are acquired with multiple digital cameras on a single platform. These cameras are placed at specific angles with respect to the ground. These images acquired at different angles allow for the construction of DTMs and other geographical products by matching images from various view directions (Tian *et al.*, 2013; Zhang *et al.*, 2017). Oblique photographic technology avoids common vertical aerial photographic problems such as blind angles and covered objects. Thus, this technology could play a valuable role in constructing high-fidelity DTMs as well as other GIS products for environmental monitoring (Li *et al.*, 2015).

The popularity of digital cameras has made close-range photogrammetry another research focus in photogrammetry and computer vision (Zhang and Zhang, 2005). This method involves acquiring images or video from cameras with different viewpoints using either intrinsic parameter calibration or non-calibration. In the intrinsic parameter calibration method, density surface points are identified and polygon feature-based image matching is used to construct high-fidelity DTMs (Jia and Li, 2014; Ke *et al.*, 2009; Zheng and Zhou, 2012). In the non-calibration method, feature extraction is performed first, followed by image-matching; finally, the structure from motion (SFM) method is used to capture points and construct high-fidelity DTMs (Jiang *et al.*, 2008; Ling *et al.*, 2012; Xiao *et al.*, 2009).

2.3 Real-time dynamic geographical scene modelling

Real-time dynamic geographical scene modelling is generally thought to be distinct from geomorphometry in GIS. However, the terrain surface, which forms part of a geographical

scene, can also be constructed when modelling the geographical scene. Thus, real-time dynamic geographical scene modelling can use the photogrammetric methods described above (see section 2.2) to digitally construct geographical scenes after surveying or taking multiple videos of a scene.

Various models, including geometrical models, image models, voxel models and point cloud models, have been used to express a geographical scene using the photogrammetric method of multiple surveying. However, the geographical scenes expressed by these models are always static and can therefore only be used to obtain simple geometrical measurements (Chen *et al.*, 2015; Li *et al.*, 2014; Liao *et al.*, 2014; Zhang *et al.*, 2015). Therefore, video-based real-time dynamic geographical scene modelling is being pursued by Chinese scholars.

Recent achievements in video-based real-time dynamic geographical scene modelling include 3D self-adapted scene construction using videos, the geographical positional method of constructing 3D scenes from videos, feature extraction and modelling of targets in videos, and integration and expression of multiple geographical data and video 3D geographical scenes (Dong *et al.*, 2014; Hu *et al.*, 2014; Liang *et al.*, 2013; Liu *et al.*, 2014; Wang *et al.*, 2014; Zhen *et al.*, 2014). In addition, portable devices, such as mobile phones, are being used to update local geographical scenes. These achievements represent a unique research direction both in real-time dynamic geographical scene modelling and in real-time dynamic terrain modelling of geomorphometry.

3 Methods of digital terrain analysis

3.1 Extraction of terrain derivatives

Terrain derivatives (also called terrain factors) are parameters or indices with specific geographical meanings that can be used to investigate surface morphology characteristics. The extraction of terrain derivatives is a core research focus of DTA. Algorithms for various hill-slope-based terrain derivatives have been developed using DEMs and are now being refined. In addition to traditional hillslope-based terrain derivatives (slope, aspect, plan curvature, profile curvature, slope length, terrain roughness, terrain relief, elevation variation coefficient, and terrain cut depth) (Yang *et al.*, 2009), Chinese scholars have proposed new terrain derivatives and algorithms based on local geographic characteristics and their specific research needs. These include the terrain information content (Dong and Tang, 2012; Tao *et al.*, 2010), terrain complexity index (Wang *et al.*, 2004), terrain driving force (Li and Tang, 2006), potential factor for water erosion (Liu *et al.*, 2012), erosional slope length and regional slope length factor (Zhang *et al.*, 2012; Zhang *et al.*, 2013), and others. These results significantly enrich the usefulness of terrain derivatives.

Because so many terrain derivatives have been proposed, various authors have classified all terrain derivatives into several main types (Tang *et al.*, 2005; Zhang, 2013; Zhou and Liu 2006). For instance, Zhang (2013) categorized terrain derivatives according to their application, calculation methods and scale characteristics. This work provided an important basis for improving analytical efficiency and applying terrain derivatives. In addition, the algorithms used for terrain derivatives, including algorithms for slope, slope aspect, terrain roughness and terrain relief, have been refined by many Chinese scholars (Chen *et al.*, 2008;

Lang *et al.*, 2007; Tao and Tang, 2011; Xie *et al.*, 2013; Zhao *et al.*, 2012). Suitable window size and the optimal scale for extracting slope have also been discussed (Liu *et al.*, 2009; Zhao *et al.*, 2012).

The terrain derivatives discussed above can express terrain characteristics for a pixel and even a local area, and these characteristics can then be used to determine large-scale patterns and landform spatial structures. However, these pixel-based terrain derivatives have significant limitations with regard to analysing the characteristics of large-scale landforms. Therefore, Chinese scholars have developed several new methods to describe large-scale landforms. For instance, the slope spectrum method (Tang *et al.*, 2008) uses a second-order terrain derivative that reflects the characteristic slope in a specific area. Similarly, the catchment profile spectrum (Zhang, 2011) and the hypsometric integral spectrum (Zhu *et al.*, 2013) were developed to investigate large-scale landforms on the Loess Plateau of China. Other studies have focused on terrain texture and slope-landscape structure to better understand how landform morphology variations are generated (Liu *et al.*, 2012; Sun, 2011; Zhao, 2012).

3.2 Extraction of geomorphological features

Geomorphological features are specific features (geomorphological points, lines and polygons such as peaks, saddles, ridges, and gullies) on the land surface that can help recognize and classify landform types. These features control the spatial geomorphology of an area and are therefore important components of surface morphology.

Chinese scholars have proposed several methods of extracting geomorphological points from DEMs. Some examples are the extraction of surface peaks from reverse DEMs (Zhong *et al.*, 2009), the extraction of stream runoff nodes (Yi *et al.*, 2003), and the extraction of saddles based on runoff concentration simulations or extreme elevation points along watershed boundaries (Kong *et al.*, 2013; Xiong *et al.*, 2013; Zhang *et al.*, 2011). Gully knick-points can be extracted using the energy accumulation and the gully profile (Bi *et al.*, 2011; Liu *et al.*, 2013), and this information can be used to infer gully formation processes and related tectonic activity (Sun *et al.*, 2012; Zhang *et al.*, 2012). Gully head points have also been extracted based on geomorphological structures (Jiang *et al.*, 2014). In addition, Luo (2008) proposed the concept of terrain feature point clusters, which can be determined from the spatial relationships between geomorphological points. These point clusters can be used to classify landforms based on the organization of peaks, stream runoff nodes and saddles. Peak clusters were also used to identify upland planation surfaces (Xiong *et al.*, 2017a)

Chinese scholars have also made significant progress in methods for the extraction and analysis of geomorphological line features. Ridge and gully lines are the most typical line features and represent major terrain structures; thus, methods for their extraction have received much attention. These methods can be divided into data source-based and algorithm principle-based methods. In the former, the data sources used for ridge and gully line extraction include contour maps (Jin *et al.*, 2006; Zhang *et al.*, 2013), TIN (Ai *et al.*, 2003), grid DEMs (Chen and Liu, 2001; Kong *et al.*, 2012; Zhou *et al.*, 2007) and LIDAR point clouds (Li *et al.*, 2013). In the latter, the algorithms include flow direction-based methods, image-based methods, surface morphological structure-based methods, or a combination of surface morphological structure and flow direction methods (Huang, 2001; Luo, 2008; Zhou

et al., 2007).

The extraction and analysis of geomorphological line features are also a focus of research regarding the Loess Plateau of China and especially the area's loess shoulder line. The loess shoulder line is considered an important geomorphological boundary for classifying loess landform units and representing loess landform morphological characteristics (Xiong *et al.*, 2014c). Therefore, methods for extracting the loess shoulder line are a major research focus in DTA of the plateau. To improve the accuracy and efficiency of loess shoulder line extraction, Chinese scholars have proposed a series of methods for extraction of the loess shoulder line, including methods based on slope variation (Zhu *et al.*, 2003), flow path characteristics (Liu *et al.*, 2006), morphological structure (Lu *et al.*, 1998), LOG edge detection (Yan *et al.*, 2011) and a snake model (Song *et al.*, 2013; Zhou *et al.*, 2013).

In recent years, many Chinese scholars have investigated geomorphological polygon feature extraction. Research achievements in this area have mainly centred on positive and negative terrain extraction in loess landforms (Chen *et al.*, 2012; Zhou *et al.*, 2010a; Zhou *et al.*, 2010b), upland planation surfaces extraction on the Tibetan Plateau (Xiong *et al.*, 2017a), and fenglin and fengcong landform extraction in karst landforms (Huang *et al.*, 2014; Liang and Xu, 2014; Xue *et al.*, 2009). In addition, object-based image analysis (OBIA) methods have been used to classify geomorphological polygon features, leading to a new area of landform classification research (Zhao *et al.*, 2017).

3.3 Watershed hydrology-based DTA

Watershed hydrology is a key issue in both geomorphometry and geography. Surface morphology profoundly affects water flow generation and routing in watershed hydrology. In addition, differences in terrain features can lead to spatial differences in hydrological characteristics. The topological relationships and geometrical shapes of terrain features directly influence the properties of a watershed (Ren and Liu, 2000). Chinese scholars have mainly addressed two aspects of watershed hydrology-based DTA, static analysis of hydrological characteristics and dynamic modelling of hydrological processes. The former aspect addresses hydrologically correct DEMs (Yang *et al.*, 2007), methods of processing DEM data from flat areas and depressions (Xie *et al.*, 2005; Xu *et al.*, 2007), the design of flow model and flow routing algorithms (Chen *et al.*, 2014; Qin *et al.*, 2007; Xiong *et al.*, 2014c; Zhou *et al.*, 2011), and the extraction of hydrological feature objects (Yi *et al.*, 2003; Zhu *et al.*, 2012). The latter aspect concerns methods of constructing distributed hydrological models (Wang *et al.*, 2002), the effects of DEM scale on hydrological models (Gao and Jin, 2012), and how different watershed delineation strategies influence the simulation of hydrological processes (Qiu *et al.*, 2012; Zhang *et al.*, 2004). A specific research direction in watershed terrain analysis concerns the delineation of watersheds by DEMs and the detailed terrain characteristics of watersheds. This research direction takes the watershed as a basic statistical unit and strives to create a hierarchical structure pattern of topographical, geomorphological and hydrological features at different watershed scales with the goal of characterizing geographical and hydrological processes in a reasonable way (Xiong *et al.*, 2016a).

In recent years, a series of hydrological models have been introduced based on GIS and geomorphometry (Guo *et al.*, 2000; Li *et al.*, 2009; Li *et al.*, 2011; Ren and Liu, 2000; Wang *et al.*, 2002; Zhang *et al.*, 2004). These models aim to dynamically simulate hydrological

processes in different areas and on different scales (Liu *et al.*, 2003; Wan *et al.*, 2010; Wang *et al.*, 2008). Because terrain analysis is closely related to hydrological modelling, investigating the role of terrain analysis in hydrological modelling could help use terrain factors to support the development of hydrological models and expand the applications of terrain analysis methods to hydrology.

3.4 Strata structure-based DTA

As geospatial simulation science advanced, research in geomorphometry has expanded to include terrain modelling and analysis of underlying strata. The investigation of underlying strata gradually came to represent a specific research direction in geomorphometry. Currently, strata structure-based DTA includes modelling of the underlying strata and terrain analysis of the strata. Chinese scholars have used a variety of 3D geological modelling methods to model the underlying strata (Li *et al.*, 2013). These methods can be divided into data source-based methods and spatial simulation function-based methods. Data source-based methods reconstruct the underlying strata using information from drilling (Liu *et al.*, 2009; Lin *et al.*, 2013; Wu *et al.*, 2007; Zhu *et al.*, 2004), geological profiles (Cheng *et al.*, 2007; Guo *et al.*, 2009; Ma and Guo, 2007; Ming *et al.*, 2008; Wang *et al.*, 2003; Zhou *et al.*, 2013), seismic data (Ma *et al.*, 2003; Xiong *et al.*, 2016b; Zhao and Lin, 2010), or the integration of multiple data sources (Wu *et al.*, 2005; Zhong *et al.*, 2007; Zhou *et al.*, 2007). In contrast, reconstruction of underlying strata using spatial simulation functions involves surface simulation with discrete or incomplete data using some mathematical function, such as linear TIN, IDW, spline, natural neighbour interpolation, or kriging. All these functions can be used to simulate the strata, which are then analysed to understand landform evolution processes.

Using reconstructed strata, Chinese scholars have also conducted terrain analysis of the strata themselves and the relationship between the strata and the modern surface (Cheng *et al.*, 2010; Xiong *et al.*, 2014a, 2014b). For instance, the landform inheritance characteristics of loess areas was explored by comparing reconstructed strata underlying the loess to the current loess landforms (Xiong *et al.*, 2014a). In addition, two terrain derivatives, the terrain-relief change index (TRCI) and the bedrock terrain controllability index (BTCI) were proposed to explain the spatial variation of loess deposition landform evolution and loess gully formation (Xiong *et al.*, 2016a; Xiong *et al.*, 2017b).

3.5 Ocean dynamics-based DTA

The surface of the ocean offers another interesting surface morphology that can be geomorphometrically constructed using satellites. In previous research, the ocean surface has generally been described based on its mean elevation. However, the ocean surface has morphological characters, which is determined by mean wave length, height, period, speed, and direction (Song *et al.*, 1998; Zhang *et al.*, 2010).

Waves can be short or long, and their length is influenced by ocean dynamics. Normal ocean waves are short waves with high frequencies, and can be caused randomly by wind, storms, and tsunamis (Kong *et al.*, 2008; Liu *et al.*, 2005; Ye *et al.*, 2013; Zhao *et al.*, 2010). While these events always produce short waves, the waves may differ in height, periodicity, speed and direction. Because the surfaces of short waves change rapidly and randomly, the

surface morphology of the ocean is not easy to measure in real time. In contrast to short waves, long waves are determined waves with low frequencies and they are caused by celestial bodies motion. In particular, an astronomical tide refers to the specific ocean surface morphology caused by tide-generating forces exerted by the sun and moon on the terrestrial ocean. Generally, ocean surface morphologies associated with high or low tide level appear within a certain time period, and this time period can be inferred from the relative positions of the earth, moon, and sun. In addition, the ocean surface morphological features caused by astronomical tides can be modelled and forecasted in real time by harmonic analysis method.

In recent years, spatial variations in the ocean's surface along the northwest Pacific margin have been explored using satellite altimetry and tide level data (Jia *et al.*, 2000; Lin *et al.*, 1997; Wang *et al.*, 2008; Yu *et al.*, 2008). In addition, mean sea level variability related to the El Niño-Southern Oscillation (ENSO) have been analysed to understand ENSO's effects on regional to global ocean surface morphology (Yuan *et al.*, 2009). These studies have contributed to monitoring regional to global changes in ocean surface morphology. In addition, the high accuracy and resolution of satellite altimetry data greatly facilitate research on the spatiotemporal patterns and evolutionary processes associated with changes in ocean surface morphology.

3.6 Socioeconomic spatial structure-based DTA

Geomorphometry is often used in the natural sciences but is generally considered to have little relationship to the social sciences. However, if a DTM is conceptualized as a field model and its elevation attribute generalized, it can be used to express the spatial structure of any social phenomenon. Thus, geomorphometry can also be used in social science. This section uses the social factor of accessibility as an example and then demonstrates the feasibility of socioeconomic spatial structure-based DTA.

The index of accessibility refers to the level of difficulty of accessing one area from another area; thus, it reflects the spatial difficulties that people need to overcome during travel (Li and Lu, 2005; Jiang *et al.*, 2013). Accessibility is quantitatively expressed in terms of distance, time and cost. The analysis of accessibility is gradually becoming a reference for the reasonable arrangement of urban public service facilities. Using geomorphometry, the distance, time and cost factors of accessibility constitute the attributes of a field model that can be used in further analysis (Pan and Liu, 2014). For instance, several studies have described accessibility using a field model and explored changes in accessibility using the weighted least distance calculated by Bayesian neural network algorithms (Liao *et al.*, 2015; Ma and Cao, 2008; Shang *et al.*, 2014; Zhang and Lu, 2013).

The spatial analysis of accessibility can be categorized based on whether it uses vector or raster data (Jin *et al.*, 2010; Meng *et al.*, 2014). Vector data-based accessibility analysis integrates the true conditions of a road network, including detailed parameters such as road speed, road conditions and turnaround in all directions. However, acquiring vector data is complicated and requires high accuracy and precision (Liu *et al.*, 2010; Sun *et al.*, 2012). In contrast, raster-based accessibility analysis divides an entire area into raster cells. Each cell represents various accessibility attributes in different layers, so the full accessibility characteristics of an area can be described by stacking the layers. However, these characteristics do

not include the degree of connectedness between cells in an area (Chen *et al.*, 2015; Shen *et al.*, 2012). Together, these issues form a new research direction concerning the socio-economic spatial structure of accessibility-based DTA (Chen *et al.*, 2009; Zhu *et al.*, 2011).

4 Applications of geomorphometry

The theory and methods of geomorphometry have provided new approaches and technologies that can be used in traditional geographical studies. In recent years, Chinese scholars have applied geomorphometry to a wide variety of topics in geoscience, including global climate change, the Taihu Lake Plain, the Loess Plateau, the Tibetan Plateau, and the lunar surface.

4.1 Global topography and climate change

The morphology of the Earth has been regarded as the result of internal and external forces and Earth dynamics. The internal forces provide the basis for the surface morphology formation of Earth, while the external forces create the details of the Earth's surface morphology. In terms of the global-scale surface morphology, the interactions of different 'plates' are the main internal forces that shape the macroscale topography of Earth. Notably, such processes include plate subduction and extrusion (Zhou, 2013; Zhang *et al.*, 2017). However, the topography itself also affects the process of globe climate change. Terrain derivatives such as slope, aspect, and elevation greatly affect variations in surface solar radiation, which further influences the spatiotemporal distribution of climate factors. Therefore, Chinese scholars have applied geomorphometry to the field of climate change. These studies fall into two main categories. First, some applications involve using DEMs to create models capable of estimating climate factors. For instance, studies have described a distributed model for calculating astronomical radiation using a DEM (Zeng *et al.*, 2005), as well as a model for total radiation (Hao *et al.*, 2009; Yang *et al.*, 2004). Other scholars have used geomorphometry to model rainfall-runoff (Wu *et al.*, 2002), simulate land surface evapotranspiration (Liu *et al.*, 2007), model temperature fields in mountainous areas (Mo and Zhang, 2007), and air pollution (Zhang *et al.*, 2014a, 2014b, 2016). Second, some applications involve the use of DEMs to develop interpolation methods for climate factors. These include spatial interpolation methods for precipitation (Liu *et al.*, 2010) and surface air temperature (Pan *et al.*, 2004; Yang *et al.*, 2007). In addition, on a global scale, spatial variations related to ENSO have been linked to changes in ocean surface morphology (Yuan *et al.*, 2009).

4.2 Taihu Lake Plain

In addition to the application of geomorphometry in mountainous areas, another interesting application area of geomorphometry is associated with the Taihu Lake Plain in the low reach of the Yangtze River. This plain area contains many interconnected river networks, lakes, reservoirs, and polder areas. The polder areas are man-made geographical features that were created to protect against the floods that frequently occur in this part of southern China. The polder areas change water flow routing, which increases the complexity of watershed hydrological processes in the plain area (Gao and Han, 1999; Mo, 2001). Three methods have been used to deal characterize the polder areas in this region. First, the traditional workflow

for mountainous areas was used to simulate watershed hydrology and the characteristics of polder areas were ignored (Huang *et al.*, 2011; Lai and Yu, 2007). Specifically, the polder areas were automatically classified into a specific subwatershed. Second, the polder areas were regarded as independent watersheds, and their hydrological processes were simulated (Luo *et al.*, 2013; Xu and Wang, 2010). Third, the Soil and Water Assessment Tool (SWAT) was used to simulate the hydrological processes in polder areas based on the relationship between polder areas and the neighbouring watershed units (Li *et al.*, 2013; Wang, 2006). Although Chinese scholars have made many advances in watershed hydrological modelling in polder areas, a distributed hydrological model that accurately describes the interactions between human and natural effects in polder areas is still needed in future watershed hydrology-based digital terrain analysis.

4.3 Loess Plateau

Geomorphometric research on the Loess Plateau of China has focused on the spatial variability and the evolutionary processes of loess landforms. For example, a second-order terrain derivative, the slope spectrum, has been used to explore spatial variations in loess landforms on the plateau (Tang *et al.*, 2008). Other scholars have incorporated terrain derivatives into studies of loess landform morphology and spatial variability, including the core topographical factor (Zhang *et al.*, 2013), hypsometric integral (Zhu *et al.*, 2013), terrain texture (Liu *et al.*, 2012), positive and negative terrain (Zhou *et al.*, 2010), and catchment profile spectrum (Zhang, 2011). Chinese scholars have also studied the formation and evolutionary mechanisms of loess landforms on both watershed and regional scales. On the watershed scale, Fu *et al.* (1994) and Wang *et al.* (2007) investigated landscape loess morphology and soil erosion mechanisms. A cellular automata (CA) model was also used to simulate the evolution of positive and negative terrain in loess landforms using DEM data from different time series (Cao *et al.*, 2013; Zhang *et al.*, 2012). On a regional scale, landform evolution modelling and paleotopographic reconstruction was used to discuss landform inheritance characteristics (Xiong *et al.*, 2014a, 2014b).

4.4 Tibetan Plateau

There are three major ways that scholars have applied geomorphometry to Tibetan Plateau research: terrain visualization, extraction and analysis of terrain derivatives, and integration of multidisciplinary data for the plateau. In the first case, Liu *et al.* (1999) reconstructed the DEM of the planation surface in the northeastern part of the plateau, which aided in visualization of the specific planation surface for geological investigation. Second, the relationship between plateau topography and uplift processes were explored using terrain derivatives extracted from DEMs and geological profiles (Han *et al.*, 2012; Xiong *et al.*, 2017a; Zhao *et al.*, 2009). Landform divisions on the plateau were also classified using extracted terrain derivatives (Yao *et al.*, 2007). Finally, the availability of RS images and DEMs has meant that integration of these data in the fields of geology, sedimentology, tectonics, and geomorphology has a major focus in studies of the Tibetan Plateau. These studies include drainage system analysis (Li *et al.*, 2012; Zhang *et al.*, 2006), tectonic active structure analysis (Ji *et al.*, 2011), paleosurface reconstruction (Gao and Liu, 2013), and periglacial geomorphology monitoring (Zhao *et al.*, 2007).

4.5 Lunar surface

As space exploration technology has advanced, geomorphometry has also been applied to morphological investigation of the lunar surface. Using data from the lunar orbiter of the Chang'e satellite, Chinese scholars have constructed a 500-m resolution DEM of the entire Moon, as well as a partial geomorphological map (Chen *et al.*, 2012; Chen *et al.*, 2013; Ding *et al.*, 2012; Li *et al.*, 2010). Because lunar craters are the basic unit of the lunar surface, lunar morphology research focuses on lunar craters. Using lunar DEMs, Chinese scholars have extracted lunar craters and analysed their features. These works include DEM-based exploration of the distribution of the Moon's gravitational field (Huang *et al.*, 2009) and various methods for extracting lunar craters, such as an object-oriented method and a mathematical morphological approach (Yuan *et al.*, 2013; Yue *et al.*, 2008). In addition, extracted craters have also been used to analyse lunar crater morphology (He *et al.*, 2012; Yue *et al.*, 2012; Zhou *et al.*, 2012), and the spatial distribution of lunar landforms has been examined (Zhou *et al.*, 2011).

4.6 Other applications

Geological disasters such as earthquakes, landslides, and collapses are closely related to topography. DEMs are a key data source for the application of geomorphometry to the analysis of geological disasters (Cui, 2014). For example, Chinese scholars have applied geomorphometry to landslide susceptibility mapping (Zhu *et al.*, 2014) and used analysis of terrain derivatives to investigate landslide triggering factors (Bai *et al.*, 2005; Lan *et al.*, 2002).

The application of geomorphometry to soil science has mainly centred on soil sampling, soil erosion and the investigation of soil attributes. In the area of soil sampling, DEMs are used to inform sampling strategy design and soil mapping (Yang *et al.*, 2011), while soil attribute investigations have used DEMs to investigate the topographic wetness index (TWI) (Qin *et al.*, 2006; Zhang *et al.*, 2006). Other studies have explored the relationship between soil erosion and topography and assessed soil erosion in a large-scale watershed (Fu *et al.*, 2005). In addition, regional-scale soil erosion modelling has been conducted using terrain derivatives (Liu *et al.*, 2004; Yang *et al.*, 2006; Yang *et al.*, 2009), and this type of modelling has also been used to analyse the variability in regional-scale soil erosion (Bi *et al.*, 2013; Guo *et al.*, 2009).

In addition to the applications of geomorphometry in traditional domains, Chinese scholars have also applied geomorphometry in several novel areas, including specific terrain rendering of maps, remote sensing, and human geography. In addition to traditional terrain-rendering methods such as level of detail (LOD), elevation classification and rendering, and hill shading, the development of computer graphics has led to new methods for rendering surfaces, such as painting rendering from DEMs (Chen, 2011). In addition, the combination of geomorphometry and remote sensing has been used to guide agricultural production and the assessment of natural resources with high accuracy and high renewal frequency (Long *et al.*, 2007; Wang *et al.*, 2010). Finally, geomorphometry has been applied to studies of the spatial distribution and planning of urban man-made buildings (He *et al.*, 2012; Zhang *et al.*, 2011).

5 Conclusion

Because topography and geomorphology are basic research topics in geography, geomorphometric research is an important component of GIS. Since the development of geomorphometry nearly half a century ago, significant progress has been made in the related theory, methodology and applications. Chinese research in geomorphometry in China has proceeded along with international studies. This paper's review describes the recent advances in geomorphometry in China. Many high-impact and internationally significant achievements have been made by Chinese scholars, especially in the fields of high fidelity-based digital terrain modelling, extraction of geomorphological features, and strata structure-based DTA, as well as in the geomorphometry of the Loess and Tibetan Plateaus. In 2006 and 2013, two international conferences on geomorphometry occurred at Nanjing Normal University of China, Geomorphometry 2006 (TADTM, Terrain Analysis and Digital Terrain Modelling) and Geomorphometry 2013 (see <http://geomorphometry.org/>); these conferences demonstrate the international respect earned by the Chinese scholars.

As DEM data acquisition methods progress, the acquisition of high-resolution DEM data should become more efficient and convenient. There are significant opportunities in geomorphometry for Chinese scholars. First, future Chinese research on geomorphometry should emphasize the concept of geoscience attributes. These attributes should include elevation, and other geospatially related information, such as underlying strata, ocean surface characteristics, and social phenomena. In addition, exploration of the theory and methods of geomorphometry should continue, and research directions should be expanded. For instance, studies should shift their focus from the geomorphometry of traditional mountainous areas to that of areas of plain river networks or submarine topography, and from the spatial variability of modern surface morphology to process- and mechanism-based landform evolutionary modelling. In particular, geomorphometric research ideas and methods could be expanded to other field models in geoscience, and a universal field model in geoscience with its own theory and method could be proposed and developed.

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