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Author(s): Y. W. Jiang, O. W. H. Wai, H. S. Hong and Y. S. Li

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A Geographical Information System for Marine Management and its Application to Xiamen Bay, China

Y. W. Jiang[†], O. W. H. Wai^{*}, H. S. Hong[‡], and Y. S. Li[†]

[†]Department of Civil and Structural Engineering
The Hong Kong Polytechnic University
Hong Kong
P. R. China
ceonyx@polyu.edu.hk

[‡]Key Lab. for Marine Environmental Science of Ministry of Education
Xiamen University
Xiamen
P. R. China

ABSTRACT

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Use of GIS (geographical information systems) is an effective and efficient method for gathering and processing large quantities of marine data, such as three-dimensional (3-D) time series of velocity vectors and suspended sediment and pollutant concentrations, and for visual display for result interpretation. A MGIS (marine geographical information system) has been developed for Xiamen Bay and other coastal regions in China. The system can handle object spatial property and a variety of data formats. Besides the standard data manipulation, plotting, and retrieval functions of GIS, two hydrodynamic/mass-transport numerical models for tidal flows, sediment transport, and pollutant dispersion have also been incorporated into the MGIS. Most of the modeling pre- and post-processing operations can be finished within the system. The pre-processing includes mesh generation, gathering of boundary and parallel computation information. The post-processing includes result posting, plotting and analysis. The MGIS has been implemented for more than three years and proven to be a useful integrated tool for generating and revealing various kinds of marine environmental information. Output from the MGIS may provide an important tool for harbor management, and feasibility or environmental impact assessment studies for new coastal structures. The system can be easily adopted in other marine areas through loading new databases and re-verifying the numerical model in the new domain.

ADDITIONAL INDEX WORDS: *Parallel computation, sediment transport, MapInfo.*



INTRODUCTION

Environmental management of marine systems is highly complex, and requires large quantities of information in almost all marine research areas, e.g. sediments, physics, chemistry and biology. It is tedious to deal with these data manually without the help of computer information technology. GIS makes use of advance in computer and database tools, which can offer efficient spatial data handling tools for this purpose.

At present, most commercial hydrodynamic numerical model companies are developing linkage with GIS. For example, Delft Hydraulics (Netherlands) has released a GIS function for its Delft 3D

(DH STAFF, 2000), while the Danish Hydraulics Institute (DHI, Denmark) and ESRI (USA) signed an alliance agreement (DHI STAFF, 2002) enabling DHI's models to integrate into the ESRI ArcGIS platform in the future. The linkages of Delft 3D and the DHI's MIKE 3FM and 21FM with GIS are relatively simple through an import and export function in the GIS software. Most of the pre- and post-processing for the numerical models are carried out separately.

A marine geographical information system (MGIS), which integrates GIS tools and 3D hydrodynamic numerical models, has been established for Xiamen Bay in China. The major properties of this system are listed as follows:

(1) Each information component has accurate coordinates, indicated by either longitude/latitude (units: degrees, minutes and seconds), Beijing coordinates, and local city coordinates (units: km).

*Corresponding author.

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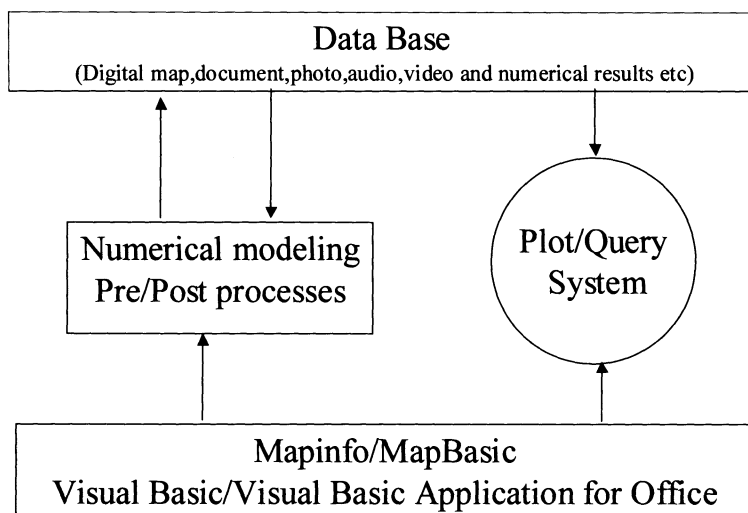


Figure 1. The four-part MGIS structure.

With this property it is possible to overlay all the information together simply based on its location.

(2) Various kinds of data (e.g. object characters, animations, images and documents, etc.) are integrated in the system, and can be retrieved and displayed easily.

(3) Digital maps and data can be sent directly to printers and to reports, e.g. reports in Word/Excel format, and used as an Office Automation system (OA) for environmental management purposes.

(4) Two hydrodynamic/mass-transport numerical models are incorporated into this system. One is the POM finite different model (MELLOR, 1998) and the other is the *Efficient Parallel Numerical Model* (EPM), (WAI and LU, 2000; WAI, *et al.*, 2003). These models produce a large quantity of hydrodynamic information for the MGIS, and the system makes the pre- and post-processing of the modeling operation more efficient.

The general GIS functions of MGIS are discussed in this paper, following which an application of the MGIS to Xiamen Bay making use of the pre- and post-processing functions of the system, will also be demonstrated.

STRUCTURE OF THE MGIS

Figure 1 shows the structure of the MGIS. The MGIS includes four parts: (i) the database; (ii) the numerical model; (iii) the Plot and Query sub-systems;

and (iv) the MapInfo/MapBasic development platform. The four parts work as an integrated system.

The MGIS development was based on MapInfo, which is one of the world's leading software for mapping and geographic analysis. Its function is similar to ESRI's ArcGIS, but it has no "polygonal line" and "vector transform" tools. Nevertheless, its advanced interface, stable property and MapBasic/OLE (Object Link and Embed) development platform are attractive to GIS programmers and numerical modelers. MapInfo provides an efficient interface for researchers to handle all types of information, such as revising digital maps, calculating the spatial property of mapped objects, and capturing different kinds of multimedia files to the system's database. Besides MapInfo's function, the MGIS offers customized tools for the Plot and Query systems, such as auto-frame tools for map plotting, points to polygon/polyline and data update tools in the Plot system. The Query system was developed with Visual Basic, Visual Basic for Applications and MapInfo OLE. Microsoft's Visual Basic is an Object Oriented facility that can make use of MapInfo OLE. The Visual Basic for Applications, a plug-in tool of Microsoft Office, can be combined in Visual Basic and operated in Word and Excel directly. Thus, it is a multifunctional integration system. With the use of MapInfo OLE, this sub-system can handle digital maps and spa-

tial database parameters, such as points, lines and areas. The Visual Basic functions are applied to handle multimedia files making this sub-system capable of showing photos, audios, and videos. The Visual Basic for Applications can operate Microsoft Word and Excel, and can transfer database and digital maps to reports and tables in a fixed template. In this way, the office automation (OA) system is constructed.

For numerical modeling, the pre- and post-processing for a finite difference or a finite element model simulation are important tasks. The pre-processing includes mesh generating, assigning depth to nodes, and re-numbering nodes for parallel computation, etc. Commercial software such as Femap and other shareware such as *Grid.f* included in the Princeton Ocean Model (POM; MELLOR, 1998) can generate meshes for the model domain. Femap can generate triangular and quadrangular finite element mesh, and *Grid.f* is for generating simple orthogonal finite difference meshes. However most of the commercial finite element analysis software such as Femap is for structural and material analysis and the mesh can not be adjusted in each element or node. This is necessary for hydrodynamic modeling of marine environments because almost all of the model domain boundaries are irregular and the nodes may not fit the requirement of the corresponding model. With the grid generation tool integrated in the MGIS, the system can revise the model mesh to suit the need of the model. Furthermore, in order to implement parallel computation of the EPM on a distributed memory parallel computer, the MGIS can divide the global domain into many sub-domains according to the quantity of available computer processors, and each of the sub-domain calculation is handled by a separate processor. For the POM finite difference model, the MGIS can decide whether the node is "water" or "land"; the latter can be excluded from the hydrodynamic computation. The MGIS also handles post-processing of the numerical model results, such as displaying the current flow and sediment concentration patterns. In the MGIS, all the model results can be imported into MapInfo via MID/MIF, which is an ASC interchange file format of MapInfo. The current flow pattern can be treated as vectors, i.e. a line type in MapInfo, and the concentrations can be shown as grid thematic maps.

Because the general GIS data management functions and the hydrodynamic/mass transport numerical models are integrated under one system

with a uniform coordinate system, sharing and exchanging information in the same database is easy. The general GIS functions can provide the bathymetry information, boundary conditions and model grid mesh for numerical model simulations efficiently, and the numerical models can generate additional useful predicted/simulated information (e.g. velocity, suspended sediment, and pollutant concentrations) that can be stored in the database directly for further usage.

Data Information Retrieval Function (Plot Query/System)

To create a user-friendly system for engineers and marine environmental decision makers, the MGIS includes practical tools for managing and displaying various types of data and information in two sub-systems, namely the Plot sub-system and the Query sub-system. The two sub-systems are described in the following paragraphs.

Map Displaying Function (With the Plot Sub-system)

MapInfo provides tools for map revising and interrogating purposes, such as combining, buffering and generating thematic maps. For a marine data handling system, these tools are not enough because the marine parameters vary with time and space more quickly than some general local land parameters, for example, the time scale of tidal water areal variation is smaller than for variation of tree coverage on land. Hence in the MGIS, additional tools have been developed to handle the marine parameters more efficiently, including for example, a Beijing/local city coordinate system converter, auto-framing tool, point-to-region/polyline tool, labeling point position with the Beijing/local city coordinate and database auto-update, etc.

In Figure 2, an interface for selecting projection and coordinate systems is shown. MapInfo does not offer both the Beijing coordinate system and the local city coordinate. The former coordinate is used widely in China and the latter suits every city in China. Thus the MGIS includes these two coordinate systems by setting the accurate projection and coordinate parameters, e.g. the ellipsoid factor, oblique azimuth and scale factor, etc. Through this setting, all the map objects will be indicated by units in degrees and kilometres. With the uniform global units in degrees, objects in difference coordinate systems can be combined in one map.

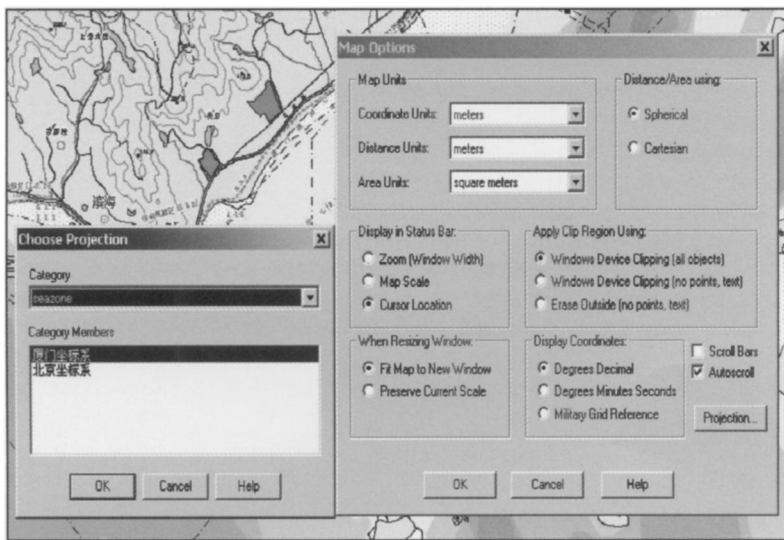


Figure 2. The coordinate system converter interface.

Frames are needed for most marine charts. An auto framing tool for drawing grids and axes has been developed. Figure 3 shows the auto-framing tool interface for prescribing the grid and axis properties for a selected area. This tool can be implemented by command or tool bar. With the use of the latter, to draw a map of selected area, clicking at two opposite corners of the interested area, a grid map with both degree and km labels will be formed. In order to build this tool, a coordinate converting algorithm between degrees and km based on the Beijing or local coordinate system has been developed for labelling axes in both units in the same frame.

In the government's Marine Office in China, marine survey is an important routine. After a cruise survey, the collected data, such as the coordinates recorded by GPS can be captured and forms a polygon or polyline directly on a digital map by a tool, namely "point-to-polygon/polyline", in the MGIS. The length and area of an object can also be calculated and stored into the database automatically. The position of a particular point can be input through this interface or imported from files that contain the coordinate information. Sometimes it is required to label the coordinates of the control points on a map. The MGIS has included a tool to label the point position in degrees or km. Under the "snap to point" condition, clicking the control

point with the mouse, the coordinates of the point will be labelled automatically.

Information Acquiring Function (With the Query Sub-system)

Although the Plot sub-system in the MGIS can capture, edit and print the data in database easily, because of the limitation of MapInfo it cannot handle multimedia files, such as audio and video files. Furthermore, the Plot sub-system is mainly designed for engineers to carry out more complex data manipulation and analysis tasks. Managers and decision makers prefer a system that can handle the multimedia files, extract information from the database, and sketch simple diagrams, etc. They do not want to accidentally modify any original data such as the coordinates of a navigation channel. The Query sub-system can satisfy this need. It offers powerful functions to query and display different types of multimedia clips and editing tools to draw simple maps without modifying the important database. The Query sub-system was developed from Visual Basic and Visual Basic for Applications based on the MapInfo OLE. The interface of this sub-system is shown in Figure 4. On the top and bottom of this interface, there is a menu bar, tool bar, map window and status bar, respectively. This sub-system contains many que-

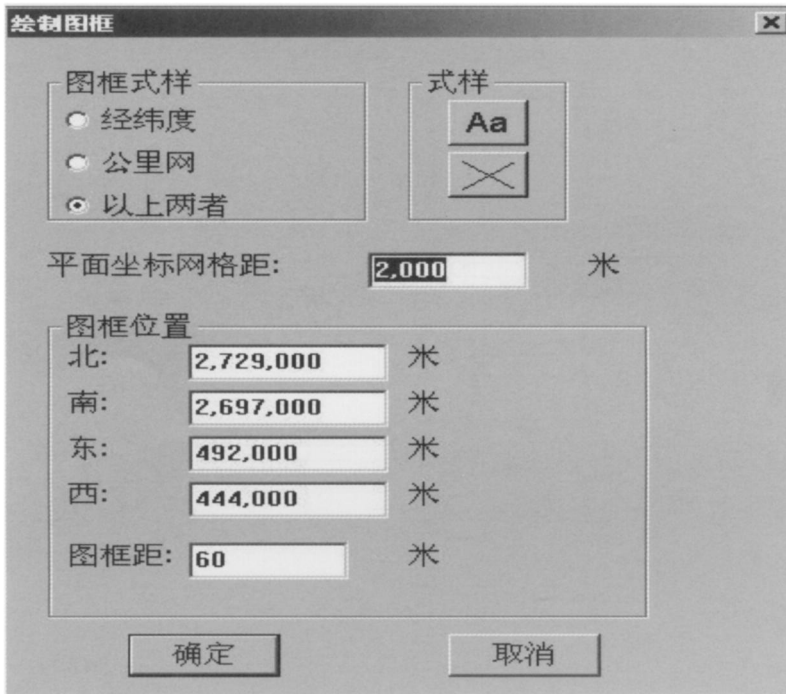


Figure 3. The auto-framing interface for the prescription of grid and axis properties (Characters in Chinese).

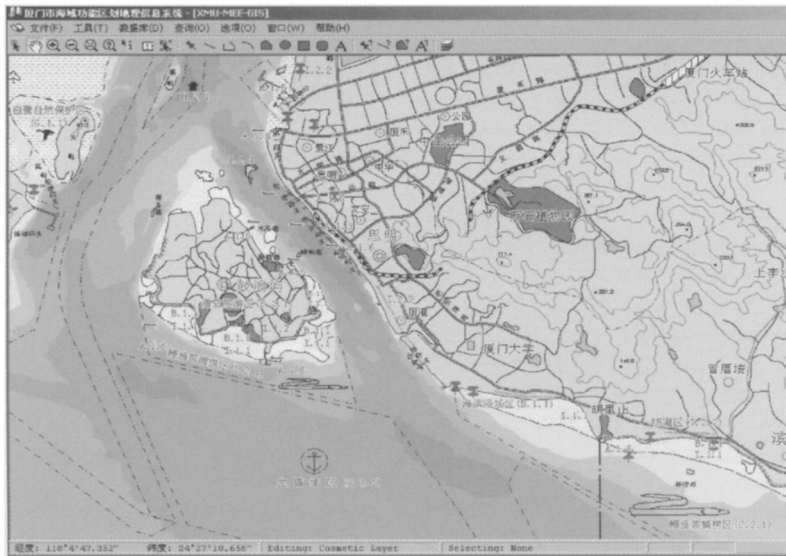


Figure 4. The query sub-system is displaying the map of Xiamen Bay.

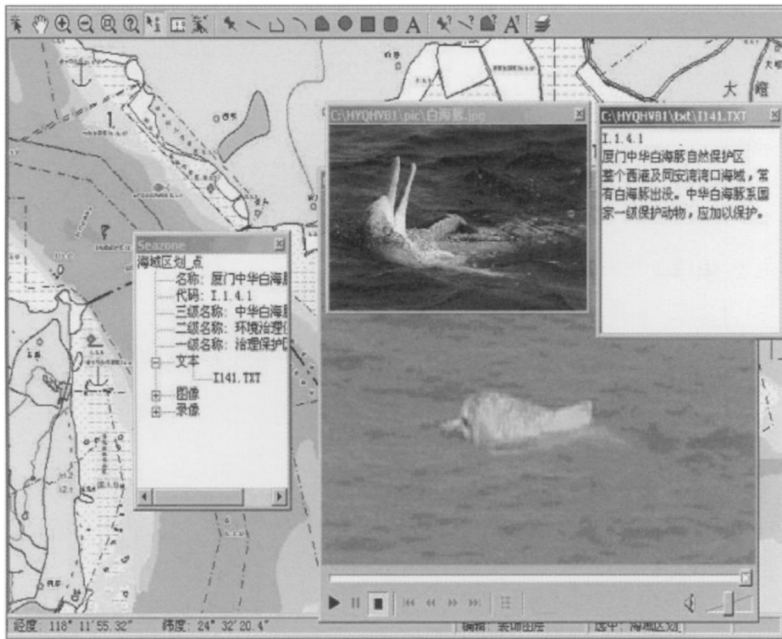


Figure 5. Click-query interface. The image, document and video linked with the Chinese white dolphin are shown.

rying tools and plotting tools, and the multimedia files can be displayed and the required information selected and exported to reports and documents automatically. Some of the main functions in the sub-system are described below.

The information stored in the database, such as coordinates, length, area, and multimedia files, is linked with the corresponding object in a digital map. The linkage property can be saved as a field of the object. Thus, when the object is queried, the linked files, e.g. a video clip or an executable file, will be opened. With the use of the "click-querying" tool, clicking on an object within the digital map, the corresponding information and files will be displayed. As an example Figure 5 shows the information relating to a Chinese white dolphin reserve in Xiamen Bay. Furthermore, a report about the object or the combination of the objects can be created via the selected object information in a fixed document template. This tool is developed from Visual Basic for Applications and can export the related data to any Microsoft Word and Excel documents automatically in a fixed format. Digital maps can be inserted into the template document as well. This will be handy for report writing.

Similar to the multimedia files, executable files

can also be included in the digital map database. Figure 6 shows the model computed time sequences of tidal elevation, tidal flow and suspended sediment concentration throughout a tidal cycle. The sequence animation was performed by an executable file. It shows the flow pattern and sediment concentration in different layers and time in the tidal cycle. This animation was produced by displaying a series of images sequentially, and the corresponding tidal elevation was indicated by a moving node on the tidal elevation process line. This function is useful for decision makers to visualize, for example, the change of flow patterns due to land reclamation.

APPLICATION OF THE MGIS TO XIAMEN BAY

Xiamen Bay is an important port and a popular tourist area in China. Consequent upon rapid economic development, the local government is facing conflicts between port development, marine aquaculture and environmental protection. To increase the port loading capability, further reclamation and deeper waterways are planned. Marine aquaculture is providing high quality seafood for residents and tourists. On the other hand, Xiamen

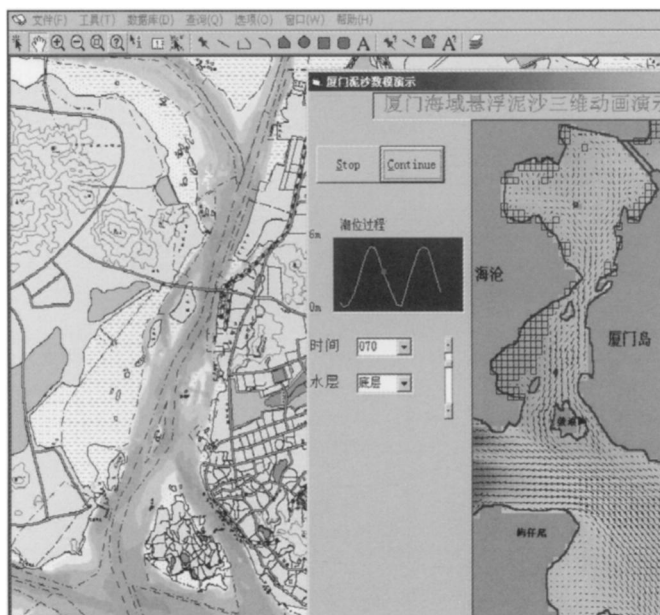


Figure 6. Animation of numerical model results. The tide elevation, flow and sediment patterns are displayed.

Bay is also a habitat to a number of endangered species, including the Chinese dolphins, egrets and lancelets. In order to consider the interest of all the parties, a project titled “Xiamen seas function zonation” was carried out by the Xiamen government. The MGIS described in this paper originated from one of the sub-projects. The main purposes of the MGIS are: (1) to collect, process and visualize the data and information provided by other sub-projects, and (2) to integrate hydrodynamic/mass-transport models to provide hydrodynamic and mass transport information in the region.

The MGIS database is composed of 19 layers of digital maps, e.g. text layer, survey point, zonation point/line/area, land boundary, bathymetry of sea bottom, topography of land, etc. The coordinate projection is based on the Xiamen local city projection. Over two hundred photos in JPG format, one hundred video clips in MPEG format, one hundred document files and several executable files are stored in the database and linked with the objects in the digital map.

The POM and the EPM models are incorporated into this system to simulate or forecast the hydrodynamic and pollutant transport patterns in the bay. Calibrations and verifications of two models applied in Xiamen Bay have been conducted in a

number of environmental impact assessment projects and the details can be referred to in WAI *et al.* (2003). As mentioned, the MGIS has efficient tools to handle pre- and post-processing tasks for general numerical modeling exercises.

The POM is a finite difference model, in which grids are rectangular or orthogonal. The rectangular grid is easy to generate, but not the orthogonal grid. There is a simple orthogonal grid generator namely *Grid.f* in POM, but it is difficult to use because it has no user-friendly interface and it cannot suit irregular boundaries. The EPM, which uses the second order nine-node quadrilateral or six-node triangular isoperimetric finite element mesh, does not have a mesh generator either. The pre- and post-processing would be difficult tasks to achieve without the help of user-friendly tools. However, with the use of the MGIS mesh, files can be captured, revised and input relatively simply into the numerical models.

Orthogonal Mesh Generation

The POM's *Grid.f* can generate orthogonal mesh for a simple boundary configuration. For complex boundaries, the mesh will not be boundary-fitted because some mesh may be set as “land mesh”,

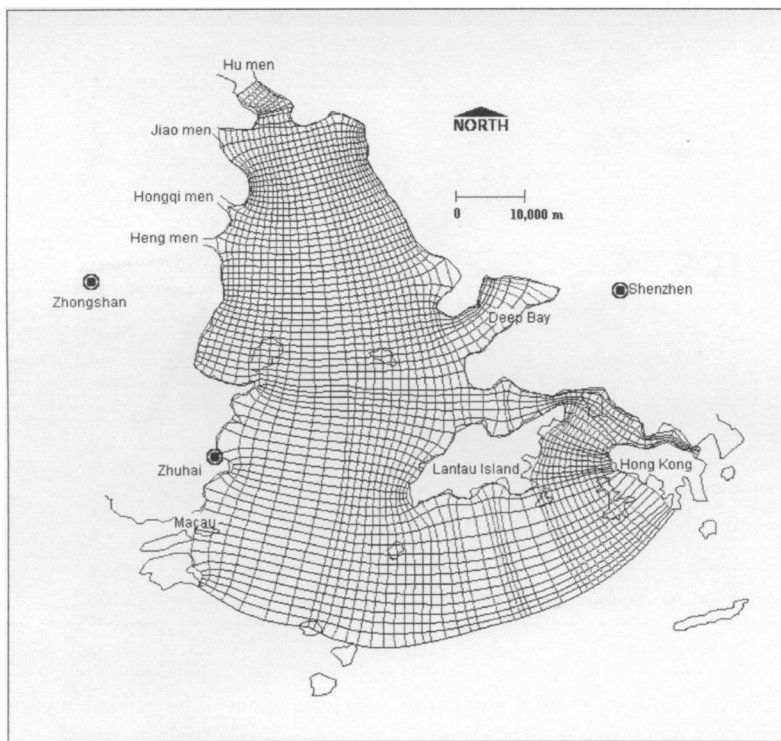


Figure 7. Orthogonal mesh for the Pearl River Estuary simulation (After CHAU and JIANG, 2001).

and the grid stairs will appear at the boundary (EZER and MELLOR, 1992). The MGIS can divide a complex model domain to several domains with relatively simple boundaries, and in each domain an orthogonal mesh is generated separately by the subroutine *Grid.f*. The mesh of each sub-domain can be combined together to form a global mesh. An application of POM with such a mesh in the Pearl River estuary is shown in Figure 7 (CHAU and JIANG, 2001).

Finite Element Mesh Generation

Most of the commercial finite element analysis software programs, such as Femap, Ansys, etc., were developed for structural mechanical and material problems. They cannot deal with very complex shapes such as estuary boundaries and the mesh can not meet the requirements of the EPM. With the MGIS, deleting redundant points along the coastal boundary can smooth the complex boundary geometry. The smoothed boundary file will then be exported to a finite element analysis

software to generate a best fitted mesh. The mesh file will be captured back in the MGIS for revision and checking for errors, e.g. duplicate points, mesh angles that exceed the critical values, etc. The revised mesh information, such as the node positions, boundary nodes and node/element relations, can be exported to another file that can be used by the EPM directly. Figure 8 shows the mesh revision interface.

Parallel Computation Function

Finite element modeling is more computationally expensive than finite difference modeling because a huge amount of time is spent on solving large linear equations. In the EPM, there are two large linear equation matrices, one is a sparse positive symmetric coefficient matrix that can be solved by the preconditioned conjugate-gradient method. The other is a sparse non-symmetric matrix that is solved by the bi-conjugate-gradient method. Both of these two iterative solvers can be parallelized easily. In order to increase the com-

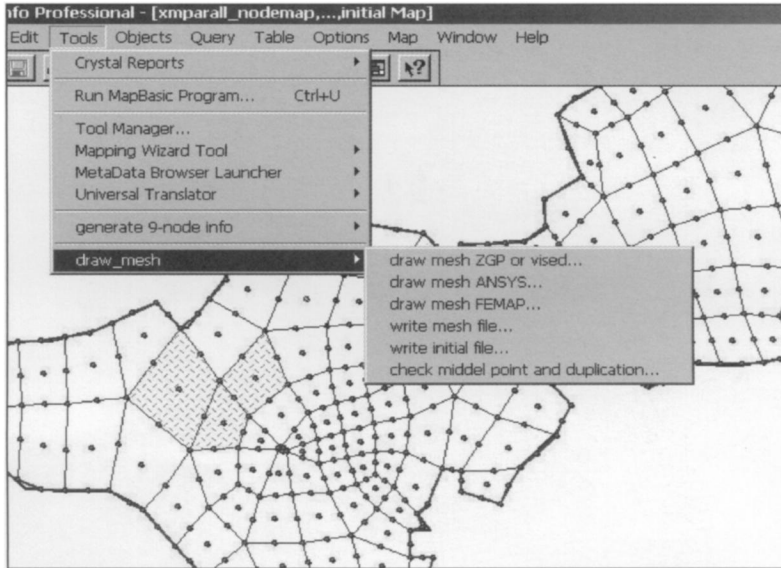


Figure 8. Mesh revision tool for the finite element model.

putation efficiency, the EPM is parallelized and running on a distributed memory parallel computer under Message Passing Interface (MPI). This computer is also named the Beowulf computer, which can be constructed by connecting several personal computers with a switch. In this application to Xiamen Bay, the model domain is divided into eight sub-domains and the computation with each sub-domain is handled by a processor. Thus, each processor knows which nodes belong to it and what information should be passed to the other neighboring processors for parallel computation. This information can be collected in the MGIS. Figure 9 shows the interface for collecting parallel computation information. The Xiamen Bay mesh used in the EPM is also shown. In this interface, if one selects the node and grid layers that will be decomposed with assigned partition pattern, every node will be reordered according to the sub-domain that it belongs to.

Post-Processing

For numerical modeling of estuarine hydrodynamics, it is important to present and interpret the model computed results in an efficient manner. MapInfo offers a simple file format namely MIF/MID for this task. The first file records the object type and position, e.g. the x, y coordinates

for each node. The second file records the attributes of the corresponding object. In the EPM, a subroutine has been developed for outputting the result in the MIF/MID format for a given time interval. The MGIS can capture these types of files directly and display the water current pattern as a vector map. The mass concentration can be presented using the "Grid thematic map", which is a function of MapInfo. Both of these two maps can be overlapped with other digital maps because they are using the same coordinate system. The information can be obtained and illustrated by mouse clicks. The information window in Figure 10 shows the information linking with the current vector numbered 1394, which is a node serial number in the EPM model. The information includes water level, water depth, velocity magnitude and direction, vertical velocity component, suspended sediment concentration and salinity. The characters on the bottom-right corner of the information window indicate the time of the flow pattern, which is 1430, 8th August, 2000. The hydrodynamic/mass-transport map can also be overlapped on the other layers, such as the bathymetry layer, sediment distribution layer, sewage outlet layer, etc. This may be useful for feasibility study projects, for example, the impact of changing flow patterns on harbor erosion and deposition activities can be analysed and evaluated.

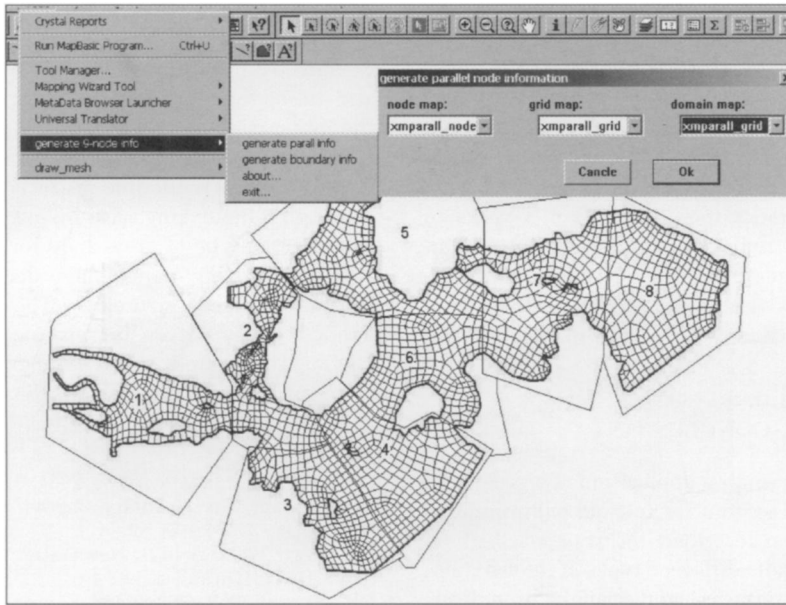


Figure 9. Parallel computation interface showing the 8 decomposed computation sub-domains.

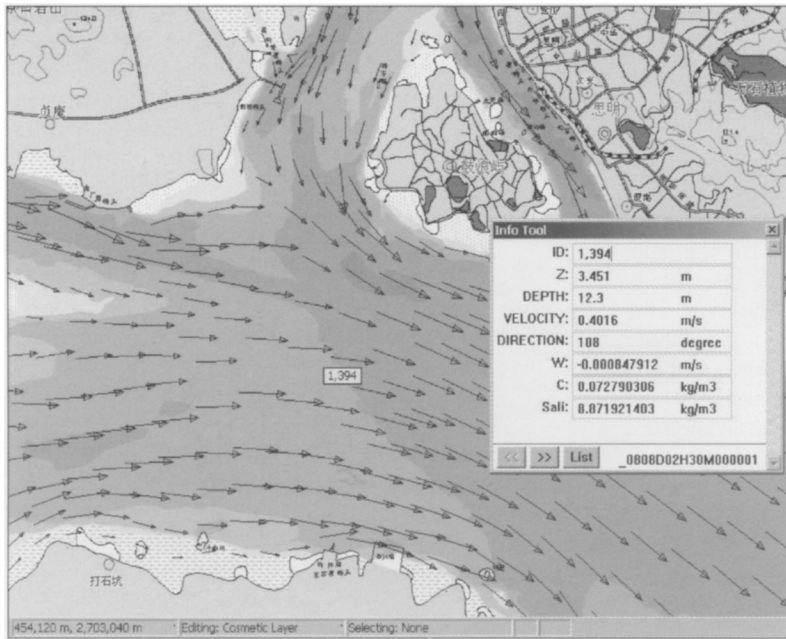


Figure 10. The post-processing tool showing the numerical results (water level, velocity, salinity, etc.) on the information window.

Partly because of the MGIS's data handling capability, accuracy and user-friendly interfaces, the "Xiamen Seas Function Zonation" conducted by the Xiamen Marine Management Office in 2002 was a success. It was clear that the efficiency and precision of the management process was enhanced with the help of the MGIS. The entire update exercise took only 7 months, whereas the first zonation assessment took more than 3 years to complete. Apart from Xiamen Bay, this system can also be applied to other estuarine, coastal and oceanic regions through loading new databases and re-verifying the numerical model in the new domain.

CONCLUSION

The functions, and an application of a geographical information system for marine environments (MGIS) have been described in this paper. With its capability to handle different types of information, user-friendly interfaces, and visualization functions, the MGIS can assist marine engineers and managers to deal with intensive data manipulation and coastal development projects more efficiently and accurately. MapBasic, Visual Basic and the Visual Basic for Applications works as a Graphic User Interface (GUI) in the MGIS that offers various tools for marine management and numerical model simulations, especially for the pre- and post-processing. This means that most of the tasks can be finished in the MGIS, and the managers do not require knowledge about advanced hydrodynamic modeling. However, the MGIS still has room for improvement in some ar-

reas, for example, there is no tool that can show the flow current and mass concentration in three dimensions, and vector animation is not available because MapInfo does not offer quick displaying and hiding functions for vector maps. In the MGIS, the integration of GIS technology and the two sophisticated hydrodynamic and mass transport models enables a one-line operation in processing, generating, analyzing, visualizing useful information that may be of great help for evaluating, revising, improving management decisions, and marine development strategies. The system can be applied easily to coastal marine areas through loading their site-specific databases and re-verifying the numerical models in the new domain.

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