RESEARCH ON CONSTRUCTION OF NATURAL RESOURCES THREE-DIMENSIONAL SPATIO-TEMPORAL DATABASE SYSTEM

Yin Gao [1], Jianjun Liu [1 *], Jianwei Liu [1], Yuanjie Zhang [1], Jian Che [1], Zhaokun Zhai [1], Bianli Zhao [1], Hao Li [1]

[1] National Geomatics Center of China, 100830, Beijing, China

KEY WORDS: Natural Resources; Three-Dimensional Spatiotemporal Database; Distributed Architecture; Database Management System; Survey and Monitoring Data; System Construction; Architecture Design.

ABSTRACT:

The construction of an efficient and practical database management system based on large-scale three-dimensional spatiotemporal databases presents a novel challenge in the field of natural resource information technology. This research, with the objective of supporting the contemporary era of unified natural resource management and building upon the foundation of a national-level three-dimensional spatiotemporal natural resource database, proposes a comprehensive framework for a distributed architecture database management system. Subsequently, the research outlines the system's components, encompassing a service publishing system, online application system, professional management system, and operational supervision system, and designs core functionalities for the integrated management of natural resource elements within a three-dimensional spatiotemporal context. Building upon this framework, the research utilizes cloud-based database software and hardware environments, along with distributed technology pathways, to establish a national-level three-dimensional spatiotemporal database management system for natural resources. Furthermore, it conducts typical applications in the field of natural resources. The results demonstrate that the database management system effectively achieves the integration, representation, and analytical application of large-scale natural resource survey and monitoring data within a three-dimensional spatiotemporal context. It plays a crucial supportive role in the development of a national-level three-dimensional spatiotemporal natural resource database and holds valuable insights for the construction of provincial-level database management systems and other related systems in various domains.

1. INTRODUCTION

With the advent of the era of big data in Earth observation, China has entered a new phase in its ecological civilization construction and natural resource management. To enhance the unified survey, evaluation, and monitoring of natural resources and to improve the regulatory system for natural resources, the Ministry of Natural Resources has issued the "Overall Plan for the Construction of the Three-dimensional Spatiotemporal Database of Natural Resources"(China 2021a; Jun et al. 2022). It proposes to focus on seven categories of natural resources under the jurisdiction of the Ministry of Natural Resources, including land, minerals, forests, grasslands, wetlands, water, and maritime areas and islands. A national-level three-dimensional spatiotemporal database of natural resources is to be established, consisting of one main database and nine sub-databases, achieving a unified three-dimensional management of survey and monitoring data at the central level, and forming a unified base map and dataset for natural resource survey and monitoring(China 2021b). Among them, the sub-databases are responsible for the integrated management of specialized survey and monitoring data results of various natural resources, while the main database handles the logical integration of the survey and monitoring sub-databases based on a unified spatial foundation, physically migrating and integrating some data results, and facilitating the comprehensive application of various natural resource survey and monitoring data(Jianjun et al. 2022).

Surface three-dimensional (3D) data mapping serves as the spatial foundation for constructing a 3D spatiotemporal database, and the measurement and research of 3D data have consistently been focal points in the international surveying and mapping arena(Prasad et al. 2022). In 2016, the United States initiated the 3D Elevation Program (3DEP), managed by the U.S. Geological Survey's National Geospatial Program, in response to the burgeoning demand for high-quality topographic data and various other 3D data encompassing the nation's natural and built features(Stoker and Miller 2022; Sugarbaker et al. 2017). By 2020, elevation data of high precision and resolution, covering 78% of the nation, had been obtained, with nationwide coverage anticipated by 2023. Switzerland developed a novel geographic information product termed the 3D Terrain Landscape Model (3DTLM), containing 10 layers of elements with each geographic datum possessing 3D coordinates(Stoter et al. 2016). The accuracy in the X, Y, and Z dimensions surpasses 1 meter, which, upon completion, will expedite the updating of Switzerland's geographical information. France undertook a 3D digital national cartography project, mapping the terrestrial and subterranean 3D geological structures, geothermal features, and groundwater across mainland France and its overseas territories(ActuIA 2021). Countries like Japan employed LiDAR for nationwide 3D elevation data collection, culminating in 3D topographic maps(Avtar et al. 2015).

Advanced nations have even embarked on global high-precision real-world 3D construction. Building on the foundation of the global 30-meter resolution SRTM digital elevation model, produced in 2000 via radar onboard space shuttles, the U.S. issued an update in 2014 with an absolute vertical accuracy of less than 16 meters(Yang et al. 2011). In 2016, the European aerospace company Airbus and the German Aerospace Center (DLR) leveraged the TanDEM-X and TerraSAR-X radar satellites to complete the WorldDEM global elevation model, achieving a 12-meter resolution model spanning all terrestrial areas(Antony et al. 2016). Japan launched the global digital 3D map AW3D, covering the entire terrestrial domain including Antarctica, representing the most precise global 3D mapping service currently available, with accuracies in major urban regions ranging from 0.5 to 2 meters(Takaku and Tadono 2017).

With the progression of digital twin and metaverse technologies, tech giants epitomized by Google have spearheaded innovative research in this domain, striving to formulate high-fidelity urban and indoor/outdoor 3D models via sophisticated image-matching algorithms, and subsequently offering these services on commercial platforms like Google Earth(Horota et al. 2020).

China has long conducted nationwide fundamental mapping operations. Around 2010, a 1:50,000 digital elevation model covering the entire country was completed(Jun et al. 2010). Provincial mapping departments were continuously organized to produce 1:10,000 digital elevation models. Around 2020, efforts were furthered to promote the construction of a realistic 3D China, employing efficient multi-source methods such as stereoscopic surveying satellites and oblique aerial photography to develop high-precision realistic 3D data(CHEN et al. 2022). High-precision modeling pilots or experiments were executed in cities of varying scales, including Wuhan, Chongqing, Guangzhou, Shanghai, Beijing, Qingdao, Tianjin, Hangzhou, Harbin, Ningbo, and Deqing, witnessing substantial progress.

Built upon the 3D foundational data, the construction of the 3D spatiotemporal database also encompasses integrated modeling of various 2D and 3D data, 3D visualization, and spatial analysis. This domain has historically been a research hotspot in the international GIS field. In 2000, the International Society for Photogrammetry and Remote Sensing (ISPRS) prioritized 3D data model design, modeling, and visualization, endorsing research on automatic surface reconstruction based on novel multi-sensor data, 3D object modeling considering geometric-semantic-temporal elements, simulations, visualization, and animation techniques(Baltsavias 2000). Subsequently, research expanded to encompass multi-dimensional, intricate spatiotemporal dynamic modeling, digital twins, automated updates, and scenario-based expressions.

Supported by the National Natural Science Foundation of China, institutions such as Wuhan University, the National Geomatics Center of China, and the Hong Kong Polytechnic University initiated research on "Multi-dimensional Dynamic GIS Spatial Data Processing" and "3D GIS Data Modeling and Updating". Since 1997, they have consecutively hosted seven international academic seminars on "Multi-dimensional Dynamic GIS", laying the foundation for 3D spatial modeling and application in China's GIS(Jun et al. 2004).

In the industrial sector, internationally recognized GIS software enterprises such as ESRI, Skyline, and SuperMap have consistently been dedicated to the development of 2D and 3D GIS software. Foundational software solutions, including ArcGIS, Skyline, and SuperMap, tailored to 2D and 3D data, have substantially bolstered the advancement of the entire field. The open-source community, passionate about innovating in 3D GIS technology, has developed globally renowned open-source 3D GIS software platforms like Cesium and Babylon, leveraging cutting-edge graphical technologies such as WebGL and WebGPU. These platforms have laid a solid software foundation for the construction of 3D spatiotemporal databases(Lü et al. 2019).

Research on three-dimensional spatiotemporal database systems has been conducted for several years. Compared to two-dimensional databases, as databases upgrade from a planar dimension to a three-dimensional space, the computational costs in storage scheduling, display, and overlay analysis experience a geometric increase(Wang et al. 2019). Consequently, traditional three-dimensional systems, primarily focusing on micro-scale visualization and urban simulation, are insufficient in supporting the three-dimensional representation and integrated application of large-scale spatial data(Breunig et al. 2020). Thus, how to construct a multi-scale comprehensive three-dimensional spatiotemporal database system presents a novel challenge in the field.

This study originating from the current data status of the three-dimensional spatiotemporal database of natural resources and the comprehensive management requirements at the national level, and adhering to principles of advancement, practicality, inheritance, integration, openness, and extensibility, a holistic framework and system composition for a database management system encompassing core components such as "service publishing system, online application system, professional management system, and operation & maintenance supervision system" was proposed. This led to the formulation of a technical framework for the construction of a three-dimensional spatiotemporal database management system for natural resources. Subsequently, based on a cloud architecture for the database's hardware and software environment, a national-level management system for the three-dimensional spatiotemporal database of natural resources was established. With this national-level database as the foundation, typical application analyses were conducted, providing technical guidance for the construction and application of the national-level database management system. It also offers valuable references for the construction of subsequent sub-database management systems and local database management systems at various levels.

2. METHOD

2.1 General Framework

The database serves as an integral component of the Three-dimensional Spatiotemporal Database for Natural Resources. Core data from the nine sub-databases is physically migrated and integrated into the main database. Under secure network connectivity conditions, the content of these nine sub-databases is logically integrated into the database through service invocation. Concurrently, the sub-databases can access the main database's data content using a similar data-sharing exchange method, facilitating horizontal connectivity between the main and sub-databases. Operating under secure network conditions, the main database, adhering to unified service interfaces, invokes online data services from databases at various regional levels. These regional databases can also access data services from both the main and sub-databases, achieving vertical integration between the main database and regional databases. The main database online invokes the Real-scene Three-dimensional Map of China, which integrates terrain-level, city-level, and component-level three-dimensional data, thereby providing a unified three-dimensional spatial framework for the intuitive representation of various natural resources within the database. The main database is connected to the National Territorial Spatial Basic Information Platform and the "One Map" of Natural Resources, offering data services for territorial spatial planning and natural resource management applications. Relevant departments and operational units, as authorized users, can access the data resources within the database through the National Territorial Spatial Basic Information Platform. The general framework of the natural resources three-dimensional spatiotemporal database is shown in Figure 1.

2.2 Integration and Fusion of Multi-type Natural Resource Data Based on Spatiotemporal Information Model

A novel three-dimensional spatio-temporal information model is employed, facilitating the temporal and spatial association and information fusion of various subterranean, terrestrial, and aboveground natural resources. The three-dimensional spatio-

https://doi.org/10.5194/isprs-archives-XLVIII-4-W9-2024-175-2024 | © Author(s) 2024. CC BY 4.0 License.

temporal data model for natural resources is a physical model that embodies the integrated expression of natural resources in terms of time, space, semantics, management, and services (Figure 2).

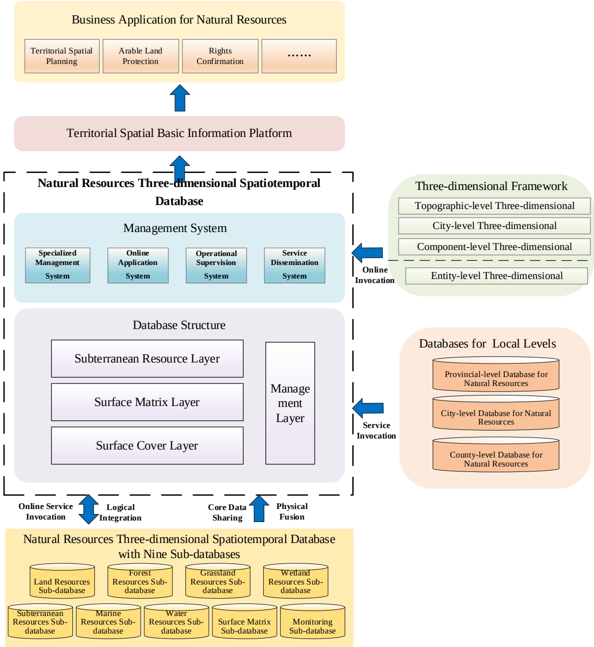

Figure 1. General framework of the natural resources three-dimensional spatiotemporal database

This model incorporates the entity expression model, spatio-temporal evolution model, Earth space grid model, and business relationship model. By considering the entity as the subject, geometric expression is realized based on points, lines, surfaces, and bodies, temporal segmentation is achieved based on spatio-temporal processes, location encoding is implemented based on Earth grid units, and logical relationships are established based on business. This accurately reflects the quintuplet spatio-temporal-attribute relationship of the temporal state, location, quantity, quality, and ecology of natural resource entities, enabling the integrated expression of natural resources.

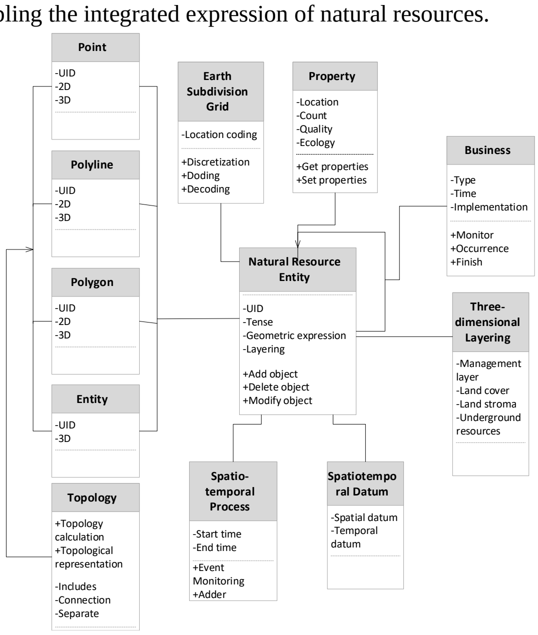

Figure 2. Spatiotemporal information model for natural resources data connection and fusion

2.3 Integration, Representation, and Application of Spatiotemporal Data Based on Three-Dimensional Scenarios

In response to the emerging requirements for three-dimensional management of natural resources, and taking into account the practical scenarios of natural resource analysis applications, a technical approach for the construction of an integrated expression and application system of a three-dimensional spatiotemporal database has been proposed. The technical approach is shown in Figure 3.

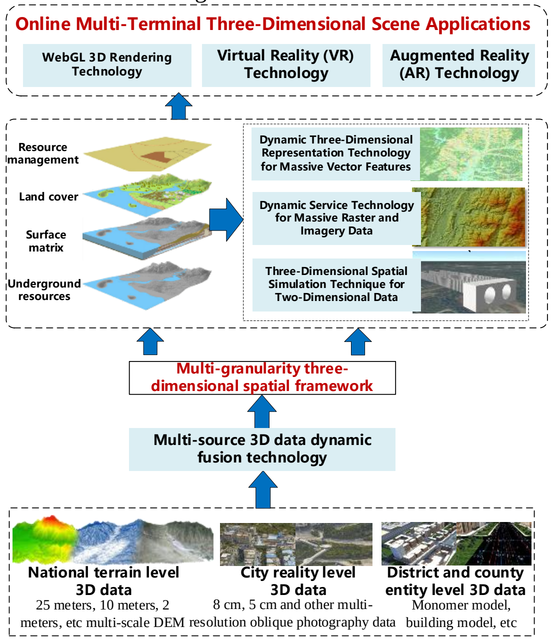

Figure 3. 3D technology framework for data integration expression and application

2.3.1 Design of Distributed Spatiotemporal Database for Massive Data: Techniques were developed for parallel and efficient data validation, model reconstruction, data warehousing, and scheduling optimization, ensuring efficient aggregation and parallel construction of extensive survey and monitoring data. By adhering to innovative and pragmatic principles, lightweight and distributed database architectures were employed for vast spatiotemporal data resources, such as national land surveys, change investigations, geographical monitoring, and specialized surveillance. Foundational support for efficient database management and immediate services was provided through this design. On this foundation, a comprehensive set of techniques supporting efficient, parallel data warehousing was developed, resolving challenges in aggregating and warehousing large-scale datasets and ensuring timely and efficient completion of database construction tasks.

2.3.2 Multidimensional Spatial Representation and Spatiotemporal Information Modeling: Models were constructed to represent above-ground, surface-level, and subterranean natural resources in their entirety. Temporal extrapolations of natural resource entities, grid subdivisions, and business association models were established, leading to an integrated model reconstruction and multidimensional information coupling. Referring to the design techniques used for the three-dimensional spatiotemporal database of natural resources, various models were developed, including entity representation, temporal extrapolation, grid subdivision, and business associations. This provided comprehensive spatial representation, temporal change extrapolation, grid-aware partitioning, and business-related services, bolstering the database's information service capabilities.

2.3.3 Three-Dimensional Spatiotemporal Digital Platform Services: Systems were devised for multi-scale topographical integration, real-time scheduling of vast remote sensing imagery, massive vector element services, and multi-dimensional grid computation and analysis. This offers a holistic service platform for database information in three-dimensional representations and applications. Addressing the prevalent issues of over-representation and under-utilization in traditional 3D service systems, a comprehensive set of 3D spatiotemporal digital platform service techniques was proposed. This resulted in the development of multi-scale topographical integration, real-time remote sensing image dispatching, services for massive vector elements, and multi-dimensional grid analysis, ensuring efficient, element-level experiences for full-scale database information services.

2.3.4 Standardized Data Sharing, Exchange, and Open Services: Mechanisms for open-standard data entity exchanges and service interconnectivity interfaces were established, facilitating a new database system that bridges national main and sub-databases and seamlessly integrates national and local data. Addressing challenges in upstream data aggregation and downstream service delivery for databases, standardized data sharing, and open service techniques were adopted. An entity data exchange mechanism and standardized service interconnectivity interface were designed, enabling fluid data and service exchanges between main and sub-databases, national and local databases, and upstream and downstream platforms, thus providing institutional and technical safeguards for the database's horizontal and vertical connectivity.

2.4 Database System Framework

The database management system of the natural resources three-dimensional spatiotemporal database is designed with an overarching framework that emphasizes "unified architecture, collaborative operations, and interconnected information." The logical structure of the system is divided into the infrastructure layer, data layer, service layer, and application layer. The overall framework of the system is shown in Figure 4.

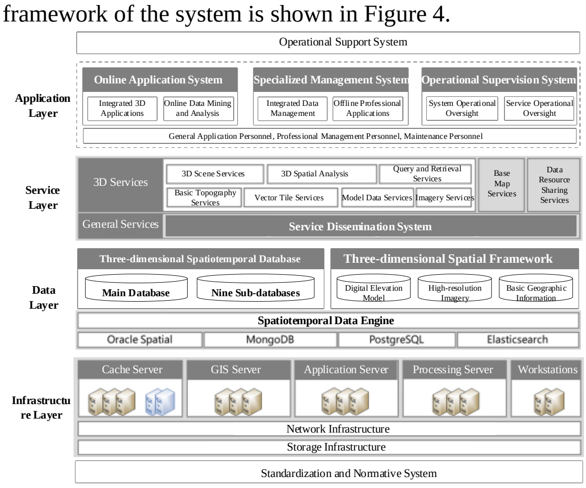

Figure 4. General framework of the database management system

2.4.1 Infrastructure Layer: The infrastructure layer constitutes the fundamental hardware and software environment underpinning the entire database management system. This layer primarily comprises basic hardware (such as data centres, servers, storage devices, security devices, and network devices), foundational software (including operating systems, databases, GIS platforms, and various middleware), and IT infrastructures like computer networks (both LAN and classified networks) and cloud platforms.

2.4.2 Data Layer: The data layer represents the data assets of the entire database management system. It primarily encompasses the surface coverage, surface substrates, subterranean resources, and management data of the three-dimensional spatiotemporal database for natural resources, as well as the topographical 3D, urban-level 3D, and component-level 3D data of the 3D spatial framework. Physically, the data layer employs storage mechanisms such as relational databases, non-relational databases, and file databases for massive distributed data. Logically, a unified spatiotemporal data engine is utilized for standardized organization and unified access to all data resources. Based on data usage frequency, a data management model featuring high-frequency data online and low-frequency data offline is adopted.

2.4.3 Service Layer: The service layer acts as the logical interface between the application and data layers. Through standardized data and service interfaces, unified connections and efficient invocations of the database are achieved. It predominantly includes service-level access interfaces for 3D, vector, and raster data, entity-level operation interfaces, as well as application services such as place-name address services, directory sharing services, information query and retrieval, and 3D spatial analysis.

2.4.4 Application Layer: The application layer presents the interactive interface and operational functionalities offered to users by the entire database management system. The primary users of the three-dimensional spatiotemporal database for natural resources include general application personnel, specialized management personnel, and system maintenance personnel. Tailored functionalities like online applications, professional management, and operational maintenance are provided to cater to these diverse user needs, ensuring comprehensive management and application services for the database.

2.5 System Composition

In response to core requirements such as shared dissemination, online application, specialized management, and operational supervision of the three-dimensional spatiotemporal database for natural resources, the management system encompasses subsystems like service dissemination, online application, specialized management, and operational oversight. These support integrated storage management, browsing and querying, statistical analysis, results application, and shared services of the natural resources three-dimensional spatiotemporal database, ensuring the smooth operation of the territorial spatial basic information platform and serving the "two unifications" duty fulfillment. The system's functional composition is shown in Figure 5.

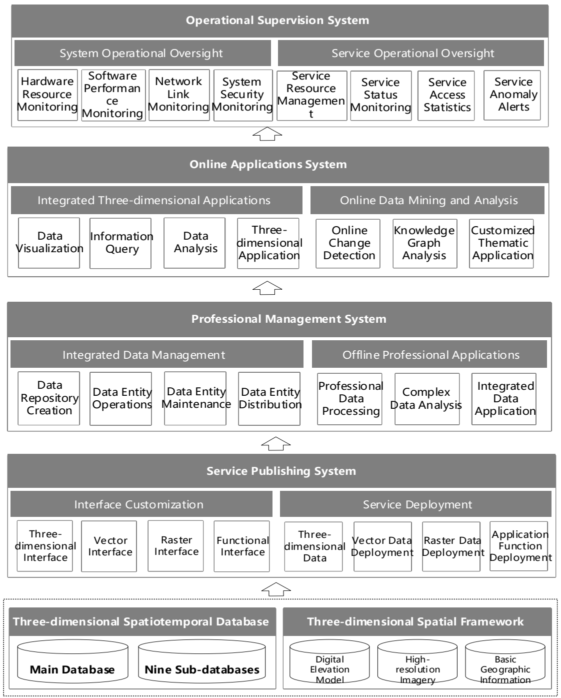

Figure 5. System Composition

2.5.1 Service Publishing System: The service dissemination system, tailored for the physically dispersed yet logically unified construction requirements of the three-dimensional spatiotemporal database for natural resources, operates based on standardized service interface protocols. Through clusterized and parallelized high-performance computing strategies, efficient access and dissemination of vast data resources are realized, offering service support to all database management subsystems. The system consists of two segments: service interface customization and service deployment system.

2.5.2 Professional Management System: The specialized management system addresses the complexity and specialized application demands of the three-dimensional spatiotemporal data of natural resources. Utilizing a C/S design framework and through entity-level and cross-database data access and scheduling, it provides extensive and advanced data entity management and intricate analysis capabilities. The system comprises two modules: integrated data management and offline specialized application.

2.5.3 Online Application System: Targeting the foundational and generic application needs of the three-dimensional spatiotemporal data of natural resources, the online application system adopts a B/S design architecture with a lightweight design. Through efficient service scheduling and streamlined online access, comprehensive representation and application capabilities of voluminous spatiotemporal data under three dimensions are provided. This system is divided into two sections: integrated 3D application and online mining analysis.

2.5.4 Operational Supervision System: The operational supervision system, designed considering the distributed storage, online invocation, substantial data volume, and high-security prerequisites of the three-dimensional spatiotemporal database for natural resources, employs a B/S design architecture. Through comprehensive operational monitoring and multi-tiered access management, it ensures stable and efficient database system operation and oversight. The system is bifurcated into system operational supervision and service resource oversight modules.

3. RESULTS

Upon the foundation of technical design and leveraging 3D real scene data combined with natural resources survey and monitoring results, database construction and system development were undertaken. A three-dimensional spatiotemporal database system, which holistically reflects the actual status of territorial space, was successfully established. This system has crafted a nationally unified three-dimensional spatial framework, integrated various types of natural resource survey and monitoring data, accomplished data modeling and system development, and conducted three-dimensional reconstruction of massive, diverse, multi-scale, and multi-temporal data. It facilitates a true three-dimensional representation of geospatial data, comprehensive spatial overlay, and real-time online application capabilities, providing a novel avenue for decision-making within a three-dimensional context.

3.1 Construction of a Unified National Three-Dimensional Spatial Framework

By fully harnessing the results of basic surveying and mapping, a nationwide unified three-dimensional spatial framework, encompassing multiple scales, temporalities, and elements, has been developed.

3.1.1 Basic Three-Dimensional Framework Based on Digital Elevation Model (DEM): National-scale surveying and mapping achievements include the 1:50,000 DEM data, covering the entire terrestrial territory of the country with a currency date of 2020, totaling 24,201 map sheets, featuring a 10-meter grid. In addition, provincial-level surveying and mapping outcomes have produced the 1:10,000 DEM data, spanning approximately 60% of the nation's terrestrial area, with about 210,000 sheets (Figure 6).

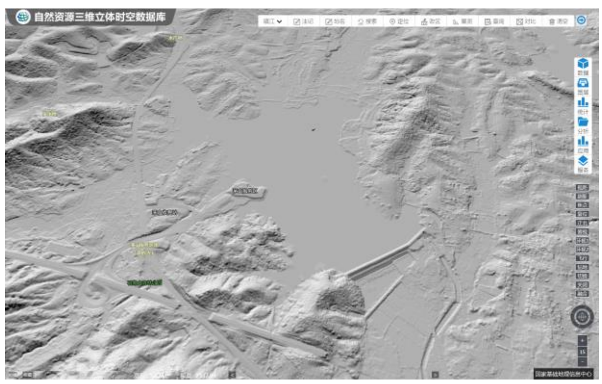

Figure 6. The DEM serves as the foundational 3D layer

3.1.2 Land Surface Background Based on Multi-temporal Remote Sensing Imagery: This imagery covers the country's entire terrestrial territory, spanning a decade in temporal depth. Annual versions were produced from 2014-2020, and starting from 2021, quarterly versions were developed. The 2014 and 2018 images have resolutions finer than 1 meter, amassing 500,000 scenes, amounting to 4PB.

3.1.3 Building Spatial Framework Based on Basic Geographic Information: The fundamental geographic information encompasses the entire terrestrial territory of the nation, presented in three scales (1:50,000, 1:250,000, 1:1,000,000). Annual editions have been produced consecutively for twelve years, from 2011 to 2022. Each edition demonstrates comprehensive elements - approximately 180 million per edition - including hydrology, residential areas, transportation, pipelines, boundaries, landforms, vegetation, toponyms, and so forth, summing up to 470 element types.

3.1.4 Urban Three-Dimensional Model as a Framework for Detailed Focus Areas: Oblique photographic data from cities such as Beijing, Shanghai, Tianjin, Chongqing, Wuhan, Hangzhou, Harbin, Ningbo, Deqing, Linyi, and Jinyang have been included. These models incorporate individual structures, architectural models, underground pipelines, geological structures, underground mineral bodies, and submarine terrains among others (Figure 7).

Figure 7. Three-dimensional model as a fine space framework

3.2 Integration and Modeling of Natural Resources Spatiotemporal Data Based on Three-Dimensional Framework

A comprehensive amalgamation of diverse natural resource survey and monitoring data has been achieved, which encompasses the Third National Land Survey data, land change survey data, national geographical condition monitoring data, and combined ecological survey data on forests, grasslands, and wetlands. Additionally, a considerable volume of historical data has been included, with the consolidated data totaling 1TB and comprising 1.4 billion polygons (Figure 8).

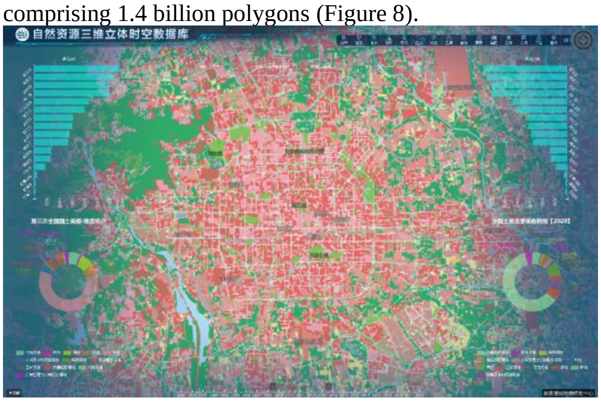

Figure 8. Natural resource surveys and monitoring have been integrated in 3D scene

4.2.1 The Third National Land Survey Data: Data spans the national breadth, covering 2,884 counties and accounting for 310 million polygons with a data volume of 240GB.

4.2.2 Multi-Year Land Change Survey Data: Land change survey data from the years 2020 and 2021 covers the entire nation, representing 2,875 counties with 650 million polygons and a data volume of 530GB.

4.2.3 National sequential monitoring data of geographical conditions: Nationwide geographical condition monitoring data from 2015 to 2022 incorporates 2,874 operational units with a representation of 400 million polygons and a data volume of 250GB per year.

4.2.4 Comprehensive Ecological Survey Data of Forest, Grassland and Wetland: Forest, grassland and wetland ecology survey data from selected pilot regions encompasses 2 counties, amassing 300,000 polygons with a data volume of 500MB.

3.3 Database Management System for Computation and Business Support

3.3.1 Database management system: Encompassing online applications, professional management, service deployment, and operational oversight has been developed. This system not only facilitates rapid browsing and flexible querying capabilities but also boasts professional capabilities such as spatiotemporal change analysis and resource quantity statistics.

3.3.2 Efficient Browsing and Flexible Data Querying Under 3D Browser Scene: The system offers the ability to handle massive data, efficient browsing, customized displays, integrated overlays, attribute queries, conditional filters, and spatial measurements, mirroring the direct manipulation of spatial data in professional desktop GIS platforms.

3.3.3 Professional Functions for Statistics and Analysis Aimed at Real-Time Computing: The system is capable of real-time statistics and analyses of up to a billion polygons. Flexible statistics methods include multi-level administrative regions, geographic units, arbitrary range, real-time buffer statistics, and flexible combined statistics; real-time analyses cover spatiotemporal change retrievals, spatiotemporal evolution analyses, three-dimensional space analyses, and slope calculation analyses.

3.3.4 Spatiotemporal Change Analysis Based on Any Time Dimension: Analyses can be conducted on any specific points in time, facilitating real-time discovery, statistics, and evolution of natural resource changes. The system accommodates arbitrary units such as nation, province, city, and county; arbitrary ranges, be it chosen units or drawn boundaries; various land classifications from primary to tertiary levels; and arbitrary periods, for example, 2019, 2020, and 2021.

3.3.5 Real-Time Thematic Modeling and Statistics of Natural Resources Quantity: With the integration of statistical models for topics like land, forests, and grasslands, the system can execute real-time resource quantity statistics under any condition. Statistical units comprise multi-level administrative regions, geographic units, arbitrary scopes, real-time buffers, and flexible combinations; the types of resource quantities include land area, forest volume, grass yield, and so on.

3.4 Typical Natural Resource Management Applications Based on a Three-Dimensional Spatiotemporal Database

3.4.1 Supporting the Construction of National Level Natural Resources "One Map" and Land Space Basic Information Platform: Connected to a dedicated network, it serves the "Unified Map of Natural Resources" and the "National Land and Space Information Platform," providing both data and functional services.

3.4.2 Providing Three-Dimensional Analysis Support for Geological Disaster Platform: Integrated with the Geological Environment Monitoring Institute's three-dimensional geological disaster platform system, it offers online data services. A universal access plug-in for three-dimensional data services has been developed, addressing challenges in cross-platform service invocation.

3.4.3 Cultivated Land Slope Verification Based on Scientific Computing: Slope maps submitted by provincial survey offices have been sampled and verified. Consequently, the verified slope maps were utilized for a comprehensive check of the survey's land plots, ensuring the authenticity and accuracy of the survey's land slope results.

3.4.4 Protection of Permanent Basic Farmland: Using three-dimensional terrain and slope analyses, the distribution of basic farmland with slopes exceeding 25° has been vividly displayed.

3.4.5 Cultivated Land Monitoring: Employing high-precision terrain and slope calculations, sections of the Yellow River's suspended river course have been identified. The condition of cultivated lands within the Yellow River's embankment and tender beaches has been verified through spatial overlay analysis.

3.4.6 Natural Landform Changes Analysis: Utilizing the three-dimensional spatiotemporal database, changes in islands, sandbars, and coastlines in the Yalu River area have been analyzed, as well as the impacts of such changes on navigable waterways.

4. DISCUSSION AND CONCLUSION

The construction of three-dimensional (3D) geospatial data resources and information systems has emerged as a global research hotspot in the field of geographic information in recent years. The 3DEP project in the United States is dedicated to the collection of high-quality topographic data and various other 3D data related to the country's natural and structural features, predominantly focusing on the acquisition of 3D foundational data. However, reports on the construction of application systems based on high-precision 3D data are yet to be seen (Stoker and Miller 2022). The Swiss 3DTLM project concentrates primarily on the construction of 3D foundations and frameworks based on 3D terrain (Stoter et al. 2016). The French 3D digital national topographic mapping project is more involved with the surveying of surface and subsurface geological structures, geothermal energy, groundwater, and other information (ActuIA 2021).

In the domain of global change, Chen Jun has led the creation of public data covering 30-meter global surface and established a global surface coverage service system for knowledge services, offering inquiries and statistics on ten categories of global land use information based on two dimensions (Chen et al. 2017). Furthermore, commercial companies, represented by Google Earth, have developed a 3D map service system on a global scale capable of refined 3D browsing of global terrain, cities, and other multi-scale details. However, there are no known instances of integrating this system with mass vector data related to natural resources (Yu and Gong 2012).

China has also prioritized the construction of basic geographic information resources in recent years. Since the establishment of the national 1:50,000 basic geographic information database in 2011, annual updates of basic geographic information have been ongoing, and a national basic geographic information system has been set up, aggregating and servicing massive geographic information elements in two-dimensional space (CHEN et al. 2010). In the field of natural resources, large-scale resource surveys such as land, forest, wetland, and water resources have all established domain-specific information systems. However, these systems are primarily constructed based on two-dimensional geographic information, with a focus on applications such as 3D terrain visualization (CAI et al. 2015; CAO et al. 2022).

Compared with previous research related to the construction of 2D and 3D geographic information resources and information systems, this study has for the first time designed and built a national-level large-scale integrated 3D database system containing massive 3D data and natural resource spatio-temporal data. This system, on the one hand, constructs a nationwide unified 3D foundation that takes into account aboveground and underground spatial dimensions based on 3D data on multiple scales such as terrain, cities, and components. On the other hand, it realizes spatial modeling and information integration of various natural resources such as mountains, waters, forests, fields, lakes, and grasslands on a unified spatio-temporal information model, further achieving 3D display and spatial decision analysis of natural resources based on the 3D geographic information framework. This system has also achieved typical applications in national-level natural resource analysis and evaluation, farmland protection, spatial planning, supervision and law enforcement, ecological restoration, and other aspects.

Compared with previous domain-specific natural resource business information systems established based on two-dimensional geographic information, such as land, forest, wetland, and water resources, this system can better reflect the spatio-temporal distribution characteristics of various natural resource elements in 3D space and support natural resource business management based on spatio-temporal information. It realizes speaking with geographic data, judging in 3D space, and deciding based on scientific facts, better meeting the fine management needs of natural resources in the era of Earth observation big data.

Building 3D information systems based on large-scale spatial data is a recognized challenge in the GIS field. From the perspective of 3D information system design and construction, the distributed architecture of the natural resource 3D spatio-temporal database system designed in this study has been proven to effectively address the challenge of integrating expression and analysis applications for large-scale natural resource data in 3D space. The 3D spatio-temporal database management system proposed in this study achieves unified calling, 3D management, and online application of various natural resource data from the main database and sub-databases, effectively supporting the basic needs of the new era's unified natural resource management for survey monitoring spatio-temporal data. It plays an important supporting role in further building a national spatial information platform, a national spatial planning supervision implementation platform, etc., and has significant potential for national-level natural resource management and other industry applications in the era of big data.

REFERENCES

ActuIA,2021. The national Lidar HD programme: 3D mapping of the entire French territory. In. France: ActuIA.

Antony, J.W., Schmidt, K., Schwerdt, M., Polimeni, D., Tous-Ramon, N., Bachmann, M., & Alfonzo, G.C.,2016. Radiometric accuracy and stability of TerraSAR-X and TanDEM-X. In, *Proceedings of EUSAR 2016: 11th European Conference on Synthetic Aperture Radar* (pp. 1-4): VDE.

Avtar, R., Yunus, A.P., Kraines, S., & Yamamuro, M., 2015. Evaluation of DEM generation based on Interferometric SAR using TanDEM-X data in Tokyo. *Physics and Chemistry of the Earth, Parts A/B/C* 83(1), 166-177.

Baltsavias, E.P.,2000. Report on the ISPRS Journal of Photogrammetry and Remote Sensing (PRS) for the period 1996–2000. In (pp. 217-229): Elsevier.

Breunig, M., Bradley, P.E., Jahn, M., Kuper, P., Mazroob, N., Rösch, N., Al-Doori, M., Stefanakis, E., & Jadidi, M., 2020. Geospatial data management research: Progress and future directions. *ISPRS International Journal of Geo-Information* 9(2), 95-100.

CAI, Y., XIE, W., FU, J., CHENG, Y., CHEN, Z., & CHENG, J., 2015. Some Key Technologies of Geospatial Information System for China Water Census. *Acta Geodaetica et Cartographica Sinica* 44(5), 585-589.

CAO, L., ZHOU, K., SHEN, X., YANG, X., CAO, F., & WANG, G., 2022. The status and prospects of smart forestry. *JOURNAL OF NANJING FORESTRY UNIVERSITY* 46(6), 83.

Chen, J., Cao, X., Peng, S., & Ren, H., 2017. Analysis and applications of GlobeLand30: a review. *ISPRS International Journal of Geo-Information* 6(8), 230.

CHEN, J., LIU, J., & TIAN, H., 2022. Basic Directions and Technological Path for Building 3D Realistic Geospatial Scene in China. *GEOMATICS AND INFORMATION SCIENCE OF WUHAN UNIVERSITY* 47(10), 1568-1575.

CHEN, J., WANG, D., SHANG, Y., LIAO, A., ZHAO, R., LIU, J., ZHU, W., & LI, L., 2010. Design and development for updating national 1:50,000 topographic databases in China. *Acta Geodaetica et Cartographica Sinica* 39(1), 7-10.

China, M.o.N.R.o.t.P.s.R.o.,2021a. Notice from the Office of the Ministry of Natural Resources Regarding the Issuance of the 'Comprehensive Framework for the Establishment of a Three-Dimensional Spatiotemporal Database of Natural Resources. In O.o.t.M.o.N. Resources (Ed.). Beijing: Ministry of Natural Resources of the People's Republic of China.

China, M.o.N.R.o.t.P.s.R.o.,2021b. Overall plan for the construction of three-dimensional spatio-temporal database of natural resources. In M.o.N.R.o.t.P.s.R.o. China (Ed.) (pp. 1-15). Beijing: Ministry of Natural Resources of the People's Republic of China.

Horota, R.K., Aires, A.S., Marques, A., Rossa, P., De Souza, E.M., Gonzaga, L., & Veronez, M.R., 2020. Printgrammetry—3-D Model Acquisition Methodology From Google Earth Imagery Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 13(1), 2819-2830.

Jianjun, L., Jianwei, L., Yin, G., Wenhao, Z., Zhaokun, Z., Jian, C., & Bianli, Z., 2022. Technical Framework for Three-dimensional Spatio-temporal Main Database Construction of Natural Resources. *GEOMATICS WORLD* 29(3), 37-42.

Jun, C., Donghua, W., Yaoling, S., Anping, L., Renliang, Z., Jianjun, L., Wu, Z., & Limeng, L., 2010. Design and development for updating national 1:50,000 topographic databases in China. *Acta Geodaetica et Cartographica Sinica* 39(1), 0-82.

Jun, C., Hao, W., & Jixian, Z., 2022. Building natural resources surveying and monitoring technological system: direction and research agenda. *Acta Geographica Sinica* 77(5), 1041-1055.

Jun, C., Zhilin, L., Jie, J., & Qing, Z., 2004. Dynamic and Multi-dimensional Spatial Data Modeling: Models and Methods. *GEOMATICS AND INFORMATION SCIENCE OF WUHAN UNIVERSITY* 29(10), 858-862.

Lü, G., Batty, M., Strobl, J., Lin, H., Zhu, A.-X., & Chen, M., 2019. Reflections and speculations on the progress in Geographic Information Systems (GIS): a geographic perspective. *International journal of geographical information science* 33(2), 346-367.

Prasad, J.R., Vidhate, A., Patiyat, D., & Patil, K., 2022. Review of Advanced Image Processing Techniques: Digital Elevation Model. *International Journal for Research in Applied Science & Engineering Technology* 45(1), 2733-2737.

Stoker, J., & Miller, B., 2022. The accuracy and consistency of 3D elevation program data: a systematic analysis. *Remote Sensing* 14(4), 940-950.

Stoter, J., Vallet, B., Lithen, T., Pla, M., Wozniak, P., Kellenberger, T., Streilein, A., Ilves, R., & Ledoux, H., 2016. State-of-the-art of 3D national mapping in 2016. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 41(1), 653-660.

Sugarbaker, L.J., Eldridge, D.F., Jason, A.L., Lukas, V., Saghy, D.L., Stoker, J.M., & Thunen, D.R.,2017. Status of the 3D elevation program, 2015. In: US Geological Survey.

Takaku, J., & Tadono, T.,2017. Quality updates of 'AW3D'global DSM generated from ALOS PRISM. In, *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (pp. 5666-5669): IEEE.

Wang, H., Pan, Y., & Luo, X., 2019. Integration of BIM and GIS in sustainable built environment: A review and bibliometric analysis. *Automation in construction* 103(41-52.

Yang, L., Meng, X., & Zhang, X., 2011. SRTM DEM and its application advances. *International Journal of Remote Sensing* 32(14), 3875-3896.

Yu, L., & Gong, P., 2012. Google Earth as a virtual globe tool for Earth science applications at the global scale: progress and perspectives. *International Journal of Remote Sensing* 33(12), 3966-3986.