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Research and Application of a Big Data-Driven Intelligent Reservoir Management System

Qiang Yue[†‡]*, Fusheng Liu[†‡], Yanfang Diao[†], and Yanmin Liu[§]

[†]College of Water Conservancy and Civil Engineering
Shandong Agricultural University
Tai'an 271018, China

[‡]Agricultural Big Data Center
Tai'an 271018, China

[§]Faculty of Computer Science
Dalhousie University
Halifax, NS, Canada

ABSTRACT

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In view of multisource information integration difficulties, the lack of real-time data acquisition capability, and the low level of management intelligence in current reservoir management, the intelligent monitoring node of a remote internet of things is applied for real-time acquisition of reservoir operation data and the establishment of a four-layer browser and server system framework. An intelligent reservoir management system with flexible configuration and strong scalability is developed based on the dynamic big data drive concept. The system achieves highly efficient application of the internet of things and cloud computing technology in the reservoir management field; fully considers the high demand of the massive monitoring data on the management system; integrates reservoir health and the operation of big data analysis; can conduct accurate monitoring, diagnosis, analysis, forecasting, and management optimization of the reservoir operation condition' and achieves real-time output through charts. The system's user can get a quick access to multisource data sharing and decision support services *via* LED display and computer and intelligent mobile terminals. The demonstration project application shows that the system has integrated application of massive data and practical, scalable, and user-friendly features, which can provide comprehensive and efficient information technology support for the intelligent management of reservoir operation and has broad application prospects.

ADDITIONAL INDEX WORDS: *Reservoir, dynamic data drive, internet of things*.

INTRODUCTION

Reservoirs play important roles in solving the contradiction between urban and rural water supply and demand in water shortage areas and in improving the aquatic ecological environment. As a channel for human and natural communication, it is important to maintain a reservoir health (Xiao and Liang, 2005). With the rapid development of information technology, it is urgent to integrate diversified water resources, realize information sharing and deep data mining, and develop an intelligent management system of reservoir information so as to improve reservoir management efficiency, capacity, and level of economic and social development services.

Many institutions and scholars have applied GIS, computer simulation, and other technologies in reservoir safety monitoring and other fields. They also have developed practical management systems or platforms such as the flood remote sensing information system established by the Canadian Emergency Management Agency, the flood assessment system developed by the Australian National University, the reservoir monitoring information processing system developed by Italy and France, and the river information management system built by the Tennessee River Authority (Mascolo *et al*., 2014; Tan *et al*., 2014). Chinese researchers and organizations have carried out a lot of rewarding research and exploration on aspects of reservoir information management, safety monitoring, and flood forecasting and has developed many application systems, such as the National Reservoir Dam Information Management System developed by Nanjing Hydraulic Research Institute, the Hydropower Station Dam Safety Information Management System developed by the National Dam Safety Supervision Center, and the Reservoir Information System and the Earth Rock Fill Dam Security Monitoring Management System of the Yangtze River Water Conservancy Commission (Liu and Li, 2006; Wu *et al*., 2016). The preceding systems, whether for a single reservoir, a river basin, or a region, are developed for specific targets. They have some common problems, such as poor compatibility, weak sharing capacity, information isolation, poor scalability, nonsynchronized data acquisition and storage, and lack of massive data-processing capacity, restricting the reservoir from improving the level of intelligent management.

With the extensive application of modern information technology, such as the internet of things, big data, and cloud computing, data types and quantities are expanding at an alarming rate, and how to realize the organization, storage, analysis, and application of massive data of water resources is of keen concern (Meng and Ci, 2013). The application of big data technology in reservoir management can carry out analysis of real-time monitoring data flow and achieve real-time diagnosis and prediction of reservoir health, and it is the premise and basis of intelligent reservoir management (Li *et al*., 2015).

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*Corresponding author: qiangyue@sdau.edu.cn

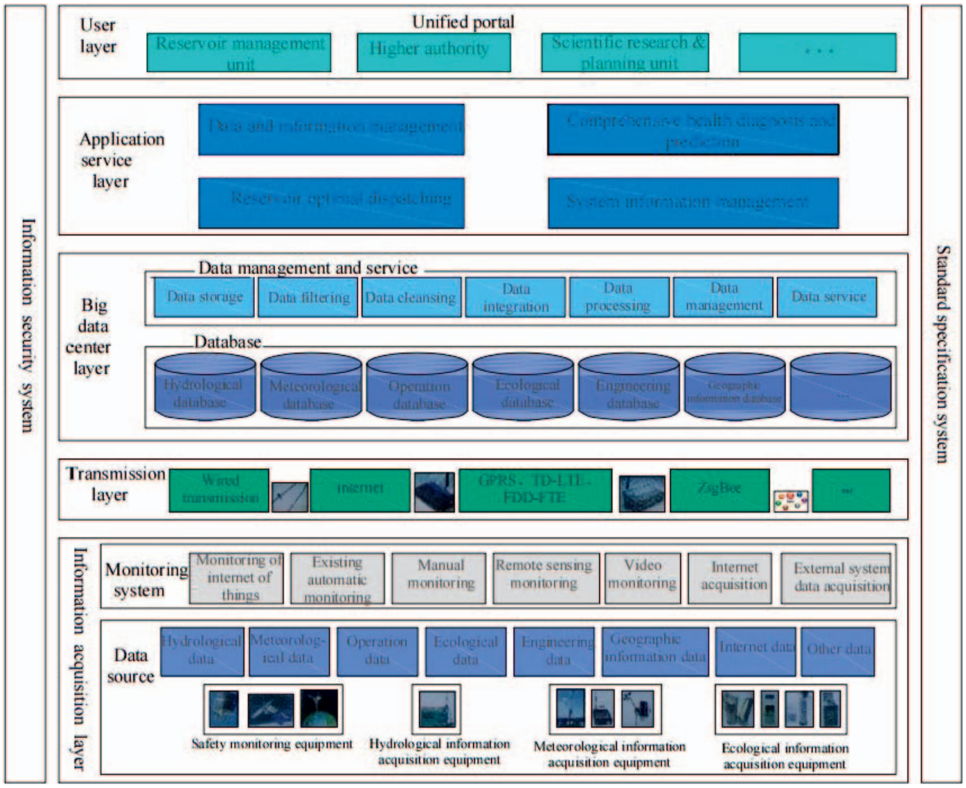

Figure 1. Frame structure of the system.

In view of the preceding problems, this paper analyzed the business demand of intelligent reservoir management, based on the dynamic data-driven technology framework and stratified according to the internet of things system; adopted advanced cloud computing; and developed an intelligent reservoir management system platform to improve the poor reliability, poor stability, and difficult maintenance problems in a traditional reservoir automonitoring system. The proposed system has strong big data analysis capability, which saves software, hardware, and other costs and strengthens efficient and safe collaboration, data transmission, and exchange among users, thus providing intelligent management services to reservoir management personnel and protecting the efficient, safe, and healthy operation of the reservoir.

OVERALL DESIGN OF THE SYSTEM

System Architecture Design

The system is developed from the actual reservoir situation and needs of administrative (admin) users, building a hierarchical structure following cloud computing and the internet of things and giving full consideration of the requirements of sustainable development in the design to maximize the needs of the project. The system adopts browser–server architecture, which consists of an information acquisition layer, a transmission layer, a big data center layer, and an application service layer, as shown in Figure 1. The cloud computing platform arranges the data warehouse and Web application; assumes the core functions of the system; processes the data information, storage, and analysis; and provides real-time reservoir health prediction and management information for the user. Users do not need to buy complex hardware or software; using the browser as a client, through data interaction between Web application and data warehouse, solves the high cost of traditional client–server architecture, integration, and maintenance, avoiding a lot of repetitive work and providing good scalability and sustainability.

System Function Design

According to the needs and processes of reservoir operation and management, the system mainly supports business data management, comprehensive health diagnosis and prediction, reservoir optimal dispatching, and system information management. The business data management function consists of basic information management, spillway information management, output and input of pumping station information management, water condition information management, and hydrometeorological information management. The comprehensive health diagnosis and prediction function consists of basic information and comprehensive health diagnosis and health prediction. The reservoir optimal dispatching function consists of scheduling decision making and actual scheduling. Finally, the system information management function consists of reservoir management and user management. A functional schematic diagram of the system is shown in Figure 2. Considering the continuous development of the comprehensive

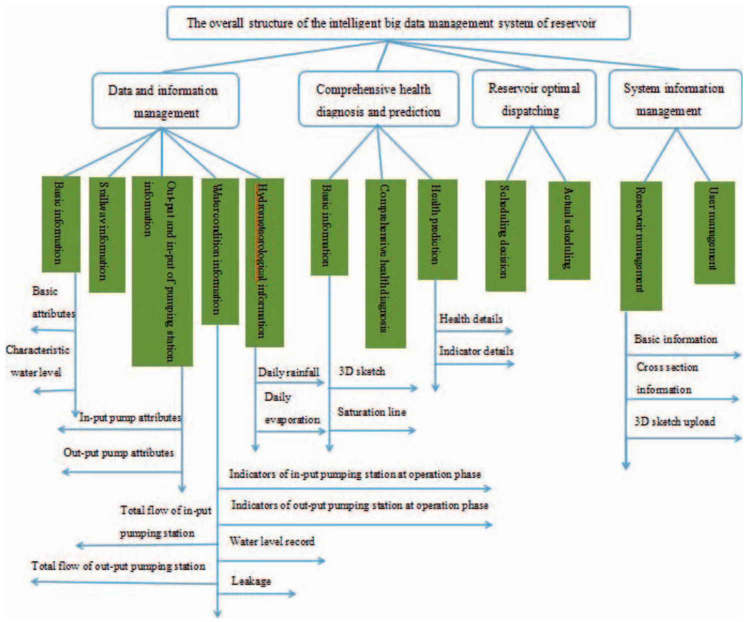

Figure 2. Functional schematic diagram of the system.

health diagnosis and prediction level of the reservoir, the system is based on the idea of "modular design, component development and integrated application." The system is designed and developed to ensure its scalability, operability, and applicability.

Big Data Cloud Computing Platform

The cloud computing platform provides powerful, highly scalable computing resources and storage facilities for an intelligent reservoir management system, taking charge of processing, exchange, analysis, and sharing of hydraulic big data while sending the analysis results down to the network layer and sensing layer. The system development process only needs to use the cloud computing platform interface, which not only simplifies system architecture design and development but also is conducive to system updates and upgrades. Reservoir-related hydraulic departments and enterprises can obtain the appropriate information and services from the platform through data exchange, achieving resource sharing and on-demand services while avoiding becoming an information-isolated island.

System database structure and interrelation are the focus of the design and function realization. According to the data characteristics involved in the intelligent reservoir management system, there are three types of data: basic data of reservoir characteristics that are basically constant, reservoir operation data, and hydrometeorological data. According to the characteristics of the data types, the system designed the work condition database, water condition database, and hydrometeorological database to manage the system data.

Database table structure design takes full account of data query, data docking, and data exception handling and other complex situations of a real-time monitoring system. It is conducive to system expansion, value shifts, and data management. Table 1 lists the database tables for types of work conditions.

Table 1. *Database tables for types of work conditions.*

S/N	Item Name	Table Name	Application Description
1	Reservoir attribute table	resAttr	Basic information about the storage reservoir
2	Water level–capacity relation	z_v	Storage water level–capacity relation data
3	Water level–area relation	z_f	Storage water level–area relation data
4	Capacity–area unit	vf_unit	Storage capacity and area units
5	Characteristic water level table	SysZspecials	Characteristic water level describing the reservoir
6	Reservoir unit characteristic water level table	Res_Z_Specials	Characteristic water level recording the reservoir
7	Characteristics of spillway equipment	spillways	Basic information about the storage of reservoir spillway equipment
8	Single-hole water level–spillway relation	zq_spillway	Data for the storage reservoir single-hole water level–spillway relation
9	Types of spillway calculation methods for spillway equipment with different opening states	zq_method	Data for the spillway calculation methods for storage and spillway equipment with different opening states
10	Input pump attribute table	Inputpump	Basic information about the storage input pump
11	Output pump attribute table	Outputpump	Basic information about the storage output pump

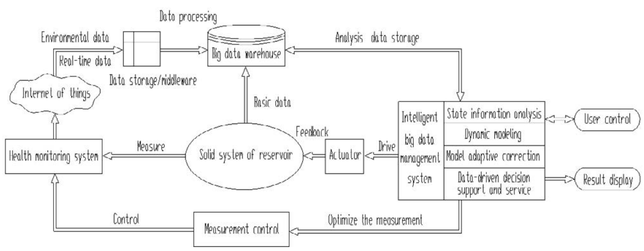

Figure 3. Functional block diagram of system simulation based on DDDAS.

System Security Design

According to the Open Systems Interconnection network security protocol, the system security is designed from the network level, transmission level, system level, and application level. A personalized hierarchical user management mechanism is adopted, and the system users are divided into ordinary user, general admin user, and super admin user, where the super admin user has the highest authority and authorizes the distribution of management permissions and browsing access to the other users. Different application requirements, management departments, and reservoir units or individuals can operate within the authority of the operation and management.

The admin user of a specific reservoir cannot access the database data by super user login; the use of the database at all levels is under strict authority management, and the processing authority for each datum of the database is controlled. The operation by users at all levels is recorded and audited, the basic data table is stored and protected, a specific database user should be established for a particular application system, allocating specific permissions. The system code, model files, and critical business data should be backed up in a timely manner to ensure that should system problems occur, any version can be quickly restored. System administrators should regularly update the operating system patches, kill viruses, update the system security policy, check whether the system's access permissions are reasonable, and check whether the user's account at all levels is normal.

KEY TECHNOLOGIES

Dynamic Big Data Drive

In 2000, the National Science Foundation defined a dynamic data-driven application system (DDDAS) as a new collaborative simulation and measurement system model whose simulation application model integrates dynamic operation, real-time measurement, real-time judgment, automatic feedback, and control (Darema, 2005; Zhou, Huanu, and Hu, 2009). The big data drive starts from data analysis, which does not depend on the model, and can extract hidden value information from the data; it also can realize the monitoring, diagnosis, decision making, and optimization of the system through the processing and mining of the massive data, which is especially suitable for complex process control with strong nonlinearity and high uncertainty (Guan *et al*., 2015).

DDDAS broadens the application of simulation technology through the introduction of real-time control. The environment, measurement, and analysis data under dynamic conditions are put into the simulation process in real time. Then, dynamic feedback of the simulation analysis and judgment results is made to the solid system to optimize and control the measurement and rational system operation. As a result, the entity and simulation constitute a dynamic system of mutual feedback.

A reservoir intelligent big data management system based on the DDDAS principle is shown in Figure 3. The management system and the reservoir's operation system are connected by a closed-loop system. The management system collects the data collected by the internet of things in real time, concentrates the massive data of the reservoir operation, and analyzes the data according to the decision goals to realize the health diagnosis and prediction of the reservoir. The management system issues commands to one or more control terminals based on the result of big data analysis to dynamically control the system operating status. The control, scheduling, decision making, diagnosis, and prediction of the whole system are based on massive online data analysis.

Intelligent Detection System of the Internet of Things for a Reservoir

The intelligent detection system of the internet of things for a reservoir uses the internet of things to detect, reliably transmit, and intelligently handle the three-tier architecture. Multiple sensor nodes of the internet of things are placed in the key positions of reservoir operation, forming a self-organizing network subsystem. Sensor nodes complete monitoring of the reservoir water level, piezometric level, evaporation, rainfall, and other information, gaining real-time access to reservoir operation environmental data. The monitoring data transmission of the internet of things is as shown in Figure 4.

Each sensor node consists of a sensor, a sensing terminal of the internet of things, a transmission terminal of the internet of things, a wireless transmission system, a power system, and support. Multiple sensor nodes form a sensing layer of the internet of things, and a wireless network is used for data transmission between the nodes. Collector nodes collect the perceptual information of the internet of things and then transmit it first to the Internet, through the remote transmission terminal of the internet of things, and then to the intelligent reservoir management system on the cloud computing platform *via* the Internet.

Big Data Analysis

There are many influencing factors involved in reservoir health. The magnanimity, randomness, uncertainty, and ambiguity of the data make health diagnosis and prediction difficult to adapt to the efficient operation of the reservoir (Yue, Liu, and Liu, 2016). The traditional data analysis method cannot explore the potential value information deep in the massive data, and an efficient and practical data mining method under a big data environment needs to be studied.

The decision tree algorithm is one of the core technologies of big data analysis. By analyzing and sorting the attributes of massive disordered data samples, the decision tree can find the information with application value in big data, providing the basis for judging and forecasting scientific decisions. The analysis process does not need to fix the specific function form or sample the prior distribution hypothesis (Zhang and Zhong,

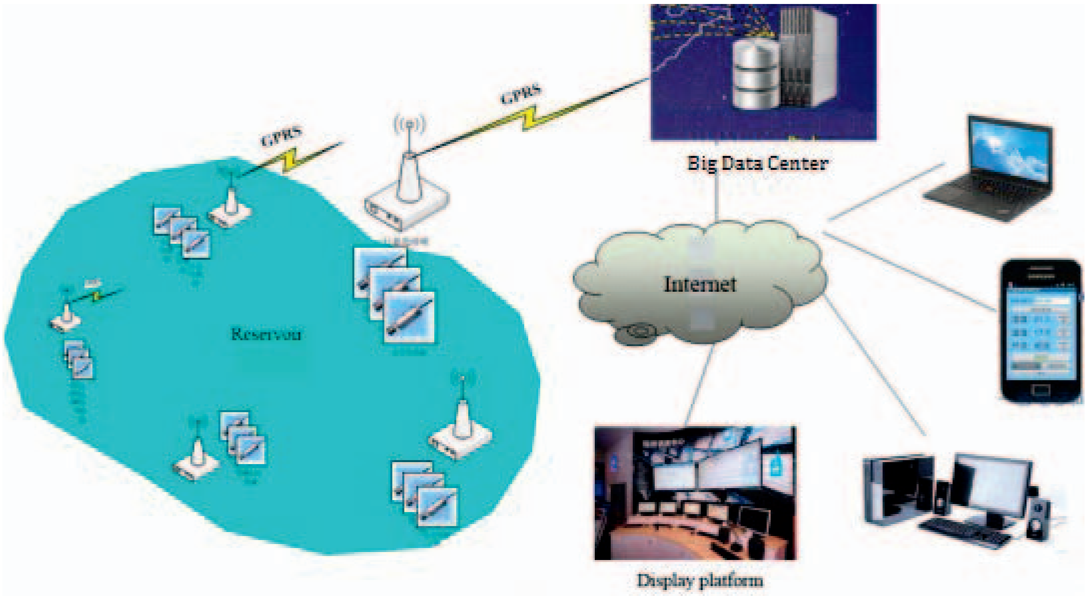

Figure 4. Intelligent detection system of the internet of things for a reservoir.

2013). The advantage of the decision tree algorithm is real-time mining, running in a distributed environment, that is suitable for big data sets and streaming data. When the mobile data stream is infinite, the complete data can be stored for the retraining decision model, and even in data containing noise, a compact decision tree can be generated and higher prediction accuracy can be obtained.

The reservoir health status data set includes reservoir safety, ecoenvironmental function, social function, state persistence, the health comprehensive index, and other attributes (Yue, Liu, and Liu, 2016). The health comprehensive index of the reservoir is set as the decision attribute, where, S is n sets of data samples. The decision attribute has m values, and m categories are defined as $P_i(i=1,2,\ldots,m)$. Set n_i as the number of samples in category P_i. Then, the information entropy is:

$$I(p_1,p_2,\cdots,p_m) = -\sum_{i=1}^{m}\frac{n_i}{n}\log_2\left(\frac{n_i}{n}\right) \tag{1}$$

Set the set satisfying condition attribute A as $\{a_1,a_2,\ldots,a_k\}$. The set S can be decomposed into k subsets $\{C_1,C_2,\ldots,C_k\}$ by A, and the node branch of category set P corresponds to the subset. Set n_{ij} as the number of samples in category C_j. Then, the entropy of the subset divided by A is:

$$E(A) = -\sum_{j=1}^{k}\left[\frac{n_{1j}+n_{2j}+\cdots+n_{mj}}{n} \times I(p_{1j},p_{2j},\cdots,p_{mj})\right] \tag{2}$$

$$I(p_{1j},p_{2j},\cdots,p_{mj}) = -\sum_{i=1}^{m}\frac{n_{ij}}{n_j}\log_2\left(\frac{n_{ij}}{n_j}\right) \tag{3}$$

where, $(n_{1j}+n_{2j}+\ldots+n_{mj})/n$ is the weight for the jth subset and $I(p_1,p_2,\ldots,p_m)$ is the expected information for subset C_j.

The information gain is obtained from the information mathematical expectations and entropy values:

$$\mathrm{Gain}(A) = I(p_1,p_2,\cdots,p_m) - E(A) \tag{4}$$

The information gain rate is:

$$\mathrm{GainRatio}(A) = \mathrm{Gain}(A)/\mathrm{Split}I(A) \tag{5}$$

$$\mathrm{Split}I(A) = -\sum_{j=1}^{k}\frac{n_{ij}}{n_j}\log_2\left(\frac{p_{ij}}{n_j}\right) \tag{6}$$

The decision tree C5.0 algorithm introduces the adaptive enhancement boosting technique to increase the robustness of the rule in the test set by adding the sample set to the repeated sampling of the samples. Decision tree growth takes the information rate of return as the criterion to find the best grouping variables and dividing points, building a branch structure from top to bottom. A node indicates the attribute test, a branch indicates the test output, a leaf node indicates the category distribution, and decision tree pruning is from leaf node upward layer by layer, as shown in Figure 5. See the related literature for details on the decision tree (Ben Haim and

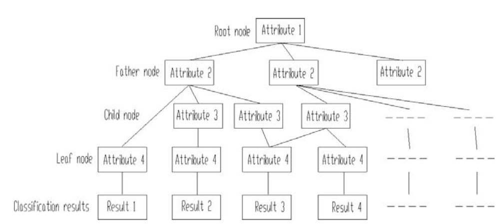

Figure 5. Classified forecasting decision tree.

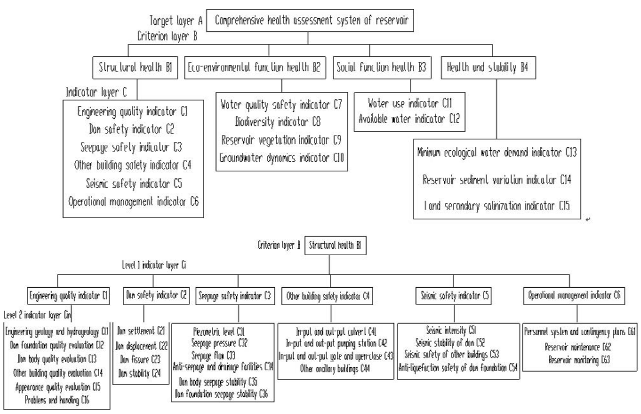

Figure 6. Health warning indicator system of a plain reservoir.

Tom Tov, 2010; Cheon *et al*., 2016; Franco Arcega *et al*., 2012; Fu and Liu, 2017; Kim, Choi, and Chun, 2016; Li, Han, and Gu, 2018; Liu, 2017; Mi *et al*., 2015; Zhang and Zhong, 2013; Zhi-Guo, Cheng, and Dong-Ming, 2018; Zwierzewicz, 2015).

Intelligent Management

Intelligent hydraulics is the advanced stage of hydraulic informatization. Through the intelligent equipment and a three-dimensional (3D) sense of hydraulic engineering information in all directions, mass perception, storage, processing, and analysis of data transmission are achieved, managing all aspects of hydraulic engineering in a more sophisticated and dynamic way.

The intelligent management module is the core of the system. System management is mainly composed of data and information management, comprehensive health diagnosis and prediction, scheduling optimization, and system information management. Dam safety, ecological environment, social function, and state persistence can be used to evaluate the health status of the reservoir and establish an indicator system of reservoir health assessment, as shown in Figure 6 (Yue, Liu, and Liu, 2016).

The internet of things can perceive reservoir water level, piezometric level, evaporation, rainfall, and other information and then input the information to the intelligent reservoir management system for data management and mining through wireless transmission. Fuzzy and hierarchy analyses, according to the health evaluation indicator system of a plain reservoir, can be used to conduct an accurate diagnosis of the reservoir health. Based on decision tree C5.0 technology, which is suitable for big data analysis, the reservoir health is established according to the relevant information of the reservoir culture. The early warning rules are obtained, and the health status of the reservoir is forecasted.

The integrated reservoir data warehouse containing hydrometeorological, water, and work conditions; scheduling operations; and other types of data is used to seamlessly connect the internet of things to the data monitoring platform. Big data mining technology is used to summarize and then formulate the opening and closing times, flow, and water delivery capacity of output and input pump stations while guaranteeing water supply and reservoir safety as the basis for guiding reservoir dispatching. The decision tree is used to analyze the water, rain, work condition data, and scheduling operation data of the plain reservoir over the years. The scheduling rule set is summarized based on the experience of reservoir science management and then combined with real-time information to generate the optimal scheduling scheme to ensure efficient, safe operation.

SYSTEM IMPLEMENTATION AND APPLICATION

Development Environment and Development Tools

By using the browser–server mode and the cloud computing platform as the center, the user only needs a standard browser for access, with easy operation and versatility; maintenance and development focus on the platform, with easy maintenance, scalability, and practicability. The development environment and development tools are as follows:

(1) Development language: Java
(2) Development tool: Eclipse
(3) Database: Oracle 11gR2 (64-bit)
(4) Database structure design tool: PowerDesigner 15.0
(5) Model forecasting tool: IBM SPSS Moduler 15.0
(6) System back-end technology: spring3.1+struts2+mybatis+Log4j+decorators
(7) System front-end technology: jsp+javascript+jquery+ajax+echarts+ligerUI
(8) Cache frame: Ehcache

System Applications

The system has been applied in the Dezhou Dingdong reservoir. The user logs into the system through the user login, opens the reservoir condition interface, and sees the 3D sketch of Dingdong Reservoir, as shown in Figure 7.

Using logistics network monitoring data, the user can get real-time access to the reservoir dam saturation line through the network, as shown in Figure 8. According to the health evaluation indicator system, fuzzy and hierarchy analyses are used for real-time diagnosis of the health status of the reservoir; and massive data related to the reservoir status are classified to establish an early-warning decision tree of reservoir protection. Real-time prediction of reservoir health is as shown in Figure 9.

The system can show the water supply, leakage, precipitation, spillover, evaporation, water delivery capacity, and other historical data of reservoir scheduling, as shown in Figure 10. The historical scheduling data can be used to predict the forecast data for the next year and thus provide a water delivery capacity forecast for decision makers. Reservoir operation schedule management is shown in Figure 11.

DISCUSSION AND CONCLUSIONS

Based on the internet of things intelligent monitoring system, the key data affecting the health operation of a reservoir are obtained through dynamic real-time access. The dynamic data drive and big data analysis improved the rapid

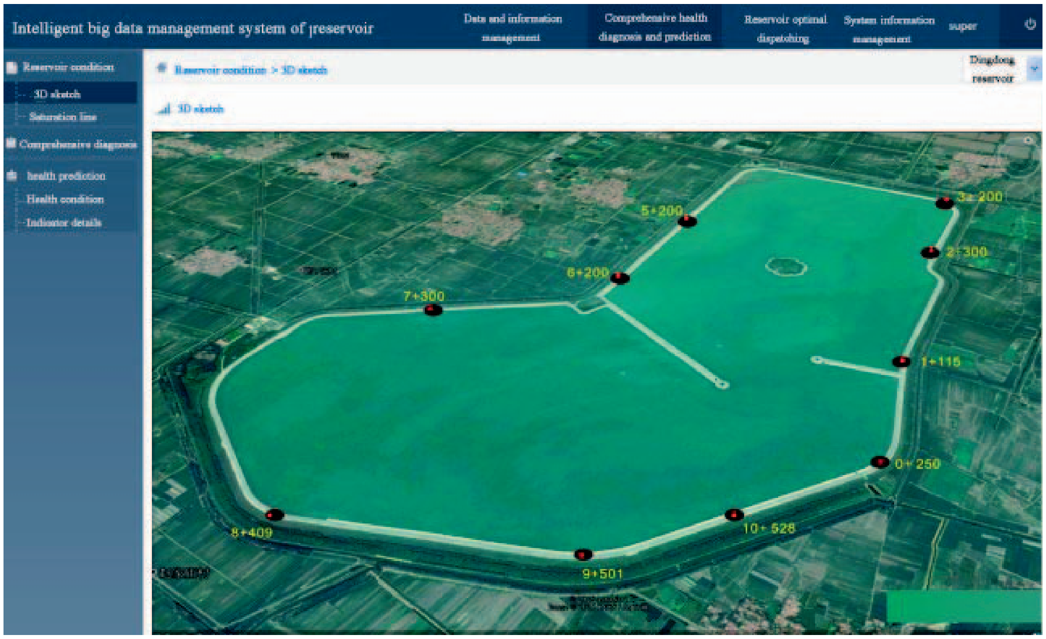

Figure 7. 3D sketch of the reservoir.

response and decision making of reservoir health and the accuracy and real-time capability of optimal scheduling.

The intelligent reservoir management system based on cloud computing is an integrated management service system

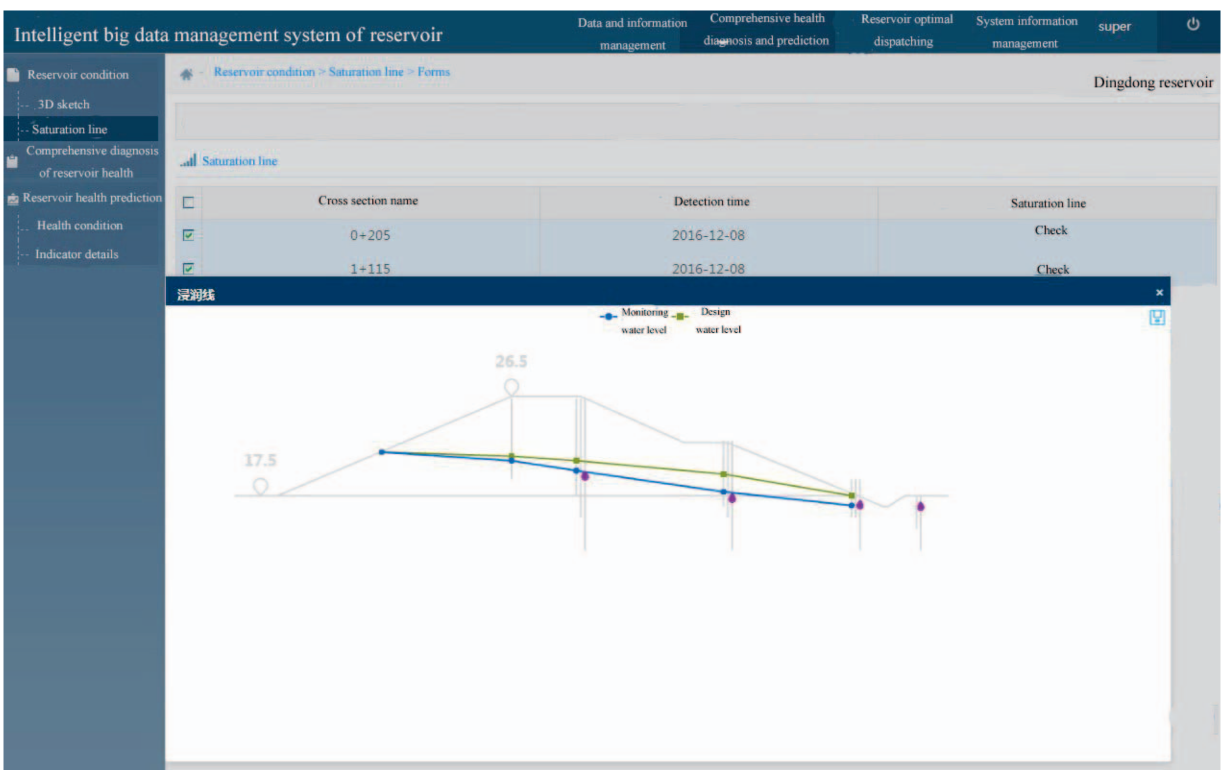

Figure 8. Saturation line of the reservoir dam.

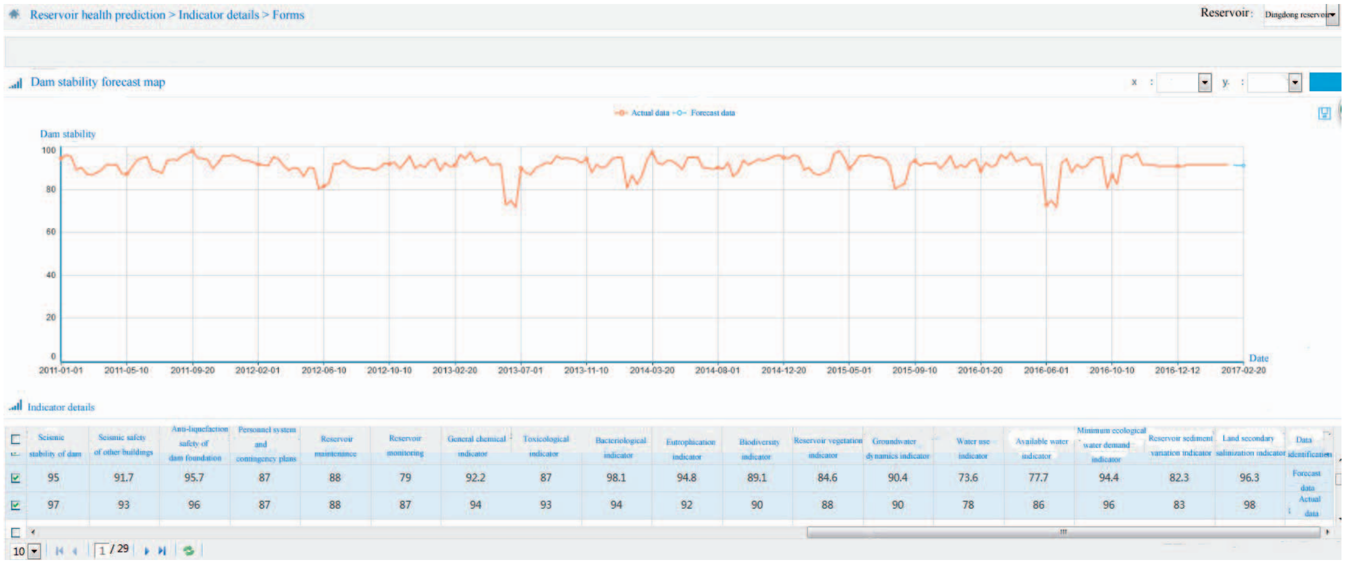

Figure 9. Reservoir health prediction.

platform that provides intelligent, visual reservoir information management applications and integrated services to hydraulic business departments. It's real-time regulation of reservoir sanitary risk enhances the scientific management of the reservoir information and improves the level of public services.

Hydraulic big data analysis based on the decision tree algorithm reflects the regularity of the massive hydraulic historical data; the concept is clear, and the results are easy to apply. Big data analysis starts from data application, efficiently recycles big data resources, and improves the level of intelligent reservoir management.

The system uses four-tier architecture and browser–server mode design, so the user only needs a standard browser. The

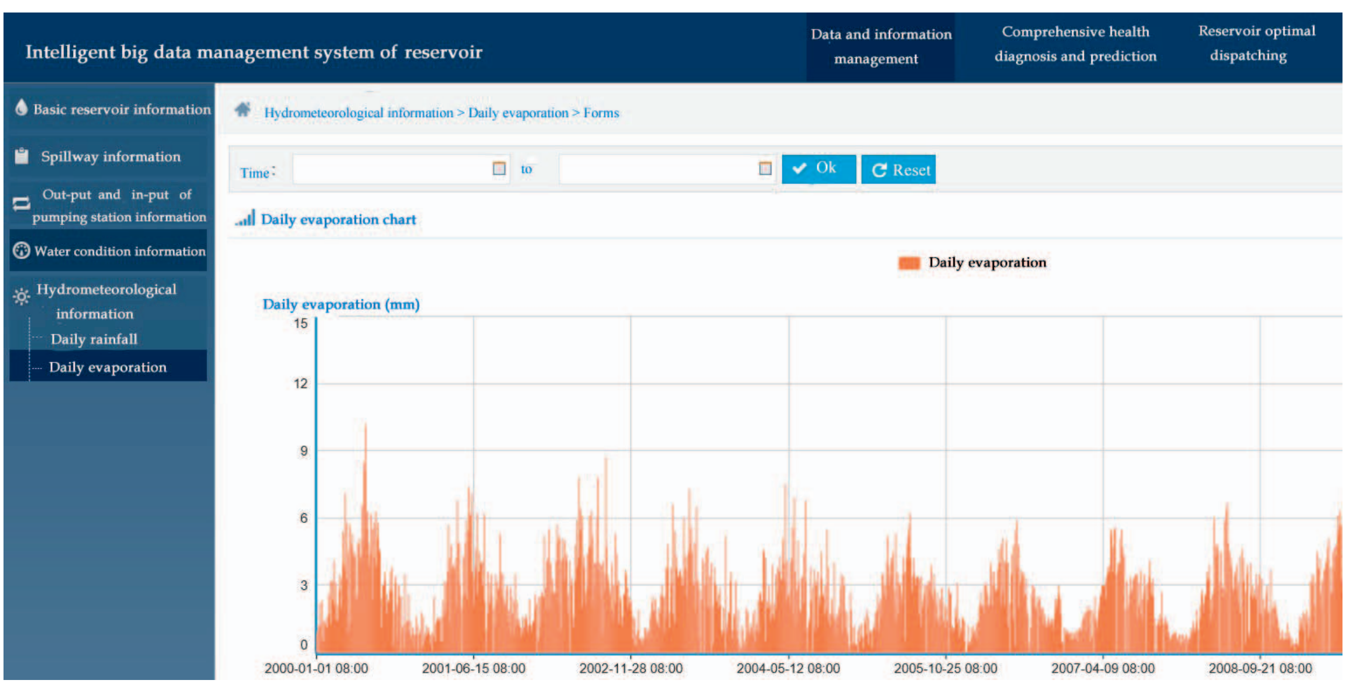

Figure 10. Query interface of daily evaporation.

Year	Month	Ten-day	Water supply (ten thousand cubic meters)	Leakage (ten thousand cubic meters)	Natural precipitation in reservoir area (ten thousand cubic meters)	Spillover of drain cavern (ten thousand cubic meters)	Natural evaporation on reservoir surface (ten thousand cubic meters)
2017	1	Early ten-day of the month	301.713	21.1	0.608	0	1.777
2017	1	Middle ten-day of the month	301.713	21.1	0.608	0	1.777
2017	1	Late ten-day of the month	301.713	21.1	0.608	0	1.777
2017	2	Early ten-day of the month	302.883	21.1	2.592	0	4.627
2017	2	Middle ten-day of the month	302.883	21.1	2.592	0	4.627
2017	2	Late ten-day of the month	302.883	21.1	2.592	0	4.627
2017	3	Early ten-day of the month	304.053	21.1	0.363	0	15.885
2017	3	Middle ten-day of the month	304.053	21.1	0.363	0	15.885
2017	3	Late ten-day of the month	304.053	21.1	0.363	0	15.885
2017	4	Early ten-day of the month	305.223	21.1	5.945	0	19.27

Figure 11. Decision interface of reservoir dispatching.

high versatility ensures the easy maintenance, scalability, and practicality of the system.

The application demonstration of the system shows advantages such as accuracy and speed in reservoir health prediction and optimization. However, because of the complex factors influencing the operation of reservoir health and the large regional differences, the health diagnosis indicators and forecasting method need to be constantly improved. The massive data analysis method needs to be optimized to complete system functions and improve system universality, which are the focus of future research.

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