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Integration of USEPA WASP model in a GIS platform*

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Abstract: The integration of water quality analysis simulation program (WASP) with a geographical information system (GIS) is presented. This integration was undertaken to enhance the data analysis and management ability of the widely used water quality model. Different types of data involved in WASP modeling were converted and integrated into GIS using a database method. The spatial data modeling and analysis capability of GIS were used in the operation of the model. The WASP water quality model was coupled with the environmental fluid dynamics code (EFDC) hydrodynamic model. A case study of the Lower Charles River Basin (Massachusetts, USA) water quality model system was conducted to demonstrate the integration process. The results showed that high efficiency of the data process and powerful function of data analysis could be achieved in the integrated model, which would significantly improve the application of WASP model in water quality management.

Key words: Water quality analysis simulation program (WASP), Geographical information system (GIS), Integration, Environmental fluid dynamics code (EFDC), Water quality model

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1 Introduction

Water quality modeling plays an increasingly important role in water environment protection, management and decision-making support. It helps to predict and assess water quality responses to natural phenomena and man-made pollution. With water quality modeling, it is possible to improve the understanding of relationships between the cause and effect that influence aquatic ecosystems, and then improve the decision-making for environmental management (Fitzpatrick, 2009).

The objective of water quality modeling is to study the characteristics of the spatial and temporal distributions of water quality variables. The presentation, analysis, and management of model input and output data are critical to the success of modeling because these allow the modeler to interpret certain aspects of the water body. Geographical information systems (GISs), which are recognized for their ability to model and enable analysis of spatially distributed phenomena, are being introduced into water quality management and to improve the operation of water quality models. The integration of a water quality model and a GIS platform has become a promising and powerful method in water quality modeling research (McKinney and Cai, 2002).

In this paper, the application of GIS platform was introduced into the modeling process of water quality analysis simulation program (WASP), a widely used water quality modeling program for aquatic systems developed by US Environmental Protection Agency (USEPA). This integration method can enhance the data presentation, analysis, and management capacity of WASP model.

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1.1 Water quality analysis simulation program

The WASP is a dynamic compartment modeling program for aquatic systems, including both the water column and the underlying benthos. As a generalized modeling framework, WASP can be used to analyze a variety of water quality problems in such diverse water bodies as ponds, streams, lakes, reservoirs, rivers, estuaries, and coastal waters. It allows the modelers to investigate 1D, 2D, and 3D systems, and a variety of pollutant types. It helps the modelers to interpret and predict water quality responses to natural phenomena and man-made pollution for various pollution management decisions (Ambrose *et al*., 1993; Wool *et al*., 2001).

WASP was first developed by Di Toro *et al*. (1983) and is supported by the Watershed and Water Quality Modeling Technical Support Center (WWQTCS) of USEPA. It is continually being updated and enhanced by USEPA, and is used as an important modeling tool for the development of total maximum daily loads (TMDLs) (Shoemaker *et al*., 1997). Enhancement has been made in its latest version, WASP7, to support the TMDL program.

WASP has been widely used on many different water bodies over the years and is proven to be effective in a variety of conditions. An early version of WASP was used to examine eutrophication in the Potomac Estuary (Thomann and Fitzpatrick, 1982), the Green Bay of Lake Michigan (Bierman *et al*., 1992), the upper Mississippi River and Lake Pepin (Lung and Larson, 1995), and the Tampa Bay (Wang *et al*., 1999). It was also used for modeling contaminant fate and transport in surface waters, such as mercury in the Middle and Lower Savannah River Watersheds, Georgia (USEPA, 2001). There are also many applications of WASP in TMDL development and project decision-making process, such as the Neuse River Estuary, North Carolina (Wool *et al*., 2003).

Originally, WASP contained two kinetic water quality submodules to simulate two of the major classes of water quality problems: EUTRO and TOXI. EUTRO is applicable to modeling the conventional pollution, mainly incorporating the water quality variables of dissolved oxygen (DO), biochemical oxygen demand, nutrients, and eutrophication, while organic chemicals, metals, and sediment are simulated in TOXI. In WASP's newer versions, besides the enhancements of the former submodules, several new ones were developed to solve some specific problems, such as temperature and fecal coliform submodules and mercury submodules (Wool *et al*., 2008). An advanced eutrophication sub-module was developed to simulate the multiple and benthic algae in surface water.

A hydrodynamics submodel (DYNHYD) is also included in the WASP model system, which simulates the transport of water while the water quality model simulates the transport and interaction of pollutants within the water. WASP can also be linked with other hydrodynamic models, such as the environmental fluid dynamics code (EFDC).

In practical developments of TMDL nowadays, many applications are based on WASP incorporated with EFDC, which is also listed in the tool box of TMDL by USEPA, as the hydrodynamic model (Tetra Tech, 2006). EFDC has its own specialty in simulating 1D, 2D, and 3D flow and transport processes in surface water systems including rivers, lakes, estuaries, reservoirs, wetlands, and near-shore to shelf-scale coastal regions (Tetra Tech, 2002). The integration of EFDC into WASP model system gives it more flexibility in the complicated and multi-dimensional aquatic systems. In the integration procedure of EFDC into WASP, a hydrodynamic linkage file can be generated by EFDC, which is capable of providing multi-dimensional volume, depth, and velocity data to WASP for solving the mass transport equations during its execution.

However, the operation of the WASP model requires considerable expertise in environmental data and model application. Although WASP currently has its own graphic user interface and graphic post-processor, its ability is limited to graphical presentation of water quality data and may not be sufficient for the needs of water quality management. For example, in WASP model system, there is no dataset management function for information of the whole aquatic system. The methods of presentation, analysis and management of model output data may not handle all the post-processing needs of every different case. Although there is a GIS interface included in the post-processor of the model, it is only capable of reading simple geographic information used as the map of the aquatic system. Other detailed information such as hydrology, human activity, and different scenarios cannot be integrated into the post-processor.

The model output water quality data and other detailed information cannot be exported to other GIS systems. As a result, it will be difficult for the modelers to share the model information and data with other communities who are interested in the water body but not very familiar with the operation of water quality model. To overcome these shortcomings, a GIS platform should be introduced into the application of WASP model. The water quality data and other detailed information can be integrated into the GIS platform, processed and analyzed according to the different needs of modelers and other communities.

1.2 Geographical information system application in water quality modeling

GIS is an information system that integrates, stores, edits, analyzes, shares, and displays geographic data. Its abilities include pre-processing data into a platform which is suitable for analysis, supporting spatial analysis and modeling directly, and post-processing results (Goodchild, 1993). It allows users to create interactive queries (user-created searches), analyze spatial information, edit data, maps, and present the results of all these operations.

Most of the water quality models, which solve hydrodynamic and pollutant fate problems in water body, involve large amounts of geographically-referenced data, and thus involve great effort in the pre-processing of model input data, as well as in the representation and interpretation of model output data. GIS gives the water quality modelers a solution to integrate the data from different sources during the modeling process and manage the model data efficiently (Patino-Gomez *et al*., 2008). GIS can represent the geographically-referenced characteristics and spatial relationships of water bodies. The visual display capacity of GIS compliments the user interface of water quality models, allowing the modelers to take more control of data input and manipulation. For water resource managers, GIS can combine the different environmental and social factors related to the water body into a database and present it as an integrated view or map in the decision-making process. By comparing different scenarios in the GIS-based water quality system, managers can gain the insight into how a water body responds to environmental changes or human activities.

To take advantage of GIS to improve water quality modeling, it is an attractive idea to integrate GIS with traditional water quality models (Liao and Tim, 1997). Leipnik *et al*. (1993) conducted a comprehensive discussion on the potential for GIS application in water resources. Miles and Ho (1999) discussed the general issues of GIS application in civil engineering, such as the limitations, alternatives, and context. Tremendous efforts in the integration of GIS with water quality model have been made in the last decade (Pinho *et al*., 2004; Ng *et al*., 2009).

WASP, as a multi-dimensional and general purpose water quality model, requires management of large amount of aquatic system and water quality data in model application. However, as mentioned above, the existing applications and software for this model are developed focusing only on the pre- and post-process of the model, not the GIS-based model data management. In this study, the integration of WASP and GIS was conducted to build a connection platform between the model and GIS that is sufficiently simple and robust to allow interactive interrogation. The result of the WASP application can be passed among different groups of users, such as modelers of relevant research who may be interested in the model application or managers of water resource with little model expertise.

2 Integration of WASP model and GIS platform

2.1 Basics of WASP model

The basic principle of WASP model system is the conservation of mass. The water volume and water-quality constituent masses being studied are tracked and accounted for over time and space using a series of mass balancing equations. In WASP system, one mass balance equation for dissolved constituents in a body of water must account for all the material entering and leaving through direct and diffuse loading, advective and dispersive transport, and physical, chemical, and biological transformation.

The mass balance equation which describes an infinitesimally small fluid volume is (Ambrose *et al*., 1993)

$$\frac{\partial C}{\partial t}=-\frac{\partial}{\partial x}(U_xC)-\frac{\partial}{\partial y}(U_yC)-\frac{\partial}{\partial z}(U_zC)+\frac{\partial}{\partial x}\left(E_x\frac{\partial C}{\mathrm{d}x}\right)+\frac{\partial}{\partial y}\left(E_y\frac{\partial C}{\mathrm{d}y}\right)+\frac{\partial}{\partial z}\left(E_z\frac{\partial C}{\mathrm{d}z}\right)+S_\mathrm{L}+S_\mathrm{B}+S_\mathrm{K}, \quad (1)$$

where C is the concentration of the water quality constituent, mg/L or g/m^3; t is the time, d; U_x, U_y, U_z is the longitudinal, lateral, and vertical advective velocity, m/d, respectively; E_x, E_y, E_z is the longitudinal, lateral, and vertical diffusion coefficient, m^2/d, respectively; S_L is the direct and diffuse loading rate, g/(m^3·d); S_B is the boundary loading rate (including upstream, downstream, benthic, and atmospheric), g/(m^3·d); and S_K is the total kinetic transformation rate (positive is source, negative is sink), g/(m^3·d).

By expanding the infinitesimally small control volumes into larger adjoining "segments", and by specifying proper transport, loading, and transformation parameters, WASP implements a finite difference form of this equation, in which the derivation of the equation will be for a 1D reach for brevity and clarity.

Assuming vertical and lateral homogeneities, Eq. (1) can be written as (Ambrose *et al.*, 1993)

$$\frac{\partial}{\partial t}(AC)=\frac{\partial}{\partial x}\left(-U_xAC+E_xA\frac{\partial C}{\mathrm{d}x}\right)+A(S_\mathrm{L}+S_\mathrm{B})+AS_\mathrm{K}, \quad (2)$$

where A is the cross-sectional area, m^2.

The input dataset of WASP implementation can be divided into four major sections as follows: environment parameters which define the basic model identity, including the segmentation, simulation type and control; transport parameters which define the advective and dispersive transport of simulated model variables, including advective flows, sediment transport velocities, dispersion coefficients, cross-sectional areas, and characteristic lengths; boundary parameters including boundary concentrations, waste loads, and initial conditions; transformation parameters including spatially variable parameters, constants, and kinetic time functions for the water quality constituents being simulated.

Besides these groups of parameters, hydrodynamic modeling results can be incorporated into WASP. For example, if used for multi-dimensional unsteady state water quality simulation, EFDC modeling results (hydrodynamic file denoted by *.HYD) should be imported into WASP. The hydrodynamic file will provide WASP with the information of multi-dimensional model segment structure, flow and mass transport of the water.

The output from WASP is written in a binary file format (denoted by *.BMD), which can be imported into its post-processor. WASP can also output data in ASCII format according to the demand of modelers during the running of the model or in post-processor.

Data flow of aquatic system and water quality information is shown in Fig. 1.

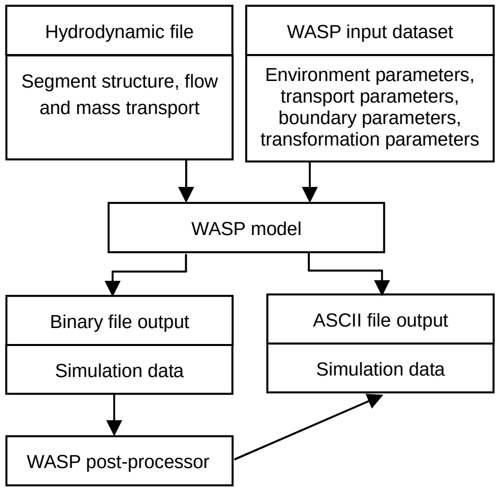

Fig. 1 Data flow in WASP model system

2.2 General methodology of integration of WASP model with GIS platform

In the integration procedure of WASP and GIS platform, a database is built to process all the data involved in the application of the model. This database is setup in the framework named "geodatabase", which is used for data storage and management in GIS platform. It is the combination of "geo" (spatial data) and "database" (data repository) which creates efficient spatial data storage and management.

In the integration of WASP model and GIS platform, a geodatabase can generally be divided into spatial database and attribute database. In the application of multi-dimensional simulation the operation of WASP model needs a detailed description of the spatial characteristics of the water body. The output information of WASP model is also highly related to the spatial data. Usually the data related to the water body are obtained from various sources and in different formats, such as the atmosphere record of the study area, the flow and water quality data of the upstream and tributaries of the water body, point sources of pollution in the study area, etc. These attributed data can also be converted and imported into the geodatabase of GIS platform. Then an index between the spatial and attribute data is built in the geodatabase to create a relationship. With this index and other data process function in GIS, modelers can accurately and conveniently access the data stored in the geodatabase. The details of the integration process are discussed in the following section.

2.3 GIS application in pre-process of WASP modeling

In pre-process of WASP modeling, GIS is used to enhance the preparation of the model input data. The maps of the study area and the water body can be collected and stored in geodatabase (in shape file) as the spatial data. The terrain data of the watershed can also be handled efficiently in GIS as a digital elevation model (DEM).

EFDC will be used first in the preparation of hydrodynamic file for WASP. In the application of EFDC modeling, the water body is generalized as a computational domain and separated into a series of interconnected segments or cells (grid). With the spatial modeling capability of GIS, the generalization of the water body can be achieved much more efficiently. In the process of grid generation, several kinds of information are needed to specify the geometric and topographic properties and other related characteristics of the computational grid. A cell type array should be defined to illustrate that every cell in the computational grid indicates dry land, water, or the border between them. With the map data in GIS platform, a cell map of water body can be drawn in GIS shape file by the modelers and the cell type array can be defined efficiently. The center coordinate and size of each cell should also be provided for the input data of EFDC, which can be conveniently achieved with the coordinate query and distance measuring function in GIS platform. The initial depth of each cell can be directly read in DEM. Hydrodynamic file, generated by EFDC, will provide WASP model with the information of flow, mass transport, and grid (denoted as a segment in WASP) structure.

The attribute data include the historical data of the water level, inflow and outflow of the water body, water quality data collected by the monitoring stations, the pollutant load of point and non-point sources and the weather data. These different data, in different formats of table files, can be imported and stored in the geodatabase containing multiple dBASE table files. The data stored in a dBASE table file is cataloged by different fields. For example, a dBASE table file for the water quality data of the monitoring stations will have the fields of “monitoring station name”, “sample date”, “water quality variable name”, “variable value”, “variable unit”, etc. Multiple dBASE table files corresponding to the data from different sources can be stored in the geodatabase, which will be processed and imported as the environment, transport, boundary, and transformation parameter datasets in WASP. The operation of different data for the preparation of the WASP input data with GIS integration is shown in Fig. 2.

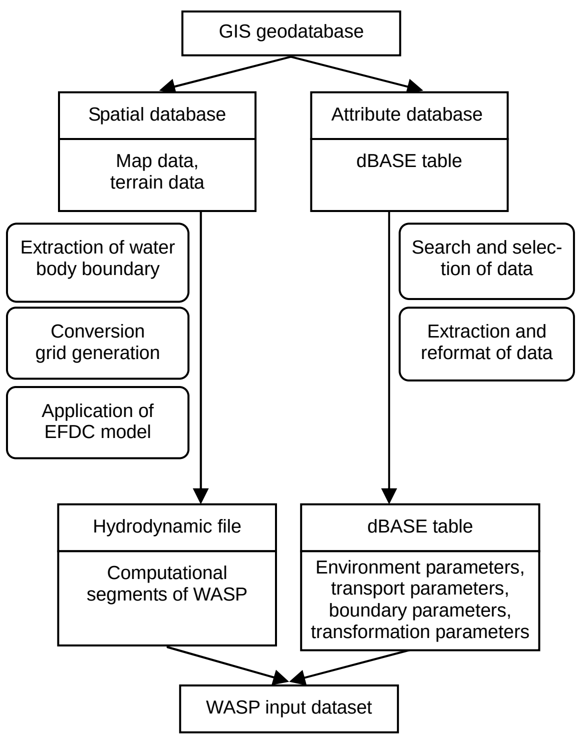

Fig. 2 GIS-based data operation in the pre-process of WASP modeling

2.4 GIS application in post-process of WASP modeling

In the post-process of WASP modeling, GIS is used to enhance the presentation, process, and management of the model output data. The output of WASP is the spatial and temporal distributions of certain variables in the model, such as the concentration field of some water quality constituents. With its unique spatial data analysis and graphical output capability, GIS allows the modeler to achieve a better understanding of the characteristics of the water body.

The WASP output data, together with the flow field data derived from EFDC, can be stored in GIS geodatabase as spatial data and attribute data. The flow field or concentration field data of model output can be reformatted and converted to GIS dBASE table or text table file as attribute data. The water quality information of the water body is stored in GIS in this way.

The computational grid of the water body in EFDC modeling (or denoted as a segment in WASP) should be stored in GIS spatial database. If the grid is prepared in GIS during the pre-process of the model as discussed above, the shape file can be directly used to represent the segment of WASP. When the grid is prepared by other EFDC pre-processors, it should be converted into GIS shape file. Several input files related to the model grid in EFDC contain the necessary information of the spatial coordinate data which define the center coordinate and size of the cells in the grid. Then the coordinate system of the shape file should be integrated with the map of water body stored in GIS.

For 1D and 2D models, only one shape file is used to represent the whole grid. In the case of 3D model, since multiple layers are contained in the grid, the same number of shape files is needed for all the cells. Each shape file represents a layer in the grid. These shape files share the same horizontal coordinates, but the attribute data of water depth are different to define the vertical relationship of the cells.

In computational grid of EFDC model, each cell has a unique index number as its identification. The segments in WASP share the same index with EFDC grids. This index number should be contained in GIS shape file corresponding to the WASP model segments. With this index, the modeler can relate the attribute data and spatial data together and build mapping between the water quality data and the polygons. For a 3D model, a vertical profile of cross-section in water body can also be created by modelers. The segments in different layers at the same vertical cross-section have the same horizontal coordinates but different index numbers. In a vertical profile, the water quality data of the segments are shown according to different layers. These operations in GIS platform will be shown in Section 3.

The operation of WASP output data with GIS integration is shown in Fig. 3.

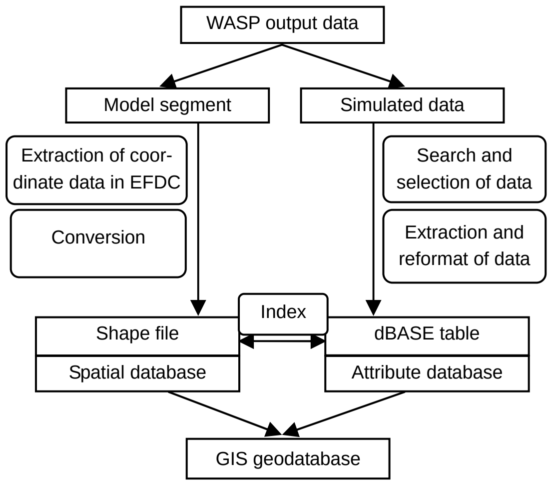

Fig. 3 GIS-based data operation in post-process of WASP modeling

2.5 GIS geodatabase setup

The WASP input data and output data can be integrated into one GIS geodatabase. The modeler can use this geodatabase to analyze the model data with the standard GIS functions, such as custom layer and data query.

Generally, the data flow in the integration of WASP model and GIS platform is shown in Fig. 4.

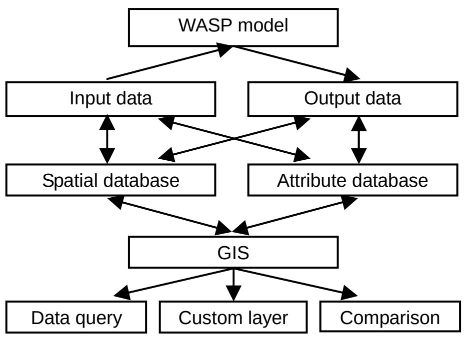

Fig. 4 Data flow in the integration of WASP model and GIS platform

3 Case study

A case study was conducted to show the process of integration of WASP and GIS platform. This 3D WASP water quality model, coupled with EFDC hydrodynamic model, was developed based on the implementation of a TMDL for the Lower Charles River Basin in metropolitan Boston, Massachusetts (Tetra Tech, 2005a). The lower portion of the basin is impounded and has a long retention time during low flows, allowing algal blooms to become well established and severe during the summer months. Eutrophication process in the basin was simulated for the TMDL development. The geographic, hydrodynamic, and water quality data involved in the model was originally obtained from the modeling report of this TMDL development (Tetra Tech, 2005b).

3.1 Modeling domain and setup

The Lower Charles River Basin is at the downstream end of the Charles River Watershed, approximately 1.9 km upstream from its outlet to Boston Harbor and the Atlantic Ocean. It is located in eastern Massachusetts and flows through portions of Norfolk, Middlesex, and Suffolk Counties. This basin is an impounded section of the Charles River that is 14 km long and covers approximately 2.73 km^2. It can be divided into two parts. The majority of this area is the lower portion downstream of the Boston University (BU) Bridge (lower basin). The lower basin is 4.2 km long and has widths varying in the range of 90 to 600 m. Its water volume accounts for approximately 90% of the entire water volume of the basin. Water depths are in the range of 1.8 to 3.6 m in the basin upstream of the BU Bridge and 2.7 to 11 m in the lower basin (MADEP, 2000), respectively.

The modeling domain is the section of the river between the Watertown Dam and the New Charles River Dam where the river flows into Boston Harbor. The horizontal grid that constructed this section used curvilinear horizontal grid cells.

The EFDC model was set up first for the generation of a hydrodynamic file. A varying-size grid of 50 to 400 m was used and 8 vertical layers were set in the horizontal grid having varying thickness in a range of 0.25 to 1 m throughout the modeling domain. The number of total water cells at the surface layer is 56.

The EFDC modeling setup involves a series of EFDC input files including the master input file, files specifying the grid and bathymetry, atmospheric forcing files, an inflow and outflow file, salinity and temperature boundary condition files, power plant withdrawal, temperature rise, and discharge files, and water column initial salinity and temperature concentration distribution files. After running of the EFDC model, the hydrodynamic file was obtained and imported into the WASP model. Another model input dataset includes environment parameters, transport parameters, boundary parameters, and transformation parameters involved in the water quality model. To achieve WASP model output data, a run of the model was conducted for a period of 360 d. A complete run of the model took approximately 7 h for one trial on a 2.4 gigahertz Core 2 Duo based IBM compatible computer.

3.2 Integration of WASP model dataset into GIS geodatabase

As described in Section 2, the computational segment data and water quality output data of the Lower Charles River Basin from WASP model are integrated into GIS geodatabase according to the needs of model data analysis. Users of this GIS geodatabase can access the water quality data and create different views of the basin.

For example, a theme map containing several layers can be created to form a map of relative surface water elevation data of EFDC based on model initial computation water elevation (0.000 m) (Fig. 5) or DO concentration field of the water body in the study area calculated by WASP (Fig. 6 for the surface layer and Fig. 7 for the bottom layer of water, respectively) at any time in which the modeler is interested (on the 180th computation day for example). In Fig. 6 the DO concentration in the lower basin is much lower than that of the upstream part of the basin, which is consistent with the fact in the basin. This low DO concentration in the lower basin is mainly attributed to the high nutrient loadings from the upper watershed and along the basin, and the long retention time of the water (Tetra Tech, 2005b). Fig. 7 shows that in the bottom layer the DO concentration is much lower than that of the surface layer. Users can also create the DO concentration vertical profile of a cross-section (Segment A and Segment B of the model are included in this cross-section, which are shown in Fig. 6) in the basin to represent the vertical stratification in the water body (Fig. 8). Water quality data can be geographically related to the water body map while data query of water quality constituent concentration can be performed in the GIS map. Users can directly obtain the water quality data of the basin by identifying the properties of different locations in the map, without searching in the whole water quality data output file (Fig. 9).

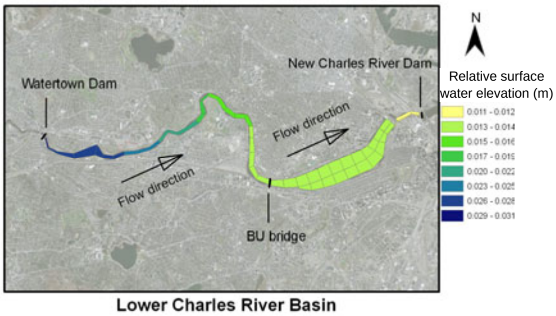

Fig. 5 Relative surface water elevation on the 180th computation day

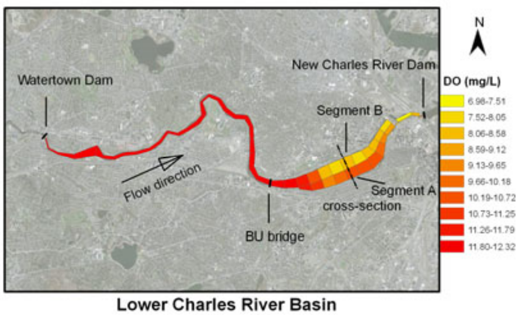

Fig. 6 Surface dissolved oxygen concentration field distribution on the 180th computation day

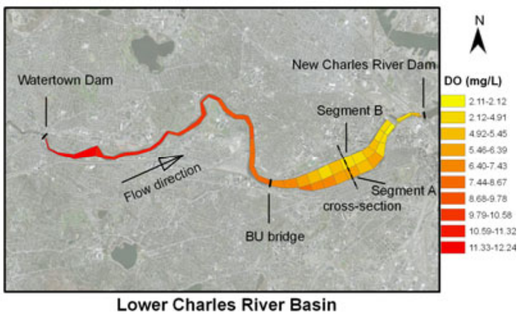

Fig. 7 Bottom dissolved oxygen concentration field distribution on the 180th computation day

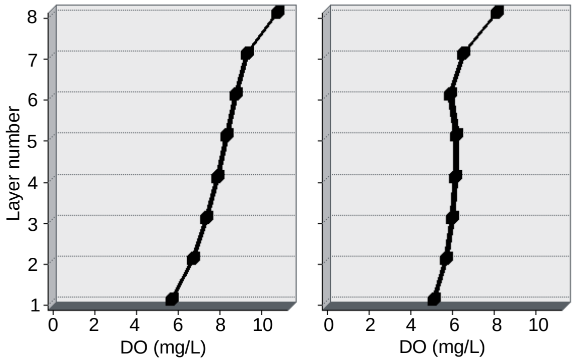

Fig. 8 Dissolved oxygen concentration. Vertical profiles of Segment A (a) and Segment B (b)

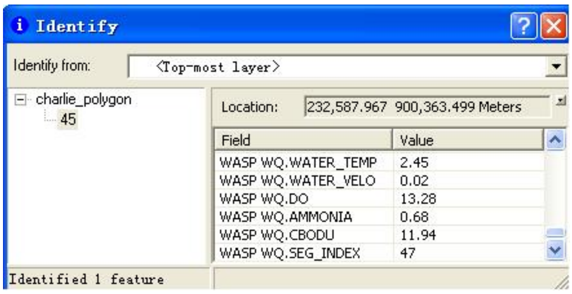

Fig. 9 Water quality data query in GIS geodatabase

WATER_TEMP is the water temperature, °C; WATER_VELO is the velocity of water, m/s; DO is the dissolved oxygen, mg/L; AMMONIA is the ammonia nitrogen, mg/L; CBODU is the ultimate carbonaceous biochemical oxygen demand, mg/L; and SEG_INDEX is the number of the segment in WASP model

In model calibration and verification, with the measured water quality data from monitoring stations in the GIS geodatabase, the modeler can compare the measured data with the simulated data of the model. Fig. 10 and Fig. 11 show the surface temperature and DO concentration data comparisons between monitored and simulated results using the WASP model at one monitoring station, respectively. Fig. 12 and Fig. 13 show the scatter plots of the monitored data versus simulated results at the same monitoring station with correlation coefficients (R) of 0.9892 and 0.8879 for temperature and DO, respectively. Based on GIS platform, the modelers can also share the model information and data much more conveniently with others who might even not be familiar with the operation of water quality model.

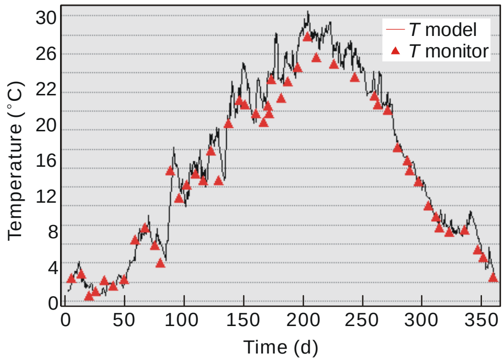

Fig. 10 Comparison of surface temperature data

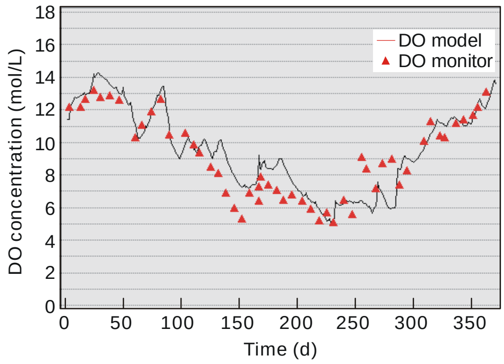

Fig. 11 Comparison of surface dissolved oxygen concentration data

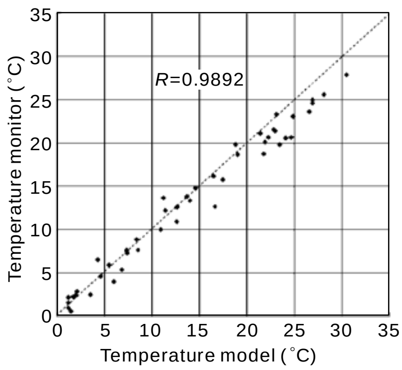

Fig. 12 Scatter plot of the monitored versus simulated temperature

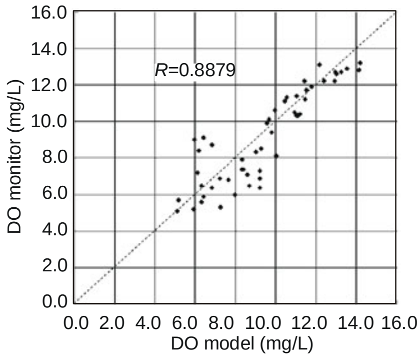

Fig. 13 Scatter plot of the monitored versus simulated dissolved oxygen concentration

4 Conclusions

The integration of WASP model and GIS platform was presented in this paper. The advantages of the integration are summarized as follows: (1) the application of GIS improves the model data collection and pre-process; (2) the input and output data of the model can be integrated into a GIS database, which facilitates convenient data management and share; (3) a high quality map of the concentration distribution of water quality variables can be achieved; (4) the simulated data of the model can be easily accessed in the map; (5) the interface of the model data operation is more user-friendly, which improves the application of the model.

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