Integration of Environmental Fluid Dynamics Code (EFDC) Model with Geographical Information System (GIS) Platform and Its Applications

S. Peng[1], G. Y. Z. Fu[2,*], X. H. Zhao[1] and B. C. Moore[2]

[1]*School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China.*
[2]*Department of Construction Management & Civil Engineering, Georgia Southern University, Statesboro, GA 30460-8047, USA*

ABSTRACT. Data management and analysis are important for the application of water quality modeling in water environmental protection. The integration of the Environmental Fluid Dynamics Code (EFDC) model with Geographical Information Systems (GIS) is discussed in this paper. The data management and analysis ability of this widely used water quality model was enhanced by the integration. Database methods are used to integrate the different types of modeling data into a GIS platform. The spatial data modeling and analysis capacity of GIS is used in the pre-processing and post-processing of EFDC. The integration application is demonstrated by a case study of the Lower Charles River Basin water quality model, which was built with EFDC and has 56 varying-size curvilinear horizontal grids and 8 vertical layers. The case study shows that the integrated system significantly improved the application of EFDC with more efficient data processing, organization and analysis, and can be used as a powerful tool for water environmental management and decision making.

Keywords: Environmental Fluid Dynamics Code (EFDC), Geographical Information Systems (GIS), integration, database, water quality model

1. Introduction

Water quality modeling plays an increasingly important role in water environment protection, management and decision making support. It helps people predict and assess water quality responses to natural phenomena and man-made pollution. With water quality models, people can improve understanding of the relationship between the cause and effect that influences aquatic ecosystems and then improve decision making for environmental management (Fitzpatrick, 2009). The purpose of water quality modeling is to characterize the spatial and temporal distribution of water quality variables. The presentation, management and analysis of model input and output data are critical to the success of modeling because it allows the modeler to interpret the characteristics of water bodies.

Geographical Information Systems (GIS), being recognized for their ability to analyze spatially distributed phenomena, were introduced into water quality management and significantly improved the operation of water quality modeling (McKinney and Cai, 2002). GIS is an information system that integrates, analyzes, and displays geographic data. In a water quality modeling application, not only does it offer the capability of spatial data representation, but also it provides model data integration and management. The application's abilities include pre-processing model input data into a platform which is suitable for analysis, post-processing model output results, supporting spatial analysis and modeling, and managing relative data in a modeling application (Goodchild, 1993). In order 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 application of GIS in water resources. Miles and Ho (2001) discussed the general issues of GIS application in civil engineering, such as the limitations, alternatives, and context. Numbers of efforts aimed at the integration of GIS with other water quality models have been made in the last decade (Pinho et al., 2004; Ng et al., 2009; Menezes and Inyang, 2009).

Environmental Fluid Dynamics Code (EFDC) is a general purpose modeling system for simulating one-dimensional, two-dimensional, and three-dimensional transport and water quality processes in surface water systems including: rivers, lakes, estuaries, reservoirs, wetlands, and near-shore to shelf-scale coastal regions. It has been listed as a tool for the development of Total Maximum Daily Load by the US Environmental Protection Agency (US EPA, 1997; Shoemaker et al., 2005). The model has been extensively tested, documented, and applied in environmental studies worldwide by universities, governmental agencies, and environmental consulting firms. The model has also been used for studies of estuarine processes (Ji et al.,

2001; Kuo and Hamrick, 1996), wetlands hydrologic processes (Moustafa and Hamrick, 2000), and water quality/eutrophication studies (Tetra Tech, 1999; Jin et al., 2007).

For EFDC model application, not only is the representation of the model data necessary, but also model data management and processing will be useful and important for water quality planning and management. However, the application of the GIS platform in EFDC modeling is not reported in any peer reviewed papers. In this paper, the integration of EFDC and GIS was conducted to overcome the limitations and enhance the data management and analysis capacity of the model, which improved the model application in water environmental management.

2. Methodology

2.1. Model Application of EFDC and Its Limitations

The EFDC model was originally developed at the Virginia Institute of Marine Science for estuarine and coastal applications as a hydrodynamic model (Hamrick, 1992). In addition to hydrodynamic, salinity, and temperature transport simulation capabilities, EFDC is capable of simulating cohesive and non-cohesive sediment transport, near-field and far-field discharge dilution from multiple sources, eutrophication processes, the transport and fate of toxic contaminants in the water and sediment phases, and the transport and fate of various life stages of finfish and shellfish (Park et al., 1995; Tetra Tech, 2002, 2006a, b, c, d).

Four primary models are included in EFDC: (1) a hydrodynamic model, (2) a water quality model, (3) a sediment transport model, and (4) a toxics model. The EFDC hydrodynamic model can solve the three-dimensional, unsteady, free surface, turbulence averaged equations of motion for a variable density fluid (Hamrick, 1992). The second moment turbulence model, developed by Mellor and Yamada (1982) and then modified by Galperin et al. (1988), is used for turbulent closure. EFDC uses orthogonal curvilinear or Cartesian horizontal coordinates and a stretched sigma vertical coordinate for its coordinate system (Park et al., 2005). The hydrodynamic model predicts water depth, velocities, and water temperature. These outputs of the hydrodynamics model can be directly coupled to the EFDC water quality model (US EPA, 2000). It can also generate a hydrodynamic linkage file for connection with other water quality models. The water quality portion of the model uses the results from the hydrodynamic model to compute the transport and transformation of the water quality variables. The water quality model computes the fate of up to 21 water quality parameters including dissolved oxygen, phytoplankton (three groups), benthic algae, various components of carbon, nitrogen, phosphorus and silica cycles, and fecal coliform bacteria. The sediment transport and toxics models use the hydrodynamic model results to calculate the settling of suspended sediment and toxics, resuspension of bottom sediments and toxics, and bed load movement of noncohesive sediments and associated toxics (US EPA, 2000).

For a regular model application of EFDC, model configuration parameters and environmental data of the water bodies

should be provided in the model input files by the modelers. The input files can be grouped by function as follows: general data and run control files, horizontal grid specification files, initialization and restart files, and time series forcing and boundary condition files. All these model input files are free-format ASCII text files, which offer modelers a lot of editing flexibility. However, it also involves a large amount of work for modelers to prepare the model input data based on the geographical and hydrologic information of the water body. The output files produced by EFDC can be grouped as: diagnostic output files, restart and transport field files, point sample analysis output files, and concentration graphics and visualization files. These output files are also in ASCII free-format, which requires extensive work to enable presentation and analysis.
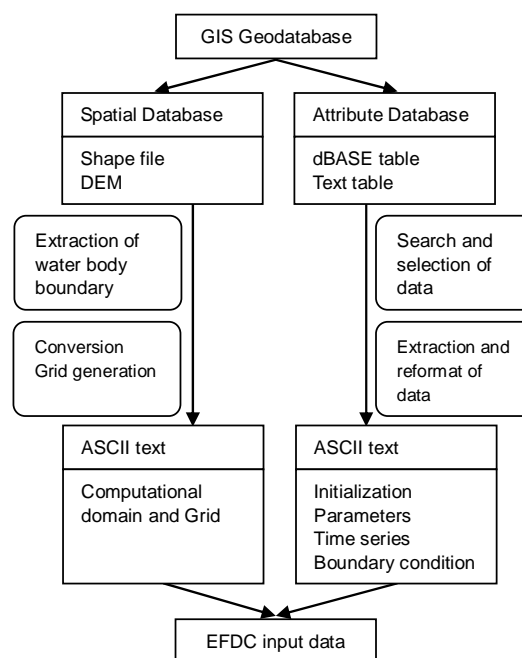

Figure 1. GIS based data operation in pre-processing of the EFDC modeling.

There are a few software packages developed to facilitate the pre-processing and post-processing of the model. GEFDC is a grid generation program offered by EPA for use with the EFDC model, which also uses free-format files to generate grid files (Tetra Tech, 2002). EFDCview (US EPA, 2010) is a Windows-based interface for creating necessary input files and displaying output results for the EFDC model. EFDCview uses a visual orthogonal grid generation (VOGG) system to prepare grid files for model pre-processing, which is also capable of converting grid files to GIS shape files. This interface significantly decreases the repetitive effort typically required through manual grid generation methods. EFDC_Explorer is another Windows-based interface system for EFDC model application. It supports model pre-processing and post-processing including: model set-up, grid generation, testing, calibration, and visualization of model output results (Craig, 2009).

In practical applications, most of the time the model will be run and analyzed in different scenarios for water quality management and decision making, or with different model input datasets for model calibration and validation. There will be a large amount of input and output data for modelers to manage and compare during the application of the model. Although the current software packages for EFDC were enhanced with the functions of model pre-processing and post-processing, they were more focused on grid preparation and output data visualization. The methods of presentation, analysis and management of model data offered by the software packages may not handle all the needs in every case. Some of them have the GIS interface only for grid display, but not for data storage and management, which may not be compatible with the batch-oriented model application. Grid-only displays have become the major limitation for the further application of this model.

The model also requires considerable expertise in environmental data of water bodies and knowledge of the model to operate EFDC. So it will also be difficult for modelers to share the model information and data with other communities which are interested in the water body but are not very familiar with the operation of a water quality model.

2.2. General Methodology for the Integration of the EFDC Model with a GIS Platform

Most of the water quality models, which solve hydrodynamic and pollutant fate problems in a water body, will use and generate large amounts of geographically-referenced data, and thus involve great efforts in pre-processing of model input data and in representation and interpretation of model output data as well. The visual display capacity of GIS facilitates the representation of geographically-referenced characteristics and spatial relationships of a body of water. GIS also enables the water quality modelers to integrate the data from different sources during the modeling process and manage the model data efficiently, allowing the modelers to have more complete control of data input, access, and manipulation (Patino-Gomez et al., 2008).

In this paper, the development of the EFDC and GIS integrated system is carried out using GIS Software ArcGIS Version 9.2, developed by the Environmental Systems Research Institute, Inc. (ESRI). In the integration procedures, a database is built to process all the data used in the application of the model. This database is setup in the framework named "geodatabase" which is used for data storage and management on ArcGIS platform. It is the combination of "geo" (spatial data) and "database" (data repository) which creates efficient spatial data storage and management.

A geodatabase is a physical store of geographic information (spatial, attribute, metadata, and relationships) inside a relational database management system (RDBMS). A relational database management system is a type of database in which the data can be spread across several tables that are related to each other. Data in related tables are associated by shared attributes. Geodatabase offers many advantages for users including, but not limited to, centralized data storage, support for advanced

geospatial relational models, more accurate data entry and editing, multiuser access and editing environment.

In the integration of the EFDC model and the GIS platform, a geodatabase can be generally divided into a spatial database and an attribute database, in which the spatial database stores the spatial coordinate data and the attribute database contains the attribute data corresponding to the specific spatial location. The computational domain of the EFDC, the map of water bodies, and other data related to coordinate specifications are stored in spatial database. 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. Then an index of the spatial and attribute data is built in the geodatabase to create a relationship. With this index and other data processing functions in GIS, modelers can accurately and conveniently access the data stored in the geodatabase. Two separate flows of data are established between EFDC and GIS, one is for pre-processing and the other is for post-processing. All the data will be stored in geodatabase. The details of the integration process are discussed in the following sub-section.

2.3. GIS Application in Pre-Processing and Post-Processing of EFDC Modeling

In the pre-processing stage of EFDC modeling, GIS is used to enhance the preparation of the model input data. As shown in Figure 1, the maps of the study area and the water body can be collected and stored in a geodatabase (in the shape file) as the spatial data. The terrain data of the watershed can also be handled efficiently in GIS as the digital elevation model (DEM), which is the basis of some critical data in EFDC modeling. In the application of EFDC modeling, the water body is generalized as a computational domain and separated into a series of interconnected partitions (a grid). A sequence of input files should be prepared to describe the spatial data of the model grid in the format of an ASCII text file. In the past, this was done manually by the modeler and required a great amount of work. But with the spatial modeling capability of GIS and the support of the third-party software discussed in Section 1.3, the generalization of the water body can be achieved much more efficiently.

The attribute data include the historical data of the water level, inflow and outflow of the water body, water quality data collected by the monitor stations, the load of point and nonpoint sources and the weather data. These different data, in differently formatted table files, can be imported and stored in geodatabase (a in dBASE table or text table file) and can be reformatted and used as the initialization, parameters, time series forcing and boundary condition files for EFDC model input data, which are also in an ASCII text format file.

In post-processing of EFDC models, GIS is used to enhance the presentation, process and management of the model output data. As shown in Figure 2, the output of EFDC is the spatial and temporal distribution of certain variables in the model,
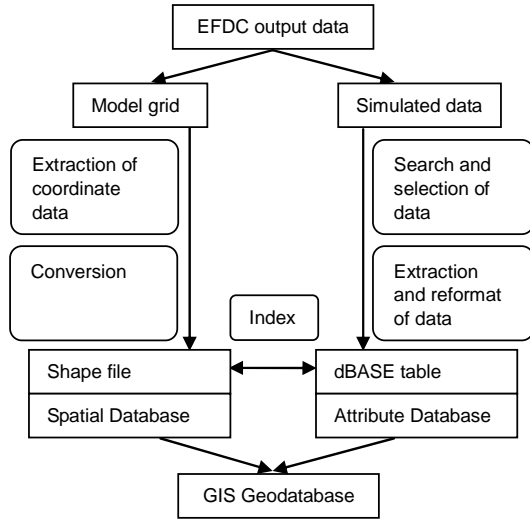
Figure 2. GIS based data operation in post-processing of the EFDC modeling.

such as the flow field of the water body and the concentration field of some water quality constitutes which can also be stored in the GIS geodatabase as spatial data and attribute data. The flow field or concentration field data from the model (i.e. the model output) can be reformatted and converted to a GIS dBASE table or text table file as attribute data.

The computational grid of the water body in EFDC modeling should be converted into a GIS shape file and stored in a GIS spatial database. Several input files, related to the model grid, contain the necessary information from the spatial coordinate data to accommodate the conversion. With the spatial coordinate data, the model grid can be converted into a GIS shape file with polygons representing the model cells.

In the computational grid of the EFDC model, each cell has a fixed index number as its identification. This index number should be contained in a GIS shape file corresponding to the EFDC model cells. With this index, the modeler can relate the attribute data and spatial data and build mapping between the water quality data and the polygons. Generally, the data flow in the integration of the EFDC model and GIS platform is shown in Figure 3.

The EFDC input data and output data can be integrated into one GIS geodatabase. In order to integrate the GIS with the EFDC model, it may take longer time for the modelers to process and convert the EFDC modeling data and set up the geodatabase in GIS. However, the integration can significantly enhance the data management capability. The modeler can use this geodatabase to analyze the model data with the standard GIS functions, such as a custom layer and data query. In practical application, the model will be run with a different input dataset for scenario analysis or model calibrations. The different model input and output data can be integrated into a geodatabase. Metadata, which are used in the ArcGIS platform for description and documentation, can also be added into the geodatabase. Metadata will make it more convenient to share the model data and information among different users.
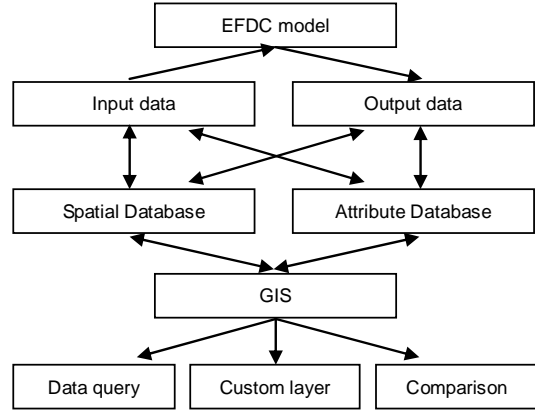

Figure 3. Data flow in the integration of the EFDC model and GIS platform.

3. Case Study

A case study was conducted to demonstrate the integration of EFDC and the GIS platform. This EFDC model application as a coupled hydrodynamic and water quality modeling system is one part of the implementation of a eutrophication total maximum daily load (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. Algal dynamics and dissolved oxygen levels in the basin was simulated for the TMDL development.

For Lower Charles River Basin area, the input dataset of the EFDC model application includes geological, atmospheric, hydrological and water quality information of the water body. The output of the model also contains large quantity of spatial data in different types. The information of industry loads, measured water quality data from the monitored stations and other kinds of information of the area are also important for the study. The complexity of the model data makes it necessary to apply the integrated system of EFDC and the GIS platform in this study area.

3.1. Modeling Domain and Modeling 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 the 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 from about 90 ~ 600 m. Its water volume accounts for approximately 90 percent of the entire water volume of the basin. Water depths range from 1.8 to 3.6 m in the basin upstream of the BU Bridge and 2.7 ~ 11.0 m in the lower basin (MADEP, 2000).
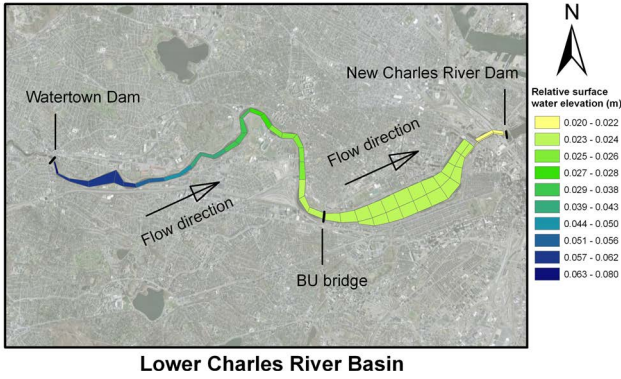
Lower Charles River Basin

Figure 4. Relative surface water elevation.
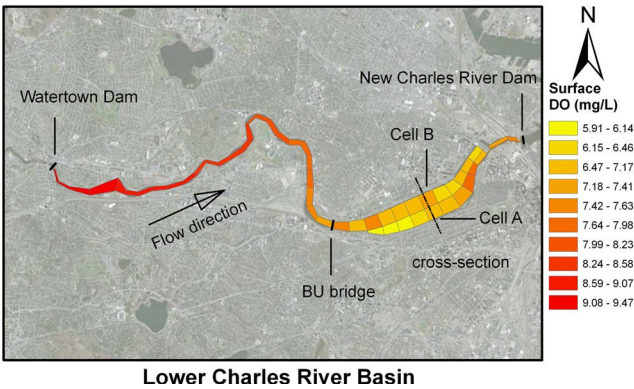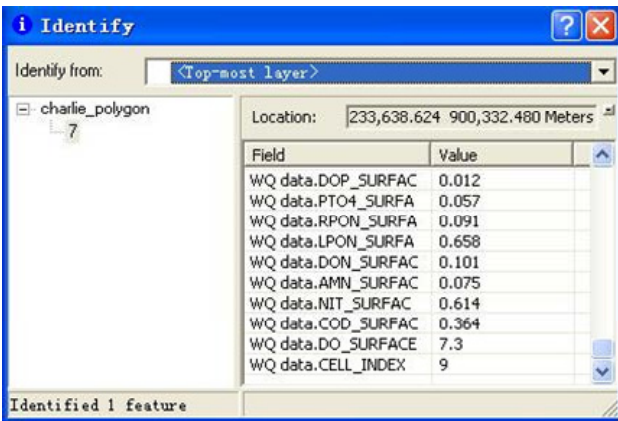

Lower Charles River Basin

Figure 5. Surface dissolved oxygen concentration field distribution.

Notes: where all values have units of mg/L except CELL_INDEX; DOP is dissolved organic phosphorus, PTO4 is total orthopho- sphate, RPON is refractory particulate organic nitrogen, LPON is labile particulate organic nitrogen, DON is dissolved organic nitrogen, AMN is ammonia nitrogen, NIT is nitrate nitrogen, COD is chemical oxygen demand, DO is dissolved oxygen, and CELL_INDEX is the number of the cell in EFDC model.

Figure 6. Water quality data query in the GIS geodatabase.

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 constructed for this section used curvilinear horizontal grid cells. A varying-size grid of 50 to 400 m was used and 8 vertical layers were set in the horizontal grid having varying thickness ranging from 0.25 to 1 m throughout the modeling domain. The total num- ber of water cells at the surface layer is 56.

The 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 and inflow concentration files; power plant withdrawal, temperature rise and discharge file; water column initial salinity and temperature concentration distribution files; and other input files for a EFDC water quality sub-model. After the implementation of the EFDC model, the output files of the EFDC were available, such as flow field of the water body and the concentration field of some water quality constitutes. In order to achieve EFDC model output data, a run of the model was conducted for a period of 360 days. The model is set up according to the model study report of the Lower Charles River Basin (Tetra Tech, 2005b). A complete run of the model took about 6 hours for one trial on a 2.4 gigahertz Core 2 Duo based IBM compatible computer.

3.2. Integration of EFDC Model Dataset into GIS Geodatabase

As described in Section 2, the grid data and water quality output data of the Lower Charles River Basin EFDC model is integrated into the 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, with the index built between the attribute data and spatial data of the model, users can relate the hydro-dynamic and water quality information with the corresponding location of the model grid. Different theme maps can be created with the simulation data of the model and the map of the study area. Users can customize multiple layers in the theme map to represent different types of information. Figure 4 is the map of relative surface water elevation based on the model's initial calculation water elevation (0.000 m). Figure 5 is the map of the surface dissolved oxygen concentration field of the water body in the study area. In Figure 5 it is shown that the dissolved oxygen concentration in the lower basin is much lower than that of the upstream part of the basin, which is consistent with the actual conditions in the basin. The low dissolved oxygen 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).

As shown in Figure 6, water quality data can be geographically related to the water body map and data queries of water quality constitute concentration can be performed using the interactive capability of the GIS platform. Users can directly get the water quality data of the basin by identifying the properties of different locations in the map without searching through the whole water quality data output file (Figure 6). Vertical stratification in the water body can be analyzed with vertical profiles created by the users. As shown in Figure 7, Cells A and B are included in a cross-section of the model (shown in Figure 5). The vertical profile is achieved by accessing the dissolved oxy-
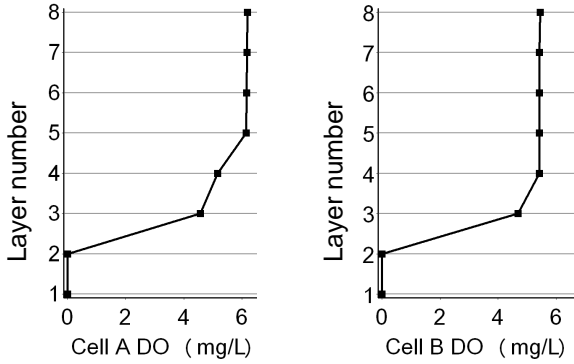
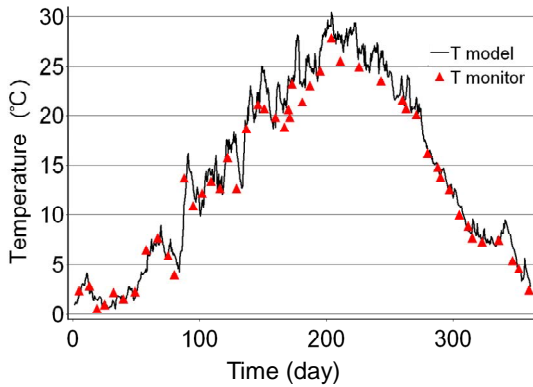**Figure 7**. Dissolved oxygen concentration vertical profiles of Cell A and Cell B.

Figure 8. Surface temperature data comparison.

Figure 9. Surface dissolved oxygen concentration data comparison.

Figure 10. Scatter plot of the monitored temperature versus simulated temperature.

Figure 11. Scatter plot of the monitored dissolved oxygen concentration versus simulated dissolved oxygen concentration.

gen concentration data in different model layers of Cells A and B.

The measured water quality data from monitor stations of the study area can also be introduced into the GIS geodatabase. The modeler can compare the measured data with simulated data of the model in model calibration and verification process. The correspondence between the measured and simulated data can be analyzed by plotting the data and calculating the correlation coefficients (Rs). Figures 8 and 9 show the surface temperature and dissolved oxygen concentration data comparisons between monitored and simulated results using the EFDC model at one monitor station, respectively. And Figures 10 and 11 show the scatter plots of the monitored data versus simulated results at the same monitor station with Rs of 0.9892 and 0.8478 for temperature and dissolved oxygen, respectively.

3.3. Environmental Implication of the Integrated System

For the modelers, the integration of EFDC and the GIS platform provides a better solution to process and manage the model data, which improves the efficiency of model operation. Modelers can create interactive queries (user-created searches), analyze spatial information, edit data and maps, and present the results of all these operations. Modelers can also add descriptions about the input data, the running control parameters, or any other necessary details about the model with metadata in the geodatabase, which makes it more convenient to share the model information and data with other people.
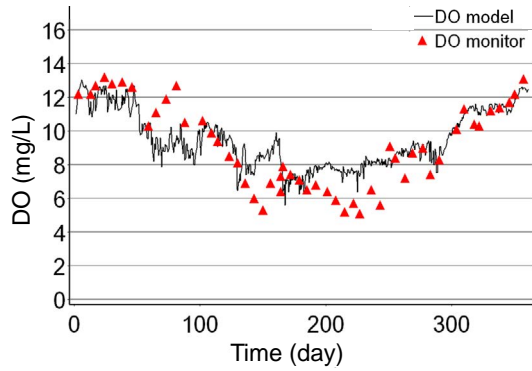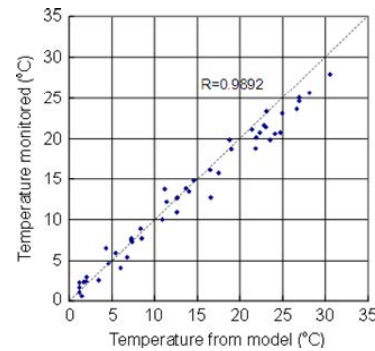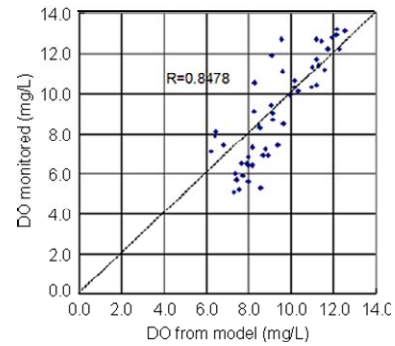
For water resource managers, the integrated system can combine the different environmental and social factors related to the water body into a geodatabase and represent it as an integrated view or map for the decision-making process. By comparing different scenarios in the integrated system, managers can gain insight into how the water body responds to the environmental changes or human activities, and evaluate the consequences of various water management options on the water body.

In this case study, the input dataset from the modeling report for the TMDL and the output dataset generated by the model were integrated into one geodatabase. Different users can

access the model data through GIS-based interface, getting to know the relative information of the study area and the predictive result of the model. The integrated system could be used to support decision making for future TMDL.

4. Conclusions

The integration of the EFDC model and GIS platform was studied in this paper. The advantages of the integration are summarized in the following aspects: (1) the application of GIS improves the model data collection and pre-processing; (2) the input and output data of the model can be integrated into a GIS database, which facilitates convenient data management and sharing; (3) high quality maps 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 will improve the application of the model. With the powerful capacity of the GIS platform, the integrated system facilitates efficient data management and analysis of the EFDC model and improves its practical application. It will help the modelers and water resource managers in water environmental research, water resource protection, planning and management. Further study should be carried out to modify the source code of the EFDC model. The format of model input and output files can be transformed for direct storage and processing in the GIS database.

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