Study on a water pollution simulation and analysis system based on WebGIS: A case study of Liyang City, Jiangsu Province

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Abstract. A surface water quality analysis and pollutant diffusion simulation system was studied and developed using WebGIS. This paper introduces the structural design, technology development and main functions of the system. Using Liyang City of Jiangsu Province as an example, an environmental water monitoring database was established. Based on the database, a comprehensive analysis and evaluation of water quality in Liyang City were determined and provided decision support for pollution management. In addition, two authoritative water pollution diffusion analysis models (including a one-dimensional model and a two-dimensional model) were integrated, and a dynamic simulation of water pollution accidents was constructed with the support of GIS technology.

1. Research background

The environment provides the basic conditions for human survival and development. Environmental pollution has become one of a number of problems threatening human survival, especially water pollution, which directly endangers the health and safety of humans. With the accelerated urbanization in China, environmental water problems have become increasingly significant. Long-term ineffective governance has led to more serious water pollution in some areas than ever before. In recent years, with an emphasis on environmental water quality, water pollution has been gradually brought under control, and more research has been focused on the field of water quality analysis and pollutant diffusion simulation. The Geographic Information System (GIS) has been widely used in environmental water quality analysis and water pollutant diffusion simulations due to its powerful spatial data visualization tools and analytical process.

The Watershed Water Management Decision Support System (DSS-CWM) developed by the Dublin National University of Ireland is a typical example of GIS for regional water environment management [1]. In 2010, Loos et al used GIS technology to investigate and analyse groundwater pollution in Europe and established a Pan-European groundwater quality spatial database [2]. In 2003, Ding et al [3] combined GIS with a water pollution model, using one-dimensional water flow and two-dimensional water diffusion to simulate water pollution accidents, reflecting both the water pollution caused by pollution incidents and the changing processes of pollution incidents in terms of time and space. Fu et al [4] established water pollution simulation models for complex water flow conditions and water quality dispatching requirements based on 3S technology and created automatic water pollution monitoring systems and emergency decision-making processes. In 2009, Wu et al [5] used a one-dimensional water quality model to simulate sudden river pollution events and created real-time...
dynamic visualization of pollution calculations using the ArcGIS platform. From the water pollution models and simulation analyses, the above research produces one-dimensional simulations of water pollution in a single-machine or LAN environment but does not achieve two-dimensional simulations of water pollution. Developments in networking capabilities allow for the combination of the Internet with water pollution simulation and analysis technologies. The design of a system for water pollution simulation and analysis based on WebGIS is urgent due to current global environmental concerns.

This paper analyses both the annual and seasonal changes in water quality of 69 water quality monitoring sections of Liyang City in Jiangsu Province (including assessment sections required by The Action Plan for Prevention and Treatment of Water Pollution (“The Ten Measure Water Action Plan”), regional compensation sections, routine monitoring sections and four types of monitoring sections required by town assessment sections). This paper also outlines research on one- and two-dimensional water pollution diffusion simulations of water pollution emergencies and presents the implementation scheme of this system. The scheme adopts a client-server computing mode. The whole system, distributed on the Internet, consists of a client, Web server and application server. The client can seamlessly overlay and visualize the vector and raster maps and can enlarge, shrink, roam, query, analyse, simulate and perform other operations. This paper will introduce the structural design, technology development and main functions of the system.

2. System structure
The water pollution simulation and analysis system studied in this paper is composed of a basic data layer, support layer and application layer. As shown in figure 1, the main functions of each layer are summarized as follows:

- **Data layer**: The data layer is used to store and provide all data needed by the system, including cross-sectional monitoring data, sewage outlet data, pollution source monitoring data, water resources thematic data, and basic geographic data. Cross-sectional monitoring data is the core business data of the system. According to the management category, the cross-sectional monitoring data of Liyang City can be divided into four types: regional compensation cross sections, routine monitoring cross sections, “Ten Measure Water Action Plan” cross sections and town assessment cross sections, totalling 69 water quality monitoring cross sections. The monitoring indexes of the “Ten Measure Water Action Plan” and routine monitoring cross sections include permanganate index, ammonia nitrogen, total nitrogen, total phosphorus, pH, heavy metals and 29 pollutants. Regional compensation sections monitor three pollutants: permanganate index, ammonia nitrogen and total phosphorus. Town assessment cross sections monitor 4 pollutants: permanganate index, ammonia nitrogen, total phosphorus and dissolved oxygen. The system database stores monitoring data for the above four sections dating back to 2010.

![Figure 1. Framework of the water pollution simulation and analysis system.](image-url)
Supporting layer: The supporting layer provides all software and hardware environments needed for system construction, including GIS software, database software, programming language, water pollution diffusion calculation model, etc. This system uses ArcGIS software to process spatial data, publishes GIS layers for map services, calls Baidu API and creates a seamless link between the map services of ArcGIS and Baidu map. The database software uses Microsoft’s SQL Server database management system by creating a seamless connection between the spatial data and the attribute data through the spatial data engine ArcSDE. The development language of this system is JavaScript. The recognized pollutant transport and diffusion model is used to dynamically simulate the river pollutant diffusion process.

Application layer: The application layer provides users with an interactive interface, including analysis of water quality in various sections, display of dynamic simulation results for water pollution, interactive application of monitoring data, dynamic release of information and decision-making support for emergency plans. The water quality analysis of cross sections achieves annual and quarterly analyses for four types of monitoring sections. The dynamic simulation of water pollution produces the one- and two-dimensional simulations of the pollutant diffusion process.

3. Water pollution diffusion analysis model

In the study of water environments, the water quality model is the main technique for water quality analysis and predictions. Streeter-Phelps established the first water quality model [6], the classical Streeter-Phelps water quality model (S-P model), when he studied the pollution of the Ohio River in the United States. Subsequently, scholars from around the world have done a great amount of work in the development and research of water quality models [7-9] and have produced a series of water quality models that can be simulated and calculated using computers, such as the zero-, one- and two-dimensional river water quality models, estuary water quality model, lake (reservoir) uniform mixing attenuation model, non-uniform mixing model, eutrophication model and so on. Taking the changes in pollutant concentration and the diffusion parameters in the longitudinal and transverse directions of the river into account, the one- and two-dimensional water quality models adopted in this paper, which are especially suitable for use with GIS technology, are commonly used in domestic river pollution diffusion simulations.

The research uses a quadrilateral grid method to do spatial discretization of the studied and simulated river channel according to the hydrological characteristics of the Liyang River. One- and two-dimensional instantaneous discharge water quality models are integrated with GIS to produce the water pollution accident simulation and the dynamic demonstration of simulation results. The data needed in this paper include remote sensing image maps, river system maps, monitoring section maps, pollution source distribution maps, administrative division maps, hydrological data, section monitoring data and so on. Various basic maps are digitized in ArcGIS, and hydrological data and water quality monitoring data are input into the SQL Server database.

3.1. One-dimensional river water quality model

The one-dimensional water quality model is a relatively simple environmental water model. When rivers or lakes are polluted, this water pollution prediction model is often used when the difference between the concentration distribution of cross sections and the average concentration of cross sections is small [10]. It mainly studies variations of pollutant concentration distribution along the river and the variations over time in each section. The one-dimensional model only considers the transportation and distribution characteristics of pollutant concentration and its diffusion parameters in the longitudinal direction, i.e., the flow direction (generally set as the x-axis). When pollutants are transported along the river, not only the flow but also the self-purification of the river should be considered. The corresponding water quality model [11,12] is as follows:

$$ \frac{\partial C}{\partial t} = E_x \frac{\partial^2 C}{\partial x^2} - U_x \frac{\partial C}{\partial x} - KC $$

(1)
Here, C denotes the concentration of pollutants in rivers, t denotes time, EX denotes the diffusion coefficient in the X direction, Ux denotes the average discharge, and K denotes the decay rate coefficient of the pollutants.

Because the finite difference method allows for easy construction of the system dynamics model, the finite difference method is chosen to calculate the numerical difference of the model. Obtained by deduction and rearrangement:

\[ C_{i}^{j+1} = C_{i}^{j} + \left( E_{i} \frac{C_{i+1}^{j} + C_{i-1}^{j}}{\Delta x^2} + u_{i} \frac{C_{i}^{j}}{\Delta x} \right) \Delta t - \left( E_{i} \frac{2C_{i}^{j}}{\Delta x^2} + u_{i} \frac{C_{i+1}^{j} + k_{i}C_{i}^{j}}{\Delta x} \right) \Delta t \]  

(2)

In the formula, Ei is the longitudinal dispersion coefficient of section I; uI is the average velocity of section I; Ki is the pollutant decay rate coefficient of section I; \( \Delta x \) are steps in the X direction; \( \Delta t \) are the time steps; i is the section I; and j is the time, j.

From the formula, the concentration value at time (j+1), section I can be calculated iteratively from the concentration value at time j, section (i+1), (i-1) and other parameters (diffusion coefficient Ei, average velocity uI, time steps\( \Delta t \), position steps\( \Delta X \) and pollutant decay rate coefficient Ki).

### 3.2. Two-dimensional river water quality model

When pollutants enter the water body, it is impossible to achieve uniform concentration mixing of the whole section in a short time. When there are significant differences in both the vertical and horizontal directions, the one-dimensional model cannot meet the needs of the system and the two-dimensional simulation model should be used [13]. The basic form of the two-dimensional water quality model for rivers [11,12] is as follows:

\[ \frac{\partial C}{\partial t} = E_{x} \frac{\partial^2 C}{\partial x^2} + E_{y} \frac{\partial^2 C}{\partial y^2} - U_{x} \frac{\partial C}{\partial x} - KC \]  

(3)

In the formula, the dispersion coefficients Ex and Ey are in the x and Y directions, respectively. Ux is the velocity component in the X direction, and K is the decay rate coefficient of the pollutants. Since the essence of the system dynamics model is a set of differential equations, the finite difference solution of the two-dimensional river water quality model is as follows:

\[ C_{i,j}^{n+1} = C_{i,j}^{n} + \left( \frac{E_{x}^{n}C_{i,j+1}^{n} + E_{j}^{n}C_{i,j-1}^{n}}{\Delta x^2} + \frac{E_{y}^{n}C_{i+1,j}^{n} + E_{y}^{n}C_{i-1,j}^{n}}{\Delta y^2} + \frac{u_{i,j}^{n}C_{i,j}^{n}}{\Delta x} \right) \Delta t \]

\[-\left( \frac{2E_{x}^{n}C_{i,j}^{n}}{\Delta x^2} + \frac{2E_{y}^{n}C_{i,j}^{n}}{\Delta y^2} + \frac{u_{i,j}^{n}C_{i+1,j}^{n} + k_{i,j}^{n}C_{i,j}^{n}}{\Delta x} \right) \Delta t \]  

(4)

Here, \( E_{x,j}^{n} \) is the longitudinal dispersion coefficient of the I and J sections, \( E_{y,j}^{n} \) is the transverse dispersion coefficient of the I and J sections, \( U_{i,j}^{n} \) is the average flow velocity of the I and J sections, and \( k_{i,j} \) is the decay rate coefficient of pollutants in the I and J sections.

### 3.3. Integration of the model and GIS

Creating the pollutant diffusion process simulation by integrating the model with GIS is challenging [14]. In the model, there are spatial variables X and Y and time variable t. Therefore, the relationship between parameters X and Y in the model and coordinates (x, y) in GIS becomes the key to the integration of the model and GIS. In this paper, the relationship between spatial variables X and Y in the water quality model and coordinates (x, y) in GIS is established by the method of river spatial discretization.

First, a two-dimensional grid of rivers is generated. The goal of this process is to divide the river surface data into grids. The specific steps are as follows: 1) Obtain the river boundary and the control points on the river central axis; 2) divide the river central axis; 3) find the intersection points of the vertical line on the river axis and the river boundary; 4) divide the vertical lines of the river; and 5)
form grids. The above work can be implemented in ArcGIS Desktop. Second, the transformation of map coordinates and model coordinates occurs. The model calculation requires that the sewage discharge points be placed in the coordinate system of the prediction model, and the formed sewage discharge points have both a geographic coordinate system and a model coordinate system. Therefore, the geographic coordinates of the discrete points should be converted into the river grid coordinates. The transformation formula is as follows:

\[
x' = (x - a)\cos\theta + (y - b)\sin\theta = x\cos\theta + y\sin\theta - a\cos\theta - b\sin\theta
\]

\[
y' = (x - a)\sin\theta + (y - b)\cos\theta = -x\sin\theta + y\cos\theta + a\sin\theta - b\cos\theta
\]  

In the formula, \(\theta\) is the rotation angle; \(x\) and \(y\) are coordinates in the original coordinate system (map coordinate system); and \(a\) and \(b\) are the origin coordinates of the new coordinate system (pollution accident point) in the original coordinate system.

Finally, the simulation results can be visualized. Visualization of GIS is a process of grading certain attribute data of spatial information and representing each level with a different color. Therefore, the pollutant concentration at the centre of each grid should be calculated and stored in the attribute table of the grid data set. Then, the visualization of the simulation results can be executed by using the rendering function of GIS, and the dynamic demonstration of the simulation results can be produced by automatically, continuously updating the calculation results.

4. System implementation

The system uses a B/S development framework. The front uses Bootstrap and Dojo for dynamic page rendering and the back uses Spring MVC, MyBatis for business processing and uses ArcMap, SQL Server, and ArcGIS Server for data analysis. The system also uses ArcGIS API for JavaScript technology to execute the functions of map rendering, buffer analysis, and water pollution model construction and combines Echarts visualization components in the visual display of analysis results.

The system mainly executes the functions of GIS query display of basic environmental information, analysis of water quality monitoring data and simulation of water pollution diffusion.

4.1. GIS query display of basic environmental information

The base functions of GIS include: map browsing and operation, distance and area measurement, classified query and retrieval of information, overlay analysis, buffer analysis, thermal map display, radar map contrast analysis, thematic map display and so on. This function is based on a map of environmental protections and provides users with a visualization of the current water environment information for Liyang City. The above GIS functions, such as buffer analysis, can be implemented in ArcGIS desktop software. By calling the buffer analysis tool in the ArcGIS Toolbox through Geoprocessor, a GP service can be created and distributed to the server side. Users only need to set the buffer distance and units on the interface and describe the corresponding water system, and then the river basin buffer can be dynamically generated.

4.2. Water quality analysis

The system performs the water quality change analysis annually, seasonally and monthly. The analysis is based on spatial statistical units of Liyang water quality monitoring stations including “The Ten Measure Water Action Plan” sections, regional compensation sections, routine monitoring sections, town assessment sections, etc. The system also executes the multi-visualization of the analysis function. To enhance the visualization effect of the data, this project introduces the open source chart library ECharts to draw various analysis charts. ECharts provides users with data visualization services in the form of Web services and JavaScript packages. JavaScript packages are stored in Web services by default. When data visualization is carried out, the Echart.js graphics library is used as a template, and corresponding JS files are introduced. Relevant data are invoked from the database, transferred into the encapsulated graphics library in the form of parameters, and displayed in the web services. It can execute many data visualization functions such as histogram, polyline graph, scatter plot, pie
chart, thermodynamic chart, radar chart, K-line chart and so on. Figure 2 illustrates the annual and seasonal variations of pollutants in the regional compensation sections by using a broken line diagram and showing the trend in the variations of pollutants over time.

![Figure 2](image)

**Figure 2.** Analysis of the trend in pollutant concentrations over time in a regional compensation section (Tangdong Bridge section) of Liyang City.

4.3. Water pollution diffusion simulation

The system integrates the water pollution diffusion model and provides one- and two-dimensional water pollution diffusion simulations. Users only need to specify the location of pollution sources (or the location of pollution events). By setting different parameters such as pollutant concentration, dispersion coefficient and pollutant decay rate coefficient, the system can automatically simulate the diffusion situations and the impacts of different pollutants in different situations. The specific method is as follows: dividing rivers or reservoirs into 10 m*10 m grids, setting the corresponding colours of different pollutant concentration intervals, using a user-selected point as the origin, calculating the concentration of pollutants in the corresponding spatial range (i.e., each grid) at different time intervals under the current simulated parameter state through the above model, rendering the map with gradient colours and shapes to visualize the simulation on a network map and dynamically simulating the whole process of pollution diffusion. In addition, the model can show the trend and specific values of concentrations of pollutant sources over time by means of broken line diagrams and data tables, quantitatively showing the diffusion of pollutants in water.

As shown in figures 3 and 4, the highlighted part of the map window is the pollution point source. Under the "Pollution Concentration Analysis" window, relevant parameters such as pollution source concentration and water flow velocity can be set. Click the Start Analysis button. The dynamic broken-line graph will show the trend in pollution source concentration over time. The pollutant concentration report will show the concentration of each unit time, and volume values can be derived as Excel tables. Select the analysis time again and click the draw button; the gradient colour will visually demonstrate the diffusion and influence range of the effluent pollution in the specified time.
5. Conclusions

This system adopts a B/S mode and utilizes advanced GIS technology. Taking Liyang City of Jiangsu Province as an example, a water quality monitoring and water pollution diffusion analysis and simulation system for urban rivers is developed. This development is a change from the traditional working mode of environmental protection, which is cumbersome, time-consuming, highly error-prone and provides slow feedback. The system covers a wide range of aspects involved in environmental water monitoring and protection. It is not only a platform for environmental protection information display but also a platform for collaborative office work. It can provide convenient daily management services for environmental protection workers, as well as decision-making information support services for department leaders.
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