

Article

Research on the Construction of Landfill GIS “One Map” Information Management System Platform

Jiantao Zhang ¹, Di Wang ^{2,*} and Shufang Zhai ¹

¹ School of Civil Engineering, Henan University of Technology, Zhengzhou 450001, China; 2025930298@stu.haut.edu.cn (J.Z.); zhaishufangcqu@126.com (S.Z.)

² China Institute of Geological Environment Monitoring, Beijing 100010, China

* Correspondence: wangdi01@mail.cgs.gov.cn

Abstract

Landfilling remains a widely used method for municipal solid waste disposal but may pose long-term risks to soil and groundwater. To address the fragmented management of landfill-related environmental information, this study developed a geographic information system (GIS)-based “One Map” framework that integrates landfill facilities, hydrogeological information, environmental monitoring data, pollutant indicators, and sensitive receptors into a unified spatial database. The framework links spatial features with attribute information and supports visualization, multi-criteria queries, statistical analysis, groundwater-quality assessment, and the preliminary screening of potentially undetected environmental risks. A municipal solid waste landfill in Xichuan County, Nanyang City, China, was selected as a case study, and groundwater quality was evaluated using the single-factor pollution index and Nemerow comprehensive pollution index. No Class III standard exceedance was identified at the five monitoring wells during the sampling event; however, the available hydrogeological and operational data were insufficient to attribute differences among wells to landfill-derived contaminant transport. The primary contribution is not a new GIS engine, but a landfill-specific data model and workflow that integrate fragmented survey outputs into a spatial decision-support environment. Because the case study comprises five wells and a single monitoring campaign, the findings represent a point-specific workflow demonstration rather than temporal or regional validation. Interpretation followed a source–pathway–receptor framework, but source attribution remained constrained by the absence of contemporaneous hydraulic-head data, a verified operational chronology, and quantitative leachate-management records. Repeated monitoring, an upgradient baseline, and a denser well network are required for stronger environmental inference.

Keywords: landfill; geographic information system; environmental information management; groundwater quality; spatial decision support



Academic Editor: Nathan J. Moore

Received: 22 June 2026

Revised: 21 July 2026

Accepted: 24 July 2026

Published: 26 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Municipal solid waste (MSW) is commonly managed through several treatment and disposal pathways, including landfilling, incineration, composting, and material recovery. Among these approaches, landfilling remains widely adopted due to its relatively simple operation, established engineering practices, cost-effectiveness, and capacity for large-scale waste disposal [1]. However, precipitation infiltration and moisture contained within the waste mass can generate leachate, which may pose long-term risks to surrounding soil and groundwater environments [2]. Groundwater is an essential freshwater resource for

urban and rural water supplies, with its hydraulic head, flow dynamics, temperature, and hydrochemical characteristics varying spatially and temporally [3]. Therefore, effective groundwater management around landfill sites requires the systematic integration of hydrogeological conditions, landfill operational information, and environmental monitoring data to better understand groundwater variations and potential contamination risks. Landfill-related contamination may not be immediately apparent in routine monitoring because pollutant release and subsurface transport can be spatially heterogeneous, intermittent, and delayed. Potential environmental risks may therefore remain undetected when soil, groundwater, hydrogeological, and operational information are examined separately. An integrated investigation framework is needed to associate observed anomalies with potential sources, migration pathways, and environmental receptors and to identify areas requiring more detailed monitoring or field verification.

Conventional landfill environmental-management practices often rely on fragmented data sources, including reports, spreadsheets, maps, and monitoring records, which can result in data redundancy, delayed updates, limited spatial visualization, and inefficient information sharing [4]. GIS provides an effective approach for integrating spatial data with associated attribute information, enabling visualization, spatial analysis, and environmental decision support. Previous studies have demonstrated the potential of GIS in various environmental applications, including groundwater and surface-water nutrient assessment, integration of remote sensing with groundwater-flow modeling, the development of web-based groundwater-quality information systems [5], the coupling of GIS with distributed groundwater-flow simulation [6], the spatiotemporal analysis of groundwater-monitoring data and contaminant-plume dynamics [7], groundwater-vulnerability assessment, and groundwater-potential mapping [8]. However, these representative applications generally focus on individual datasets or specific analytical objectives rather than providing an integrated framework that links landfill facilities, hydrogeological conditions, monitoring records, assessment results, and sensitive receptors for comprehensive environmental management.

Groundwater contamination at landfill sites often involves complex mixtures of inorganic and organic constituents, requiring integrated consideration of landfill characteristics, hydrogeological conditions, monitoring observations, and surrounding environmental receptors [9,10]. Although general GIS and WebGIS technologies provide mature capabilities for spatial data storage, visualization, publication, and querying [11], landfill-related environmental information is often maintained in heterogeneous and weakly connected formats. The absence of a unified data model and spatial-linkage mechanism limits the integrated analysis of these datasets for environmental assessment and regulatory decision support [12,13].

Therefore, this study aimed not to develop a new GIS engine, but to establish a landfill-specific framework for environmental information integration and spatial decision support. Based on groundwater investigation and assessment projects conducted at landfill sites in Henan Province, China, the proposed GIS-based “One Map” platform organizes landfill boundaries, operational facilities, hydrogeological information, monitoring locations, analytical results, and sensitive receptors within a unified spatial database. By linking geographic entities with environmental attributes and assessment outputs, the framework enables integrated data retrieval, environmental interpretation, and management-oriented decision support.

The study makes three main contributions: (1) it establishes a landfill-specific thematic data model for standardizing and integrating multisource spatial and attribute data; (2) it creates explicit spatial relationships among landfill facilities, environmental monitoring points, pollutant indicators, hydrogeological elements, and sensitive receptors; and (3) it

incorporates groundwater-quality assessment results into the same GIS environment as the underlying monitoring and management data. Together, these contributions extend GIS use beyond isolated map visualization toward domain-specific environmental information integration and spatial decision support.

2. Design of the GIS-Based “One Map” Platform

2.1. System Architecture

The landfill GIS-based “One Map” platform was implemented using a browser/server (B/S) architecture. As shown in Figure 1, the system comprises six layers: user, service, application, interface, data, and infrastructure. This layered design separates user interaction, business logic, service interfaces, data management, and computing resources while supporting web-based visualization and manipulation of geospatial data. The architecture is described here as a functional design; computational performance is addressed separately.

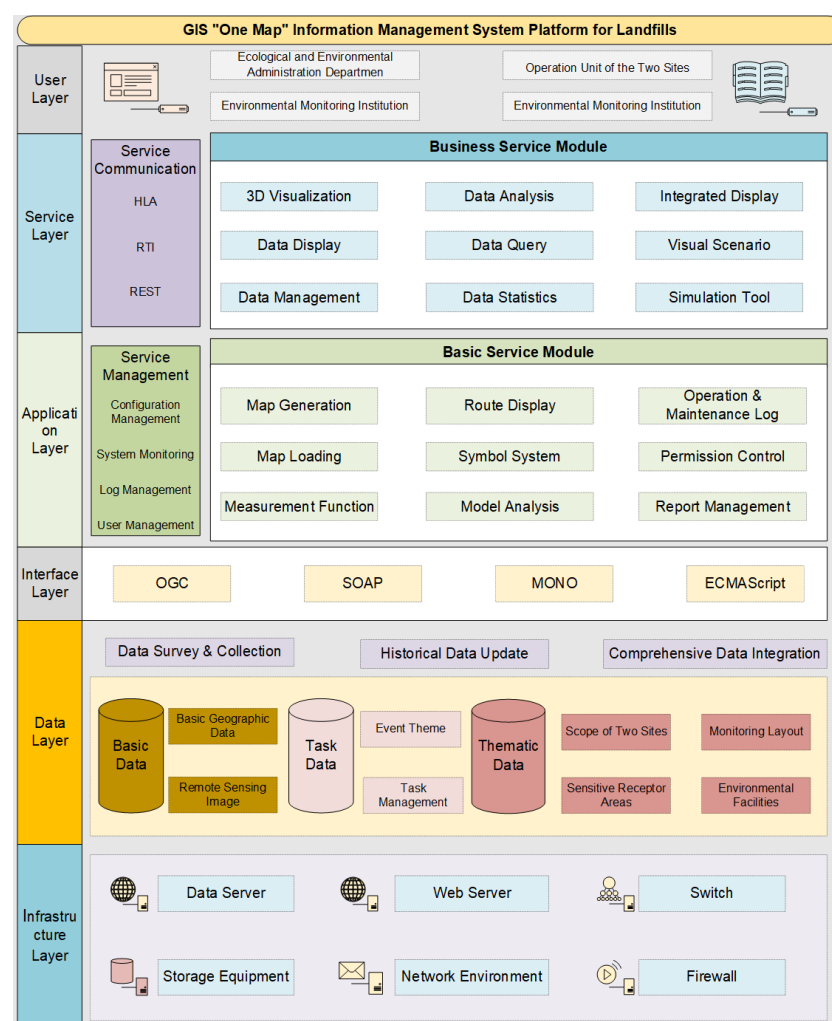


Figure 1. Six-layer architecture of the landfill GIS-based “One Map” platform, integrating users, GIS services, management functions, standardized interfaces, multisource environmental data, and supporting infrastructure for visualization, query, analysis, and environmental supervision.

1. User Layer

Before platform development, user requirements were collected from key stakeholders, including the Henan provincial environmental authority, landfill operators, and environmental monitoring institutions. The user-oriented architecture was designed to reflect their distinct responsibilities and information needs. Environmental authorities require functions

for data retrieval, regulatory oversight, leachate-management supervision, and sensitive-receptor protection. Landfill operators require structured management of construction and operational records, whereas monitoring institutions require access to groundwater, surface-water, and soil monitoring data with corresponding analysis and visualization tools. The platform supports web-based and mobile access to facilitate role-specific environmental management tasks.

2. Service Layer

The service layer translates user requirements into business, data-management, and security services. Business functions include landfill-information retrieval, statistical analysis, and risk-warning workflows, whereas data services support standardized reading, writing, verification, and processing of spatial and attribute records. The web service handles user requests and business logic, the GIS service publishes maps and spatial-analysis functions, and the security service provides identity authentication, role-based access control, and protection of data transmission and storage. Response time and operational stability were treated as design objectives rather than as validated performance outcomes.

3. Application Layer

The application layer provides interfaces for data retrieval, spatial analysis, map visualization, landfill life-cycle information management, and environmental warning. Functional workflows and prototype interfaces were used to define the operating logic and streamline user interactions. These modules demonstrate workflow integration but do not, by themselves, provide quantitative evidence of response efficiency.

4. Data Layer

The data layer is structured into three components: a fundamental geographic database, a thematic database, and remote-sensing basemaps. The fundamental geographic database provides essential reference information, including administrative boundaries, transportation networks, terrain data, and other spatial layers required for landfill localization and regional-scale analysis. The thematic database is designed for landfill-specific environmental management and includes spatial features such as landfill boundaries, monitoring locations, operational facilities, and sensitive receptors, together with corresponding identifiers, classifications, operational attributes, and monitoring records. Spatial databases based on PostGIS and geodatabases provide spatial indexing and geographic processing capabilities, while the linkage between spatial features and attribute records enables integrated storage, retrieval, and analysis of environmental information. Online and offline Tianditu imagery is used as the default basemap, with additional electronic maps and remote-sensing layers incorporated when needed.

The B/S architecture reduces client-side installation and maintenance requirements. On the server side, data, application, and GIS services are separated: the data server stores survey and business records, the application server executes business logic, and the GIS server provides mapping and spatial-analysis services. This separation clarifies responsibilities and facilitates maintenance and future extension. Nevertheless, scalability and operational stability depend on hardware, network conditions, service configuration, caching, and workload and were not quantitatively established in this study.

2.2. Platform Development Workflow

The platform development workflow is shown in Figure 2. Project archives were first organized, standardized, and integrated in accordance with relevant technical specifications to create a database of groundwater-environment investigation and assessment results for landfill sites in Henan Province. The provincial GIS-based “One Map” platform was then developed to combine spatial and attribute information within a unified map environment.

The resulting system supports data retrieval, visualization, and management-oriented analysis; no claim of high processing efficiency is made without controlled benchmark evidence.

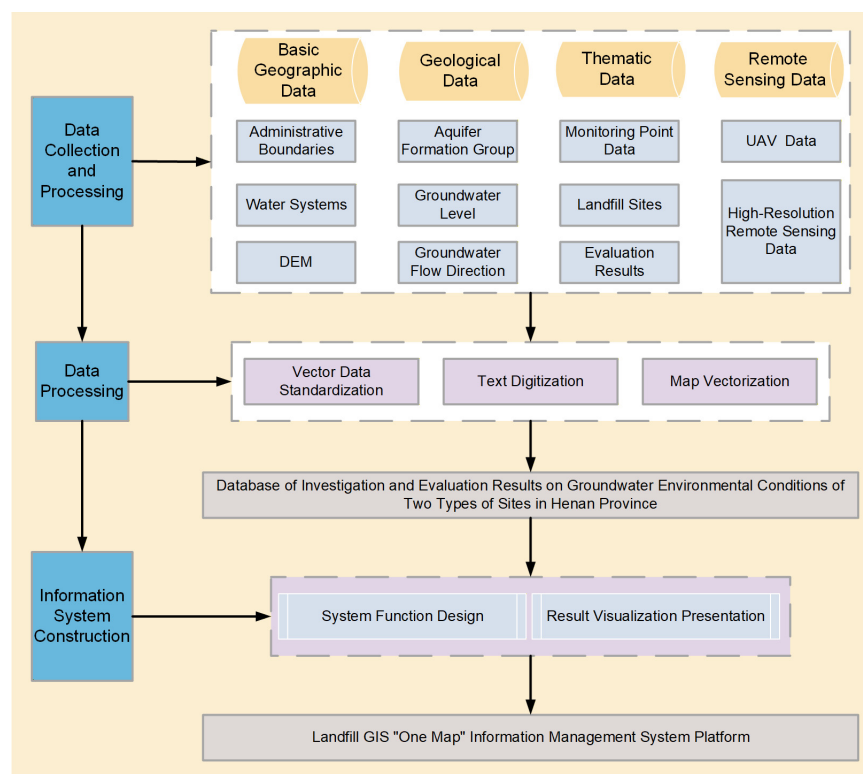


Figure 2. Platform development workflow, including multisource data collection, standardization and digitization, integrated database construction, functional design, result visualization, and final deployment of the landfill GIS-based “One Map” platform.

3. Key Technologies for Platform Development

3.1. Database Feature Extraction

The source datasets comprised three major categories: text-based records, including investigation reports and statistical tables; raster data, such as engineering drawings and remote-sensing imagery; and vector spatial datasets. These heterogeneous data sources were standardized, harmonized, and integrated into a consistent data structure to support the construction of the environmental information database [14,15]. Table 1 summarizes the main database entities, which are organized into six categories: fundamental geographic information, hydrogeological information, thematic geographic features, municipal solid waste landfills, hazardous-waste disposal sites, and sensitive receptors.

Table 1. Organization of spatial features in the project database.

No.	Element Category	Layer Name	Geometry Type
1	Basic Geography	Municipal Administrative Boundaries	Polygon
2		County Administrative Boundaries	Polygon
3		Township Administrative Boundaries	Polygon
4		River and Water Systems	Polygon

Table 1. Cont.

No.	Element Category	Layer Name	Geometry Type
5	Hydrogeology	Groundwater Contour Lines	Line
6		Measured and Inferred Groundwater Flow Directions	Point
7		Surface Water Flow Directions	Point
8		Water Resources Zones of Henan Province	Polygon
9		Hydrogeological Zones of Henan Province	Polygon
10	Thematic Elements	Groundwater Sampling Points of Municipal Solid Waste (MSW) Landfills	Point
11		Surface Water Sampling Points of MSW Landfills	Point
12		Soil Sampling Points of MSW Landfills	Point
13		Groundwater Sampling Points of Hazardous Waste Disposal Sites	Point
14		Surface Water Sampling Points of Hazardous Waste Disposal Sites	Point
15		Soil Sampling Points of Hazardous Waste Disposal Sites	Point
16		Groundwater Quality Sampling Points	Point
17		Sampling Points with Excessive Groundwater Pollutants	Point
18		Surface Water Quality Sampling Points	Point
19		Sampling Points with Typical Surface Water Pollutants	Point
20		Soil Quality Sampling Points	Point
21		Sampling Points with Typical Soil Pollutants	Point
22		Control Hydrological Points	Point
23	MSW Landfills	Survey Scope of MSW Landfills	Polygon
24		Red-line Boundary of MSW Landfills	Polygon
25		Plane Layout of MSW Landfills	Polygon
26		MSW Landfill Location Points	Point
27	Hazardous Waste Disposal Sites	Survey Scope of Hazardous Waste Disposal Sites	Polygon
28		Red-line Boundary of Hazardous Waste Disposal Sites	Polygon

Table 1. *Cont.*

No.	Element Category	Layer Name	Geometry Type
29	Sensitive Receptors	Plane Layout of Hazardous Waste Disposal Sites	Polygon
30		Hazardous Waste Disposal Site Location Points	Point
31		Polygonal Sensitive Receptors	Polygon
32		Point-shaped Sensitive Receptors	Point
33	Sensitive Receptors	Drinking Water Source Protection Zones	Polygon
34		Groundwater Drinking Water Source Points	Point

The spatial-layer inventory in Table 1 reflects the scope of the source groundwater-environment investigation projects and does not constitute a complete geological-hazard database. Seismic ground-motion parameters and active-fault information were not included because the source projects focused on groundwater environmental assessment rather than engineering seismic-safety evaluation. When the framework is applied to landfill siting, engineering design, or long-term structural-integrity assessment, official seismic-zonation data and, where required, site-specific seismic-safety information should be incorporated as additional thematic layers. Other region-specific geological hazards, including volcanic activity where relevant, can also be accommodated through the configurable database schema.

3.2. Data Integration

1. Integration of Fundamental Geographic Data

The fundamental geographic datasets for Henan Province include administrative boundaries, transportation networks, topography, and geomorphology. These data provide the spatial reference framework for landfill location and regional analysis. Following format conversion and quality control, landfill boundaries, monitoring locations, site layouts, and related spatial datasets were imported in Shapefile or geodatabase format. Spatial indexes were configured to support query execution, although their effect on performance was not independently benchmarked.

2. Integration of Landfill Investigation Data

Landfill investigation records were integrated as linked spatial and attribute datasets. Spatial layers include landfill boundaries and site layouts, such as administrative areas, leachate-regulation tanks, and waste-disposal zones. Associated attributes include unique identifiers, official names, operational parameters, and monitoring records. Sampling datasets store the locations of groundwater, surface-water, and soil monitoring points together with water-quality, soil-quality, and pollutant-concentration results. A periodic update procedure was defined to maintain data currency, and relational links were established between spatial features and attribute tables. The municipal solid waste landfill in Xichuan County, Nanyang City, was selected as the demonstration site. Figure 3 shows the landfill boundary; Figure 4 presents the site layout, including administrative areas, leachate-regulation tanks, and waste-disposal zones; and Figure 5 shows the groundwater, surface-water, and soil sampling locations and the investigation area.

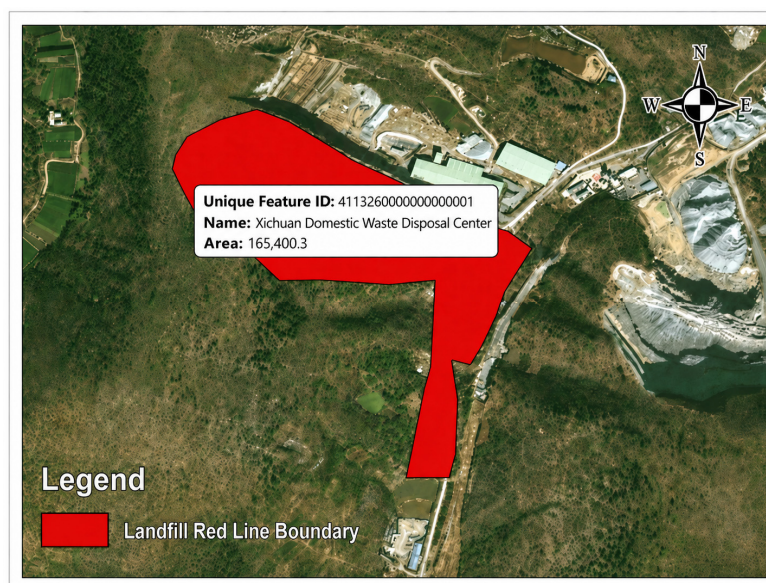


Figure 3. Red-line boundary and attribute information of the Xichuan County domestic waste landfill.

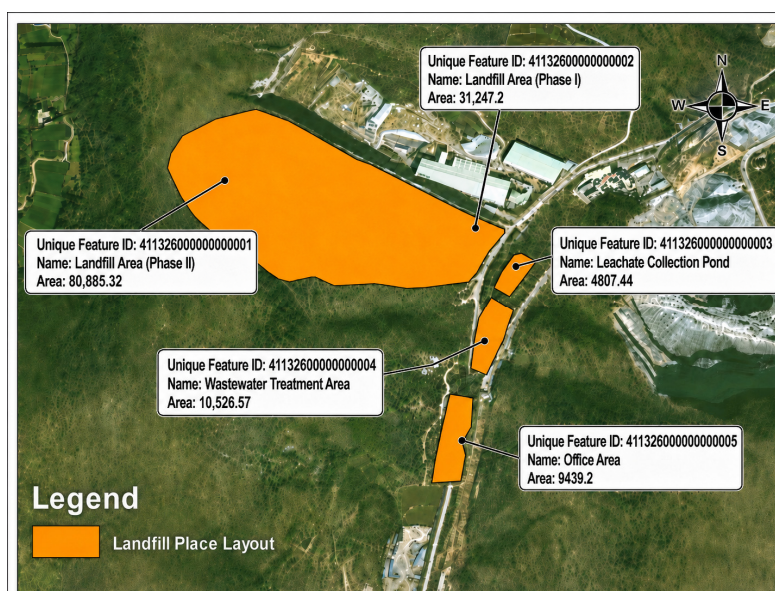


Figure 4. GIS-based layout of the Xichuan County landfill, showing the landfill phases, leachate pond, wastewater treatment area, and office area.

The unified database combines groundwater, surface-water, and soil monitoring records; pollutant data; landfill and disposal-site spatial information; and facility layouts. This structure supports consistent visualization, retrieval, and subsequent environmental analysis and provides a basis for updating groundwater archives and linking monitoring records to spatial objects. Improvements in staff productivity or operational efficiency, however, were not quantitatively evaluated.

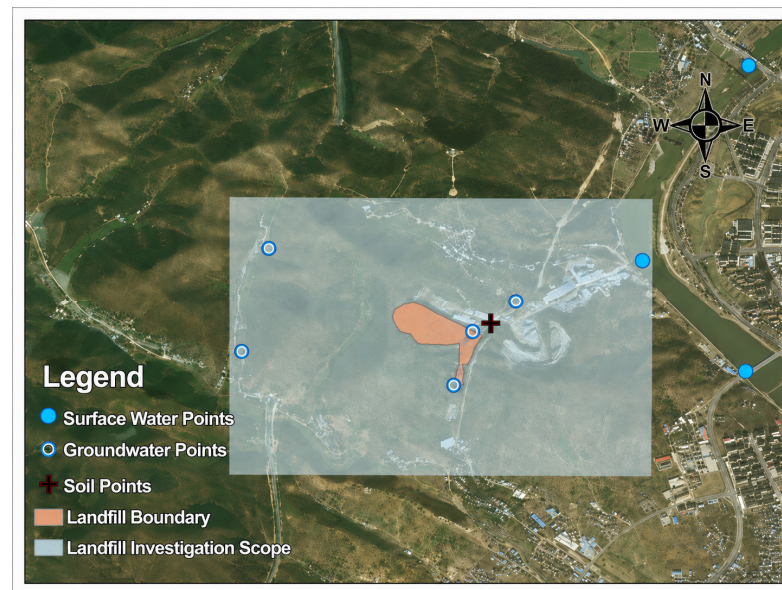


Figure 5. Spatial distribution of groundwater, surface-water, and soil sampling locations.

4. Platform Demonstration and Application

4.1. Platform Demonstration

The visualization module provides an interactive interface for displaying integrated geographic and landfill-specific information through web-based map services. Fundamental geographic layers and thematic landfill layers are dynamically loaded and visualized, enabling users to explore spatial relationships among landfill facilities, environmental monitoring locations, and surrounding geographic features. These functions are integrated within a unified map-based workflow, allowing landfill locations, operational facilities, environmental monitoring points, hydrogeological layers, and nearby sensitive receptors to be viewed together with their associated attribute records. The interface supports interactive map navigation, layer management, transparency adjustment, and spatial queries linked to attribute information. Figure 6 presents the main visualization interface for Nanyang City, Henan Province. The basemap and core landfill layers are loaded by default, while the layer-control panel allows users to overlay different geographic and thematic datasets according to specific environmental management objectives.

Figure 7 shows the attribute-query interface. Users can search by target layer (e.g., landfill boundaries or leachate-regulation tanks), attribute criteria (e.g., unique identifier or official name), and spatial extent (all data, the current map view, or a user-defined area). Matching features are highlighted on the map and listed with their associated attributes. Selecting a result centers the map on the corresponding feature and opens a pop-up containing its detailed information.

The Statistical Report Module (Figure 8) enables the aggregation and summarization of query results based on user-defined spatial dimensions and environmental indicators. For example, users can analyze the distribution of landfill sites among prefecture-level cities or identify monitoring records exceeding specified thresholds. The platform is primarily applicable to the integration of records from multiple landfill investigations, routine spatial and attribute retrieval, and the screening and reporting of monitoring results. Effective implementation requires standardized and quality-controlled data, consistent coordinate references and identifiers, reliable spatial–attribute linkages, and appropriately configured user access. Under these conditions, the platform can streamline the organization and use of study results, although improvements in operational efficiency were not quantitatively evaluated.



Figure 6. Map-browsing interface showing landfill locations, administrative boundaries, and thematic layer management.

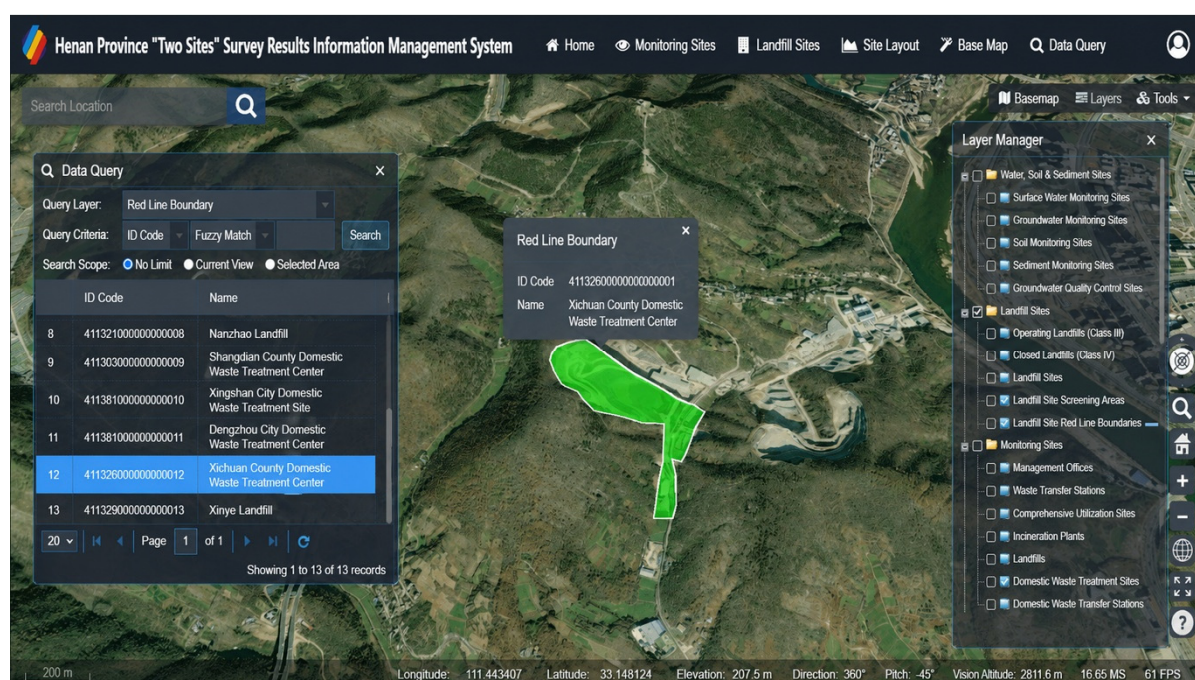
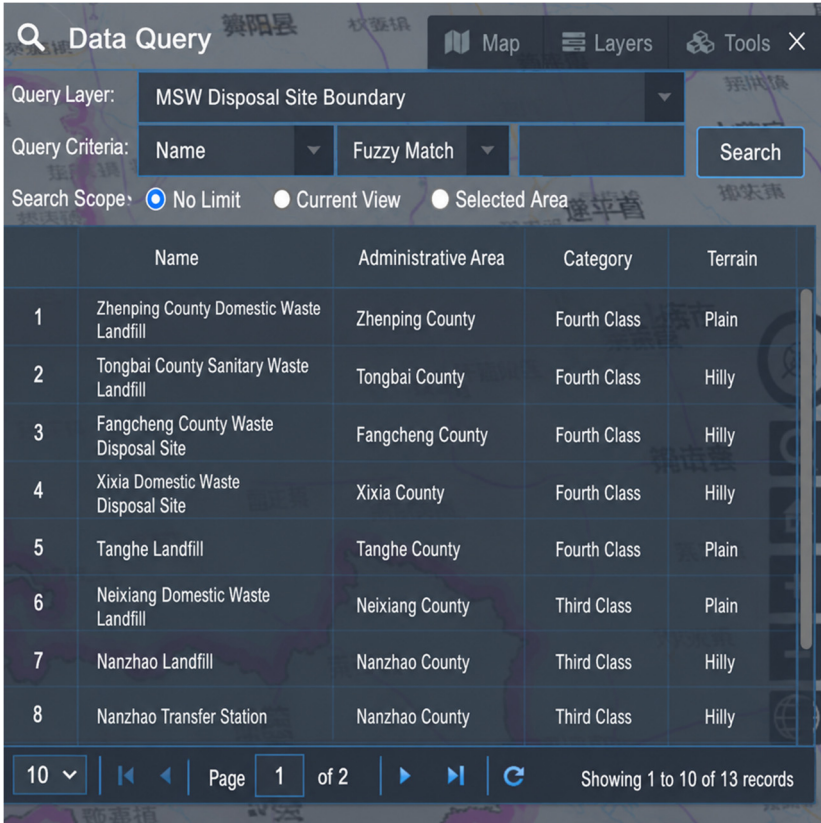


Figure 7. Attribute-query interface for locating landfill features and displaying their spatial and descriptive information.

4.2. Environmental Application and Scope of the Case Study

The provincial platform integrates investigation records from multiple landfill sites in Henan Province, whereas the quantitative groundwater assessment presented in this section is limited to the Xichuan County demonstration site. Xichuan County is located in southwestern Henan Province and forms part of an important water-source area for the Middle Route of the South-to-North Water Diversion Project [16]. Landfill leachate may threaten groundwater if contaminants migrate through the unsaturated zone and

enter the aquifer [17]. Using data stored in the GIS platform, the single-factor method and the Nemerow comprehensive pollution index were applied to demonstrate an integrated workflow linking monitoring locations, analytical records, assessment indices, and spatial visualization. The methods were selected based on the assessment objective and the structure of the available data. The single-factor method directly compares each measured constituent with its corresponding Class III limit under GB/T 14848-2017 [18] and therefore identifies individual indicators that approach or exceed the applicable criterion. The Nemerow index was used as a complementary measure because it combines the maximum and mean single-factor indices to provide an integrated characterization of each groundwater sample. Both methods are transparent and compatible with the available cross-sectional dataset and the GIS-based linkage of monitoring records and assessment results. They are used for standards-compliance screening rather than source attribution or causal analysis. The analysis is therefore presented as a site-specific environmental application of the provincial platform rather than as a comparative or province-wide groundwater-impact assessment. Interpretation follows a source–pathway–receptor framework that considers potential leachate sources, hydrogeological pathways, groundwater-flow direction, monitoring-well locations, and available landfill-management information. In this context, the groundwater assessment is used to illustrate how the platform can organize environmental evidence and screen for monitoring anomalies. It is not intended to confirm the absence of potentially undetected contamination in groundwater or soil.



	Name	Administrative Area	Category	Terrain
1	Zhenping County Domestic Waste Landfill	Zhenping County	Fourth Class	Plain
2	Tongbai County Sanitary Waste Landfill	Tongbai County	Fourth Class	Hilly
3	Fangcheng County Waste Disposal Site	Fangcheng County	Fourth Class	Hilly
4	Xixia Domestic Waste Disposal Site	Xixia County	Fourth Class	Hilly
5	Tanghe Landfill	Tanghe County	Fourth Class	Plain
6	Neixiang Domestic Waste Landfill	Neixiang County	Third Class	Plain
7	Nanzhao Landfill	Nanzhao County	Third Class	Hilly
8	Nanzhao Transfer Station	Nanzhao County	Third Class	Hilly

10 | Page 1 of 2 | Showing 1 to 10 of 13 records

Figure 8. Classification-based query interface summarizing landfill names, administrative areas, categories, and terrain types.

4.2.1. Scope of the Environmental Application

The available dataset contains five groundwater monitoring wells: XCJ01-1, XCJ01-2, XCJ02, XCJ03, and XCJ04. The case study demonstrates how the platform links well locations to analytical results, water-quality indices, and map-based outputs. The five wells

do not constitute a complete regional monitoring network and cannot validate the full range of environmental-analysis capabilities supported by the platform.

The dataset represents a single cross-sectional monitoring campaign and contains neither repeated seasonal or annual observations nor a verified pre-operation groundwater baseline. Accordingly, the available data cannot establish temporal trends, support a rigorous before-and-after comparison of landfill operation, or demonstrate causal relationships between landfill activities and groundwater conditions. The conclusions are therefore restricted to the five sampled locations and the sampling period.

4.2.2. Single-Factor Assessment

The single-factor method evaluates each constituent independently by comparing its measured concentration with the applicable groundwater-quality standard [19]. The resulting dimensionless index indicates whether an individual constituent meets the selected criterion. The index is calculated as follows:

$$P_i = C_i/S_i \quad (1)$$

where C_i is the measured concentration of the i -th constituent, and S_i is the corresponding standard value.

The ArcGIS Field Calculator was used to calculate single-factor indices for the available monitoring records. Table 2 presents the available analytical indicators for monitoring well X CJ03 as an illustrative example. All 16 available indicators—including physicochemical parameters, metals, inorganic constituents, and organic indicators—had indices below 1, indicating that none exceeded the corresponding Class III standard at the time of sampling. The largest index was observed for total hardness (0.633), followed by chromium (0.400), total dissolved solids (0.386), lead (0.316), and fluoride (0.310). This mixed profile is interpreted in Section 4.2.4 and is not treated as a landfill-specific chemical signature.

4.2.3. Nemerow Comprehensive Pollution Index and Exploratory Spatial Visualization

Because single-factor indices assess constituents independently, they do not summarize overall water quality when multiple indicators are considered. The Nemerow comprehensive pollution index combines the maximum and mean single-factor indices and has been widely applied in water- and soil-quality assessments [20]. The index is calculated as follows:

$$P = \sqrt{\frac{P_{max}^2 + P_{avg}^2}{2}} \quad (2)$$

where P_{max} is the maximum single-factor pollution index P_i , and P_{avg} is the mean of all P_i values.

The Nemerow indices for X CJ01-1, X CJ01-2, X CJ02, X CJ03, and X CJ04 were 0.42, 0.51, 0.59, 0.46, and 0.53, respectively. All values were below 0.7 under the classification adopted in this study. These indices describe samples collected from the five wells and should not be extrapolated to regional groundwater conditions or interpreted as proof of either the presence or absence of landfill-related effects. The ranking—X CJ02 (0.59) > X CJ04 (0.53) > X CJ01-2 (0.51) > X CJ03 (0.46) > X CJ01-1 (0.42)—does not, by itself, establish a hydraulic gradient, contaminant pathway, or common source.

Table 2. Groundwater-quality indicators at monitoring well X CJ03 (Class III limits from GB/T 14848-2017). (Note: Nitrate nitrogen was the only inorganic nitrogen species available in the archived analytical record used for this illustrative assessment. Ammonia nitrogen and nitrite nitrogen were unavailable and were neither assigned zero values nor included in the index calculation.)

Category	Indicator	Measured Value	Class III Limit	Index
Physicochemical Indicators	pH	7.2	6.5–8.5	0.133
	Total Hardness	285 mg/L	≤450 mg/L	0.633
	TDS	386 mg/L	≤1000 mg/L	0.386
	Arsenic	0.0013 mg/L	≤0.01 mg/L	0.13
	Lead	0.00316 mg/L	≤0.01 mg/L	0.316
Heavy Metals	Cadmium	0.00021 mg/L	≤0.005 mg/L	0.042
	Chromium	0.02 mg/L	≤0.05 mg/L	0.4
	Mercury	0.0001 mg/L	≤0.001 mg/L	0.1
	Selenium	Below the detection limit	≤0.01 mg/L	0
	Copper	Below the detection limit	≤1.0 mg/L	0
Inorganic Substances	Zinc	Below the detection limit	≤1.0 mg/L	0
	Nitrate Nitrogen	4.56 mg/L	≤20.0 mg/L	0.228
	Fluoride	0.31 mg/L	≤1.0 mg/L	0.31
	Chloride	17.6 mg/L	≤250 mg/L	0.071
	Benzene	Below the detection limit	≤0.01 mg/L	0
Organic Indicators	Volatile Phenols	Below the detection limit	≤0.002 mg/L	0

To demonstrate the platform’s spatial-visualization workflow, inverse distance weighting (IDW) in ArcGIS was applied to the Nemerow indices measured at the five wells. IDW was selected as a deterministic and transparent distance-based method because it does not require estimation of an empirical variogram. Ordinary kriging was considered but not adopted because five observations are insufficient to derive a stable and defensible spatial-correlation model, including reliable nugget, sill, and range parameters. The selection of IDW, therefore, reflects the severe data limitation and the exploratory purpose of the map; it does not imply that IDW is more accurate or statistically superior to ordinary kriging. The calculation formula is presented as follows:

$$\hat{Z}(x_0) = \frac{\sum_{i=1}^n \lambda_i Z(x_i)}{\sum_{i=1}^n \lambda_i} \quad (3)$$

where $\lambda_i = \frac{1}{d_i^p}$, λ_i is the weight assigned to observation i , d_i is the distance between observation i and the prediction location, and p is the power parameter.

Interpolation used inverse-square distance weighting with a power parameter of $p = 2$ and a variable search neighborhood containing all five wells. Cross-validation was not performed, and no quantitative interpolation error (e.g., mean error, mean absolute error, or root-mean-square error) is reported. A leave-one-out procedure would yield only five residuals, which would be highly sensitive to individual observations and insufficient for robust parameter optimization, interpolation-method comparison, or generalizable accuracy assessment. The absence of an independent validation dataset further precluded defensible error estimation. Accordingly, the measured values at the five wells remain the

primary environmental evidence, and the IDW surface is retained solely as an exploratory map display.

All 16 reported single-factor indices for XCJ03 were below 1. Across the five wells, the Nemerow indices ranged from 0.42 to 0.59 and remained below 0.7 under the adopted classification. These point-based results indicate that no standard exceedance was identified in the reported samples during the sampling event. The measured well values—not the IDW surface—form the evidentiary basis of the environmental application. Any apparent spatial pattern in Figure 9 may be strongly controlled by the positions of the five wells, the inverse-square weighting assumption, and the search-neighborhood definition. Because the surface is based on only five observations and has not been quantitatively validated, it cannot establish regional uniformity, delineate a contaminant plume, predict groundwater quality at unsampled locations, infer a contaminant pathway, or confirm or exclude landfill-related effects.

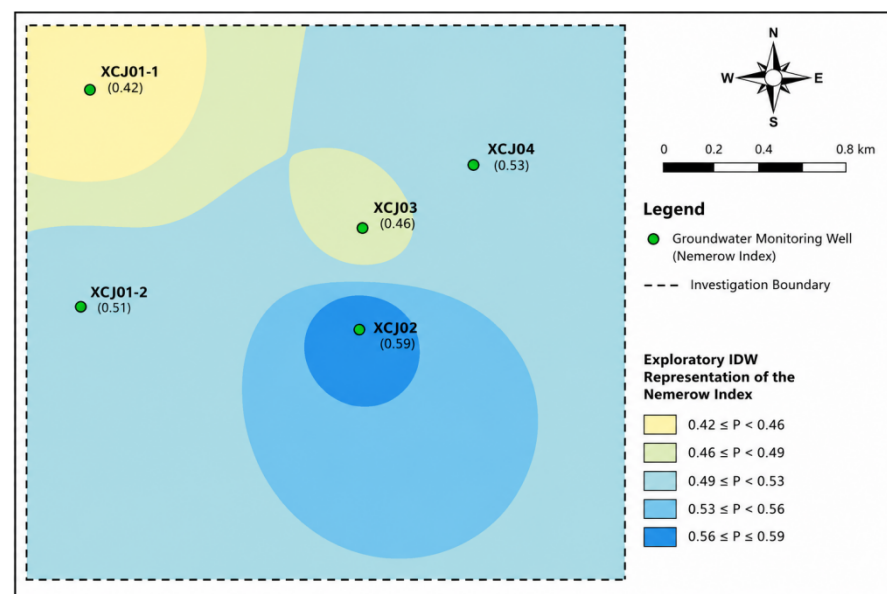


Figure 9. Exploratory IDW visualization of the Nemerow comprehensive pollution indices measured at five groundwater monitoring wells using inverse-square weighting ($p = 2$); the surface is not a validated regional prediction.

4.2.4. Environmental Interpretation of the Groundwater Results

The pollution indices indicate compliance with the adopted groundwater-quality thresholds but do not identify pollutant sources. Evidence of landfill-related groundwater impact would require a plausible source–pathway–receptor relationship: contaminants generated within the waste body or leachate system, migration through the liner or unsaturated zone, transport within the aquifer along the hydraulic gradient, and detection in appropriately located monitoring wells. Potential leachate-related constituents include dissolved organic matter, nitrogen compounds, chloride and other dissolved salts, selected metals, and volatile organic compounds. None of these constituents is unique to landfills, because natural water–rock interactions and other anthropogenic sources can produce overlapping chemical signatures.

At XCJ03, the indicators closest to their respective Class III limits—and therefore exerting the greatest numerical influence on the compliance assessment—were total hardness ($P_i = 0.633$), chromium (0.400), total dissolved solids (0.386), lead (0.316), fluoride (0.310), and nitrate nitrogen (0.228). Total hardness produced the maximum single-factor index and consequently had the strongest influence on the Nemerow index, which incorporates both the maximum and mean P_i values. These rankings indicate proximity to the regulatory

thresholds rather than the relative importance of contaminant sources. Total hardness, dissolved solids, and fluoride may reflect aquifer mineralogy and water–rock interaction, whereas chromium, lead, and nitrate may be affected by multiple natural or anthropogenic sources. Because ammonia nitrogen and nitrite nitrogen were unavailable in the archived dataset, the nitrogen-related interpretation is restricted to nitrate nitrogen and does not characterize the complete speciation or microbial transformation of nitrogen in the ground-water system. The available evidence is therefore insufficient to attribute these indicators specifically to landfill-derived transport.

Groundwater flow strongly controls whether a potential source can affect a monitoring well. The platform can store measured or inferred flow-direction layers, but the case dataset lacks a contemporaneous hydraulic-head survey, hydraulic-gradient estimates, aquifer hydraulic conductivity, well-screen elevations, and travel-time information sufficient to classify all wells reliably as upgradient or downgradient. Consequently, the relatively high Nemerow indices at XCJ02 and XCJ04 cannot be attributed to landfill-derived transport, and the Nemerow index at XCJ03 cannot be interpreted as evidence of attenuation, dilution, or effective containment.

Landfill age and leachate management also affect potential source strength. Waste-placement history and degradation stage influence leachate composition, whereas liner condition, leachate-collection efficiency, regulation-tank operation, treatment performance, and leakage or overflow events determine the potential for subsurface release. Although the GIS database contains fields for facility layouts and operational information, a verified operational chronology and quantitative leachate-management records were unavailable for this case. The observed non-exceedance, therefore, cannot be attributed to effective leachate management, nor does it exclude intermittent or historical releases. The defensible interpretation is that no threshold exceedance or consistent landfill-related source–pathway–receptor pattern was identified from the five wells during the sampling period.

4.2.5. Uncertainty, Limitations, and Future Monitoring

The principal uncertainties arise from the small monitoring network, the absence of repeated seasonal or annual observations, the lack of a verified pre-operation or upgradient baseline, and the assumptions required to interpolate a continuous surface from five observations. The IDW surface is sensitive to the selected power parameter, search-neighborhood definition, and spatial arrangement of the wells. Without robust cross-validation or an independent validation dataset, interpolation uncertainty cannot be expressed as a defensible prediction error or confidence interval. These limitations constrain environmental inference but not the platform’s database structure, which can accommodate additional wells and monitoring periods as validated data become available.

Future applications should include repeated wet- and dry-season monitoring and, where available, historical or pre-operation data. Future monitoring should include ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, and total nitrogen, together with dissolved oxygen and other redox-sensitive parameters, to support a more complete evaluation of nitrogen transformation. The network should include at least one upgradient background well, multiple downgradient wells aligned with groundwater flow, and monitoring locations near leachate-management facilities and sensitive receptors. A denser, temporally repeated dataset would permit sensitivity analysis for alternative IDW power parameters (e.g., $p = 1, 2$, and 3) and search-neighborhood settings, empirical variogram development, comparison with ordinary kriging, and leave-one-out or independent cross-validation using mean error, mean absolute error, and root-mean-square error. Monitoring campaigns should also document synchronized groundwater levels, well-screen elevations, aquifer

properties, landfill commissioning and waste-placement history, liner and collection-system condition, leachate quantity and composition, treatment performance, and leakage or overflow events. These data are needed to distinguish natural geochemical controls and other anthropogenic sources from a landfill-related signal.

4.3. Scope and Limitations of Platform Validation

The platform was functionally examined using the representative workflows described in Section 4.1: map browsing and layer control, multi-criteria attribute retrieval, and statistical report generation. The database model comprises six feature groups and 34 spatial layers, as summarized in Table 1. These observations demonstrate the scope of data integration and the operability of the principal workflows but do not constitute a computational-performance benchmark.

Controlled measurements of initial map-loading time, attribute- and spatial-query latency, statistical-report response time, database storage volume, throughput, and concurrent-user capacity were not preserved for the original deployment. A reproducible benchmark would require fixed hardware and software configurations, defined network conditions, a specified cache state, a documented database snapshot, and repeatable workloads. Retrospective numerical estimates without these controls would be unreliable. Accordingly, this study does not claim high processing efficiency, scalability, stability, or improved operational efficiency in the absence of quantitative validation.

Future validation should report server and client configurations, software versions, database size, numbers of spatial features and attribute records, cold- and warm-cache loading times, and the mean, median, and 95th-percentile latency of representative queries. Load tests should additionally report throughput, request-success and error rates, and CPU and memory utilization at increasing concurrency levels. Any numerical comparison with another GIS platform should use the same hardware, dataset, map extent, cache policy, and query workload.

4.4. International Comparison and Transferability

ArcGIS Online is a cloud-hosted, general-purpose WebGIS environment for publishing, visualizing, sharing, and analyzing geospatial data and applications [21], whereas GeoServer and QGIS Server are widely used to publish spatial data through standards-compliant services such as the Web Map Service and Web Feature Service [22,23]. These mature technologies are not direct competitors to the proposed platform. Instead, the platform adds a domain-specific layer comprising a landfill-oriented thematic database, explicit links among spatial objects, monitoring data, and assessment results, and workflows tailored to environmental supervision. Because deployment architecture, hardware, network conditions, data volume, service configuration, and caching strongly affect response time, a direct numerical comparison would be valid only under a common deployment and workload, which was not available in this study.

The comparison indicates that the proposed system is best understood as a domain-specific application layer rather than a replacement for established GIS/WebGIS technologies. Its main advantage is the integration of landfill-specific data structures, monitoring records, assessment outputs, and regulatory workflows within one application. Current limitations include dependence on the underlying GIS middleware, the absence of controlled performance benchmarking, and the lack of demonstrated large-scale concurrent operation. Table 3, therefore, compares functional roles rather than asserting superior computational performance.

Table 3. Functional positioning of established GIS/WebGIS platforms and the proposed landfill GIS-based “One Map” platform.

Platform	Primary Role	Relationship to the Proposed Platform
ArcGIS Online (https://www.arcgis.com)	Cloud-hosted WebGIS for publishing, sharing, managing, and analyzing maps, layers, data, and applications.	A general-purpose platform; landfill-specific data models and regulatory workflows require domain configuration.
GeoServer (https://geoserver.org)	Open-source server for publishing spatial data through OGC-compliant map and feature services.	Provides geospatial-service publication; domain databases, assessment logic, and user workflows require custom development.
QGIS Server (https://qgis.org)	Server software for publishing QGIS projects through OGC-compliant web services.	Provides map and service functions; landfill-specific schemas and management workflows require customization.
Proposed landfill GIS-based “One Map” platform	Landfill-specific framework for environmental information integration and spatial decision support.	Links facility layouts, hydrogeology, monitoring records, pollutant indicators, sensitive receptors, and assessment results within one workflow.

International studies illustrate complementary uses of GIS in landfill and environmental management. Mishra et al. combined leachate characterization, pre- and post-monsoon groundwater assessment, GIS-based spatial interpolation, and groundwater-flow modeling around a landfill in Varanasi, India [24]. Giglione et al. developed a database-linked WebGIS platform in Italy for managing and sharing environmental authorization, analytical-control, and industrial-emission information among public authorities and other stakeholders [25].

These studies emphasize two complementary priorities: field-based assessment of landfill impacts and multi-agency environmental-data exchange. The present platform neither introduces a calibrated contaminant-transport model nor seeks to replicate a general-purpose WebGIS. Its contribution is a provincial, landfill-oriented information schema that links facility layouts, hydrogeological units, monitoring records across environmental media, sensitive receptors, and assessment outputs within a single management workflow. This positioning entails both an advantage and a limitation: the platform provides broad domain integration for regulatory information management, but it has not yet been coupled with calibrated process models or evaluated through international pilot deployment.

The framework’s international relevance lies primarily in the transferability of its data model rather than in functions unique to Henan Province. Because the architecture uses a configurable thematic schema and standards-based GIS services, it can be adapted to other jurisdictions by mapping local data dictionaries and coordinate systems, replacing regulatory thresholds, and configuring user roles and reporting rules. The core relationships among waste-disposal facilities, hydrogeological units, monitoring points, pollutant records, sensitive receptors, and assessment outputs are common to landfill supervision, whereas regulatory standards and administrative workflows remain locally specific. Build-

ing on the Henan case, the framework's transferability could be further examined through schema mapping and pilot applications in other regulatory contexts.

5. Conclusions

This study developed a GIS-based “One Map” framework for integrating landfill investigation and assessment data in Henan Province. Rather than proposing a new general-purpose GIS engine, the framework focuses on the domain-specific organization and use of landfill spatial information, hydrogeological data, environmental monitoring records, sensitive receptors, and groundwater-quality assessment results. The main conclusions are as follows:

1. The principal methodological contribution is a landfill-oriented data model that integrates fundamental geographic data, hydrogeological elements, landfill facilities, monitoring locations, pollutant records, and sensitive receptors within a unified spatial database. This model provides a consistent basis for linking geographic entities to their environmental and management attributes.
2. Compared with general-purpose GIS/WebGIS platforms, the added value of the proposed system lies in its domain-specific data model and environmental-management workflow rather than in conventional map-rendering or service-publication functions. The platform combines data management, spatial retrieval, statistical reporting, and environmental assessment for landfill supervision. The functional comparison does not imply superior response time or scalability, because these properties were not assessed under a common benchmark. The configurable thematic schema also provides a basis for adaptation to other jurisdictions, with further evaluation through local schema mapping and pilot deployment.
3. The Xichuan County case demonstrates how groundwater monitoring records and quality-assessment results can be managed within the same spatial framework. The sampled wells met the adopted Class III groundwater-quality criteria during the monitoring event. However, the limited monitoring network constrains both environmental interpretation and spatial interpolation; the case, therefore, demonstrates the integrated workflow rather than proving the absence of landfill-related groundwater effects. The IDW layer is an exploratory visualization, not a validated spatial prediction. The available indicator pattern did not provide a verified landfill-specific chemical signature or a hydraulically supported concentration gradient. Because contemporaneous groundwater-level data, reliable upgradient–downgradient classification, landfill-age information, and quantitative leachate-management records were unavailable, the observed non-exceedance cannot be attributed to containment performance and does not exclude historical or intermittent releases. No quantitative interpolation error is reported because the five-point dataset and the absence of an independent validation set preclude a robust accuracy assessment.

The environmental demonstration is limited to five wells, one monitoring period, and no verified pre-operation baseline. It therefore cannot support temporal trend analysis, before-and-after comparison, or causal attribution of groundwater conditions to landfill operation. Further validation requires a denser monitoring network, repeated sampling, and uncertainty-aware spatial analysis. Future work should evaluate IDW parameter sensitivity, compare deterministic and geostatistical methods using quantitative cross-validation, and integrate groundwater heads, flow directions, aquifer and well-construction information, landfill operational history, and leachate-system performance so that sources, pathways, and receptors can be assessed explicitly.

The current implementation demonstrates functional integration but does not establish quantitative computational performance. No conclusion is drawn regarding processing effi-

ciency, response-time superiority, database capacity, or supported concurrent-user numbers. These properties require controlled and reproducible benchmarking in future deployments.

Author Contributions: Conceptualization, J.Z. and S.Z.; methodology, S.Z.; software, D.W.; validation, S.Z.; writing—original draft preparation, J.Z.; writing—review and editing, D.W.; funding acquisition, S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Young Scientists Fund Project of the National Natural Science Foundation of China (Grant No. 4240073024).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors thank Shiyuan Dong for his guidance and constructive comments on the data-analysis methods and platform implementation.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lv, F.; Qiu, J.J.; Zhan, J.; Zhang, H.; He, P.J. Prospects for the Development of Domestic Waste Landfill Technology in China. *Environ. Sanit. Eng.* **2024**, *32*, 27–34.
2. Kamaruddin, M.A.; Yusoff, M.S.; Rui, L.M.; Isa, A.M.; Zawawi, M.H.; Alrozi, R. An overview of municipal solid waste management and landfill leachate treatment: Malaysia and Asian perspectives. *Environ. Sci. Pollut. Res.* **2017**, *24*, 26988–27020. [[CrossRef](#)] [[PubMed](#)]
3. Hu, X. Research on Groundwater Level Control Indicators and Early Warning in Changji Prefecture. Master's Thesis, Xinjiang Agricultural University, Urumqi, China, 2022.
4. Iwanaga, T.; El Sawah, S.; Jakeman, A.J. Design and implementation of a web-based groundwater data management system. *Math. Comput. Simul.* **2013**, *93*, 164–174. [[CrossRef](#)]
5. Hoover, J.H.; Sutton, P.C.; Anderson, S.J.; Keller, A.C. Designing and evaluating a groundwater quality Internet GIS. *Appl. Geogr.* **2014**, *53*, 55–65. [[CrossRef](#)]
6. Wang, L.; Jackson, C.R.; Pachocka, M.; Kingdon, A. A seamlessly coupled GIS and distributed groundwater flow model. *Environ. Model. Softw.* **2016**, *82*, 1–6. [[CrossRef](#)]
7. Jones, W.R.; Spence, M.J.; Bowman, A.W.; Evers, L.; Molinari, D.A. A software tool for the spatiotemporal analysis and reporting of groundwater monitoring data. *Environ. Model. Softw.* **2014**, *55*, 242–249. [[CrossRef](#)]
8. Magesh, N.S.; Chandrasekar, N.; Soundranayagam, J.P. Delineation of groundwater potential zones in Theni District, Tamil Nadu, using remote sensing, GIS and MIF techniques. *Geosci. Front.* **2012**, *3*, 189–196. [[CrossRef](#)]
9. Huang, Z.; Liu, G.; Zhang, Y.; Yuan, Y.; Xi, B.; Tan, W. Assessing the impacts and contamination potentials of landfill leachate on adjacent groundwater systems. *Sci. Total Environ.* **2024**, *930*, 172664. [[CrossRef](#)] [[PubMed](#)]
10. Beneduce, L.; Piergiacomo, F.; Limoni, P.P.; Zuffianò, L.E.; Polemio, M. Microbial, chemical, and isotopic monitoring integrated approach to assess potential leachate contamination of groundwater in a karstic aquifer (Apulia, Italy). *Environ. Monit. Assess.* **2024**, *196*, 312. [[CrossRef](#)] [[PubMed](#)] [[PubMed Central](#)]
11. Bill, R.; Blankenbach, J.; Breunig, M.; Haunert, J.-H.; Heipke, C.; Herle, S.; Maas, H.-G.; Mayer, H.; Meng, L.; Rottensteiner, F.; et al. Geospatial information research: State of the art, case studies and future perspectives. *PFG J. Photogramm. Remote Sens. Geoinf. Sci.* **2022**, *90*, 349–389. [[CrossRef](#)] [[PubMed](#)]
12. Noardo, F. Multisource spatial data integration for use cases applications. *Trans. GIS* **2022**, *26*, 2874–2913. [[CrossRef](#)]
13. Huber, R.; D'Onofrio, C.; Devaraju, A.; Klump, J.; Loescher, H.W.; Kindermann, S.; Guru, S.; Grant, M.; Morris, B.; Wyborn, L.; et al. Integrating data and analysis technologies within leading environmental research infrastructures: Challenges and approaches. *Ecol. Inform.* **2021**, *61*, 101245. [[CrossRef](#)]
14. Varadharajan, C.; Hendrix, V.C.; Christianson, D.S.; Burrus, M.; Wong, C.; Hubbard, S.S.; Agarwal, D.A. BASIN-3D: A brokering framework to integrate diverse environmental data. *Comput. Geosci.* **2022**, *159*, 105024. [[CrossRef](#)]
15. Martínez, D.; Po, L.; Trillo-Lado, R.; Viqueira, J.R.R. A conceptual data modeling framework with four levels of abstraction for environmental information. *Environ. Model. Softw.* **2025**, *183*, 106248. [[CrossRef](#)]
16. Ge, L.; Wang, L. Exploring the dynamic evolution of vegetation cover in Xichuan County, Henan Province by integrating multisource remote sensing data. *Remote Sens. Nat. Resour.* **2025**, *37*, 192–202. [[CrossRef](#)]

17. Mao, X.; Zhang, S.; Wang, S.; Li, T.; Hu, S.; Zhou, X. Evaluation of Human Health Risks Associated with Groundwater Contamination and Groundwater Pollution Prediction in a Landfill and Surrounding Area in Kaifeng City, China. *Water* **2023**, *15*, 723. [\[CrossRef\]](#)
18. GB/T 14848-2017; Standard for Groundwater Quality. Standards Press of China: Beijing, China, 2017.
19. Yang, K.; Hu, X.M.; Lu, W.X. Analysis and Evaluation of Aquaculture Tail Water Quality in Chaohu Lake Basin. *J. Biol.* **2023**, *40*, 85–90.
20. Zeng, Z.C.; Zeng, Z.Z.; Hu, J.J. Distribution Characteristics and Source Analysis of Heavy Metals in Surface Water-Sediment of Coal Mining Areas in Guizhou—A Case Study of Xinzhai River. *Environ. Monit. China* **2023**, *39*, 147–157.
21. Netek, R.; Pohankova, T.; Bittner, O.; Urban, D. Geospatial Analysis in Web Browsers—Comparison Study on WebGIS Process-Based Applications. *ISPRS Int. J. Geo Inf.* **2023**, *12*, 374. [\[CrossRef\]](#)
22. Verdu-Candela, A.; Femenia-Ribera, C.; Mora-Navarro, G.; Sierra-Requena, R. Implementation of Web Map Services for Old Cadastral Maps. *ISPRS Int. J. Geo Inf.* **2023**, *12*, 413. [\[CrossRef\]](#)
23. Mano, A.D.S.; Silva, B.C.; Mocho, P.; Ortega, F. Location-Based Management of Paleontological Collections Using Open Source GIS Software. *Geoheritage* **2024**, *16*, 38. [\[CrossRef\]](#)
24. Mishra, S.; Tiwary, D.; Ohri, A.; Agnihotri, A.K. Impact of Municipal Solid Waste Landfill Leachate on Groundwater Quality in Varanasi, India. *Groundw. Sustain. Dev.* **2019**, *9*, 100230. [\[CrossRef\]](#)
25. Giglione, G.; Annibaldi, A.; Iaccarino, A.; Capancioni, R.; Borghini, G.; Ciabattini, F.; Illuminati, S.; Pace, G.; Memmola, F.; Giantomassi, G. An Integrated Web-Based GIS Platform for the Environmental Monitoring of Industrial Emissions: Preliminary Results of the Project. *Appl. Sci.* **2022**, *12*, 3369. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.