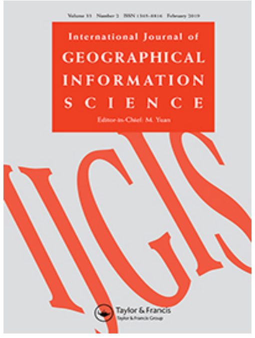


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# Reflections and speculations on the progress in Geographic Information Systems (GIS): a geographic perspective

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# Reflections and speculations on the progress in Geographic Information Systems (GIS): a geographic perspective

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**ABSTRACT**

Great strides have been made in Geographic Information Systems (GIS) research over the past half-century. However, this progress has created both opportunities and challenges. From a geographic perspective, certain challenges remain, including the modelling of geographic-featured environments with GIS data model, the enhancement of GIS's analysis functions for comprehensive geographic analysis and achieving human-oriented geographic information presentation. Several basic theoretical and technical ideas that follow the workflow and processes of geographic information induction, geographic scenario modelling, geographic process analysis and geographic environment representation are proposed to fill the gaps between GIS and geography. We also call for designing methods for big geographic data-oriented analysis, making best use of videos and developing virtual geographic scenario-based GIS for further evolution.

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Geographic Information Systems (GIS); improvement ideas; geographic perspective; geographic process; Geographic Information Science (GIScience)

## 1. Introduction

There are many definitions of geographic information and the systems that are used to store, retrieve, analyse and display data that are represented spatially or geographically. Here, we adopt a broad definition based on an information system designed to handle geographic, spatial or geospatial data for spatiotemporal use and geographic research. The term geographic is generic and follows its noun form *geography*, which refers to 'a field of science devoted to the study of the lands, the features, the inhabitants, and the phenomena of Earth' (The American Heritage Dictionary 2006). In this article, we use the acronym GIS regarding systems and technologies rather than geographic information science (GI Science), which is an even broader area that involves additional theoretical studies (Goodchild 1992, 2009, 2018).

Through continuous evolution over the past half-century, GIS has made significant contributions to mainstream geographic research and applications, and it has shown its

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potential benefits to many related disciplines (e.g. Earth System Science) (Goodchild 2010, 2018; Egenhofer *et al*. 2015; Longley *et al*. 2015). From computer mapping to spatial analysis and then to geographic problem solving, GIS embraces ideas about how we use our cognition to understand spatial configurations and perceptions (Mark *et al*. 1999). GIS has thus focused on three main goals: acquiring geographic information, studying geo-objects and their relationships and exploring advanced geographic rules that determine our spatiotemporal behaviour (Lin *et al*. 2013a). First, computer mapping and related tools are basic GIS functions that have provided users with 2D/3D visual and digital images of the physical world, with extensions to 4D along the time dimension. To some extent, this explains why GIS has become popular in daily life (Crampton 2011). Second, combined with spatial statistics, spatial analysis has pushed GIS well beyond basic mapping applications to provide users with logic for understanding spatiotemporal distributions and relationships (e.g. Burke and Khan 2006; Shaw *et al*. 2008). Recently, GIS has been employed to explore both physical and social dynamic geographic phenomena in the world, combining with other geographic research methods (Goodchild and Glennon 2008; An 2012; Kosiba and Bauer 2013). This stage emphasises processes and changes to more than just static patterns and distributions. For example, geographical analysis models, which play an important role in geographic simulation and experimentation, have been increasingly integrated into GIS for decision support and prediction, particularly for dynamic geographic processes, such as emergencies and disasters, and for detailing future scenarios in specific domains (e.g. Bhatt *et al*. 2014; Nampak *et al*. 2014; Shi and Liu 2014; Torrens 2015a). The development of GIS and associated technologies has spurred the advancement of GI Science and related disciplines (e.g. Bodenhamer 2012; Kroschel *et al*. 2013; Richardson *et al*. 2013) and resulted in the success of the geographic information industry in an active and wide market (Niraj 2011; Dempsey 2012; Kumar 2013; P&S Market Research 2016a, 2016b).

However, a successful past does not guarantee a bright future. External driving forces, such as basic progress in information technology, have had a significant impact on the development of GIS, with the computer science perspective coming to the forefront of GIS development in the last 10 years. Ground-breaking progress in multimedia technology, virtual reality (VR) technology, computer-generated graphics and imagery as well as hardware, such as large-capacity optical disks and broadband optical fibre communication technology, has driven the development of GIS towards virtualised distributed environments and has thus popularised GIS for more general use. Conversely, the internal driving forces of GIS are insufficient to ensure its continued relevance to the discipline of geography (Lu *et al*. 2013). Currently, GIS development has the option of two paths: (1) developing GIS alongside new information technologies and actively integrating GIS into mainstream information technology or (2) continuous exploration based on geographic theories and seeking impetus for development and related technologies based on distinct geographic characteristics. These paths merit further deliberation, and we will discuss them in this article.

Following its evolutionary history, this article discusses some existing challenges of previous GIS technologies. Then, some possible solutions are proposed in terms of both theoretical and technical dimensions to fill gaps, following the workflow and processes of geographic information induction, modelling, analysis and representation. Essential suggestions, such as designing methods for big geographic data-oriented analysis,

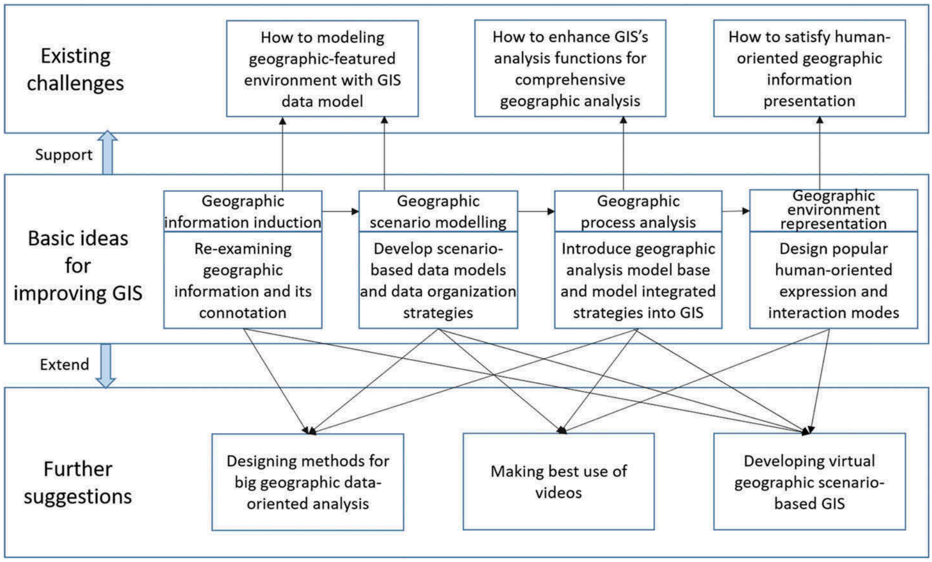


**Figure 1.** The logical structure of ideas for the improvement of current GIS.

making best use of videos and developing virtual geographic scenario-based GIS, are proposed as conclusions for further exploration. Figure 1 shows the logical structure for the following parts.

## 2. Challenges with previous GIS

### 2.1. *Modelling geographic-featured environments with GIS data models*

Cartography has provided essential support for many aspects of communication and information sharing related to the geographic world (Kraak and Ormeling 2010), and automated cartography has created many of the concepts and procedures underlying modern GIS technology (Berry 1999). One of the most important roots of GIS is the automation of cartographic workflows, with the additional aim of integrating and analysing geospatial information. This has led to the evolution of basic 'spatial data handling' methods, including the storage and representation of various spatiotemporal data in digital databases and the efficient production of maps that can be used for decision-making and understanding spatial interrelationships via spatial analysis (Jones 2013).

Following the idea of traditional automated cartography, many existing GIS data models originate from classical map models (Zeiler 2010), which use points, lines, polygons, and volumes to project nature through geometry and measurements. The elements in geographic space are typically abstracted conceptually into either continuous fields or discrete objects (Kemp 1996; Christakos *et al*. 2001; Goodchild *et al*. 2007) using raster data models, vector data models and their variants at the logical level. This type of modelling is beneficial to the expression of information related to geometry, location and attribute with the clear goals of performing measurements and spatial analyses (Dangermond 2012). In databases, geographic data are generally stored and differentiated at various scales, dimensions, types, and times in the form of layers and blocks (Jones 2013) to take advantage of easy classification and storage.

However, for geographic research, to model exact research objects, i.e. geographic environments, that have been described as the surfaces on which human societies exist and develop (Churchill and Friedrich 1968), previous data models need to be improved. The characteristics of geographic environments indicate that they are comprehensive systems that consist of natural factors (e.g. soil and water), social factors (e.g. humans) and their interactions; moreover, such environments are dynamic systems because geographic processes change over time (The Great Soviet Encyclopedia 1979). Therefore, geographic environments and the associated elements exist beyond abstract geometric structures and layers; such environments are 'holographic' systems with rich geographic information and complex geographic phenomena that emphasise geographic processes and interactions. Such environments require the modelling focus to change from a focus primarily on spatial structures and relationships to a focus that includes geographical processes and phenomena (Lu *et al*. 2018a). Currently, many GIS data models cannot effectively support the description, expression and exploration of geographic laws because complex geographic relationships (not just spatial relationships) and interaction mechanisms between geographic elements (e.g. photosynthesis as it relates to both sunshine and forests) are often ignored during modelling (Lu *et al*. 2013, 2018b). For example, data organisation-oriented spatial grids have been commonly used in previous GIS for the management and expression of global geographic data (Sahr *et al*. 2003; Goodchild 2012a); however, these grids show a limited capacity for supporting high-resolution simulations of climate change or ocean tidal waves at the global scale because the grid nodes and linking edges are designed without consideration of the interaction (e.g. movement of matter, energy transformation) between grids. Therefore, the development of global discrete grids that consider geographic laws and interaction mechanisms to bridge GIS and earth system models is still required (Lin *et al*. 2018; Zhou *et al*. 2018).

### 2.2. *Enhancing the analytical functions of GIS for comprehensive geographic analyses*

Geography is a comprehensive scientific discipline that involves natural and human elements as well as their interactions in geographic space. Geographical content involves various factors (e.g. geology, topography, hydrology, biology, climate science, human science) and their spatiotemporal distribution, evolutionary processes and interactive mechanisms, both internal and external. To better understand such complexity, modern geographic research has gradually evolved from studies of separate elements and processes to a comprehensive and integrated view that now forms a systems science based on collaborative research and interdisciplinary methods (Ziegler *et al*. 2013; Fu *et al*. 2015; Wang et al. 2018a).

As a basic tool for geographic research, GIS should grow at the same rate at which geography is evolving and changing. In fact, applications show that the typical uses of previous GIS are still predominantly mapmaking, spatial data management and spatial analysis. With the increasing demand for an understanding of 'why' and 'how' beyond 'what' and 'where', an increasing number of geographic analysis methods (e.g. agent-based, general circulation and hydrological models) in certain domains have been introduced into GIS to facilitate the exploration and explanation of geographic patterns, simulate geographic processes and predict geographic phenomena (Chen *et al*. 2008). However, GIS still has a limited capacity to reason, induce and deduce complex geographic problems (Lu et al. 2017). For example, current GIS cannot conduct complex simulations of an overall process that includes rainfall, infiltration, runoff production, plant growth and water evaporation under a geographic scenario, nor can it perform human-land interactive research. A potential solution to enable GIS to better server geographic research is to improve GIS by importing multi-disciplinary geographic analysis methods or software packages and integrating these for comprehensive analysis and predictions. Tools such as Digital Earth have established several key directions to provide a new generation with comprehensive geographic modelling and simulation (Guo *et al*. 2010; Annoni *et al*. 2011; Craglia *et al*. 2012; Goodchild *et al*. 2012; Goodchild 2012b; Yang *et al*. 2013), and these tools provide examples for improving the conceptual architecture, modelling strategies, analysis modes and methods of GIS to meet the needs of deeper geographic exploration.

### 2.3. *Satisfying human-oriented geographic information presentation*

Traditional GIS mainly uses and applies physical geo-oriented views; for example, pipeline management information systems, mineral resources planning and management information systems and virtual cities are all have been devolved. However, because geography includes both a physical part and a human part and because human-related data can be collected more easily than ever, now is the right time to pay attention to human-oriented GIS and related information presentation strategies (Gong 2008; Charleux 2014). In this regard, current challenges can be summarised as they relate two types of humans: those who use GIS and those whose data are analysed through GIS.

Regarding the former, although the geographical world is rich with natural beauty, the representation of this richness is lacking such beauty under traditional cartographic models. GIS often uses maps and images to abstractly represent the real world and describes geographic objects by using vector symbols or grid map spots. This mode can express the geographic world structurally, but is weak in terms of richness, intuition and reality. For example, in daily life, people observe the world from vivid and dynamic perspectives and can enjoy representations of their world through a realistic landscape painting style or a cartoon style. Thus, a method of improving the attractiveness of GIS presentation consistent with human cognitive habits is required to help users experience a more real and information-rich world, which would further develop the interests of users (Bratkova *et al*. 2009; Iturrioz and Wachowicz 2010).

As for the latter, human-oriented GIS need to represent both the individuals and groups in the systems. Although several achievements have been made, such as spatiotemporal polylines and heat maps, which have been employed to express traces of human behaviour (e.g. Lee and Kwan 2011; Chen *et al*. 2013), and virtual reality (VR) technologies, such as bone animation, which has been used in emergency escape scenarios (e.g. Torrens 2015a, 2015b), the representation of the interaction of humans with the physical world remains a challenge because it must represent these human dynamics not only according to physical engines but also obeying geographic interactional mechanisms.

## 3. Basic ideas for improving GIS

### 3.1. *Re-examining geographic information and its connotation*

As noted above, research subjects in geography include various types of natural and human geographic phenomena related to patterns of spatial differentiation, evolutionary processes and mechanisms of the interactions between geographic elements. Aside from what we can see, information (e.g. temperature, sound, light, electromagnetism) exists in our surroundings comprising complex geographic environments, and it helps to characterise areas. Therefore, from a geographic perspective, geographic content encompasses a wider area than spatiotemporal and geometric content per se (Batty 1997). To improve GIS to be a holographic information system for geographic exploration, the geographic information should first be re-examined because it is the abstraction and digital representation of the real geographic world and the main input of geographic observations and geographic experiments. It would also lay a foundation for further data modelling, geographic analysis, and representation mode design.

In this regard, through induction, a geographic element, object or phenomenon can be described using a combination of the following six factors to cover the geographic information it contains (although not all elements can be fully described by these six factors): geographic semantics, location, shape, evolutionary process, relationship between elements (not limited to spatiotemporal relationships) and attribute. Figure 2 shows a diagram to illustrate how the six factors compose geographic information.

(1) 'Geographic semantics' is the most important factor for the expression of geographic objects and elements (Couclelis 2010; Janowicz *et al*. 2010; Yaouanc *et al*. 2010). Geographic semantics originate in the description of the meaning and the classification of the geographic concepts, and they are often domain related. Its content can be divided into three types: the description of the concept of the elements, its classification system and a 'principle diagram'. The geographic semantic meaning can be used to answer questions such as 'What is the geographic object?' (e.g. thing/person/object),

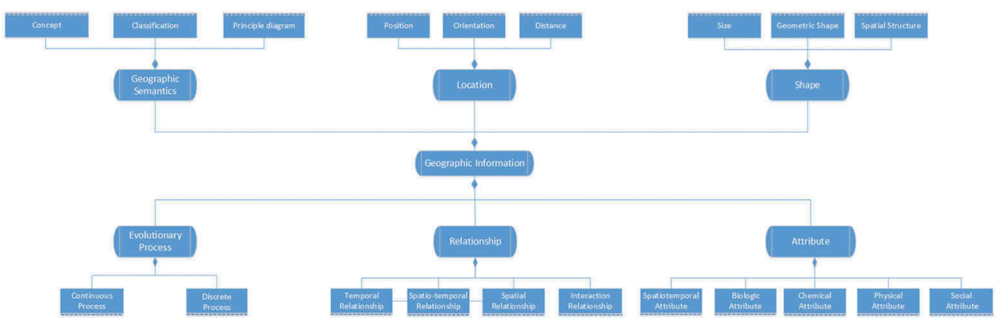


**Figure 2.** A conceptual schema of geographic information content.

'Why did it develop in this way?', 'What is its formation principle?' and 'How it is expressed using a highly abstract diagram?'.

(2) 'Location' includes position, orientation and distance in space. A geographic element may be associated with several positions under different spatial reference systems, including a global or local position, a relative or absolute position, etc. For certain geographic elements, although their positions cannot be expressed precisely, their approximate locations are useful for descriptive purposes, e.g. the area located in south of the Huaihe River or a rainy area near Purple Mountain. Normally, positions can be described using precise or approximate coordinates or place names. Moreover, some relative locations can be expressed using position combined with orientation and distance, e.g. 5 km to the southeast of Nanjing Normal University. The location of a geographic element mainly tells us where it is.

(3) The 'shape' is commonly used to illustrate the spatial characteristics, and it normally includes the size, geometric shape and spatial structure of a geographic element, especially for a physical element. In previous GIS, combined with location, shape is the key factor to represent a geographic element and for visualisation. Certain geographic elements may not have precise shapes, e.g. a typhoon, but approximate shapes can also be employed to provide a vivid description. Shapes tell us what a geographic element looks like geometrically.

(4) 'Evolutionary process' explains the dynamics and the developing and changing states of elements (Van De Ven and Poole 1995). Each geographic element is associated with an evolutionary process that involves its appearance, development and extinction. Each geographic phenomenon originates, appears, develops and disappears. During these processes, geographic elements and phenomena may change gradually or abruptly, and they may exist in a nearly immutable state according to geographic rules. Therefore, it is necessary to use both discrete and continuous equations (e.g. difference-differential equations) to describe the entire process in a unified way and ground the state of the element at a certain stage or time. In this regard, geometric algebraic theory provides a potential solution (Yuan *et al*. 2010, 2012). The evolutionary process defines the state of the geographic element and which events occur at a certain time.

(5) 'Relationship' is a general term for a spatiotemporal association or other interactive linkage among multiple geographic elements. However, in addition to spatiotemporal (e.g. topological) relationships, geographic elements have various physical, chemical and biological interactions with each other. These interactions can also be described using 'interaction relationship' types, which are important in geographic analysis (in addition to spatial analysis) and mechanism exploration. For example, when dense vegetative cover is stripped from a landscape, the underlying soil quickly loses its fertility, which creates a special relationship between the vegetative cover and the soil; another example is the relationship between mountains and wind, as mountains may obstruct wind and wind may weather rocks. Accordingly, such relationships are expected to be introduced into GIS in certain forms based on geo-knowledge and rules. This will enable GIS to become real geographic analysis-oriented tools.

(6) 'Attribute' describes the features of a geographic element and are important for classification. The differences between a semantic factor and an attribute factor is that a semantic factor provides an overall concept of an element, while an attribute factor

provides detailed features associated with the element. Similarly, aside from spatiotemporal attributes, geographic elements may have numerous other attributes, e.g. physical, chemical, biological and social attributes. Attributes represent the unique characteristics of different geographic elements in terms of aspects and can contribute to further geographic computation beyond spatiotemporal calculation.

### 3.2. *Developing scenario-based data models and data organisation strategies*

As stated in Section 2.1, most early GIS data models are expansions of cartographic models, and the existing data organisation methods generally use data layers and spatial blocks (Jones 2013). This limits the expression of connections between geographic elements at different scales and types with various semantic meanings, multiple attributes and abundant relationships (Lu *et al*. 2015). Because it is difficult for layered data to record interactive relationships, the mechanisms of interaction among elements and their evolutionary processes can seldom be explored using layered data (Lu *et al*. 2013). Moreover, geographic space is often divided into blocks (tiles) for data storage and querying, but this type of organisation method manually separates linked geographic elements, creating a discontinuous geographic space (Lu *et al*. 2013). The above facts indicate there is a need to move towards a post-cartographic data modelling paradigm.

Here, modelling GIS data from the perspective of geographic scenarios is proposed. The real world naturally comprises various geographic scenarios (Lu *et al*. 2018a) in which elements and events occur. Such scenarios can be regarded as special geographic regional syntheses with specific structures. They can be used to express geographic elements at various spatio-temporal scales as well as internal geographic interactions. Accordingly, by changing the structures of a geographic scenario, the geographic scenario can be used to express the evolutionary processes and various interaction relationships among geographic elements of a geographic phenomenon.

To organise, store, express and analyse geographic scenarios in GIS, a suitable and geographically explicit data model is needed. A geographic scenario-oriented data model (see Figure 3) should be designed as a multi-hierarchical, nested-support model to ensure that the scenario, sub-scenario and adherent elements can be described in a unified framework. First, the classification of scenario needs to be provided to fit the descriptions of various research problems, e.g. micro or macro, static or dynamic, continuous or discrete, rough or fine, in specific fields or common domains. Second, spatiotemporal distribution patterns, evolutionary process types and interaction relationships should be summarised to help customise the structure of the geographic scenario. For example, distribution patterns vary in hierarchical structures, interactive relationships produce diverse nested modes and evolutionary processes control the changing structures and modes of hierarchical and nested structures. Third, the method used to map geographic information (mentioned in the last section) into geographic elements in these scenarios should be studied to form realistic digital geographic scenarios. In this case, the schema of the scenario-based model is not fixed but it rather customisable and configurable. This is important because geographic laws and rules are considered when such a data model is developed, which benefits further geographic analysis and expression. Moreover, to overcome the conflict between the multi-dimensional data organisation method and the 1D linear storage and addressing method of a

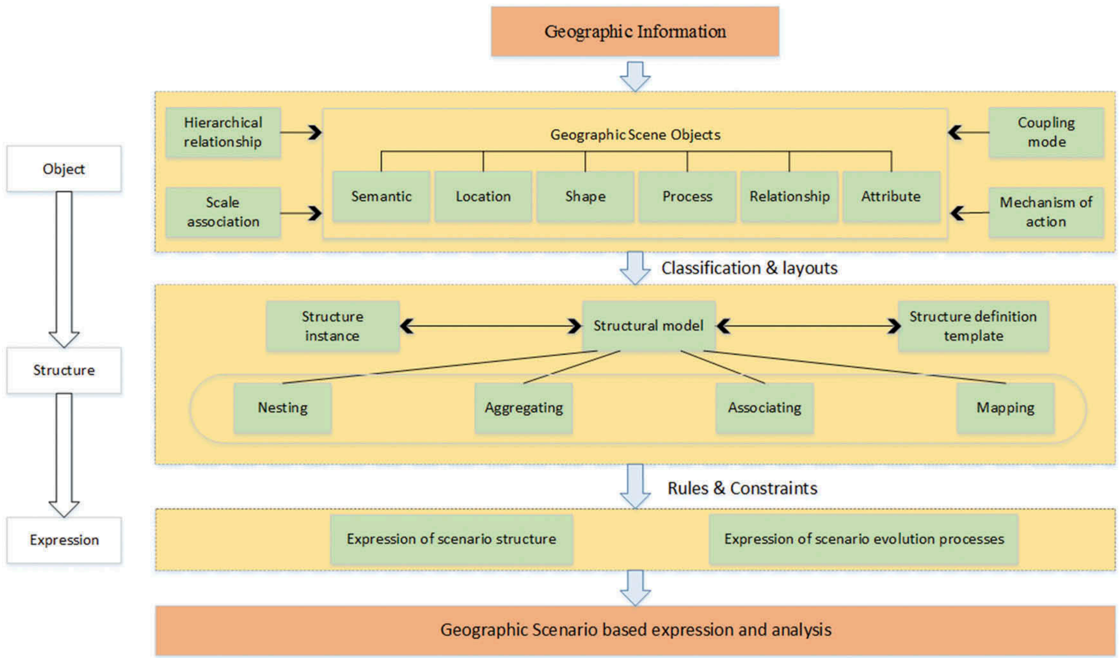


**Figure 3.** The conceptual idea of the design of scenario-based data model.

computer, as well as the inherent conflicts between the inhomogeneous distribution of geographic elements and the homogeneous distribution of internal and external storage spaces, new data storage and indexing methods based on geographic rules, rather than the characteristics of computer memory, can be re-considered accordingly (Dai *et al.* 2014; Wu 2015).

### 3.3. *Introducing geographic analysis models base and model-integrated strategies into GIS*

Previous GIS focus on the acquisition, processing, storage and analysis of geographic data that are treated as core objects. Spatiotemporal data management and sharing have drawn considerable attention and have become relatively well developed. However, with the expansion of professional applications and the increasing amount of attention paid to the analysis of the mechanisms and processes of comprehensive geographic phenomena, GIS with spatial data at its core and spatial analysis as its main function has a limited capacity for dynamic modelling and solving complex geographic problems. Therefore, GIS should go beyond the loosely bounded 'information system' stage and evolve into an integrated and open geographic analysis systems (O'Sullivan and Unwin 2010; Crooks and Castle 2011).

As with geographic databases, in view of the important role of geographic analysis models in geographic simulation and prediction, it is necessary to fully use geographic analysis models as another important type of GIS resource and to use the management, sharing, integration and reutilisation functions of these models in GIS to create a dual-core (i.e. geographic database and analysis model base) based geographic analysis tool (Lin *et al.* 2013a, 2013b; Voinov *et al.* 2018). Combined with other geographic analysis methods, e.g. geographic experiments (e.g. Gong *et al.* 2009) and remote sensing data analysis (e.g. Zhao *et al.* 2018), the comprehensive geo-problem resolution capacity of GIS can be greatly enhanced (Chen *et al.* 2017). For comprehensive geographic exploration, the analysis model base needs to collect models from multiple disciplines, ranging from models related to geophysics (e.g. Brennan *et al.* 2014; Johnson *et al.* 2016) to models related to social behaviour (e.g. Huang *et al.* 2009, 2010; Lin *et al.* 2014; Eisman *et al.* 2017).

In this regard, on one hand, numerous geographic analysis models already exist (e.g. statistic models, dynamical models and agent-based models). On the other hand, in specific domains (e.g. hydrology), a number of model bases and model integration architectures have been developed (Argent 2004; Argent *et al.* 2006; Fook *et al.* 2009; Laniak *et al.* 2013; Granell *et al.* 2013a; Zhang *et al.* 2015). There is a need to make full use of these existing achievements and integrate them to enable GIS for specific simulations of certain user-facing problems and for integrated modelling for more comprehensive understanding. In this aspect, several points should be discussed. First, geographic analysis models are characterised by high heterogeneity due to their heterogeneous modelling methods, structures (e.g. input, output and control) and execution environments. Traditional software packages and encapsulation methods originated in data resource sharing and management technologies, and when facing heterogeneous geographic analysis models, the encapsulation strategies of model functions, interfaces and deployment modes in cross-platform systems should be re-designed accordingly (e.g. David et al. 2013; Granell et al. 2013b; Yue *et al*. 2016; Wen *et al*. 2016). Second, many model resources are dispersed across networks, which leads to high cost when these models are reused and shared. The development of service-oriented model bases, such as model bases based on cloud computing and SOA architectures, has been regarded as an inevitable trend, and technologies related to this domain should receive attention (e.g. Nativi *et al*. 2013; Castronova *et al*. 2013; Wen *et al*. 2013; Granell *et al*. 2016; Li *et al*. 2017b). Third, when conducting collaborative research on comprehensive modelling using existing models in model base, sophisticated strategies are expected to decrease the cognitive differences between researchers of different domains (Pahl-Wostl 2007; Voinov *et al*. 2016). In this context, the design of visual conceptual modelling tools for idea exchange (Chen *et al*. 2009, 2011a) and the proposal of flexible descriptive strategies for expressing, classifying, indexing and managing both data and models (Tolk 2012; Turuncoglu *et al*. 2013; Yue *et al*. 2015; Chen *et al*. 2018) are expected.

### 3.4. *Designing popular human-oriented expressions and interaction modes*

Limited by the mode in which conventional maps are expressed, conventional GIS are often equipped with relatively monotonous expressions and interaction modes. However, there are differences in the cognitive habits, professional backgrounds and tool usage of individuals and groups. Additionally, the public may also have cognitive disparities due to different educational backgrounds, age and sex. Thus, it is necessary to develop multi-dimensional geographic information expression modes that are consistent with the cognitive habits of various users to promote understanding and a user-friendly environment (Poplin 2015). Here, the term multi-dimensional refers to the multi-dimensionality (e.g. 2D, 3D and even 4D) as well as the multiple styles of the expression, i.e. views should be designed with configurable and customisable features to meet the needs of both the general public and specific groups by adopting suitable modes (e.g. VR, computer-aided design or scientific visualisation computing) and customisable controls (e.g. layouts, skins and shapes).

In addition, the conventional screen-based perception and mouse-and-keyboard operation mode have limited our natural perceptions of geographic environments and scenarios and negatively affected the capacity of the public to understand geographic problems and their trends (Cai *et al*. 2007; Richards-Rissetto *et al*. 2012). The enhancement of GIS with VR, augmented reality (AR) and more recently, mixed reality (MR) has been regarded as an effective method of improving its expression and interaction capacity (Fisher and Unwin 2002; Batty 2008; Ghadirian and Bishop 2008; Hugues *et al*. 2011). Therefore, these technologies should be introduced into GIS with the aim of creating digital geographic scenarios that naturally represent the real world and improve the user experience and exploration (Batty *et al*. 2017). Moreover, previous research in GIS development has mainly focused on the enhancement of vivid visual perceptions, and there is still a long way to go in GIS design so that real human-oriented cognition can be satisfied, such as building multi-channel perception (e.g. taste or haptic perception) and operational modes (e.g. languages, poses and drawings). In this case, users can be active in GIS, e.g. feel the temperature, smell the air, experience the flood, plant the vegetation. Such functionality would both popularise GIS and contribute to the collection of human behaviour-related data for studies on human-land interactions, especially at the local and fine scales, e.g. for evacuation from a fire (Li *et al*. 2017a; Shen *et al*. 2018). However, due to the high cost of traditional equipment, e.g. immersive helmets and specific glasses, it remains an inconvenience for users to experience a virtual scenario in a GIS, even merely via visual means. Thus, it is expected that with the development of advanced VR/AR/MR technologies, and the decrease in the price of equipment (e.g. Kinect and VR glasses), virtualisation of GIS may become widespread and the users' interest can increase, making GIS more popular and widely adopted.

## 4. Further suggestions

### 4.1. *Designing big geographic data-oriented data analysis methods*

The physical world is full of geographic information, but previously GIS has taken little advantage of it due to limited functionality and design habits. Traditional geographic data acquisition has been primarily performed by governments and companies using methods such as aerial photogrammetry, remote sensing and space positioning based on emerging technologies (e.g. remote sensing satellites, laser radar and GNSS). Over the past decade, with the development of radio frequency technology, sensors and online interaction technologies, it became possible for both physical and human geographic data to be acquired and utilised in a convenient, real-time and non-expert fashion (Nittel *et al*. 2004), and volunteered geographic information (VGI) became popular globally (Sui *et al*. 2013). Currently, geographic data are available from everywhere in diverse channels. For example, data on air and noise pollution can be collected using handheld sensors for the analysis of the physical environment (Lane *et al*. 2010; Ganti *et al*. 2011), while with regard to social data, mass human activities at stations or stores can be transmitted and analysed through video cameras (Romero *et al*. 2011; Song *et al*. 2012), and personal travel paths can be collected through bus pass or metro card data (e.g. Batty 2013) and shared in combination with points of interests (POIs) using social media and social networking websites (e.g. Kang and Schuett 2013), which can provide valuable information based on 'understood as the richer set of observations tracking what we do, when and where we do it' (Gonzalez-Bailon 2013). These structured, unstructured or semi-structured data are associated with various geographic-related content (e.g. semantics, geometrics, spatiotemporal locations, relationships and attributes) and distinct 6-V (volume, variety, velocity, veracity, value and visual) characteristics; therefore, these data can be regarded as geographic 'big data'. The advent of these big data has begun to influence the development of data-driven geography and GIS (Graham and Shelton 2013) towards a customer-driven direction (Groman 2013).

Although challenges and risks, such as epistemological, methodological and ethical questions (Kitchin 2013) and issues associated with errors, accuracy and sample bias (Gorman 2013) have been suggested, we focus on the capacity of geographic phenomena and problem analysis supported by big geographic data. Because of the diversity of acquisition channels, high acquisition speeds and frequencies and the wide range of objects and contents, these big geographic data resources have become abundant and their application range has considerably expanded. Currently, to satisfy the analysis of these big geographic data via GIS, especially real-time GIS is proposed with emphasis on interactive real-time use and analysis, data models and data analysis methods (including geographic analysis models) should be upgraded. Big geographic data provide real-time GIS with the timely collection of geographic data, thus enabling GIS to be a dynamic platform for the real-time visualisation, analysis and understanding of our world (Esri 2013). Regardless of the available data, the attached information can be concluded and mapped into geographic semantics, location, shape, evolutionary process, relationships and attributes; the data model proposed in this article may provide a potential solution to modelling big geographic data, and other research has also been proposed (e.g. Gong *et al*. 2016). However, although big geographic data provides a potential resource for parameter provision for geographical analysis methods, as well as process validation, geographic data analysis methods themselves are currently mainly designed based on classic algorithms (Kitchin 2013). Only a few big geographic data-oriented analysis methods are available to handle the analysis of big data, which are being collected rapidly and often in unstructured formats. Machine learning and artificial intelligence (AI) have been increasingly introduced into big data analysis these days. For geography-characterised big data, these methods should be designed with the consideration of geographic rules and mechanisms, and the inclusion of geographic knowledge would be very helpful. Moreover, the corresponding algorithms should be improved to support high-speed computation for timely geo-featured data. With these enhancements, GIS can be expanded to support big data exploration to extract more useful geographic information, expand human knowledge and further lead to the discovery of new geographic phenomena and a deeper understanding of the rapidly changing geographic world.

### 4.2. *Making best use of videos*

Recently, volunteered geographic information (VGI) has become a trend in GIS development, and video technology is being increasingly used. As a common medium, videos are easy to acquire, and the geographic scenarios expressed in videos provide strong senses of realness. Videos communicate geographic scenarios that can be easily understood, allowing people to access information naturally. Therefore, the introduction of video technology can contribute to both data acquisition and vivid expression (e.g. Yang *et al*. 2001; Wang et al. 2018b). More importantly, compared with static images, videos contain abundant geographic process-related information beyond spatial and attribute information. If dynamic information can be parsed from videos, the mirrored geographic processes and phenomena can be reconstructed and will provide essential materials for advanced geographic dynamics analyses. Thus, integrating video into GIS development will provide GIS with dynamic side-view scenarios for experience and allow users to conduct video-based analyses, e.g. 3D analyses using video images or early warning analyses of disasters and crises based on the clues of dynamic changes in the scenarios shown in videos, in combination with technologies, such as pattern recognition and deep learning. To develop video-based GIS, it is necessary to study and establish a human-centred framework and design technologies that can extract time, space, scenes and human behaviours from locatable video scenarios and streams, store the above information, integrate location and video information, wirelessly transmit locatable video streams and rapidly model and retrieve video data, etc. Recently, deep learning has been introduced into the content analysis and recognition (e.g. action, emotion) of video content (e.g. Wu *et al*. 2015; Kahou *et al*. 2016), although the ability to rebuild dynamic scenarios from mass stream information and apply such information to computable process analysis requires additional exploration.

### 4.3. *Developing virtual geographic scenario-based GIS*

Virtual geographic scenarios provide users with not only virtual experiences but also unified workspaces for comprehensive geographic analysis (Lu *et al*. 2018a). Compared with tables and figures, scenarios that originate in daily life are familiar to many users and would benefit the exchange and understanding of GIS ideas (Tversky 2005). Combined with VR/AR/MR technologies and geographic analysis models, more advanced GIS can provide dynamic geographic scenarios for geographic analysis in a combined virtual and realistic manner (Lu *et al*. 2017), and further may enable us to enter into a real virtual geographic environment (VGE) age (Lu 2011; Konecny 2011; Priestnall *et al.* 2012; Lin *et al*. 2013b; Lin and Chen 2015; Chen *et al*. 2017; Chen and Lin 2018; Lu *et al*. 2018b).

With such systems, researchers and system designers can create dynamic virtual geographic phenomena according to geographic rules and laws, and thus provide vivid geographic scenarios to users for experience-based analysis (e.g. Chen *et al.* 2011b; Xu *et al*. 2013; Zhu et al. 2015; Torrens 2018; Rink *et al*. 2018) and collaborative experiments (e.g. Xu *et al*. 2011; Chen *et al*. 2012; Zhu *et al*. 2016). Because the capacity of users to perceive and interact with these systems has significantly improved and users interest and ability to participate have increased, the public can access these real geographic rule-based scenarios (as 'serious' games) more easily through multi-channel interactive tools. It will then be convenient for them to provide feedback; as this user feedback data increases, its continual collection will improve the systems with more experimental data for further study.

Moreover, the public could change virtual geographic scenarios to enjoy visual life and perform virtual activities, such as through the use of avatars that can actively manipulate the virtual world, thus contributing to the exploration of the human-earth inter-relationships. For example, virtual trees and vegetables can be planted in a virtual city by users if they feel that the environment and landscape of the city need to be improved. These activities and results can be collected in the virtual city and further used to re-calculate the changes in local pollution and temperature. In this case, GIS will support a second paradigm, and this fusion of virtual and real modes will enable the virtual world and the real world to be seamlessly integrated. Additionally, people will be able to realise dreams in the virtual world that are limited in the real world, thus breaking the boundary between reality and virtual reality and realising the alternation between the extension of our human existence and its evolution into virtual worlds (Chen *et al*. 2017).

## 5. Conclusion

Given that much attention has been paid to GIScience, this article is focused on the development of current systems of GIS. We first analysed contemporary challenges and opportunities in GIS, then presented several theoretical and technical suggestions that should be implemented. Additionally, this article also discerned several avenues for future research. Although GIS is a type of information system, the fundamental idea of employing GIS is to explore the geographic world, distribution patterns, evolution processes and the interactions of geographical elements to enable users to better understand the world. Thus, the core of GIS should be its geographic features, and the development of GIS should follow the mission of 'exploring the laws of nature and revealing the essence of humanity', which cannot be achieved through information technologies alone. We are motivated to do this by the necessity of bridging spatial information technologies with geographic perspective and knowledge. By doing so, GIS can provide more powerful geographic problem-solving ability. We are aware that our arguments outline only part of the solutions necessary; however, we hope these arguments will benefit GIS development.

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