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Construction of Multi-granularity Spatial and Temporal Entities for Groundwater in Polluting Enterprises Based on Digital Twin Technology

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Abstract

The adequate supervision of groundwater pollution in industrial enterprises primarily focuses on post-pollution treatment, and there is an urgent need to develop methods that go beyond merely describing pollution conditions and thoroughly understand the characteristics of pollution entities. In response to the current challenges of groundwater pollution visualization and entity modeling, based on digital twin technology and multi-granularity spatiotemporal object models, this study innovatively proposes an entity modeling framework that integrates the spatial, temporal, and behavioral attributes of the enterprise-groundwater system, clarifying the definition and division basis of multi-granularity levels to support decision-making requirements at different scales. Taking the groundwater pollution of a specific chemical plant in Huizhou as an example, a digital twin of groundwater pollution with dynamic data assimilation capabilities for this site was constructed based on borehole data, historical monitoring records, and the deployed sensor network. The results demonstrate that the digital twin system enables the visualization and simulation of pollution dynamics by integrating near-real-time data. The multi-granularity spatio-temporal object model successfully captured the spatial heterogeneity, temporal evolution characteristics, and polluter-receptor interaction behavior of pollution. This research not only provides a more refined and dynamic cognitive tool for groundwater pollution but also lays scalable technical support for integrating multi-granularity spatiotemporal object models with digital twin technology for environmental supervision.

1. Introduction

Digital Twin (Tao and Qi, 2019) refers to the creation of a virtual replica of the physical world using digital technology, including physical devices, systems, processes, and environments. It is composed of four parts: physical entities, digital models, data, and services, and their functions are realized through the connection and interaction among them. Through this connection and interaction, digital twins can gain a deep understanding of the characteristics, behaviors, and future trends of physical entities, thereby providing services such as real-time monitoring, intelligent maintenance, and optimized decision-making, helping to enhance the operational efficiency and reliability of physical entities (Tao et al., 2023). Digital twin technology, which utilizes real-time data and simulation techniques, can accurately reflect the state, behavior, and performance of the physical world in real time, thereby enabling the monitoring, analysis, optimization, and prediction of the physical world. It is carriers jointly empowered by clustering technologies. From specific modeling to simulation models, and then to endowing models with digital life, utilizing virtual models to predict and infer the direction of physical models, ultimately leading to better decision-making support (Peng et al., 2025).

Groundwater is an important resource for human survival and social and economic development. However, with the acceleration of economic development and urbanization, the nature of land use in industrial clusters changes frequently, resulting in a large amount of pollution generated by enterprises with backward technology and severe pollution, posing a serious threat to groundwater. Groundwater pollution not only affects the surrounding environment and the health of residents but also brings high governance costs and low efficiency. Therefore, preventing groundwater pollution is more important than trying to treat it after the fact. The traditional methods for evaluating groundwater quality have limitations and cannot visually display the spatial distribution characteristics of water quality. However, by establishing real-scene three-dimensional models of polluting enterprises and underground digital twin models, real-time monitoring data can be incorporated into the groundwater twin simulation system. Then, rapid data fusion and simulation are performed to create a comprehensive digital twin system for groundwater monitoring. This enables the physical scene of water pollution to be closely integrated with environmental early warning information, achieving two-way real mapping and interaction, making the scene more realistic and the operation smoother.

The current research on digital twins of groundwater pollution mainly focuses on constructing three-dimensional models. As shown in references (Li et al., 2020; Zhou et al., 2023; Yang et al., 2022), research on model construction, mapping modeling, and three-dimensional spatial interpolation for pollutants in soil environmental investigations has been carried out. For instance, in response to the issue of low digitalization of deep foundation, some studies (Lu et al., 2025) have introduced digital twin technology into the deep foundation scenario and designed a digital twin system for deep foundation reinforcement construction. However, these studies cannot comprehensively describe the dynamic, correlation, and three-dimensional characteristics of the groundwater of polluting enterprises, and they ignore the complete expression of characteristic data, such as the geometric parameters, attributes, and relationships of the enterprise entities themselves. Furthermore, traditional GIS data organization methods and data models can no longer meet the new expression requirements, especially the demand for real-time dynamic correlation in multimodal situations (Chen et al., 2020). Therefore, it is necessary to adopt a more efficient way to organize and manage the characteristic data of enterprise entities and select an appropriate data model to model enterprises and underground scenes. Based on the multi-granularity spatio-temporal object data model (Zhao et al., 2024), we described multi-granularity spatio-temporal entities from aspects such as temporal and spatial referencing, spatial forms, spatial position, and constituent structure. We also innovatively added descriptions of feature information, including attribute features, behavioral capacities, and cognitive abilities. It can also help achieve the precise construction of the twin entity model of groundwater in polluting enterprises, providing support across all scales, types, and attributes and meeting the demand for comprehensively and dynamically depicting the entity of groundwater in a multidimensional manner.

This paper proposes a multi-granularity spatiotemporal entity modeling method for constructing digital twins of groundwater contaminated by industrial enterprises. Taking the drilling data of a particular chemical plant in Huizhou as an example, we constructed twin models. They achieved a three-dimensional visualization of the factory and workshops, as well as underground drilling holes. The results demonstrate that this method has strong practical applicability for digital twin modeling of groundwater in polluting enterprises. This model demonstrates better spatio-temporal decision support and simulation analysis capabilities in data management, visual expression, spatial analysis, and practical applications. This research provides an effective method and data model basis for the precise construction of groundwater twin entity models for polluting enterprises and digital twin application services, helping these enterprises better manage environmental data, achieve real-time monitoring and early warning, and reduce the risk of groundwater pollution.

2. Literature review

2.1 Multi-level classification of entity elements

According to the geographic information classification system and the spatial data specification of geographic entities, the groundwater entity elements of polluting enterprises are classified, and multi-granularity analysis of temporal and spatial characteristics is carried out. The entities are abstracted into multi-granularity spatio-temporal entities, providing a reliable basis for subsequent modeling and data analysis. According to the classification system (Zhu et al., 2020) of GB/T 25529-2010 Rules for Classification and Coding of Geographic Information and the national standard Specification for Spatial Data of Geographic Entities (GB/T 37118-2018), the classification of spatio-temporal entities of groundwater of polluting enterprises adopts the linear classification method. The classification system is constructed from high-level categories to low-level categories. The classification system comprises one category, six major categories, 12 medium categories, and multiple minor categories, forming a comprehensive high-level classification system. This classification system, based on the unique semantic characteristics of the entities themselves, summarizes six major element types of spatio-temporal entities within the spatial scope of polluting enterprises, including infrastructure-related entities, construction-related entities, geological entities, etc. The specific classification system is presented in Figure 1.

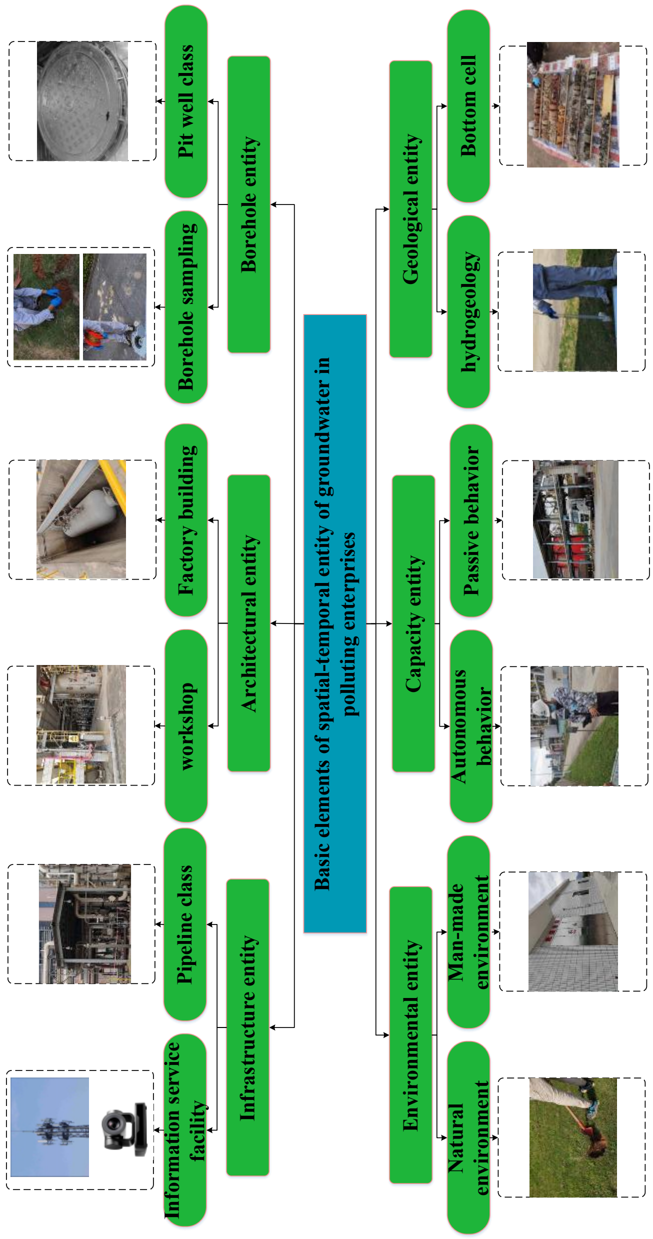

Figure 1. The classification system of spatiotemporal entity elements related to groundwater pollution from polluting enterprises.

2.2 Multi-granularity analysis of spatiotemporal entities

Multi-granularity refers to the composition and decomposition of the spatio-temporal objects of groundwater in polluting enterprises. The spatiotemporal objects and their various characteristics will change among multiple scales with different requirements for groundwater analysis. Entity spatiotemporal objects can be groundwater monitoring Wells, geological units, or even their corresponding enterprise ancillary facilities. Regardless of the scale, they all possess the characteristics of multi-granularity spatio-temporal objects. Its characteristics are reflected in multidimensional attribute features, complex relationships, and meeting the cognitive requirements for groundwater analysis of polluting enterprises. The multi-granularity of spatiotemporal entities primarily considers three dimensions: time, space, and attributes, which involve a comprehensive analysis of the groundwater entities of polluting enterprises corresponding to different scales.

2.2.1 Time granularity: Time granularity refers to the common time units, including seconds, minutes, and hours. It can also be defined as enterprise production unit time, pollution emission time, and other time concepts derived from time intervals with definite start and end times. The groundwater of polluting enterprises shows obvious dynamic change characteristics in terms of time granularity. Over time, parameters such as the quality, quantity, and flow direction of groundwater will change. These changes may be caused by natural factors, such as rainfall and evaporation, or by the large amounts of wastewater and pollutants generated in the production processes of human activities, including pollutant discharge and water resource exploitation. The flow direction and speed of groundwater will also be affected as a result.
Meanwhile, the maintenance and repair of equipment within polluting enterprises exhibit distinct time granularity characteristics, such as the frequency of equipment maintenance and the duration of downtime. These factors can affect the availability of equipment and production plans. In terms of pollutant emissions and monitoring, such as the timetable, frequency, and duration of pollutant emissions, it is also an important manifestation of the multi-granularity of time. When enterprises need to collect data on environmental parameters, such as air quality, soil, groundwater, and noise, the granularity of time can affect the frequency and interval of data collection, ranging from hourly to annual data collection. These differences in time granularity will have a significant impact on production plans, equipment maintenance, and environmental monitoring of polluting enterprises.

2.2.2 Spatial granularity: Spatial granularity typically considers various geographic spatial scales. The spatial granularity analysis of spatiotemporal entities of polluting enterprises primarily involves spatial regions, spatial elements (such as points, lines, and surfaces), and spatial units (monitoring Wells, hydrological sections, and groundwater basins), among others, for example, the granular representation of location coordinates, layout, and spatial relationships of different devices. In terms of spatial units, spatial granularity can be reflected in different spatial units such as monitoring Wells, hydrological sections, and groundwater basins. These spatial units can be used to describe the flow of groundwater, the spread of pollutants, and changes in water quality. For instance, monitoring Wells can be used to describe the water quality and quantity of groundwater; hydrological sections can be used to describe the flow direction and velocity of groundwater; and groundwater basins can be used to describe the spread range and impact degree of pollutants.

Meanwhile, the division of production areas and workshops within an enterprise reflects the spatial granularity characteristics, and each area may be used for different production processes or product manufacturing. Spatial particle size also affects the material transportation and storage of enterprises, including the layout and paths of pipelines, conveyor belts, and underground pipelines, as well as the locations and storage conditions of different storage areas, warehouses, or shelves. In terms of environmental management and monitoring, spatial particle size characteristics are reflected in the sources of pollutant emissions and the specific locations of borehole sampling, including discharge outlets, wastewater discharge points, sampling points, and other locations. The accuracy of these locations is crucial for environmental monitoring and pollution control.

2.2.3 Attribute granularity: Attribute granularity refers to the relationships among multi-granularity spatiotemporal objects and their attribute characteristics, such as superior-subordinate relationships, command relationships, and connectivity relationships. The attribute correlation relationship not only needs to pay attention to the correlation relationship but also the change in the intensity of the relationship. In terms of polluting the groundwater of enterprises, the attribute granularity can be reflected in the water quality of the groundwater, including pH value, concentration, dissolved oxygen, and other relevant attributes. These attributes can be used to assess the applicability and environmental risks associated with groundwater. Attribute granularity can also be described as attributes at different levels, such as physical attributes and biological attributes. Physical properties include temperature, turbidity, and electrical conductivity, while biological properties encompass the types and quantities of microorganisms. These attributes can be used to describe the overall characteristics and changing trends of groundwater. Meanwhile, the attribute granularity can also be reflected in the nature and behavior of pollutants, such as their type, concentration, and migration rate. These attributes can be used to describe the transmission routes, impact ranges, and environmental risks of pollutants.

3. Data and methodology

3.1 Data source and data preprocessing

Currently, the groundwater data of polluting enterprises exhibit characteristics such as a large volume, diversity, and great difficulty in collection and analysis. To express these data more efficiently and comprehensively, it is necessary to normalize and organize the enterprise's spatiotemporal data. The specific process includes data preprocessing, data integration, and data matching. The dataset for this study primarily consists of monitoring data from borehole and groundwater well sensors, including pH value and heavy metal content. It spans four years, from 2021 to 2024, at this chemical plant. The basic information of the 2023 data is presented in Table 1. The drilling position is presented in Figure 2. Data preprocessing involves cleaning up redundant data, abnormal data, and missing data. Data integration involves logically combining multi-source heterogeneous data and utilizing the network environment for efficient and stable data movement and synchronization. Data matching leverages the rules and relationships among data to facilitate matching and achieve the efficient utilization of relevant data. Meanwhile, it is necessary to strictly control data quality and ensure data consistency to construct a usable multi-granularity spatio-temporal model.

Data position	Data Type	Data Volume	
		min	max
ZX-S1	pH	6.05	6.88
ZX-S2	Arsenic	3.52	240
ZX-S3	Cadmium	0.05	0.74
ZX-S4	Chromium	0.45	4.66
ZX-S5	Lead	16.4	82.6
…	…	…	…

Table 1. Basic information on the 2023 data

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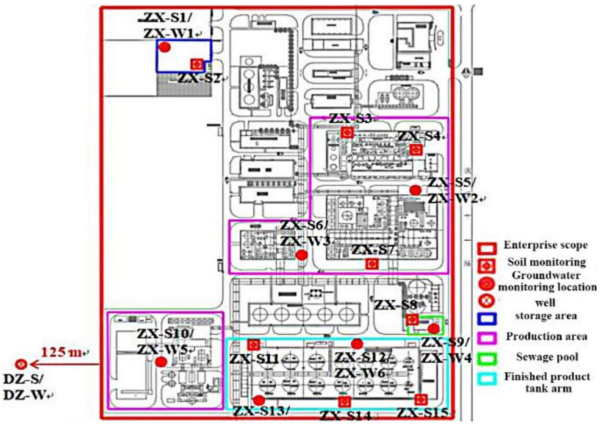

Figure 2. Drilling position.

3.2 Research Framework

The workflow of this study is presented in Figure 3. Firstly, it is necessary to conduct a multi-granularity analysis of the objective entities related to the groundwater pollution of polluting enterprises and establish the relationships among these entities at different granularities. Then, focus on the multi-characteristic information of the spatio-temporal entities of groundwater from polluting enterprises and conduct feature and relationship modeling to ensure that the multi-granularity spatio-temporal entity characteristics can be expressed in a standardized manner. Finally, based on digital twin technology, corresponding objective instance objects can be realized, and multi-granularity spatio-temporal object data models can be generated.

3.3 Multi-granularity spatiotemporal entity feature and relationship modeling method

Combined with the description framework of the multi-granularity spatiotemporal object data model, the groundwater entity objects of polluting enterprises that undergo constant spatiotemporal changes can be described in a computer virtual environment. This paper incorporates descriptions of feature information, such as attribute features, behavioral capacities, and cognitive abilities, into the framework. This framework consists of 8 description tuples: spatio-temporal reference, spatial form, spatio-temporal position, attribute characteristics, composition structure, etc.

In the composition structure of underground space entities, the entire underground space of the factory area serves as the parent object, and the child objects include pollutants, geological entities, borehole entities, pipeline facilities, water body entities, and others. With the discharge of pollution, the temporal and spatial locations, forms, and concentration attributes of different types of pollutants underground will all change. Therefore, describing the correlations, functions, constraints, and other relationships among the groundwater entities of polluting enterprises, as well as their strengths and weaknesses, is an important basis for constructing a digital twin model.
The correlation relationships among the spatiotemporal entity objects of groundwater-polluting enterprises are complex and diverse (Zhang et al., 2017), and it is necessary to conduct analysis and modeling based on the expression of the correlation relationship characteristics of multi-granularity spatiotemporal entities and the attribute characteristics and element types of entities under different granularities. Meanwhile, the correlation and strength among the physical objects of groundwater pollution enterprises will change over time and with alterations in scenarios. During the life cycle, the association relationships among entity objects are affected by various factors, resulting in changes in the strength of the relationships. Furthermore, depending on the period, the correlation between spatiotemporal objects within the spatial range corresponding to a particular moment can be regarded as a set and expressed as:

$$TSv = \{(t, Sv)\}, \qquad (1)$$

where TSv = spatial range specification
t = a specific moment
Sv = Spatial scope and correlation

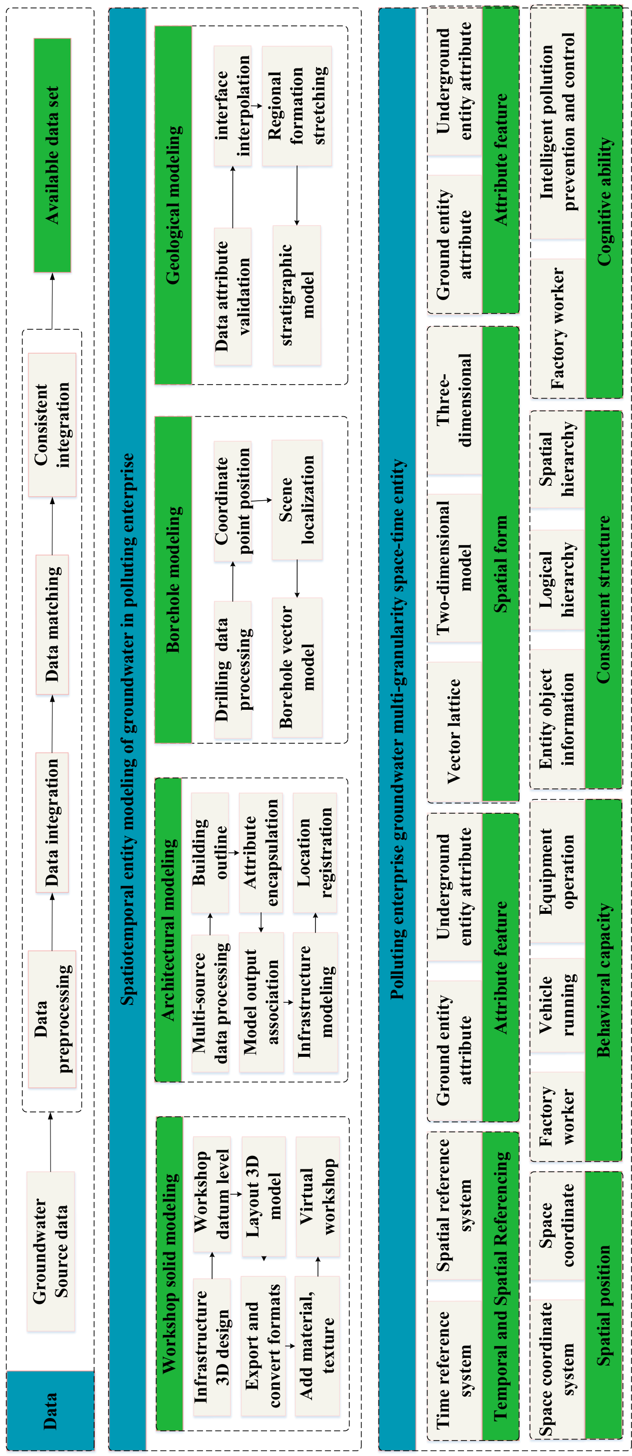

Figure 3. Workflow of this study.

Through analysis and description, the types of correlation relationships existing among the spatiotemporal entity objects of groundwater in polluting enterprises include affiliation, synergy, location, control, and symbiotic relationships. Among them, the membership relationship refers to the inclusion and composition relationship between entities, which can exist at different spatial scales. For instance, factory buildings, underground space entities, infrastructure, and other environmental entities all fall under the category of polluting enterprises and form a subordinate relationship with the sites of polluting enterprises. At the underground micro-scale, the membership relationship is reflected in the relationship between underground water body entities and underground space entities. Underground water body entities belong to the category of underground space entities, which include borehole sampling entities, underground pipelines, and underground water layers, among others. The collaborative relationship refers to the ability of entities to cooperate and the relationship of coordination and cooperation in the overall development and operation process of entities. For instance, enterprises' production and operation, as well as equipment manufacturing, require pipelines to transport liquids for collaborative processing. There is also a collaborative relationship between underground water bodies and pipeline facilities. Positional relationship refers to the relative position or spatial layout relationship between different entities in space. The positional relationship between groundwater bodies and other entities will affect the degree of groundwater pollution and the distribution of boreholes. For instance, the locations of production workshops, waste treatment workshops, and waste storage areas affect the locations of pollution sources, thereby forming a causal relationship. The control relationship refers to the ability of one entity to control and manage other entities or processes. For instance, the staff has control over the processing unit to ensure its regular operation and maintenance, and the underground water body entity is also controlled and managed by the processing unit. Symbiotic relationships refer to the interdependent and mutually beneficial relationships between different entities. As time passes and the objects disappear, symbiotic relationships will also fade away. A symbiotic relationship exists between the buildings and other facilities in the factory area and the surrounding groundwater environment. The changes to the groundwater body entity will impact the operation and safety of buildings and other facilities in the factory area.

Based on the previous text, the data related to the groundwater entities of polluting enterprises were sorted out and organized. The practical information was screened and organized. By utilizing appropriate computer storage logic, data corresponding to features such as spatial location, attributes, and association relationships was stored in the database, and object versions were stored and updated in the form of sequential snapshots. The construction of models, including point form, line form, surface form, and three-dimensional form, for polluting enterprise entities was largely achieved. The integration of data and models was completed, and a multi-granularity spatio-temporal object data model was generated. This data model can comprehensively describe the spatiotemporal, spatial, and attribute characteristics of groundwater entities associated with polluting enterprises, facilitating the construction of a digital twin model for these enterprises. The basic model is presented in Figure 4.

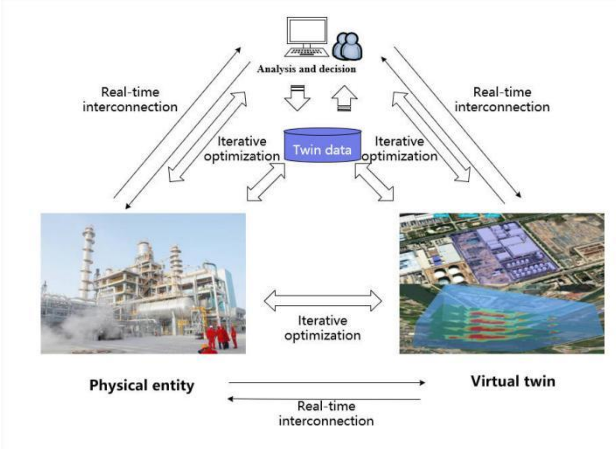

Figure4. The basic model of the correlation relationship of groundwater entity objects of polluting enterprises.

4. Analysis results

4.1 Construction of a data model instance for a particular chemical plant

This section takes a specific chemical plant in Huizhou as an example, integrating the objective entity data above and below ground, and utilizes the Hadoop distributed storage framework for storage, storing both structured and unstructured data in the corresponding data storage layer of HDFS. Then, a variety of digital twin technologies and 3D modeling technologies were utilized to achieve multi-level and full-attribute modeling of the polluting enterprise entities. The B/S architecture was adopted to visually display the modeling effect on the groundwater entities of the polluting enterprises.

At the macroscopic scale, when the entire chemical plant is taken as the research object, its specific set of characteristic attributes can be expressed as {" Name: A Certain Rubber Factory in Huizhou, ""Composition structure: Factory buildings, underground water body entities, environment, and other infrastructure," "Ancillary attributes: The main business of the chemical plant - manufacturing, processing and sales," "..." }, among which in the description of the composition structure, we considered multiple different scales, covering the descriptions from the contaminated site to the factory buildings, the entity of the groundwater body, the environment and other facilities, and then to their corresponding sub-objects. At the micro-scale, when a particular workshop is taken as the research object, in addition to the basic attribute characteristics, it also includes characteristic information such as machine operation status monitoring, timing management, and equipment logs. The attribute characteristics of underground drilling holes are described in terms of drilling time, sampling location, drilling depth, and water quality type in the sampling area, among other factors.

By analyzing the correlation between the above-ground and underground temporal and spatial entities of chemical plants, the interactions among the entity objects caused by production activities or changes in pollution emissions can be revealed. Within the scope of a chemical plant, the entire area where the factory is located serves as the spatial basis for the dynamic changes of other multi-granularity spatiotemporal entities it contains, and various relationships exist, including affiliation, collaborative, and spatial relationships. To demonstrate the types of association relationships that exist among the physical objects of the chemical plant, a network data form is used for display.

The association relationship between the spatio-temporal objects is shown by clicking on the relationship lines between them. For example, the relationship between the groundwater environment and other infrastructure is subordinate.

Combined with the description of the physical characteristics and correlation relationships of the chemical plant, refined modeling is carried out to verify the advantages of multi-granularity spatiotemporal entity modeling in constructing the underground water environment of the chemical plant site. When modeling the physical buildings in the factory area, remote sensing images, electronic maps of buildings, and real photos of the factory are used as data sources. The attribute information, such as the name and building area of the building model, is extracted and encapsulated in combination with document materials and image features. When conducting solid modeling of the workshop, CATIA is used to design the dimensions and surfaces of the workshop equipment and assemble the parts. According to the CAD workshop layout drawings, models of the workshop environment, including doors, Windows, walls, and passageways, are established. In Unreal Engine4, the overall 3D model of the workshop is mapped with materials and textures according to its attribute characteristics. Finally, Pixel Streaming is used to connect with the web end, and combined with the open-source WebGL technology, the visual interaction of the above-ground space scene is realized.. When conducting solid modeling of groundwater bodies, ArcGIS is used to project the data of borehole points onto a two-dimensional image according to the borehole distribution map, fill in the attribute values of the borehole points, and establish a borehole vector model that is vertically aligned with the surface. For the structural models of infrastructure, such as buildings, 3D MAX is used to independently model them in combination with point, line, surface, and material information. The modeling effect is presented in Figure 5.

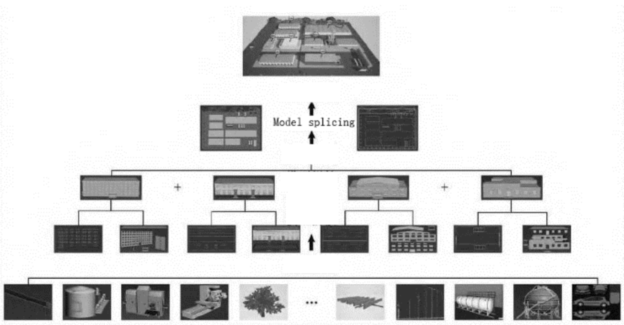

Figure 5. Construction of multi-scale twin models.

4.2 Three-dimensional visualization of virtual models for chemical plant areas and underground Spaces

The three-dimensional visualization of the digital twin system is presented in Figure 6. The changes in groundwater pollution are fed back in real-time through the monitoring system. Based on the monitored water pollution index parameters such as PH value and heavy metal pollution content, a water quality pollution model is constructed to present the water quality pollution situation, which is then fed back to the on-site machines and staff for corresponding processing, forming a digital twin data closed loop Through practical application, this method can precisely construct a multidimensional model of groundwater and describe the behaviours and interrelationships of groundwater entities in a multidimensional way. Meanwhile, the sensors inside the drilling rig provide continuous data integration for the system platform through real-time data transmission, assisting in further decision-making choices.

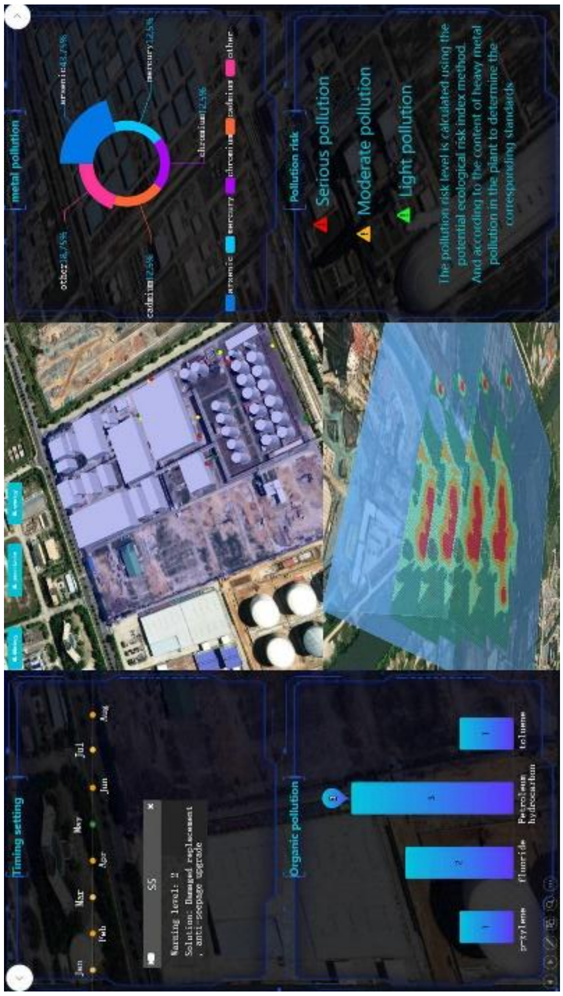

Figure 6. 3D visualization platform.

5. Conclusions

This paper studies the multi-granularity spatiotemporal entity modeling method and technical process for constructing the digital twin model of groundwater in polluting enterprises. Through the classification and analysis of the groundwater entities of polluting enterprises, the modeling of their multidimensional characteristics and relationships has been achieved. Taking a particular chemical plant in Huizhou as an example, the advantages of the multi-granularity spatio-temporal object modeling method were verified. However, the characteristics and development laws of polluting enterprises in the real world are complex, and it is still necessary to further strengthen theoretical methods, expand modeling contents, and conduct in-depth practices. Future research directions can focus on modeling and analyzing pollution particles, multi-granularity spatiotemporal entity modeling, and leveraging digital twin models to deepen research in areas such as pollution prediction and model interaction.

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