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EDITORIAL

Digital Earth—from surface to deep: introduction to the Special issue

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1 Introduction

Since the vision of a Digital Earth was first formally proposed by US then-Vice President Albert Gore in January 1998 (Gore, 1999), much impressive progress has been made in basic theories, implementing techniques, and building applications of Digital Earth. Nowadays, Digital Earth systems, such as Google Earth, NASA WorldWind, and Cesium, have been widely embraced by Earth scientists of various disciplines as convenient tools to enhance science for various application scenarios, including integrating geospatial information, improving visualization capabilities, exploring spatio-temporal changes, and communicating scientific results (Goodchild et al., 2012; Zhu et al., 2019; Guo et al., 2020). As an organizing metaphor of the Earth's surface, Digital Earth systems not only offer users the capability to explore high-resolution images and terrain data on different spatial scales, but also can be used to integrate, visualize and analyze user-generated remote sensing imageries, terrain data, 3D models and other custom geospatial information in a variety of formats (Bailey and Chen, 2011; Zhu et al., 2019).

With the continuous evolution of geospatial information acquisition technology, Earth scientists began to conveniently capture, store and process vast quantities of geospatial data sets to reveal the multi-dimensional structure and composition of the entire Earth space, including the Earth's subsurface and atmosphere, as well as the Earth's surface (Zhu et al., 2014). However, challenges remain for geospatial data processing, integration, time-dynamic analysis, 3D modeling and visualization, and their respective applications in Digital Earth.

Today it is possible to look back the history and summarize the status of the Digital Earth vision, as well as imagine its future. This special issue of Frontiers of Earth Science is initiated by the Project of Shanghai Science and Technology Committee (No. 20DZ2307200), with an aim to provide a collection of current, state-of-the-art research articles in Digital Earth and its use for geoscience applications. A total of 14 peer-reviewed original contributions are selected for publication on a variety of topics related to Digital Earth, including construction methods and implementing techniques for deep Earth objects, multi-dimensional modeling, visualization and quality assurance for the Earth's surface and subsurface, applications of digital information for urban, environmental, geographical, geological, and societal scenarios, and so on.

2 Overview of special issue papers

The 14 papers in this special issue can be categorized into two groups according to their research fields. The first half of the issue considers several broad issues related to the surface information in specific subject fields (such as soil erosion studies, urban spatial structure, land-use change, and spatio-temporal trajectory data), while the second half

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focuses on the Earth's deep, along with modeling theories, visualization, spatial analysis and quality assurance methods applicable to subsurface models.

2.1 Surface information in specific geoscience subjects

To quantitatively evaluate the intensity and distribution of freeze–thaw erosion in Tibet, Fan et al. (this issue) proposed an improved AHP method based on the aggregation algorithm of the cloud model. This method avoided the deficiencies of the traditional AHP, allowing for a more accurate and objective description of the fuzziness and randomness of the factors impacting freeze–thaw erosion. It can be easily expanded to provide a scientific evaluation to support soil and water conservation, ecological and environmental protection in the Earth's surface undergoing freeze–thaw erosion.

The urban spatial structure on the Earth's surface demonstrates the dynamic change, the spatial layout of the urban structure elements, and the underlying interactions of the city. It is essential to detect and analyze the urban spatial structure when attempting to explain and solve the increasingly serious urban problems. Zhao et al. (this issue) presented a method for urban spatial structure analysis based on the exploration of the spatial distribution patterns, development trends, and hierarchical information of urban social functions using building footprint data. They proposed an improved turning function (TF) algorithm and a self-organizing clustering method to generate the variable area units (VAUs) of high-homogeneity from building footprints as the basic research units, and constructed a set of models to quantitatively calculate the social function likelihoods with respect to the three types of social functions. A case study on the city of Munich in Germany validated that the proposed methods were effective and reliable.

The ecological environment should be at the center of our concerns about the planet Earth. Digital Earth enables a wider understanding of ecological environment issues in efficient ways. Integrating various time-series data, ecological service value (ESV) accounting, and ecological security pattern (ESP) delineation, Ye et al. (this issue) investigated the land use structure change of 2004/2010/2016 in Ezhou City, China, and simulated the land use structure in 2022 under two kinds of scenarios. This work provided the decision-making reference for coordinating the relationship between regional land resource allocation and ecological environment protection.

To reveal the influences of anthropogenic and natural factors on the quality of urban ecological space in urban areas, Zheng et al. (this issue) explored the spatial pattern of three-dimensional green volume (TDGV) and its underlying influencing factors in Lingang New City in Shanghai, China. They extracted the three-dimensional green volume and the land use intensity from high spatial resolution remotely sensed data acquired by an unmanned aerial vehicle (UAV). The results showed that the spatial pattern of TDGV was jointly affected by anthropogenic factors and natural factors, and the main factors shaping the spatial distribution of TDGV in the study area were local natural factors.

To attain the sustainable development goal in the era of a global ecological crisis, Zhou et al. (this issue) explored the interaction between ecosystem services and poverty livelihoods. They calculated the coupling degree and coupling coordination degree between the ecosystem services and the poverty livelihoods in China's 717 poverty-stricken counties from 2000 to 2015, and analyzed the temporal and spatial evolution of the coupling relationships between ecosystem services and poverty livelihoods. The result can be used to identify key counties or contiguous impoverished areas that are beneficial for governments and local policymakers to develop targeted poverty alleviation policies.

To solve problems of conventional digital elevation models (DEMs) for urban area land surfaces, Zhao et al. (this issue) proposed a new method of DEM construction based on the concept of geographic ontology. Since the morphological characteristics, semantic characteristics, and data acquisition of ground objects are integrated, the proposed DEM construction method has a significantly better performance than conventional methods.

To investigate vegetation dynamics with respect to human activities and climatic variations, Machiwa et al. (this issue) used MODIS remote sensing data, Normalized Difference Vegetation Index, meteorological, and Globeland30 land-use data sets to detect spatio-temporal trends of vegetation change in the Tanzanian coastal region. The results highlight the need for appropriate land-use planning and sustainable utilization of forest resources, and provide a fundamental basis to better understand the nature of the factors that underlie observed changes in vulnerable coastal regions.

Yang et al. (this issue) focused on the variation in reach-averaged bankfull discharge in the Yellow River Estuary during the process of river bed evolution in recent years. They investigated the bankfull characteristic parameters based on the measured hydrological data and surveyed cross-sectional profiles, and presented a reach-averaged method to calculate the reach-averaged bankfull parameters in the tail reach of the Yellow River Estuary during the period 1990–2016. The results indicated that the reach-averaged bankfull discharge was more representative than the cross-sectional bankfull discharge.

Zhang et al. (this issue) proposed a novel data-driven method for the delivery of high-quality spatio-temporal trajectory data (STTD) for autonomous vehicles, in which the meta-model of the STTD was constructed based on the domain knowledge of autonomous driving. By using long short-term memory (LSTM) networks, the vehicle behavior prediction on huge amount of STTD illustrated that the proposed approach facilitates the data-driven development for AVs.

2.2 Modeling, visualization and analysis of deep earth objects

Qadri et al. (this issue) integrated different techniques, including 1D and 3D modeling schemes, as well as other geological and geophysical methods, to model the underground characterization of source and reservoir rocks in Kupe Field, Taranaki Basin, New Zealand. The model indicated the seal and reservoir horizons and the distribution of structural features within the reservoir package. This comprehensive study demonstrated that the integrating modeling schemes were vital in identifying the self-sourced reservoir, as well as improving the understanding of the deep Farewell Formation works as a self-sourced reservoir in the Kupe Field.

In order to determine residual hydrocarbon potential, as well as visualize and analyze surface and deep subsurface geological structural trends, stratigraphic features, and reservoir characteristics at the Dhulian Oilfield, Pakistan, Khan et al. (this issue) presented an approach for integrating digital elevation modeling, seismic interpretation, seismic attributes, 3D geological structural modeling predicated on seismic data interpretation, and petrophysical analysis.

To describe geological features in covered and deep areas when using 3D geometric modeling approaches, Zhao et al. (this issue) developed a new method for automatically estimating the strike and dip by using structural expansion orientation, which is widely distributed and easily extracted from geological and/or geophysical maps/profiles. A quasi-gradient descent (QGD) method is presented to improve the time efficiency and accuracy of the objective function optimization. The case study in Australia showed that the strikes and dips estimated by the proposed method conformed to the actual geological structures more than those of the vector interpolation method did. Using the estimated strikes and dips, the implicit interfaces, and the strike/dip vector fields in 3D geological modeling scenes can be greatly improved.

Hou et al. (this issue) focused on the visualization and analysis of the impact of uncertainty on the geological subsurface. They proposed an uncertainty visualization method using vector-based parameters for the 3D geological subsurface. The method provided different models for calculating rock mechanics for subsurface constructions, and different probabilities for decision-making. An example of the bedrock surface structure for a metro station in Guangzhou city, southern China, showed that the presented method was applicable to quantitative description and visualization of inner uncertainties in 3D geological surface models.

Natural fractures in the deep reservoir are important storage spaces and serve as major pathways for fluid flow. Xu et al. (this issue) focused on the prediction of natural fracture in shale oil reservoirs. To better identify the development of fractures from conventional logs, they combined the log data and the R/S analysis method to analyze reservoir fracture characteristics. Five kinds of conventional logs were selected to identify natural fractures of the Chang 7 Reservoir in the southwestern Ordos Basin. The calculated result had a better fracture response, thus showing that the R/S analysis method can identify natural fractures by the conventional log.

3 Summary

The papers in this special issue present a small but various selection of researches showing the theories and applications of the Digital Earth science, and demonstrating how digital information has enhanced science for earth scientists and other audiences. Nowadays, the Digital Earth science is moving from modeling Earth’s surface to characterizing the Earth’s deep along with a continuous evolution of geospatial information acquisition, analysis and application technology. This development trend underpins the evolution of novel research fields beyond the traditional environmental and cultural phenomena on the Earth’s surface toward deep space, deep sea, deep interior, deep time, and deep intelligence, and finally promoting complex spatio-temporal dynamics/processes research for the entire Earth. We expect this issue will be a valuable start and open new doors for further Digital Earth studies, especially in areas like deep Digital Earth and its application domains.

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