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Research article

The architecture and application of an automatic operational model system for basin scale water environment management and design making supporting

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ABSTRACT

An advanced framework for automatic water quality forecasting and water quality management design supporting was put forward. The system is designed as a flexible and extensible service-oriented architecture with data center, system control center, model center and client center. Two operational running modes, one for water environment automatic assessment and forecast and the other for situational analysis, were set to satisfy water quality management requirements. With loosely-coupled air-land-water numerical models, the weather, pollutants sources, hydrodynamic and water quality are automatically forecasted. According to philosophy of the framework, a one-stop platform with four different subsystems for the Three Gorges Reservoir Basin (TGRB) was developed and has been in operational running for more than two years. The system can accurately assessed, forecasted and perfectly displayed the current status and future character of TGRB in air, land and water environment.

1. Introduction

Recently, the increasing number of water environment problems, such as extreme weather, rainstorm, flood, water degradation, algal bloom and water pollution have attracted global attention (Deschenes and Moretti, 2009; Wang et al., 2015). A lot of numerical models have been developed for weather or hydrologic forecasting, water quality evaluation and prediction (Kauffeldt et al., 2016). Models, such as the Next Generation Global Prediction System (NGGPS), Weather Research and Forecasting Model (WRF) and General Circulation Models (GCMs) can be used for meteorological forecast (Zheng et al., 2008; Liu et al., 2018; Cho and Pott, 2019). For hydrology and non-point source assessment, several models can be adopted, for example, the Soil & Water Assessment Tool (SWAT), Agricultural Nonpoint Source Pollution Model (AGNPS) and Storm Water Management Model (SWMM) (KIM-JoongHoon, 2015; Shi et al., 2017; Mohammed and Aziz, 2019). Additionally, the Estuarine, Coastal and Ocean Modeling System with Sediments (ECOMsed), Environmental Fluid Dynamics Code (EFDC) and Three Dimensional Model of Delft Hydraulics (Deflt3D) for hydrodynamic simulation(Burpee et al., 2015; Kang, 2018; Wang et al., 2018a, 2018b); the Stream Water Quality Model (QUAL2K), Water Quality Analysis Simulation Program (WASP) and Three-dimensional water ecological model (RCA) were widely used for water quality and ecological evaluation(Thomas et al., 2015; Zhu et al., 2015; Mbuh et al., 2019).

With numerical models, weather forecast systems have been steady in running for decades in a lot of countries (Fu et al., 2018; Johnson et al., 2018; Zhang et al., 2018; Giannaros et al., 2019). While every model has its special functions, a singular model can't satisfy all of the simulation demands facing the complex water quality prediction requirements and various water quality assessment demands. A model system integrated with different kinds of models is always used for different simulation objectives. With the model system, different models can be organized to work together to accomplish a water quality simulation task (Shchepetkin and McWilliams, 2005; Qiu et al., 2017). In the early model system, the number of different types of models is little (Zhuo et al., 2015; Rai et al., 2018; Rafaeli Neto et al., 2019). For example, the river flooding predicting system contains two kinds of

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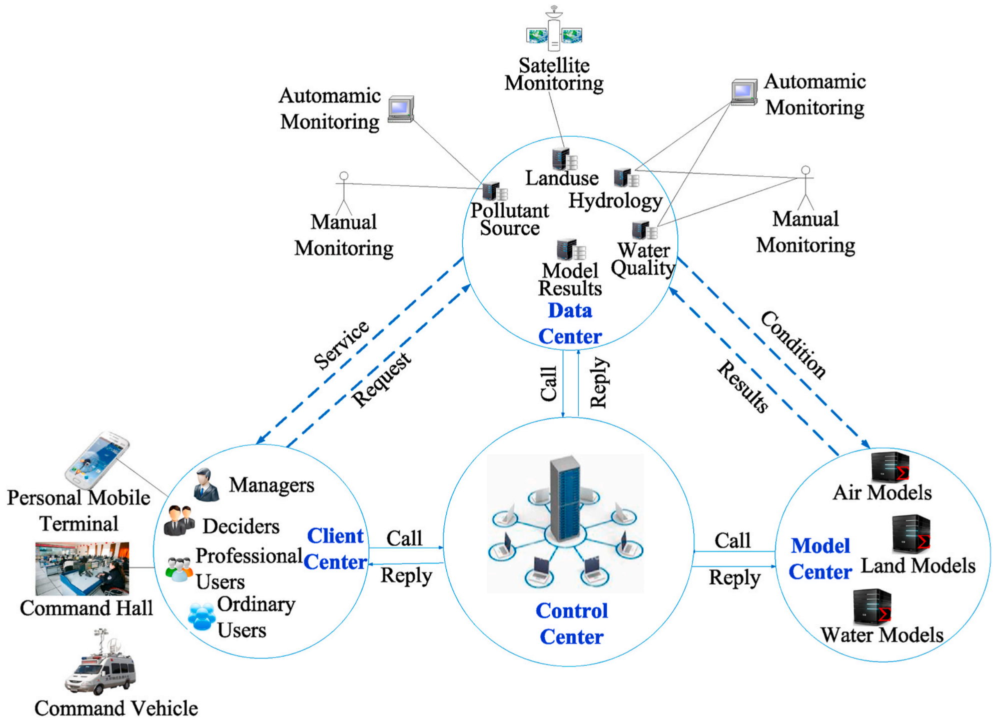

Fig. 1. Four centers designed in the system.

models, the SWAT and SWMM for basin runoff simulation, the 2D river hydrodynamic model (iRIC) for water quantity simulation(Rai et al., 2018). Along with the increasing need for environmental analysis and environmental comprehensive management, more and more different models have been integrated in a model system. However, the business processes of these systems are extremely complicated, which makes it not convenient or practicable for environmental managers who are non-professional in numerical modeling and model integration. Meanwhile, most of the previous researches on model system focus on the specific water environment situation analysis, whose interfaces are clear among water models, but weak among air, land and water models (Schlei-Peters et al., 2018; Yao et al., 2019). Few of them can forecast the water quality in an operational mode. Under these circumstances, large number of existing model systems are difficult to put into practice for basin scale water environment management and design making supporting.

Inmodernizationions water environment management, managers need a model system to not only make situational analysis, but support rule design by real-time automatic water environment prediction. Even though previous studies supported excellent experience for model integration and interface construction, there are still two issues that model systems should solve. Firstly, how to effectively integrate different models from air, land and water fields to answer the questions of the complicated water environment in the same model system frame. Additionally, how to make the model systems appropriate for both professional and non-professional users. To solve these two problems, a universal framework for air, land and water models integrated in a GIS system has been put forward. Simultaneously, a workflow aiming at automatically and semi-automatically running numerical models has been developed. The framework and workflow were implemented in a Chinese Water Environment Management System (CWEMS), which is a model system and designed for supporting operational water quality forecasting and assessment to support design making for functional government departments and administrative staffs.

The system was applied in the Three Gorges Reservoir Basin (TGRB), which covers a watershed area of about 64,000 km^2 (range 29°16′-31°25′ N, 106°–110°50′ E) in the upper Yangtze River. The TGRB is such a typical ecological sensitive area that suffers from flood, non-point and point source pollution, emergency water quality incident and eutrophication problems (Feng et al., 2015; Li et al., 2015; Xu et al., 2018). Managers of TGR were confused with these problems that how much rain would fall today and tomorrow, how rainfall would influence the watershed non-point pollution, what the trends of hydrodynamic and water quality in the water were and what they should do if water quality incident happened. There have been all kinds of systems built for TGR, but none of them can answer these questions integrally. In this study, the system is developed based on these requirements of river basin management agency, supported and used by the management organizations, such as Changjiang Water Resources Committee, Environmental Monitoring Center and environmental protection agency of Sichuan province, Chongqing City and Hubei province. The system has been in practical application for more than two years and plays a significant role in promoting the water environment management in the TGR.

2. Methods

2.1. Framework of the model system

In China, different water environment administrative departments have different responsibilities. For example, the Ministry of Environmental Protection is responsible for the environmental protection of external water. While, the Ministry of Water Resources takes charge of environmental protection and management of internal water. These two sectors have their own special industry standards for environment monitoring, data structure and environment assessment. For a lot of reasons, there are few information exchange and data sharing between these two biggest departments about water environment management in China (Peng et al., 2016). To satisfy different requirements from different departments, the Chinese Water Environment Management System is designed with four submodule centers, the data center, the system control center, the model center and the client center, as shown in Fig. 1.

The control center takes charge of operational tasks assignment and system status evaluation. It makes the other centers together to

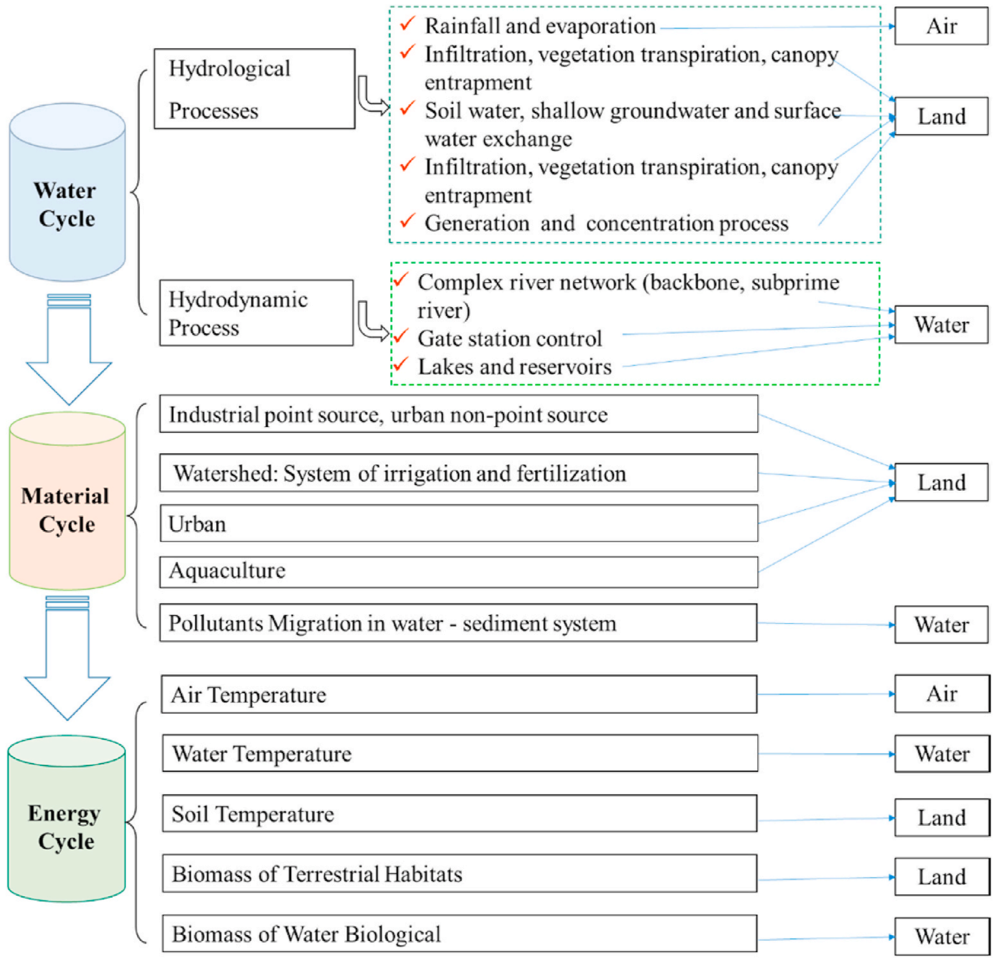

Fig. 2. Systematical cycle of a basin. Air, Land, Water means air model, land model and water model.

automatically accomplish established tasks, such as water quality prediction, and finish temporary application services requirements. At the same time, it detects the status of the whole system and alarms for errors.

The data center undertakes the work for data collection, data extraction, data storage, data query and data pre-processing. It realizes the integration and share of multi-source heterogeneous hydrological data, meteorological data, water quality data and model results data from manual monitoring, automatic data acquisition equipment in different institutions. In addition, model operation and results displaying are also supported here.

Integrated with air models, land models and water models (air-land-water models) for environment modeling, the model center receives execution instructions from the control center and accordingly reads data from the data center to make simulation, which is the basic of environment assessment and design making. These models are designed and modularized through web services and as service-oriented architecture (SOA) models.

The client center is open to the public and management with different permission providing monitoring data and model results data in a visual way. The current and predicted information of water quantity and the results of applied analysis according to users' requirement will be displayed to users. Besides, the client center is a cross-platform system, which can be deployed in command hall, environmental emergency vehicle and visited from mobile devices and computers.

The control center, model center was developed by Java. Models integrated in the model center were created by Fortran and C. The client center of online platform was built by JavaScript, html5 and CSS.

2.2. Models in CWEMS

2.2.1. Framework and functions of models

Basin scale water quality problems are generated by many factors such as social and economic development, pollution, climate and the change of water resources circulation system (Roll and Halden, 2016; Lintern et al., 2018; Giri et al., 2019). To provide technical support for river basin water quality operational forecasting and assessment of water environment management, systematical characteristics of river basin water environment system, formation mechanism of different kinds of pollution and the mechanism of hydrological cycle should be understood (Rolls and Bond, 2017). The common systematical cycle of a basin contains water cycle, material cycle and energy cycle, as shown in Fig. 2. The mechanism models, such as air models, land models and water models are based on the cycle mechanism and describe the process of this cycle.

With practical inputs, e.g., parameters, boundary conditions and initial value, a mechanism model can produce practical outputs. Commonly, parameters of models in a specific area changes infrequently after model calibration and validation, while the boundary conditions and initial value are different in different time. Air models can simulate the rainfall, air temperature and evaporation, which are the basic conditions of land models and water models. Similarly, the results of land model, such as non-point source loading, surface runoff and terrestrial sediment yield, are important inputs to water models. In water models, hydrodynamic models are the conditions models providing to water quality models, water ecological model and water quality incident model. Based on inputs and outputs of different models, the

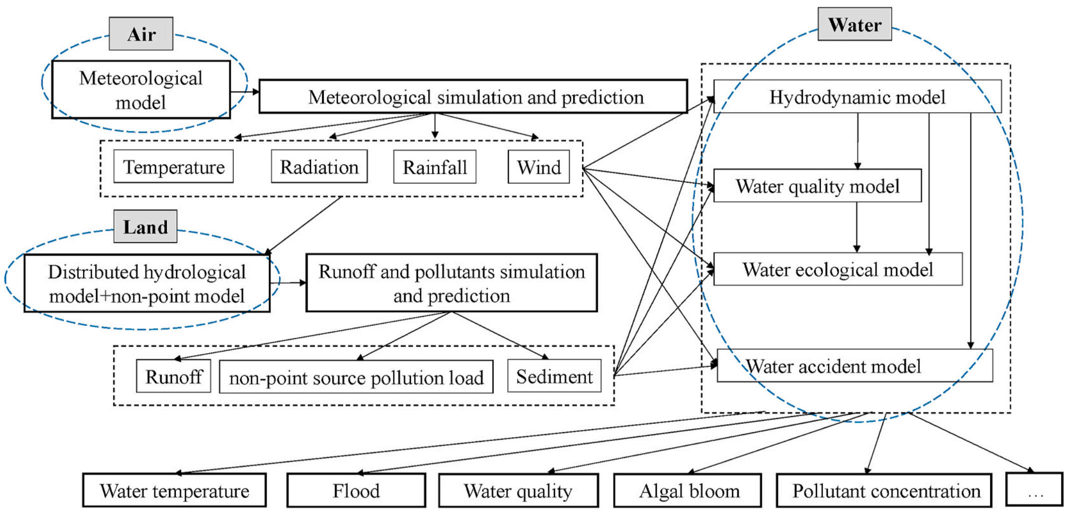

Fig. 3. Framework of the air-land-water models in the system.

Table 1
Models applied in the system.

Targets	Applied models	Advantage	Ref
Weather prediction	Weather Research and Forecasting Model (WRF)	Popular and widely used in China. With powerful user's documents and constantly improved	Skamarock et al. (2005)
Watershed runoff and NPS assessment	Soil & Water Assessment Tool (SWAT)	Open source, most widely used in China	(Arnold and Fohrer, 2005; Shi et al., 2017)
Urban runoff and NPS assessment	Storm Water Management Model (SWMM)	Open source, most widely used in China	Tsihrintzis and Hamid (1998)
Water quantity assessment and flood prediction	Estuarine, Coastal and Ocean Modeling System with Sediments (ECOMsed)	Open source, with water, temperature and sediment module, verified in many waters in China	(2002; Wang et al., 2018a, 2018b)
	Coupled water quantity–quality model (CWQQ-2D)	Developed by our group, well-adapted to the characteristics of China	Wang et al. (2016)
Water quality forecast	Three-dimensional water ecological model (RCA)	Open source, with seamless interface to ECOMSED	FIZPARTICK (2004)
Eutrophication analysis and algal bloom prediction	Bioaccumulation model (BCM)	Developed by our group, adapt to the characteristics of China	Xu et al. (2014)
Water quality accident early warning	WQ module in RCA	Open source, with seamless interface to ECOMSED	FIZPARTICK (2004)
	Early Warning Models in Ungauged River Basins (MEWSUB)	Fast and developed by our group	(Wang et al., 2015a, Wang et al., 2018a, 2018b)

organizational structure of different models in the system is shown in Fig. 3.

According to the requirements of basin scale water environment management in China, the basic functions of a model system should include weather prediction, watershed and urban runoff and non-point sources (NPS) assessment, water quantity, water quality and algal bloom analysis and prediction, and water quality accident early warning. Searching and comparing different models satisfying the need, the mature and widely used models are selected, as shown in Table 1.

Table 2
Interface between different models.

Condition model	Application model	Input variables
WRF	SWAT	rainfall, air temperature, relative humidity, wind speed
	SWMM	rainfall, snow melt, wind speed, air temperature
	ECOMSED	rainfall, air temperature, relative humidity, wind speed, short-wave radiation, atmospheric pressure , cloud cover , extinction coefficient , evaporation
	CWQQ2D	rainfall, wind speed
	BCM	air temperature
SWAT	ECOMSED	surface runoff, sediment load, NPS load, salt load
	CWQQ	surface runoff, NPS load
	RCA	NPS load
SWMM	ECOMSED	surface runoff, NPS load
	CWQQ	surface runoff, NPS load
	RCA	NPS load
ECOMSED	RCA	flow velocity, salinity, water level, water temperature, sediment
	BCM	flow velocity, water level, water temperature, sediment
	MEWSUB	flow velocity
RCA	BCM	water quality index concentration

2.2.2. Interfaces between different models

For different models, the interface is a special rule for exchanging data from one model to the other (Zhou, 2016). There are quite complex relationships among different models, including one-to-one, one-to--many and many-to-one. To accurately describe the connection, models have been made as the condition model and application model at each interface in a loosely-coupled mode. In this mode, all sub-models will be packaged as an executable program (.exe file). With launching the executable file and imputing data file, the model will be started. The condition model provides data for the application model. Each interface is special between two models as shown in Table 2.

As spatial calculating units and temporal steps may be different between models, format transformations in spatial and temporal data are needed. Two typical transformations methods in spatial data are made as shown in Fig. 4.

(1) Air models to land models and water models

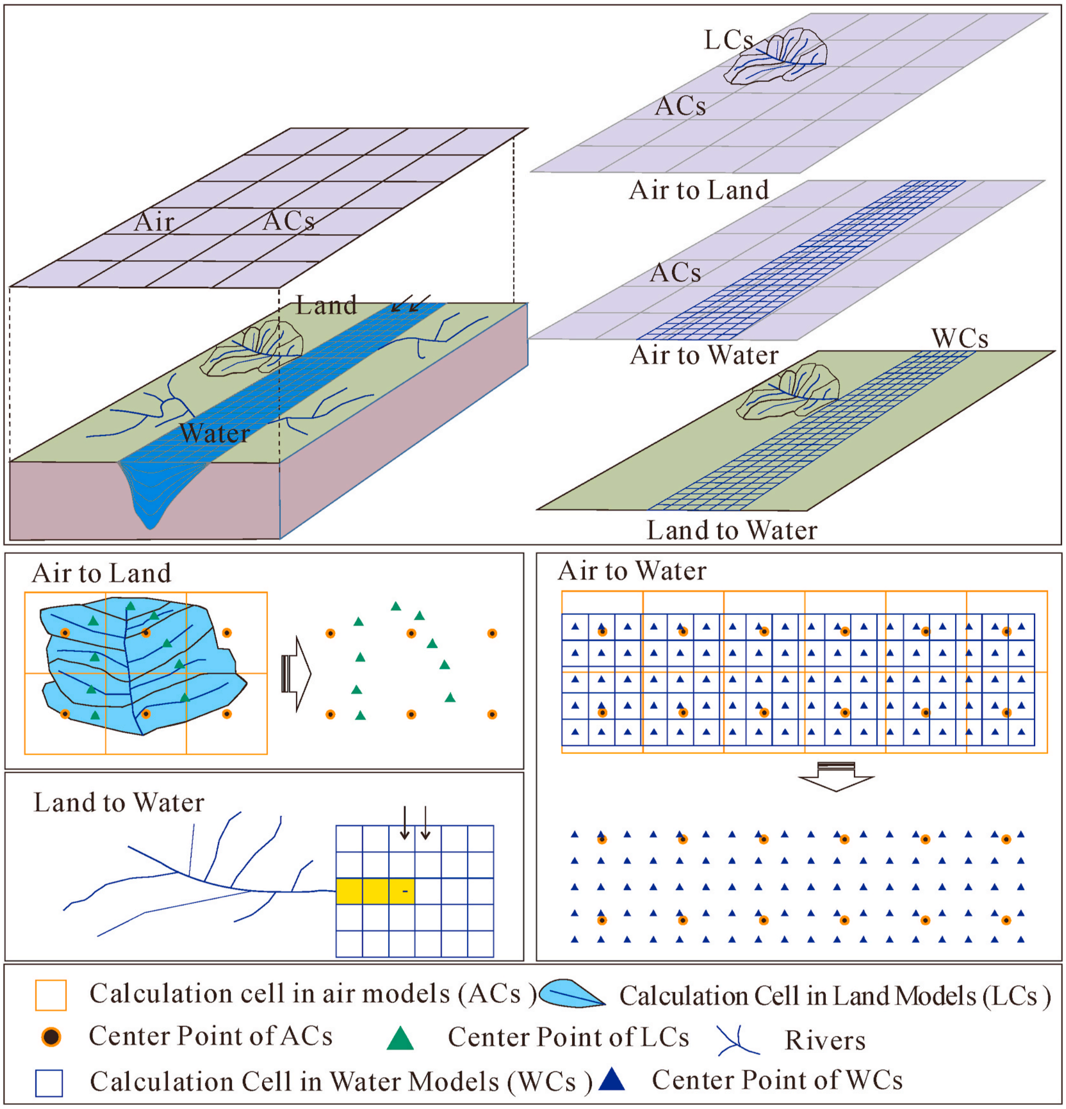

Fig. 4. The spatial relationship of calculation cells in Air-Land-Water models.

Calculation cells of air models (Acs) are relatively bigger than both calculation cells of water models (Wcs) and calculation cells of land models (Lcs). Acs are often generated to regular polygons (commonly rectangle in WRF). Hydrologic research units (HRUs) and sub-catchments are specific calculation units in SWAT and SWMM, separately. To support land and water models, the values of variable in Acs should be transmitted into Wcs and Lcs. Geometrical center of Acs, Wcs and Lcs will be confirmed as the center point where the variable values loaded. With spatial interpolation methods, such as inverse distance weighted (IDW), Co-Kriging and Thiessen polygon, variable values of Wcs and Lcs will be attained from Acs.

(2) Land models to water models

The NPS and PS are two major pollution loads from land to water. Land models give the results of NPS, whose NPS loads at outfalls are pollution source directly flow into waters. Generally, outfalls of land models are fixed and will be set at the point where the stream meets waters. As the water level changing, the junction point is always different from one moment to another. In water models, this phenomenon will be described as wet and dry scheme. When water level raises, the dry cells will turn into wet cells, vice versa. Accordingly, an inflow route from the outfalls to the deepest grid in the direction will be set as the NPS inflow stream (as shown in Fig. 4, yellow grids in water models are inflow route grids). Every time the wet and dry grids change in the inflow route, the confluent cell will be modified to the outermost wet cell.

2.3. *Workflow of operational running*

The main core objective of CWEMS is supporting operational water management. Most water management institutions care about the changing trend of water quality and water environmental response to special pollutants load. To give the changing trend of the water environment, the system is controlled in an automatic operation mode. To get the environment response to special pollutant loads, such as climatic variation, pollution changes, ecological remediation and water quality incident, the system provides functions with scenario simulation and analysis.

2.3.1. *Automatic operation mode*

The major task of the automatic operation mode, whose process is fully automatic without manual intervention, is to predict meteorological, hydrology, water quality and water ecology of the whole watershed based on water environment monitoring. The task will be started at a predetermined time every day. The data models needed will be acquired

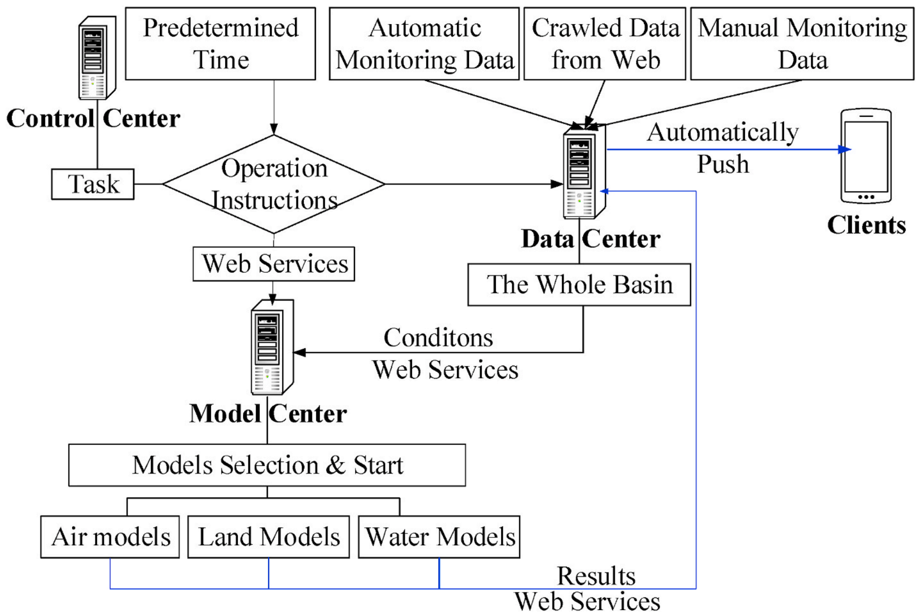

Fig. 5. Workflow of automatic operation mode in CWEMS.

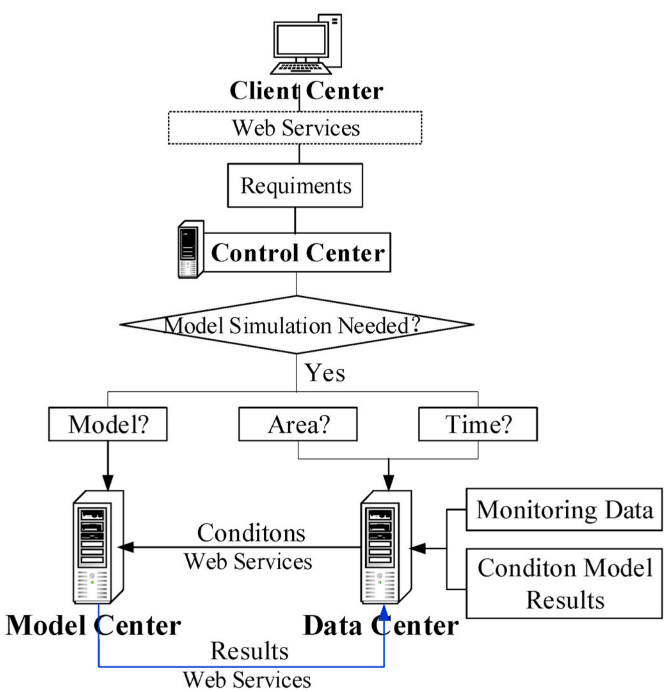

Fig. 6. Workflow of scenario simulation mode in CWEMS.

from the data center with environmental monitoring stations, web spider and manual monitoring. The workflow of automatic operation is shown in Fig. 5.

In the automatic operation mode, all of the selected air, land and water models will be started. According to the requirement and environment character, a coupling model combined with different models is made. For example, in the urban area where the two-dimensional water quality simulation is needed, the air-land-water model combination will be as WRF-SWMM-CWQQ; while for water ecological management in the mountainous area where the water depth is deep, the air-land-water mode will be selected as WRF-SWAT-ECOMSED-RCA. The simulation time of different models should be made the same. Models should be operated successively in order from air models to land models to water models according to Table 2. The model results in the automatic operation mode are basics for water quality changing trend analysis. Predicting results will be automatically pushed to clients, while these results are conditions for scenario simulation.

2.3.2. Scenario simulation mode

In the actual water environment management, regional and specific problems always need simulation and analysis. The scenario simulation mode is designed to satisfy the temporary or specific demands. After clients initiate a request, the control center will analyze the request, call corresponding data and start relevant models. The workflow of the scenario simulation mode is shown in Fig. 6.

In the scenario simulation mode, the selected model, the simulation area and the simulation time are determined according to the clients' requirements. For example, to make early warning for water quality incident in large waters, only the WQ module in RCA will be set as the application model and started. Then the simulation area will be picked out from the whole basin according to the client demands. The monitoring data and results of the condition models during the simulation time will be transmitted into the application model.

2.4. Data management

Data are divided into original data, integrated condition data and model results data. Original data is got from different sources without any data processing. Condition data contain spatial data, such as DEM, land use and soil maps, model grids or calculation cells, and original data after processed. In addition, model results data are divided into systematic results and application results. Systematic results are generated in the automatic operation mode for the whole watershed water environment simulation, while application results are made by users in the scenario simulation mode. The data structure and data management mode are shown in Fig. 7.

For the condition data, one of the most important functions of the data management is data integration with distributed heterogeneous data and data checking. Data checking is used for error data identification and clean. Additionally, for the results data, the data sharing mode between condition models and application models should be solved as a priority.

The data sets of CWEMS are very large, including different kinds of sources and different time scale. The basic geographic data come from

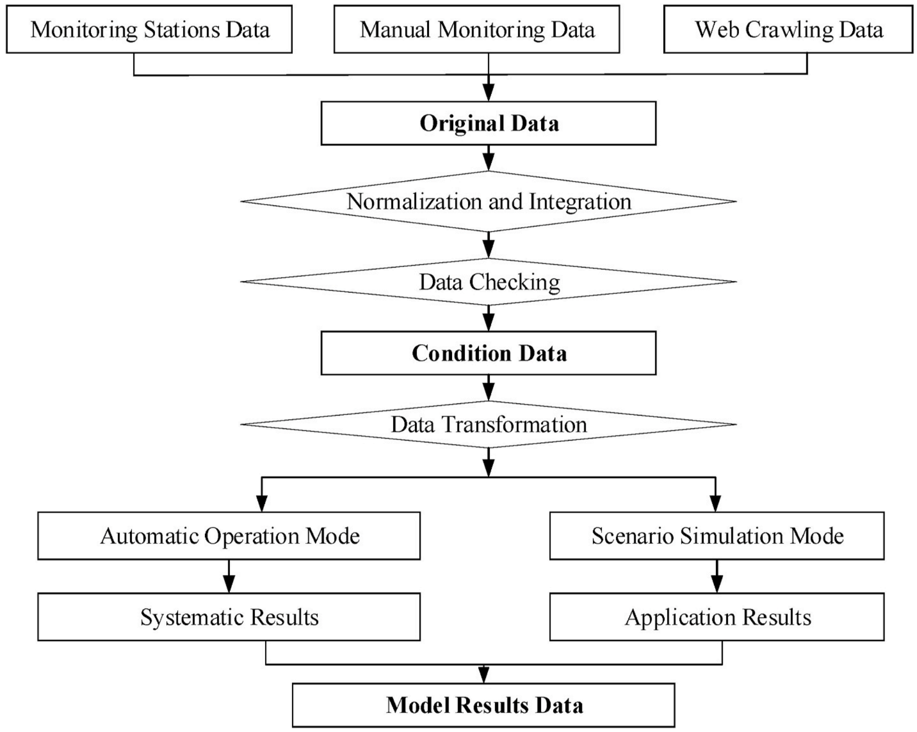

Fig. 7. Data structure and data management mode in CWEMSS.

surveying departments of different provinces, such as DEM, land use types and soil are yearly. The hydrology, water quality and meteorology data are daily, which provided by the Hydrology Bureau of the Changjiang Water Resources Commission and environmental monitoring departments of different provinces. These data have different format and various data types, as different institutions in China have their own special standard for data monitoring, storage and management. For example, the hydrology data are stored in Oracle, water quality data are stored in SQL server, while most of the manual monitoring data are stored in Microsoft Excel. Furthermore, relational table structures in different database are various. Some data are stored in column-compressed structure, but the others are stored in row-compressed. To better manage and use data, an integrated database was developed with SQL Server, where the data were transformed and integrated with row-compressed. A column-low transposed method was applied to convert the column-compressed structure data to row-compressed structure data.

Models in CWEMS have been encapsulated into Web Services with the unified format. In the automatic operation mode, models will be run every day in a whole basin scale. The results of models are temporal-spatial data, whose original formats in model center are decimal text file data (.dat or.txt). With transformation, the results data will be transferred to the data center as NetCDF file format. Results made from the automatic operation mode will be set as condition data of models in

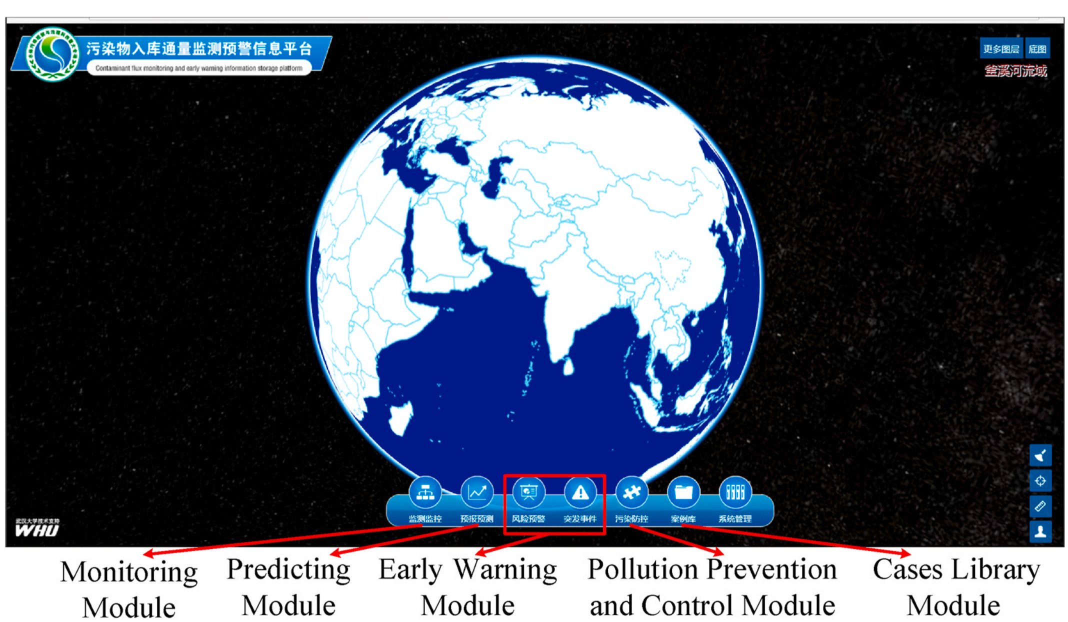

Fig. 8. System interface with main modules of a typical Chinese water environment management system (CWEMS).

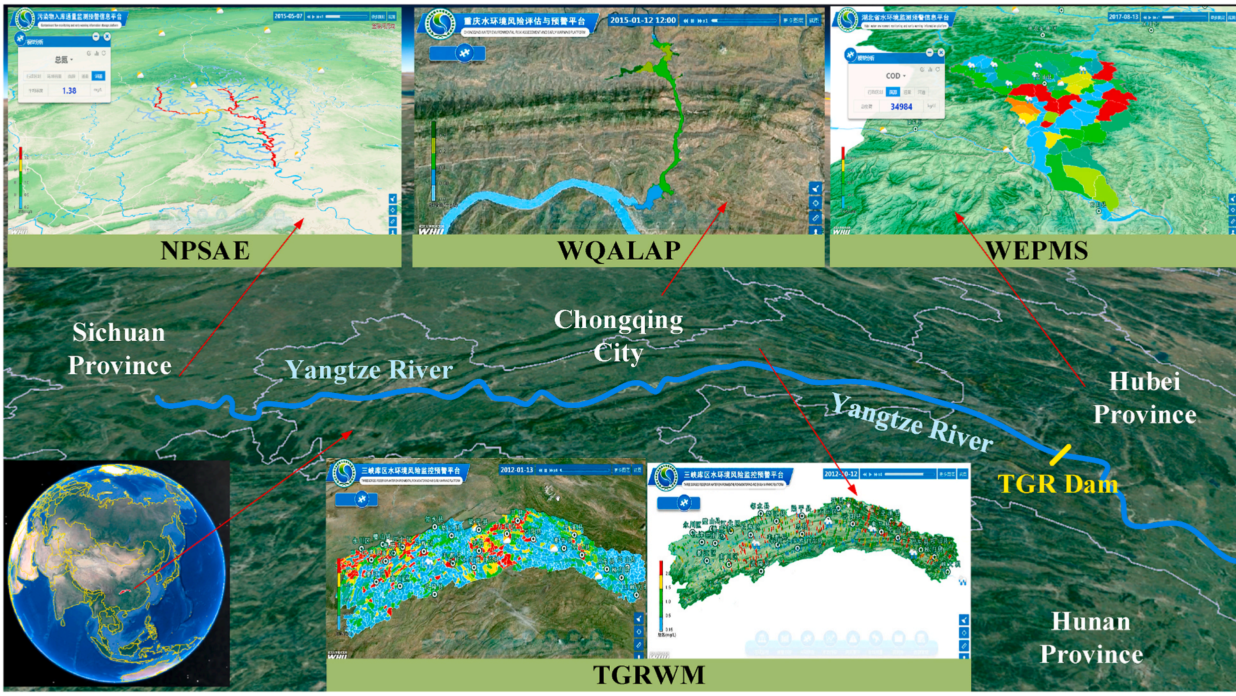

Fig. 9. Four operational water environment models systems in the Three Gorges Reservoir (TGR). NPSAS is non-point source assessment system, WQALAP is Water Quality and Algal Assessment Platform, WEPMS is Water Ecology Protection and Management System, and TGRWM is Three Gorges Basin Water Management System.

the scenario simulation mode. According to the selected models, simulation area and simulation time, the results of selected models' condition models in the local region and period will be chosen and inserted into the model center as model condition data from NetCDF files to decimal text files.

3. Case application and discussion

3.1. Structures and functions of systems

According to framework of CWEMS, a system with six modules was designed and developed to be a one-stop platform for current statues assessment, future character prediction in air, land and water environment, as shown in Fig. 8. Monitoring and results data will be visualized through an interactive and user-friendly interface. Selected models will be launched through web services.

(1) The monitoring module is used for monitoring data storing and showing. As sophisticated water environment monitoring network has been built in both developed countries and developing countries, such as the continuous water-quality monitoring network in the USA and the wireless sensor networks for water quality monitoring in Africa (Pellerin et al., 2016; Adu-Manu et al., 2017), huge number of water environmental data have been collected by governments. How to effectively express and capture valuable data from the big data is the same problem that managers confront (Carvalho et al., 2019). The monitoring module is developed to solve this problem by displaying the spatial distribution situation of monitoring stations data with GIS map and statistical graph which can help users track water quality changes over time and analyze the water environment problems. Besides, monitoring data, including atmosphere data, hydrology data, pollution source data and water quality data, can be displayed based on 3D globe engine, statistical diagram and animation video.

(2) The predicting module is based on air-land-water models for simulation and prediction of rainfall, runoff, non-point source, flow velocity, water level, water temperature and pollutant concentration. The forecast data will be showed in the client center and be pushed to the managers via telecommunication services as a text message. With models running in an automatic operation mode as shown in Fig. 5, the prediction function is automatically started at 6:00 a.m. every day and then produces next two days prediction results. Every time models simulated, the results in sections, where there are water quality unattended stations, will be assessed by relative error and R^2 analysis. According to the accurate verification results, models parameters will be optimized automatically.

(3) The early warning module is used for water quality and algal bloom risks early warning. In the module, questions about how the water quality incident will pollute the downstream, which place will be polluted by the incident and how long the pollution will continue can be answered. Pollutants diffusion process can be displayed by dynamic rendering map, while pollutants concentration changing process in different places can be showed by curve graphs.

(4) The pollution prevention and control module is used for response analysis between pollution sources and water quality. With human-computer interaction interface, managers can set different emission scenarios and the scheme of land use planning, then simulate how waters changing after different schemes. In which, models will be operated in a scenario simulation mode as shown in Fig. 6. With this, reasons for water quality problems can be identified.

(5) The cases library module is used for valuable scenarios examples storage and re-displaying, which are produced in risk early warning module and the pollution prevention and control module. History cases will produce a lot of beneficial information to environment managers.

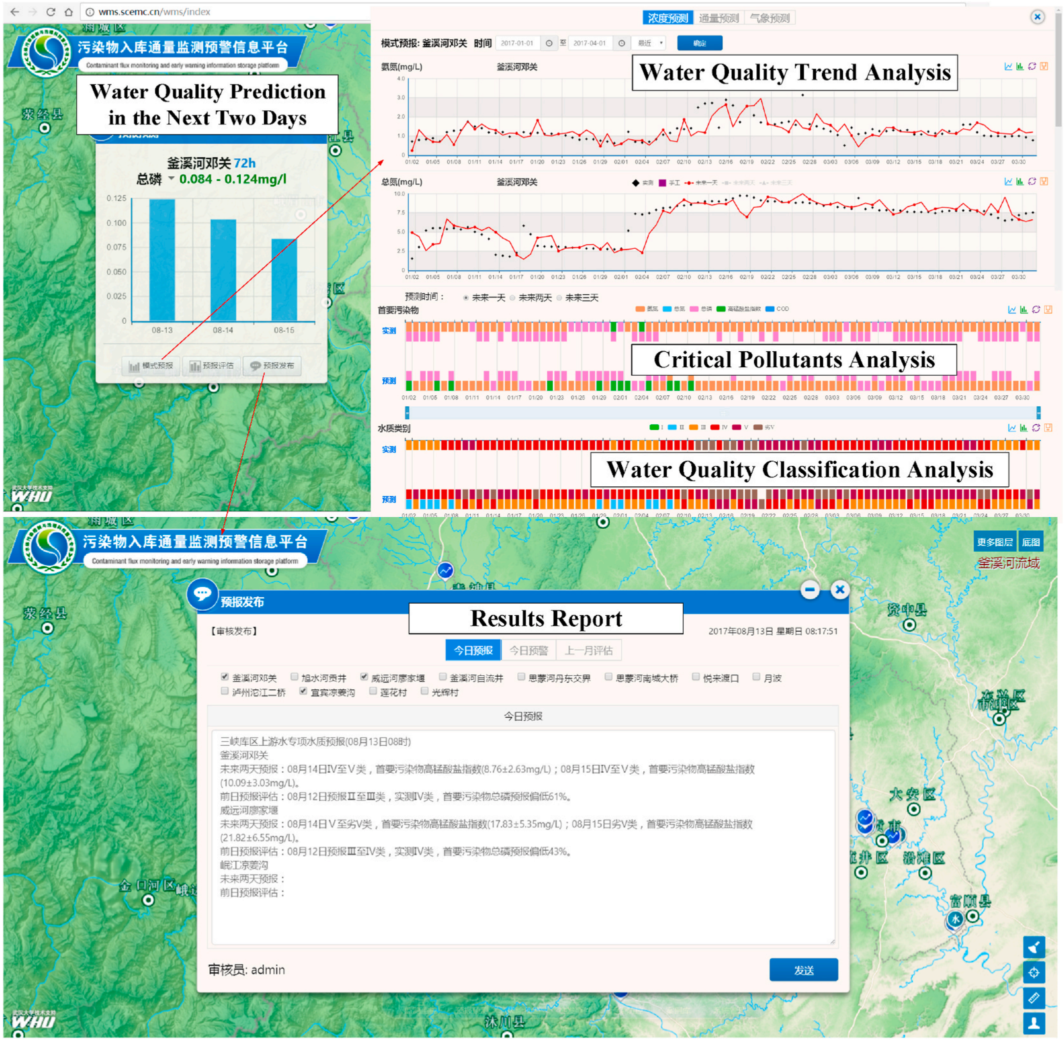

Fig. 10. Water quality prediction results displayed in the system.

3.2. Systems deployed in the application area

The Three Gorges Dam is so far regarded as the largest hydropower project in the world covering 20 county-level administrative regions, and the reservoir surface water area is over 1080 km^2 at a water level of 175 m with storage capacity of 39.3 billion m^3 (Fu et al., 2010). The Three Gorges Reservoir (TGR) has all-around benefit including flood control, generating electricity and increasing navigability (Xia et al., 2018). However, the non-point source pollution, water quality problems, algal blooms and water quality incident have threatened the water security (Shi et al., 2017) in recent years, which attracted much attention in environmental protection from the Chinese government. It is a challenge for environment divisions to fully master environmental information in this large-scale water region in real time and an accurate decision for environment management. Since 2012, the Chinese Ministry of Environmental Protection and our group have tried to develop systems for environment monitor, assessment, prediction and design making supporting in the TGR, and applied the core ideology of CWEMS in the system.

According to the architecture of CWEMS, four different systems with different objectives have been developed in the TGR as shown in Fig. 9. For non-point source load assessment and early warning, a system named non-point source assessment system (NPSAS) has been developed and in operation for more than three years without interruption in the Environmental Monitoring Center of Sichuan Province, China. As for water quality and algal blooms assessment and prediction in rivers of the TGR, a system named Water Quality and Algal Assessment Platform (WQALAP) has been deployed in Environmental Protection Bureau of Chongqing City, China. In order to manage the total TGR hydrological and water quality, the Three Gorges Basin Water Management System (TGRWM) has been developed and worked in the Changjiang Water Resources Commission, China. Additionally, the Water Ecology Protection and Management System (WEPMS) has been built in the environmental monitoring central station of Hubei province, China for water ecology protection.

All of these systems have functions of water quality prediction and scenario analysis. With more than one and half year operational running, these systems produced a lot of simulation data and assisted government in environmental management from passively treatment to active monitoring and protection.

3.3. Automatic water quality predictions

Daily water quality prediction is automatically performed by a basic workflow including data collection, hydrological simulation, NPS simulation or hydrodynamic and water quality simulation. For NPS prediction, the weather data including historical data and future data in the next two days, and cultivation management data are basic conditions. The historical weather data are collected from the weather monitoring station, while the future weather data are provided by air

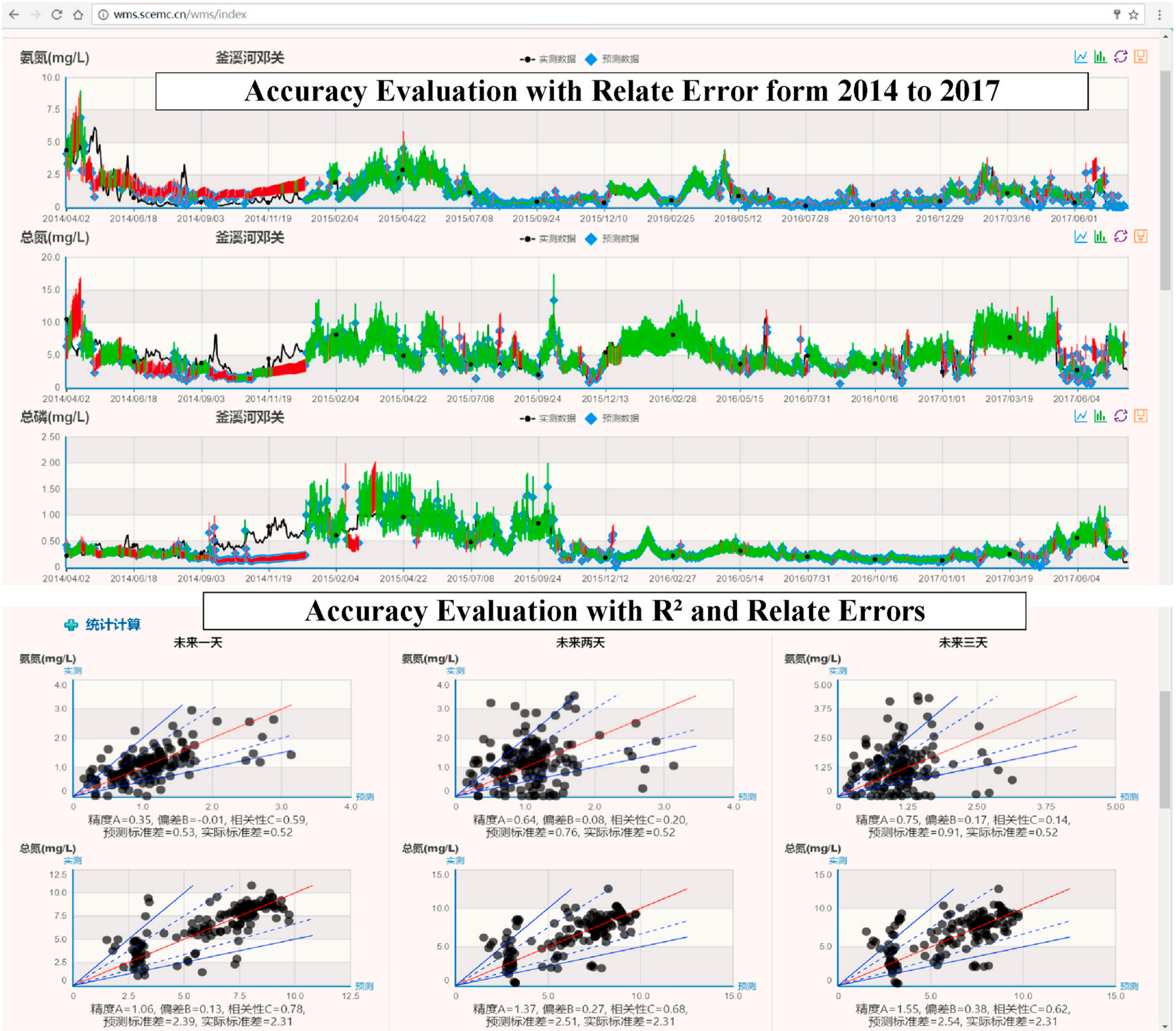

Fig. 11. Accuracy evaluation of model with results and monitoring data.

model. Cultivation management data are inputted to the database according to the statistical yearbook. For water quality prediction, the NPS simulation results will be set as conditions together with point source conditions. Boundary condition of hydrological and water quality was collected daily by instruments and sensors of automatic monitoring stations. For NPS simulation, the workflow in Fig. 5 was set to begin to run air model and land model at 0 o'clock every day. If water quality simulation is needed, the water models will be started after the land model.

In these four systems, the water quality contains the concentration of 6 regular water-quality indices, chemical oxygen demand (COD), permanganate index (COD_{Mn}), total nitrogen (TN), total phosphorus (TP), ammonia nitrogen (NH_3–N) and chlorophyll concentration (Chl). Model results will be automatically analyzed and evaluated. Taking the NPSAE for example (as shown in Fig. 10 and Fig. 11), the results will be firstly given in the main interface with histogram from the current day to the next two days once click the predicting module button. Results analysis about water quality changing process, critical pollutants and water quality classification according to China's Environmental Quality Standard for Surface Water (GB3838-2002) will be given in the main water quality control sections. Once the water quality in sections is standard-exceeding, a warning will be made. Finally, a report about water quality prediction results, water quality evaluation results, accuracy of simulation and water quality warning information will be made and sent to managers' mobile phones via text message.

To improve models accuracy, model results accurate evaluation with relative errors and R^2 will be made every time after the model simulation. In these systems, the relative error below 30% is acceptable. If the simulation results are between ±30% of monitoring data, the color of error bars will be green, otherwise it will be red, as shown in Fig. 11. Along with monitoring data increasing, model parameters have been calibrated to be more and more consistent with the actual situation with automatic parameter optimization technology. Thus, the accuracy of model results is higher and higher. As shown in Fig. 11, relative errors in the second and third year are much smaller than which in the first year NPSAE started.

All the information is available for users with PCs, tablet PCs and mobile phones. With color grading according to water quality classification, model results can be viewed through thematic rendering map overlaying statistical graphs. Fig. 9 shows the exhibition of spatial distribution of NPS results (pollutant concentration in sub-basins and pollutant flux in reaches) in the TGRWM and the WEPMS interfaces. The NPSAE and WQALAP in Fig. 9 illustrate the pollutants and alga concentration in rivers.

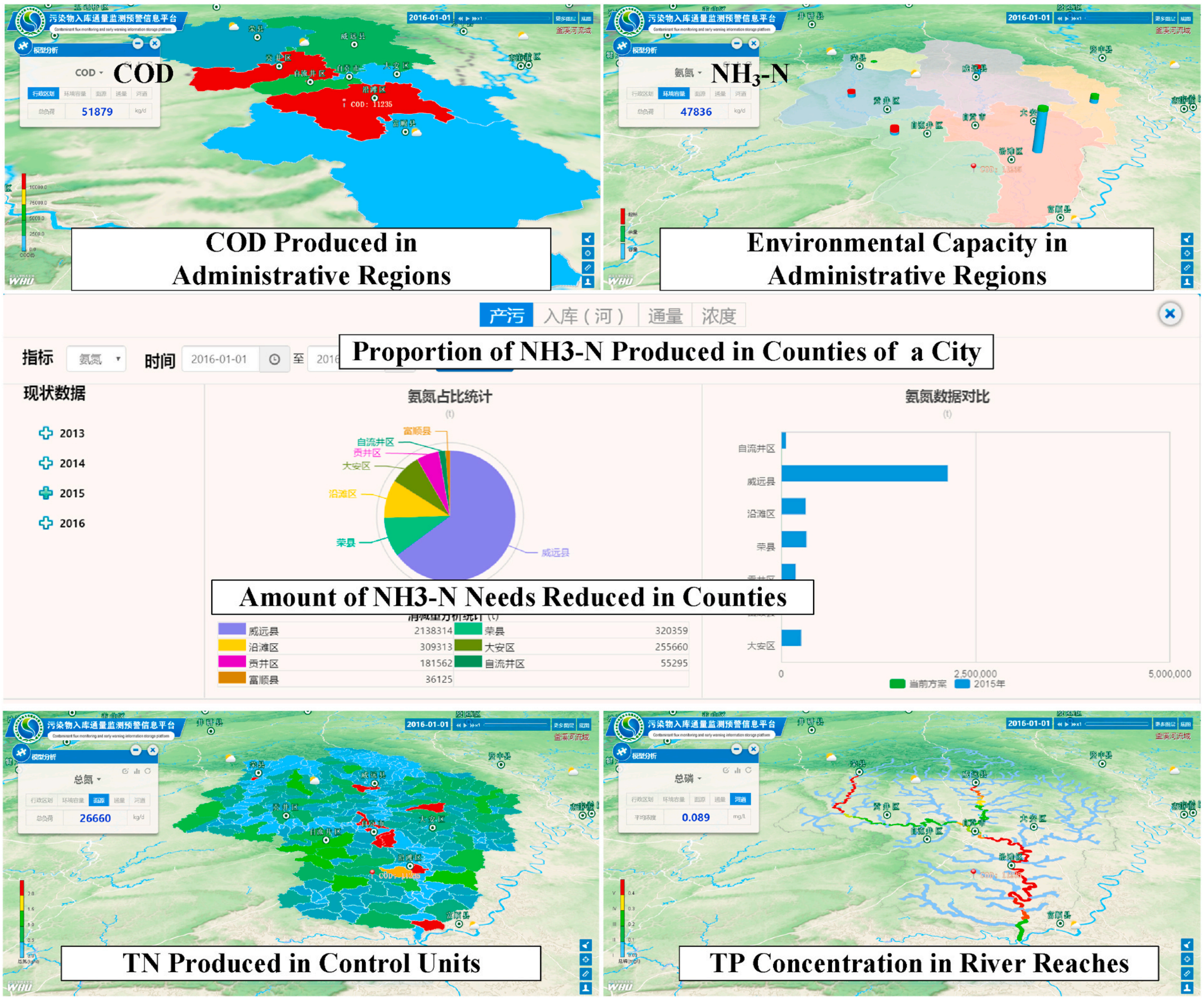

Fig. 12. NPS evaluation of Fuxi River basin in the current situation.

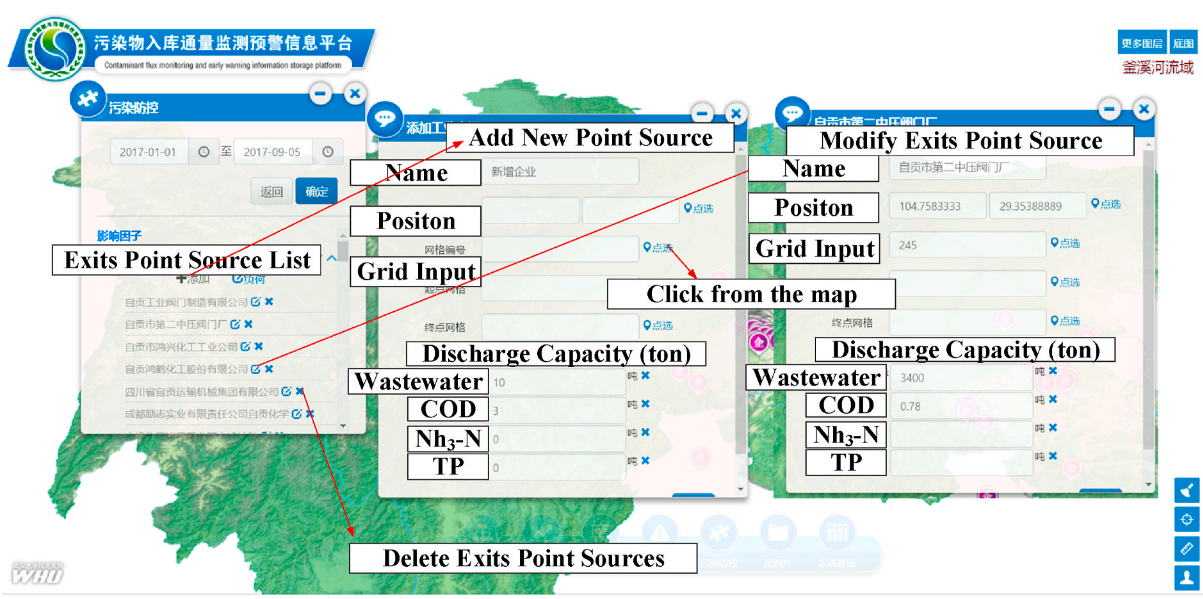

Fig. 13. Point source conditions resets in the scenario design.

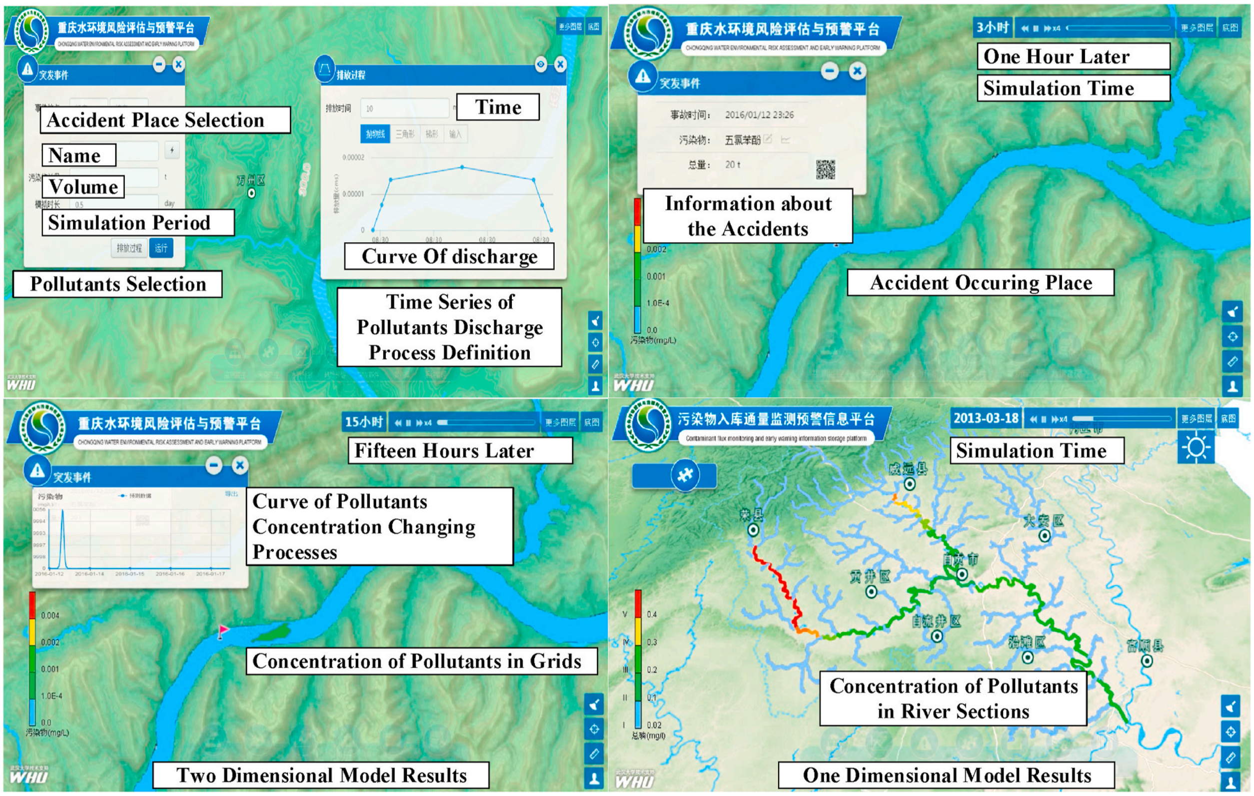

Fig. 14. Water quality incidents simulation and results showing.

3.4. Water environmental scenario analyses

Except for daily water quality forecast on the whole basin, the CWEMS can provide more accurate and faster simulation for water environment scenario analysis, such as modeling for watershed evaluation of agricultural BMPs, water quality incident early warning, sewage outlets control and other environment managements. Generally, the natural conditions, such as the climate, terrain and soil types, change very little in a short period. Whereas, conditions made by mankind are changeful. The land use, point source and water pollution are most variation conditions which may greatly affect hydrology and water quality. The CMWS provides several interfaces for users to reset and change these conditions. For example, there are three choices in NPS pollution prevention and control, including the current situation, scenario design and scenario database. The current situation is what used in the automatic water quality prediction mode. In the current situation, the NPS load produced in every administrative region, every control unit and every river reach can be viewed from map rendering method and statistical graph. Fig. 12 shows the NPS simulation and evaluation results of the Fuxi River basin in the current situation from 2016 to 2017.

Based on the current situation, changes can be made through the interface with scenario design. Outlets from point sources and sewage treatment plants and data from meteorological stations can be modified, added and deleted, as shown in Fig. 13.

After finishing the situation modification, together with parameters reassigned and modified according to the designer situation, the models should be restarted. With results analysis as shown in Fig. 11, the NPS load produced in different administrative regions, control units and river reaches can be gotten and compared with that in the current situation. For a lot of environment managers, these functions can be used for urban development planning and environmental pollution improvement testing.

3.5. Water pollution incident evaluations

Along with Chinese economic and social development, the risk of sudden and serious water environment incidents is increasing by years. It is reported that 801 environmental pollution incidents occurred from 2014 to 2015 in China (Wang et al., 2018a, 2018b). For water environment incident managing, to answer the 2W2H questions (when the pollutant will arrive at the downstream, what the peak value of the pollutant, how large the pollution areas, and how long the standard-exceeding of water quality will remain) is urgent needed. Thus, with water incident model, a core function of the system for fast and accurate early warning to water quality pollutant risk is made, which is similar to the MEWSUB (Wang et al., 2015).

The system provides a module to simulate the migration and diffusion of pollutants when water pollution emergencies happened. According to the actual situation, users can choose the emergency site (in the water), the amount or concentration of pollutants, and the process of pollutants emission (parabola, triangle or trapezoid) (Wang et al., 2015) on the interface. Once the incident pollutant was selected, the CWEMS would automatically recommend its degradation coefficient. The simulation results can be run in the background and automatically stored in the case base.

An example of water quality incident evaluation for 20t pentachlorophenol leakage in the main stream is shown in Fig. 14.

The system can simulate the process of pentachlorophenol diffusion in future time using water quality incident models. . With these existing hydrodynamic conditions which will be provided by the condition models in automatic operation mode, the simulation time of water quality model will be decreased. The results of simulation are shown by GIS with five colours (light blue, light green, dark green, yellow and red) in five levels (categorized according to the Chinese National Surface Water Quality Standards (GB3838-2002)). Besides, there are two different models for water quality incidents simulation: one is one-dimensional model used for fast and trends forecast of the pollutants

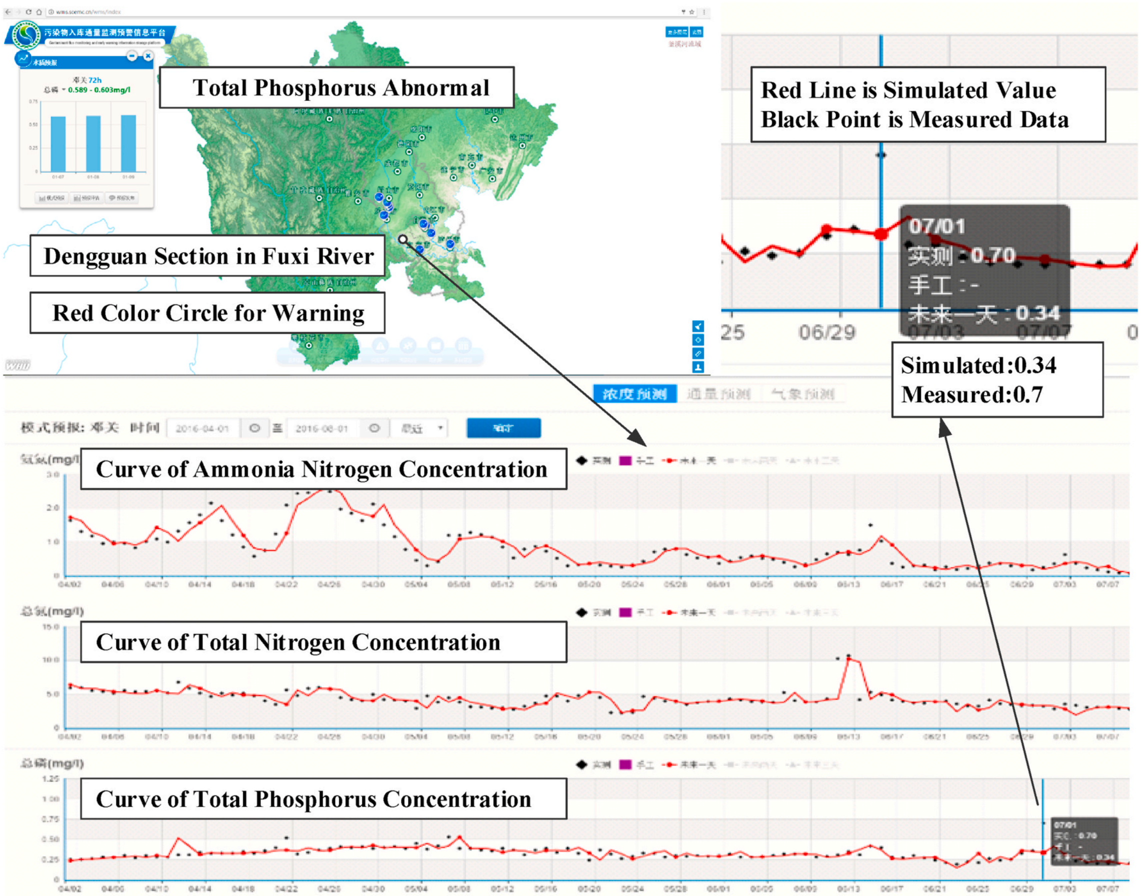

Fig. 15. Warning for total phosphorus abnormal in Dengguan section on July 1st.

in tributaries, and the other one is two-dimensional model used for accurate prediction of pollutants diffusion processes in Yangtze River. Users can search pollutants concentration at certain time and curve of pollutants concentration changing processes with point selection from clicking at calculating cells, which provides the basis information about the 2W2H questions for emergency disposal and improves the efficiency of emergency response.

3.6. Early warnings of abnormal water quality

Compared real time water quality prediction results (c_{mt}) with measured data (c_{st}) from automatic monitoring stations, the system is used for early warning of abnormal water quality. A warning value ($v_m = c_{mt}/c_{st}$) is set to define abnormal water quality early warning. It is set that when v_m is bigger than 2, the early warning of abnormal water quality will be started. As shown in Fig. 15, the label in Dengguan section turned to red when v_m was equal to 2.05 at ten o'clock on July 1st, 2016.

When the blue section label turns to red, it means that there is water quality abnormal in this section. Click on this label, the curve graph of simulated result and the scatter diagram of measured data will be displayed. The abnormal data will be highlighted automatically. With this information and the analysis of the water quality changing trend, managers can judge whether the water quality is normal. After verification, abnormal water quality was caused by illegal emissions from the upstream. This function helps managers discover the risk of water pollution timely.

4. Conclusion

As water environment is complicated and influenced by various factors, managers should largely gain information about weather, pollutants source and hydrodynamic conditions around waters. The current and future situation of the real water environment is primary demands for water environment management and design making which are difficult to be carried out without support from environment data, computing tools and software platforms. In this paper, a software as a service (SAAS) architecture of model system that contains data center, model center, client center and control center has been put forward. Air models, land models and water models are loosely coupled for water environment current situation assessment and future trend prediction. To satisfy the needs of both professional and non-professional users in numerical models for basin scale water environment management and design making, two workflow modes of models running have been created. Furthermore, the Chinese Water Environment Management System (CWEMS) has been designed with the framework and workflow. In the CWEMS, the weather or climate, the pollutants loads from land to water and the water quality changing characteristics can be automatically and semi-automatically calculated and predicted. In addition, four sub-systemss with the same architecture were developed to meet with different needs in environmental protection and governance of four provinces in the Three Gorges Reservoir Region of China. During the 3 years practical application, several environmental pollution events caused by illegal discharge of sewage have been discovered timely. Additionally, it has been used for design supporting for emergency responses in some major water pollution incidents. Practical application has proved that the CWEMS is helpful to different environmental management departments. Meanwhile, the thought and architecture of

CWEMS are also beneficial to the environmental decision support system designers and users worldwide.

While, there is still much work we can do in the future for the CWEMS. Firstly, improvement of models should be brought to the forefront. For example, a new model should be used for river net water quality simulation instead of SWAT if users need more accurate results of water quality in tributaries. Secondly, numerical models are physical mechanism based and precise, but model parameters calibration and validation are very specialized and complicated (Bennett et al., 2016), which makes the CWEMS is difficult to be promoted widely. Along with the development of environmental monitoring network and cross-department data exchange and sharing, huge data of water environment have been collected by the government. This makes it possible to analyze and forecast water quality with big data analysis technology, such as artificial intelligence, fuzzy analysis and regression forecasting. Together with numerical models, other methods will be used for information mining of water environment. Thirdly, as the delicacy water environment management, such as grid management and river chief system, has been implemented all over the world, it requires clear responsibilities of different administrative units and management departments. In this case, questions about how pollution influence environment and what leads to pollution should be answered. Therefore, functions of tracing the source of pollution and providingpollutions prevention and pollutants control advice will be developed.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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