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Construction of simulation model of rural water and soil environment based on digital twin technology and GIS

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Abstract: In-depth analysis of uncertainty factors and spatial shifts was made in this study. It combined different geographic data types using digital twin technology and geographic information system (GIS) to create a spatial database for simulating rural water and soil environments. By extensively investigating the affecting aspects, the goal was to improve the accuracy and reliability of rural water and soil environment simulations. The soil and water assessment tool (SWAT) model was explicitly used to characterise changes in soil moisture and hydrological processes. The biological processes of transpiration, photosynthesis, and vegetation development were taken into consideration in the a model for agroforestry systems (AGROFOREST). Climate change was simulated by the autoregressive integrated moving average (ARIMA) model. It was found that various rural activities had obvious effects on the soil erosion rate. In this paper, an accurate simulation of rural soil and water conditions was created by combining GIS and digital twin technology.

Keywords: water and soil environment; rural activities; digital twins; geographic information system; GIS; simulation model; AGROFOREST model.

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1 Introduction

As the primary means of human survival, agriculture affects not only the production of food but also human survival and sustainable development (Qin et al., 2021; Guo et al., 2020). Through the development of virtual replicas of real-world systems that accurately represent the complexity and unpredictability inherent in the system, digital twin technology improves simulation accuracy and reliability. With the use of GIS technology, geographical data can be gathered, integrated, and analysed. It also offers powerful tools for researching and simulating rural water and soil environments and facilitates spatial analysis and visualisation.

This paper constructs a rural soil and water environment simulation model that integrates digital twin technology with a GIS, enabling the integration and spatial analysis of multi-source geographic data. This innovative coupling of the SWAT, AGROFOREST, and ARIMA models forms a closed-loop, interactive dynamic simulation system. This system fully considers the co-evolutionary mechanisms of climate, hydrology, vegetation, and human activities, significantly improving simulation accuracy and spatial representation capabilities, providing scientific support for the precise assessment and sustainable management of rural ecological environments. The SWAT, AGROFOREST, and ARIMA models are dynamically coupled through a digital twin framework. Climate data predicted by the ARIMA model serves as input to drive both SWAT and AGROFOREST. The SWAT model is applicable to watershed geographical environments with complex terrain, land use and soil type heterogeneity. It is particularly suitable for simulating hydrological processes in large, non-urbanised watersheds dominated by agriculture, and can effectively analyse the impact of topography, rainfall, vegetation and human activities on the water cycle. Simulated soil moisture from SWAT directly influences vegetation growth in AGROFOREST. Conversely, vegetation cover information from AGROFOREST influences hydrological cycle parameters in SWAT. The three models form a closed-loop system of mutual influence and coordinated evolution. The research's innovation lies in the first-ever construction of a multi-model, closed-loop digital twin system powered by GIS. This system breaks through the limitations of traditional single-model or static simulations, integrating multi-source data fusion, spatially explicit representation, and dynamic system feedback. This significantly improves the accuracy of rural soil and water environment simulations and the ability to analyse ecological processes.

The results show that the constructed model closely matches measured data in wind speed and rainfall simulations, validating its high accuracy and reliability. Rural activities significantly impact the soil and water environment: crop cultivation reduces soil erosion rates by increasing vegetation cover (from 3.9 mm/year in 2019 to 2.6 mm/year in 2024), while irrigation, pesticide spraying, weeding, and poultry farming exacerbate erosion,

with irrigation contributing to 6.6 mm/year. Total nitrogen concentrations in water bodies increased from 1.4–1.6 mg/L in 2019 to 2.1–2.6 mg/L in 2024, and dissolved oxygen levels increased due to the influence of irrigation water sources. All five types of rural activities resulted in a decrease in the Shannon-Wiener index and an increase in the Simpson index, indicating a continued decline in biodiversity. The study confirmed that the digital twin and GIS fusion model can accurately quantify the ecological effects of rural activities, providing a scientific basis for sustainable agricultural management. Recommendations include promoting ecological planting, controlling pesticide use, returning farmland to forest and grassland, and constructing ecological ditches to achieve sustainable use of water and soil resources.

This paper is divided into six sections. Section 1, an introduction, explains the significant impact of agricultural activities on human survival and sustainable development, and highlights the key role of rural soil and water environment simulation in addressing resource pressures and ecological degradation. It also introduces the advantages of digital twin technology and geographic information systems (GIS) in improving simulation realism and spatial analysis capabilities. This study clearly states that the goal of this study is to construct a rural soil and water environment simulation model that integrates digital twins and GIS. By dynamically coupling the SWAT, AGROFOREST, and ARIMA models, this model accurately simulates the coevolution of climate, hydrology, vegetation, and human activities. Section 2, a related work, systematically reviews the significance of rural soil and water environment analysis in sustainable development, summarises the limitations of existing research in single-factor analysis, spatial heterogeneity, and uncertainty management, and reviews the progress of GIS applications in spatial analysis and digital twins in system modelling. Furthermore, it points out the shortcomings of existing research in multi-model collaborative coupling and deep integration, laying the theoretical foundation for the innovative nature of this study. Section 3 details the model construction methodology, including multi-source data collection, GIS spatial processing, and the establishment of a digital twin model. Section 4 defines the indicator system and methods for assessing the impact of rural activities. Section 5 presents the simulation accuracy of the model and the analysis results of the impact on five types of rural activities. Section 6 is the conclusion, summarising the research results, practical significance, and future research directions.

2 Related work

By analysing the rural water and soil environment, the long-term impact of rural activities on the environment can be evaluated, and corresponding management suggestions can be proposed to promote the sustainable development of rural production systems and achieve coordinated and unified economic, social, and environmental benefits (Xu et al., 2020; Yu, 2022). Rural soil and water environment analysis plays an important role in scientifically understanding environmental conditions, identifying environmental problems, optimising rural production, guiding decision-making, improving environmental sustainability, and addressing climate change. It is an important means to promote sustainable rural development and ecological environment protection (He et al., 2020; Xu et al., 2021). Brewer Aaron's research indicated that plastic nanoparticles pose a serious potential threat to the environment and even human health. An exhaustive assessment of the environmental risk can be achieved by examining the migration of

plastic nanoparticles in various environments (Brewer et al., 2020). The sustainability of rural activities is threatened by soil erosion that happens in rural areas. Soil erosion issues on rural land are caused by intensive cultivation practices, inappropriate cultivation techniques, rainfall patterns, and topography, which have an impact on yield and environmental sustainability of degradation (Ahmad et al., 2020). Previous studies have generally recognised that analysing the rural water and soil environment is of great significance for assessing the long-term ecological impact of rural activities, optimising production models, and achieving sustainable development. Related studies have emphasised its key role in identifying environmental problems, supporting scientific decision-making, and responding to climate change. At the same time, scholars have also paid attention to specific problems such as soil erosion and water pollution caused by intensive agricultural activities, and pointed out the potential risks of new pollutants such as plastic nanoparticles. However, existing studies have mostly focused on single factors or static analysis, often separating the dynamic coupling relationship between climate, hydrology, vegetation and human activities, and insufficient consideration of spatial heterogeneity and uncertainty factors, resulting in limited accuracy and systematicity of simulation results, making it difficult to fully and truly reflect the evolution of complex rural ecosystems.

GIS-based spatial analysis can be used for environmental monitoring and prediction, monitoring the spatial changes and trends of soil and water environment, and predicting future environmental change trends, which helps to take timely measures for environmental protection and management (Ma et al., 2020; Hu et al., 2021). Orimoloye I. R used remote sensing techniques and GISs to do geographical measurements with the goal of lessening the environmental impact of gold mining activities. Mining and other human activities have a greater influence on places with low index values than on those with high index values (Orimoloye and Ololade, 2020). Some investigators have been endeavoring to create virtual models and simulate the behaviour of real systems by utilising digital twin technology. By simulating the structure and behaviour of real systems, digital twins can predict the behaviour and performance of the system in various scenarios, and simulate the dynamic changes of the system, providing a rationale for scientific decision-making (Li et al., 2023). A digital twin model is an exact replica of a real system, capable of replicating the behaviour, structure, and function of the system. Previous research has made progress in rural soil and water environment analysis, GIS applications, and digital twin technology. GIS is widely used for spatial analysis and environmental monitoring, while digital twins are used for system modelling and dynamic simulation. However, existing research is often limited to single-factor or static analysis, lacking sufficient consideration of spatial heterogeneity and uncertainty. Furthermore, there is insufficient synergistic coupling between models, and the deep integration of GIS and dynamic simulation remains weak, limiting the holistic depiction and accurate simulation of complex ecological processes.

Existing research has made some progress in modelling rural soil and water environments, but most studies focus on single processes or static analyses, failing to fully reflect the dynamic interactions and spatial heterogeneity within the system. Some studies have utilised the SWAT model (Liu et al., 2023) to assess the impacts of land use and climate change on hydrological processes, or the AGROFOREST model to simulate vegetation growth and biogeochemical cycles (Negari, 2023). However, these models often operate independently and lack multi-model synergistic coupling mechanisms, limiting their holistic depiction of complex ecological processes. Although GIS (Raihan,

2024; Di Grazia and Giuseppe, 2024) have been widely used for spatial data integration and visualisation, improving the spatial representation of environmental elements, their in-depth integration with dynamic simulation models remains insufficient. In recent years, digital twin technology has provided a new paradigm for modelling complex systems. Constructing virtual mappings of physical systems enables state perception, real-time feedback, and dynamic evolution simulation, demonstrating its potential in industrial manufacturing and urban governance. However, in the agricultural and ecological environments, particularly in rural soil and water systems, the collaborative application of digital twins and GIS (Clementi and Valentina, 2024) remains exploratory, and a closed-loop, multi-model coupling framework with feedback loops has yet to be established. This study addresses these shortcomings by innovatively integrating digital twin technology with GIS to construct a dynamic coupling system of SWAT, AGROFOREST, and ARIMA models. This system fully considers the nonlinear relationships between climate drivers, hydrological responses, and vegetation feedback, achieving an integrated approach of multi-source data fusion, spatially explicit representation, and system dynamic simulation. This significantly improves the accuracy of rural soil and water environment simulations and the ability to analyse ecological processes.

3 Methods for constructing rural soil and water environment simulation models

3.1 Data collection and organisation

With population growth, accelerated urbanisation, and the impact of climate change, the impact of rural activities on soil and water resources and the ecological environment is becoming increasingly prominent, attracting widespread social attention. By obtaining data through remote sensing satellites, meteorological observation stations, LiDAR, etc., Landsat satellites can provide comprehensive land information. The real-time meteorological data recorded by meteorological observation stations is utilised, including information such as rainfall, precipitation intensity, and precipitation duration. The use of LiDAR technology can obtain surface elevation information, thereby obtaining terrain information. The advantages of using Landsat satellite data lie in its wide coverage and periodic revisits, providing large-scale, long-term surface information. Landsat satellite data captures multi-dimensional data on land use, vegetation cover, and topography. The data is publicly available and free, making it easy to integrate into GIS platforms, providing comprehensive and continuous spatial data support for dynamic monitoring and simulation of rural soil and water environments.

The data within the Jiangxi area of China from 2019 to 2024 is collected for analysis. The analysed area is shown in Figure 1.

Figure 1 shows the analysis area of the selected area, located in Nanchang, Jiangxi. Nanchang has abundant water resources and good natural conditions, which are suitable for the development of agriculture. However, with the continuous development of rural production, soil degradation and pollution problems have gradually become prominent. It is necessary to strengthen resource protection, environmental governance, and sustainable development to promote the coordinated development of rural production and the ecological environment.

Figure 1 Selected analysis area (see online version for colours)



The collected remote sensing data is shown in Figure 2.

Figure 2 Collected remote sensing data (see online version for colours)



Figure 2 shows the collected remote sensing data. Remote sensing technology can cover a wide geographical range without geographical restrictions, and can obtain information on land use, vegetation cover, terrain and landforms on a large scale, providing extensive data support for the construction of rural water and soil environment models. Moreover, remote sensing data can be integrated with various data sources such as GIS data and meteorological observation data to build a comprehensive analysis platform for

multi-source data, providing more comprehensive and accurate data support for rural soil and water environment simulation.

The real-time meteorological data recorded by meteorological observation stations are used to collect some meteorological data, as shown in Table 1.

Table 1 Part of meteorological data collected

<i>Time</i>	<i>Temperature (°C)</i>	<i>Humidity (%)</i>	<i>Wind speed (m/s)</i>	<i>Rainfall (mm)</i>	<i>Weather conditions</i>
2022-04-07	25	70	2.0	0	Sunny
2022-04-08	24	75	1.5	0	Cloudy
2022-04-09	23	80	1.0	0.5	Shower
2022-04-10	22	85	1.2	2	Thunderstorm
2022-04-11	21	90	1.5	5	Rainstorm
2022-04-12	22	90	2.2	5	Rainstorm
2022-04-13	18	84	1.0	0.5	Shower
2022-04-14	17	73	1.5	0	Cloudy
2022-04-15	20	75	1.6	0	Cloudy
2022-04-16	25	70	1.2	0	Sunny

In Table 1, some meteorological data collected, including temperature, humidity, wind speed, rainfall, weather, etc., are presented, all of which contain time information.

To ensure the integrity and availability of the data, the collected data is pre-processed. For collecting meteorological data, data cleaning is required, and for collecting remote sensing data, radiometric calibration, atmospheric correction, and image denoising processing are required. The content of data cleaning includes handling outliers, missing values, and duplicate data (Tian et al., 2021).

First, radiation calibration is performed to convert the original digital values into surface radiation brightness or reflectivity; then atmospheric correction is performed to eliminate the effects of atmospheric scattering and absorption; finally, image denoising and geometric correction are performed to ensure accurate spatial position, thereby improving the accuracy and reliability of land use and vegetation information extraction.

After detecting abnormal data, the mean of the data items is used for replacement. For missing data, the corresponding data record is directly deleted, and for duplicate data, only one piece of data needs to be retained. The original remote sensing data is subjected to radiometric calibration, and digital values are converted into surface reflectance or radiance temperature to eliminate the influence of factors such as atmosphere, terrain, and sensor systems on the data. The formula for radiometric calibration is:

$$\rho = \frac{DN - DN_{min}}{DN_{max} - DN_{min}} \times G \quad (1)$$

In equation (1), G represents the calibration coefficient, and ρ is the surface reflectance.

By geometric correction, the position and shape of objects in remote sensing images are consistent with the actual position and shape of objects, improving the spatial accuracy of the image.

$$x' = a_0 + a_1 \cdot x + a_2 \cdot y \quad (2)$$

$$y' = b_0 + b_1 \cdot x + b_2 \cdot y \quad (3)$$

In equations (2) and (3), a_0 , b_0 , a_1 , b_1 , a_2 , and b_2 are all parameters of the affine transformation.

3.2 GIS data processing

To comprehensively analyse and understand rural water and soil environment information, various geographic spatial data are integrated through GIS, so as to intuitively and clearly display the distribution characteristics in spatial data. GIS is used for spatial data processing and analysis, including data projection, spatial interpolation, map overlay, and other operations, to help generate the spatial data required by the model and provide support for spatial analysis functions.

Longitude and latitude are used to represent geographic locations, and isometric projections are selected to maintain the same angle on the Earth's surface, ensuring that the geographic features on the map maintain the correct shape and direction. The formulas for isometric projection are expressed as:

$$x_1 = R \cdot U \quad (4)$$

$$y_1 = R \cdot \ln \left(\tan \left(\frac{\pi}{4} + \frac{V}{2} \right) \right) \quad (5)$$

In equations (4) and (5), U and V represent longitude and latitude, respectively, and R represents the radius of the Earth.

In the collected geospatial data, there may be missing values. Spatial interpolation can be used to calculate numerical data for unknown locations based on known geospatial data, thereby filling in the missing values on the map.

The formula for Kriging interpolation is expressed as:

$$Z(x_0, y_0) = \sum_{i=1}^n \lambda_i Z_i \quad (6)$$

In equation (6), $Z(x_0, y_0)$ is the estimated value at (x_0, y_0) ; λ_i is the interpolation weight; Z_i represents the observed value at a known point.

This study selected the Kriging interpolation method because it not only provides spatial predictions based on distance but also analyses the spatial autocorrelation and structure of the data through the semivariogram, providing optimal, unbiased estimates and quantifying the uncertainty of the predictions. Compared to deterministic methods such as the inverse distance weighted method, the Kriging method offers greater accuracy when dealing with environmental factors with complex spatial variation, better meeting the research's need for highly reliable spatial data.

Map overlay involves overlaying map data from different layers together, while displaying and comparing the spatial distribution and relationships of different geographic features (Keuni et al., 2021; Benaissi et al., 2022). Map overlay can help users understand the interrelationships between geospatial data and discover the patterns and characteristics of geospatial phenomena.

Different map data are converted into the same projection coordinate system to ensure spatial consistency and accuracy of map data. Layers of different map data are stacked together to create a map combination containing multiple layers. The stacked map data is

symbolised and classified to highlight the spatial distribution and characteristics of different geographical features. Different symbol styles, colours, and transparency can be set as needed to distinguish different categories of geographic features. This paper integrates different types of geospatial data through GIS to construct a spatial database of rural water and soil environment.

3.3 Establishment of digital twin models

Digital twins can assess the impact of rural activities on soil and water environment, thereby helping people quantify environmental risks and develop corresponding environmental protection and restoration measures (Huang et al., 2022). In order to fully describe the changes in soil moisture and hydrological processes, the SWAT model can be used to accurately evaluate the impact of factors such as land use, soil, and climate change on watershed hydrological processes and water resource management (Puno et al., 2019; Briak et al., 2019). The hydrological process is shown in Figure 3.

Figure 3 Hydrological process (see online version for colours)

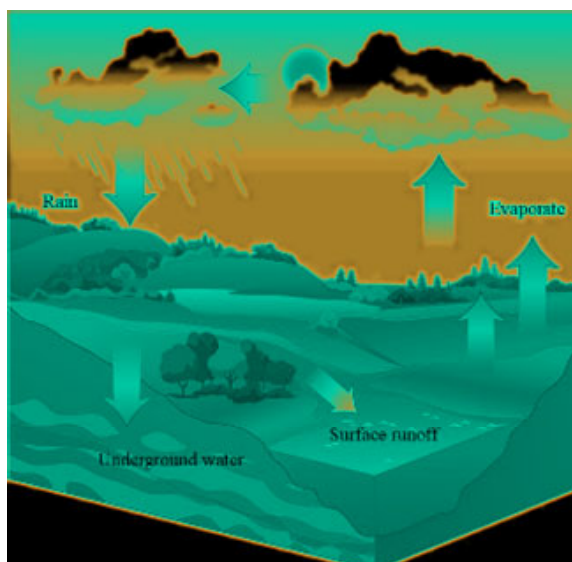


Figure 3 shows the hydrological process. Under the irradiation of the sun, water is transferred from soil and vegetation surfaces to the atmosphere, and water evaporation is a vital loss process in the water cycle of a watershed. Water vapour in the atmosphere condenses into liquid water or solid crystals, which fall to the surface and affect the water volume in the watershed through rainfall processes. Surface runoff refers to the water flow that flows through the surface of the earth towards rivers, lakes, or other water bodies when rainfall exceeds the infiltration capacity of the soil. Surface runoff is the fastest responding hydrological process in rainfall events, influenced by factors such as soil type, slope, and soil moisture content. Groundwater is water that naturally exists in underground rocks, replenishing surface water bodies through groundwater runoff and leakage, affecting river flow, lake water levels, and wetland ecosystems.

The formula for evapotranspiration is:

$$E = K \cdot ET_0 \quad (7)$$

In equation (7), K represents the soil evaporation regulation coefficient, and ET_0 is the reference transpiration.

The formula for surface runoff is:

$$Q = \sum_{i=1}^n P_i \cdot A_i \quad (8)$$

In equation (8), Q is the surface runoff flow rate; P_i represents the effective rainfall over a period of time; A_i represents the corresponding watershed area.

Soil moisture change analysis can help evaluate the impact of human activities on soil moisture, timely identify the causes and trends of abnormal changes in soil moisture, and take corresponding environmental protection measures, thus reducing environmental problems such as soil erosion and land degradation (Zhou et al., 2021; Green et al., 2019). The soil moisture balance formula is expressed as:

$$\Delta S = \Delta P - \Delta E - \Delta R - \Delta Q \quad (9)$$

In equation (9), ΔS represents the change in soil moisture, while ΔP , ΔE , ΔR , and ΔQ respectively represent rainfall, evapotranspiration, soil moisture consumption, and underground runoff over a period of time.

Biological processes such as vegetation growth, photosynthesis, and transpiration are considered through the AGROFOREST model. The AGROFOREST model can simulate the growth and development process of different vegetation types, considering the effects of factors such as light, temperature, water, and nutrients on plant growth (Pantera et al., 2021). The process of growth is expressed as:

$$W(t) = W_0 + \sum_{i=1}^n G_i \quad (10)$$

The AGROFOREST model comprehensively considers the impact of multiple environmental factors on vegetation growth, including light, temperature, water, and nutrients, accurately simulating the growth and development of different vegetation types. Its advantage lies in its ability to dynamically reflect key biological processes such as photosynthesis, transpiration, and biomass accumulation. It is applicable to complex agroforestry systems and provides a scientific basis for ecosystem management and sustainable development.

Using meteorological data and ARIMA models, climate change is simulated (Lai and David, 2020; Shivhare, 2019). The well fitted ARIMA model is used to predict future climate, obtain time series predictions of climate change, and estimate the confidence interval of the prediction results. The SWAT model, AGROFOREST model, and ARIMA model are coupled to influence and interact with each other, forming a complete rural water and soil environment simulation model. The soil moisture changes simulated by the SWAT model affect vegetation growth in the AGROFOREST model, while meteorological data from the ARIMA model serve as input to drive the operation of other models.

Historical meteorological data and field observation data are used as inputs for simulation operations, and the changes and impacts of rural water and soil environment are analysed based on simulation results. The established digital twin model is integrated with GIS data, fully considering the influence of spatial factors on simulation results. GIS

data is used as a constraint to ensure that the simulation results match the spatial characteristics of the real environment.

By correcting the model with negative mean square error feedback, the accuracy of model simulation can be improved. The formula for mean square error is expressed as:

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (11)$$

4 Assessment of the impact of rural activities on soil and water environment

With the growth of the global population and economic development, rural production is putting increasing pressure on land, water resources, and the ecological environment. In order to achieve the goals of environmental protection and sustainable development, it is necessary to conduct scientific assessment and management of the rural soil and water environment (Wang et al., 2023; Zhang, 2022). This paper provides rich spatial environmental data through remote sensing data, meteorological data, etc. By integrating digital twins with GIS, the simulation of rural water and soil environment can be achieved.

The rural activities set up include planting crops, raising poultry, irrigation, spray insecticide, and weeding. By observing changes in soil erosion, water quality, biodiversity, and other content, the impact of different rural activities on the soil and water environment is analysed.

Soil erosion is represented by the rate of soil erosion, and the formula is:

$$T = T_1 \times T_2 \times T_3 \times T_4 \times T_5 \quad (12)$$

Indicators like total nitrogen and dissolved oxygen can show changes in the quality of the water. The amount of oxygen in water is reflected in the dissolved oxygen. Higher dissolved oxygen levels aid in promoting promote the life and growth of aquatic species, which is are dependent on the oxygen concentration of the water to sustain their existence.

The total nitrogen in the water can indicate whether eutrophication has occurred there. Total nitrogen is the total of all types of nitrogen present in the water. A surplus of total nitrogen promotes the growth of aquatic plants and algae, leading to eutrophication of water bodies and the production of large amounts of blue-green algae.

To explore the simulation accuracy of the model constructed in this paper, the fusion method of digital twin technology and GIS is compared with digital twin technology and observed data. The smaller the difference with the observed data, the higher the accuracy of the model simulation.

This study is applicable to the subtropical monsoon climate zone, where water and heat conditions are abundant and the intensive agricultural structure dominated by rice cultivation has a significant impact on the water and soil environment. It has high reference value and applicability to the middle and lower Yangtze River plain areas with similar climate and agricultural patterns.

5 Results

5.1 Simulation accuracy

By simulating the rural water and soil environment, it is possible to comprehensively analyse the impact of rural activities on the environment, thereby promoting sustainable development of agriculture and achieving coordinated development of the rural economy, society, and environment. Accurate simulation results can provide a deeper understanding of rural water and soil environment systems. The simulated data is compared with the actual observed data to analyse the accuracy of the model simulation. The simulation accuracy results are shown in Figure 4.

Figure 4 Simulation accuracy results (a) wind speed data (b) rainfall data (see online version for colours)

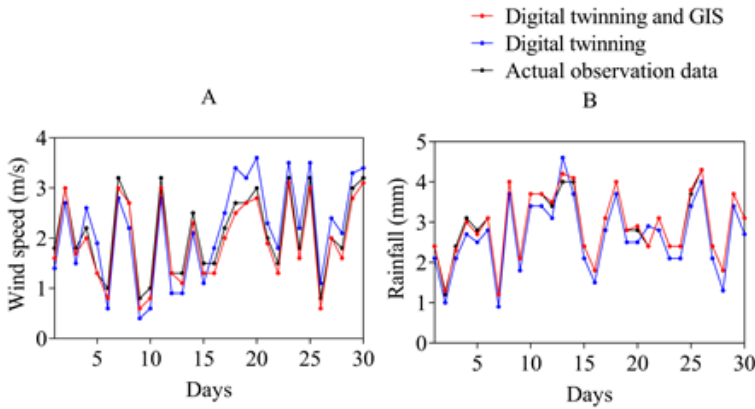


Figure 4 shows the results of the model simulation, comparing digital twins and their combination with GIS and actual observation data. The horizontal axis selects data from June 2024. Figure 4(a) shows a comparison of wind speed data. The combination of digital twins and GIS provides wind speed data that is closer to actual observation data. GIS can integrate geographic information into the simulation process, considering the impact of geographic features such as terrain, land use, and land cover on the simulation results, making the simulation results more realistic. The comparison of rainfall data is shown in Figure 4(b). The ARIMA model can accurately simulate meteorological data. By observing the trend of data changes within a month, the combination of digital twin and GIS can more accurately simulate rainfall data compared to simple digital twin technology. The combination of digital twins and GIS can fully utilise spatial information and geographical features, improve simulation accuracy, and simulate the behaviour and changes of geographic spatial systems more comprehensively and accurately. Therefore, simulation accuracy is better than that of simple digital twins.

5.2 Soil erosion impact

Soil erosion is a serious process of land degradation, which leads to gradual erosion and loss of soil layers, resulting in a decrease in soil quality. Rural activities have a certain

impact on soil quality. The impact of different rural activities on soil erosion is shown in Figure 5.

Figure 5 Impact of soil erosion (see online version for colours)

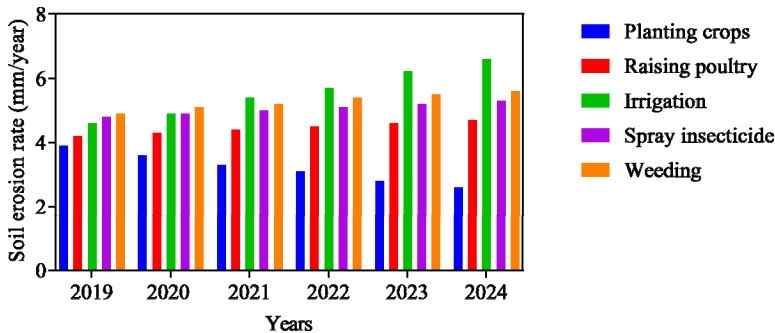


Figure 5 shows the impact of rural activities on soil erosion, with the horizontal axis representing different years. In the simulation model of the rural water and soil environment constructed, 5 rural activities are set up to observe the impact of each rural activity on soil erosion. Planting crops leads to a decrease in the soil erosion rate. Planting crops can increase the vegetation coverage on the soil surface, reduce the degree of soil surface exposure, and lower the rate of soil erosion. Raising poultry causes a slight increase in the soil erosion rate. Raising poultry increases soil compaction and causes local soil erosion, especially in areas where poultry manure is concentrated.

Irrigation causes an increase in soil erosion rate, and irrigation increases soil moisture content, leading to an increased risk of soil loss and erosion. Spraying insecticide and feeding have an impact on soil microorganisms and soil structure, reducing soil erosion resistance and causing an increase in soil erosion rate. The soil erosion rates of planting crops, raising poultry, irrigation, spray insecticide, and weeding in 2019 are 3.9 mm/year, 4.2 mm/year, 4.6 mm/year, 4.8 mm/year, and 4.9 mm/year, respectively, and the soil erosion rates of those in 2024 are 2.6 mm/year, 4.7 mm/year, 6.6 mm/year, 5.3 mm/year, and 5.6 mm/year, respectively.

5.3 Changes in water quality

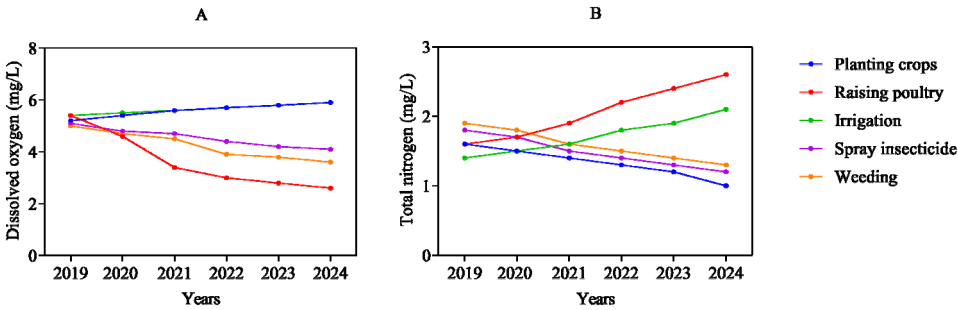
Water is an important component of ecosystems, and the quality of water directly affects the survival and reproduction of aquatic organisms. The impact of rural activities on water quality is shown in Figure 6.

Figure 6(a) shows the changes in dissolved oxygen in water. Planting crops leads to an increase in dissolved oxygen, and rural activities for planting crops generally use water resources as irrigation sources. However, the high oxygen content in irrigation water increases the dissolved oxygen content in the water.

Figure 6(b) shows the changes in total nitrogen in water bodies. The total nitrogen content in the water body increases due to rainfall and precipitation. The total nitrogen levels of rainfall and precipitation in 2019 are 1.6 mg/L and 1.4 mg/L, respectively. The total nitrogen levels of rainfall and precipitation in 2024 are 2.6 mg/L and 2.1 mg/L, respectively. Raising poultry produces a large amount of feces, which contain high concentrations of nitrogen. Irrigation water contains a certain amount of nitrogen

compounds, and excessive use of irrigation water can lead to an increase in total nitrogen in the water body.

Figure 6 Changes in water quality (a) changes in dissolved oxygen (b) changes in total nitrogen (see online version for colours)

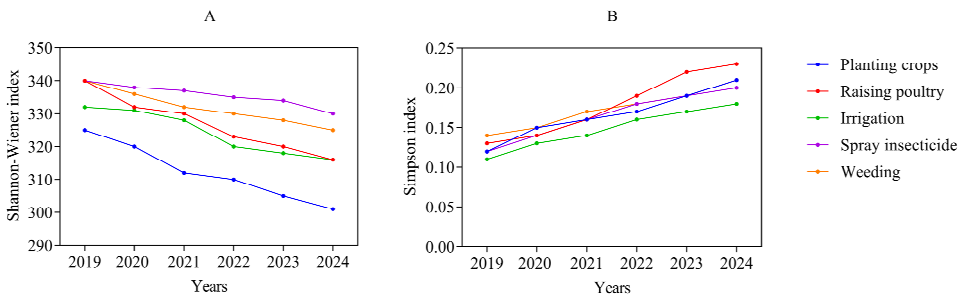


Planting crops effectively intercepts rainfall by increasing surface vegetation cover, mitigating the direct impact of raindrops on the soil. Furthermore, crop roots consolidate soil particles, enhancing soil structural stability and reducing the scouring capacity of surface runoff, thereby reducing the detachment and transport of soil particles and ultimately slowing the rate of soil erosion.

5.4 Biodiversity impacts

Biodiversity maintains the balance and stability of ecosystems, with different species playing different roles and forming complex networks of relationships. This complexity makes ecosystems more stable and better able to resist external disturbances and changes. The impact of rural activities on biodiversity is shown in Figure 7.

Figure 7 Impact of biodiversity (a) Shannon-Wiener index (b) Simpson index (see online version for colours)



The Shannon-Wiener Index comprehensively measures species richness and evenness. Higher values indicate a greater diversity of species within a community, a more even distribution of species, a more complex ecosystem structure, and greater stability and biodiversity.

The Simpson Index reflects the concentration of species. Values closer to 1 indicate a preponderance of a few species within a community, resulting in lower species diversity.

Conversely, lower values indicate a more even distribution of species and higher biodiversity.

Figure 7(a) shows the variation of the Shannon-Wiener index. It can be seen that all five rural activities lead to a decrease in the Shannon-Wiener index, thereby reducing biodiversity. The Shannon-Wiener indices for planting crops, raising poultry, irrigation, spray insecticide, and wedding in 2024 are 301, 316, 316, 330, and 325, respectively. Planting crops may lead to changes in land use types, reducing the original natural vegetation cover and thus affecting biodiversity. Raising poultry causes pollution to the surrounding ecosystem and damages the living environment of organisms. Figure 7(b) shows the variation of the Simpson index. The closer the Simpson index is to 0, the higher the biodiversity. It can be seen that all five rural activities increase the Simpson index, while rural activities reduce species diversity. Irrigation increases soil moisture, reduces the cohesion between soil particles, loosens the soil structure, and reduces its resistance to erosion. Excessive irrigation also contributes to surface runoff, which intensifies the scouring effect of water and exacerbates the separation and transport of soil particles, thereby increasing the rate of soil erosion.

6 Conclusions

With the continuous development and expansion of global rural production, the impact of rural activities on the soil and water environment is becoming increasingly prominent. This paper constructed a simulation model of the rural water and soil environment by combining digital twin technology with GIS. Various geographic spatial data were integrated through GIS, and a digital twin was used to achieve virtual replication of the rural water and soil environment, comprehensively considering factors such as soil, water resources, vegetation, and climate. The experimental results showed that the combination of digital twin technology and GIS could accurately simulate rural soil and water environment data. This paper explored the impact of five rural activities on the soil and water environment. Planting crops reduced the soil erosion rate, while the other four rural activities accelerated soil erosion, and all five rural activities led to a certain degree of species diversity decline. By constructing a simulation model of the rural soil and water environment, scientifically evaluating and controlling the impact of rural activities on the soil and water environment, environmental protection and sustainable development of agriculture can be achieved.

The current model does not incorporate socioeconomic feedback mechanisms such as farmer decision-making, policy subsidies, and market prices. Future research should incorporate farmer behaviour models to more realistically simulate the dynamic adjustments in rural activities under economic incentives or environmental policies, and their long-term impacts on the soil and water environment. Based on the simulation results, recommendations include promoting ecological planting models, strictly regulating the use of pesticides and fertilisers, implementing the policy of returning farmland to forest and grassland on erodible slopes, constructing ecological ditches and wetlands to intercept nitrogen from aquaculture wastewater, and designating core areas for biodiversity conservation to limit high-intensity agricultural activities, all to achieve sustainable management of the rural soil and water environment.

Declarations

All authors declare that they have no conflicts of interest.

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