Development of dynamic three-dimensional coastal information system: a case study in Hong Kong

Bi Yu Chen, Jianzhong Lu, Onyx W. H. Wai and Xiaoling Chen

ABSTRACT

Coastal-related data are four-dimensional in nature, varying not only in location and water depth but also in time. The heterogeneous and dynamic nature of coastal-related data makes modeling and visualization of these data a challenging task. A new object-oriented spatiotemporal data model to represent dynamic three-dimensional coastal data is proposed in this study. In the proposed model, a set of abstract data types allowing suitable spatiotemporal operations is defined to manipulate complex coastal data. In addition, a logical data model is proposed for the design of a spatiotemporal database. The proposed object-oriented and logical data models are implemented in a real-world coastal information management system in Hong Kong. An elegant visualization framework for displaying the coastal data, based on the concept of a time–depth bar, is presented in the case study.

Key words | coastal environmental management system, GIS, spatiotemporal data model, visualization

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INTRODUCTION

Background

Today, at least 40% of the world's population live on or near the coast (Bartlett 2000). Human health and livelihood have inextricable links with the coastal environment, motivated by the need for food, recreation, marine transportation, etc. Thus, it is important to understand coastal environment changes, potential changes and the necessity to manage coastal resources in a sustainable way. A huge quantity of geographically referenced hydrodynamic and water quality data gathered from various sources is required to achieve these goals. Geographic information systems (GIS), with the capacity to store, organize, manipulate, analyze, retrieve and display geographically referenced information, have the potential to play an important role in coastal management applications.

The use of GIS in relation to coastal management has received substantial attention since the 1970s when GIS was a new technology. Early GIS coastal management applications focused mainly on the storage and display of coastal data. Most applications used only spatial concepts and had limited graphics capability (Bartlett 2000). With computer hardware and GIS technological advances, GIS in coastal domains have progressed to include the use of advanced spatiotemporal analysis methods (Chen *et al.* 2006), sophisticated visualization techniques (Ng *et al.* 2007), the integration of complex hydrodynamic models (Jiang *et al.* 2004; Ng *et al.* 2009) and the development of new coastal research methods and concepts (Wright & Bartlett 2000; Balram *et al.* 2009).

Coastal-related data are four-dimensional (4D) in nature, varying not only in location and water depth but also in time (Lucas 2000). However, the current generation of two-dimensional (2D) GIS products lacks the capacity to handle complex dynamic three-dimensional (3D) coastal-related data. Considering the increasing importance of coastal environments, in part due to rising sea levels attributed to global warning, a rigorous spatiotemporal data model would be of great value to support better management and protection of coastal resources. Another key challenge in

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coastal applications is the interface design. Although elegant interface designs have been proposed for traditional 2D applications, few interface examples have been proposed to enable 4D coastal management applications. The focus of the study presented in this paper is on these two challenges, which confront the development of coastal information systems.

Literature review on the representation of space–time in GIS

Within the GIS community, field-based and object-based conceptualizations are well recognized as alternatives for representing geographical phenomena (Cova & Goodchild 2002). A spatial field is a mapping from continuous spatial locations to values from an attribute domain. A spatial object is a discrete entity with identity, location, shape and domain attributes. Geographic phenomena can be modeled using either a field-based or an object-based perspective. The choice depends on the application purpose and context. For instance, a lake is naturally represented as a discrete object in navigation applications, whereas the temperature of a lake is routinely modeled as a spatial field in the environmental application context.

The modeling of geographical phenomena becomes more complex when incorporating the time dimension. All geographic data components, including location, shape and other attributes, may change over time. In addition, the geographical phenomena may change continuously (e.g. coastal morphological changes) or discretely (e.g. constructions of coastal structures).

To represent dynamic geographic phenomena, many spatiotemporal data models have been proposed. The snapshot model is a simple field-based spatiotemporal data model, which uses spatial field sequences to represent geographic phenomena states at different times (Armstrong 1988). The event-based spatiotemporal data model (Peuquet & Duan 1995) is another field-based model. This model stores the initial state of the entire geographical area in a base map and records, as a series of events, the geographical area changes related to the initial state.

The spatiotemporal composite model is one of the most important object-based models (Langran & Chrisman 1988). It represents dynamic geographical phenomena as a set of objects which mutate over time. This model has been implemented by ESRI (a leading GIS vendor) in *Geodatabase Versioning*, to keep track of added and deleted objects in different timestamps. The moving object database model was proposed (Güting & Schneider 2005) to represent continuously changing phenomena. This model, using object-oriented techniques, implements a set of abstract spatiotemporal data types to manipulate spatiotemporal data, and develops spatiotemporal indexes to support complex spatiotemporal queries.

In contrast to the above purely field-based or object-based models, Goodchild *et al.* (2007) proposed a conceptual framework to integrate the object-based and the field-based modeling perspectives. The concept of a 'geo-atom', which is a spatiotemporal point with a set of domain properties, is derived as an atomic form of geographic information. The geo-atom theory provides a single foundation for modeling both continuous and discrete changes of geographical phenomena. Aggregated geo-atoms under a suitable rule forms higher level elements, 'geo-fields' and 'geo-objects', to respectively represent fields and objects in space–time. Fields and objects can be further integrated, referred to as 'field-objects', through the aggregation of geo-atoms.

This study addresses the problem of modeling and visualizing a dynamic 3D coastal environment. Based on the fundamental geo-atom concept (Goodchild *et al.* 2007), a new object-oriented spatiotemporal data model to represent heterogeneous coastal-related data with dynamic 3D nature is proposed. A set of abstract data types with suitable spatiotemporal operations is defined in the proposed model to manipulate the coastal-related data. In addition, a logical data model is proposed to store dynamic 3D coastal data in the database. In addition, the proposed object-oriented and logical data models are implemented in a Hong Kong real-world coastal information system. An elegant visualization framework to display the dynamic 3D coastal-related data based on the concept of time–depth bar is also presented.

This paper is organized as follows. The next section provides a background to space–time representation of the coastal environment. Section 3 presents the design of spatiotemporal data model suitable for coastal applications. Section 4 describes the implementation of the proposed spatiotemporal model and discusses the interface design issue via a case study. Finally, conclusions and recommendations for further study are given.

REPRESENTATION OF SPACE–TIME IN COASTAL ENVIRONMENT

According to their space–time characteristics, dynamic 3D coastal-related data can be classified into the three categories of stationary objects, moving objects and evolving fields. The stationary objects are long-term survey data, collected by sensors (e.g. buoys) deployed at fixed locations (or stations). In this category, hydrodynamic and water quality data at each station are collected at regular time intervals and ranges of depths. But the times of sampling and the depth of each survey station may not be identical.

Moving objects are those short-term survey data collected by moving sensor platforms, such as ships or autonomous underwater vehicles. The moving platform may travel along a pre-defined transect (or route). Trajectories of the movement can be recorded using GPS (global positioning system) devices. The hydrodynamic and water quality data are collected at regular, or sometimes variable, time intervals over a range of water depths.

The last category of evolving fields consists of the numerical results generated by 3D hydrodynamic models when simulating or forecasting a certain coastal phenomena over time. The continuous 3D space is typically discretized into a 3D mesh of finite elements representing the volume of interest. The model outputs are hydrodynamic and water quality information in 3D space is generated at certain time intervals (say, one every hour).

Sophisticated coastal management applications generally contain the above three types of data from various sources (Ng 2006). These data are heterogeneous with different spatial and temporal sampling regimes. Coastal-related data are typically a vast volume of physical, chemical and biological observations at each location and timestamp, such as temperature, pH, salinity, current velocity, dissolved oxygen, nutrients, metal concentrations, etc.

The heterogeneity and complexity of coastal-related data make modeling of costal phenomena a very challenging task. Stationary object and moving object survey data are discrete objects, which may not be well represented by existing object-based spatiotemporal data models. The spatiotemporal composite model (Langran & Chrisman 1988) is good for maintaining objects which change occasionally, but is not suited for survey data that changes frequently. The moving object database model (Güting & Schneider 2005) is used for tracking the movement of objects, and thus the spatiotemporal data types and operations defined in this model are not suitable for stationary object survey data. In addition, outputs in the evolving field category cannot be modeled using the field-based modeling approaches. The snapshot model and the event-based spatiotemporal data model (Peuquet & Duan 1995) are used to maintain the history of fields with a single attribute. By using this snapshot modeling, huge storage can be required to maintain the hydrodynamic outputs which possess a large set of hydrodynamic and water quality parameters.

DATA MODEL DESIGN

The geo-atom concept framework is described in the first subsection. A new object-oriented spatiotemporal data model for modeling dynamic 3D coastal-related data is then presented in the following subsection. A logical data model for the implementation of a spatiotemporal database is described in the final subsection.

Geo-atom concept framework

A 'geo-atom', q_i, is defined as a spatiotemporal point with a set of domain attributes or properties. It can be expressed as

$$q_i = <p, A, V> \tag{1}$$

where $p = <x, y, z, t>$ is a point in space–time, $A = \{ a_1, \ldots, a_n\}$ is an attribute scheme and $V = \{ v_1, \ldots, v_n\}$ are the attribute values associated with p. For example, a geo-atom q_i may indicate that, at the location ($x = 114^\circ$ E, $y = 22^\circ$ N, $z = -1$ m) on 1 June 2008 12:00:00 (t), temperature, pH value and sensor ID ($A = \{$ *Temperature*, *pH*, *SensorID*$\}$) were 23 °C, 8.1 and YSI201 ($V = \{$ 23, 8.1, YSI201$\}$), respectively. Goodchild *et al.* (2007) argued that the geo-atom can be regarded as an atomic form of geographic information and all geographic information, regardless of whether an object or a field can be reduced to it. For example, an object-based shoreline can be expressed as a set of vertices along the line and the field-based 3D mesh can be decomposed into a set of 3D mesh points. The geo-atom provides a single foundation for modeling both fields and objects over time. Aggregating geo-atoms under a suitable rule forms higher level elements, 'geo-fields' and 'geo-objects', to represent fields and objects in space–time, respectively.

The geo-field is defined as the variation of one or more properties over a continuous domain in space–time. A geo-field, F, can be expressed as

$$F = <Q(A, D, R)> \tag{2}$$

where $Q(A, D, R) = \{q_1, ..., q_n\}$ is a collection of geo-atoms with the same attribute scheme A, in the continuous space D and representing a time period R. The geo-object is defined as an aggregation of geo-atoms having a specific value for a certain property such as those geo-atoms having an identical ObjectID property. A geo-object, o_i, can be expressed as

$$o_i = <Q(A, V', R)> \tag{3}$$

where $Q(A, V', R) = \{q_1, ..., q_n\}$ is a set of geo-atoms with the same attribute scheme A, having the same values for certain properties $V' = \{v_i, ..., v_j\}$, and within a time period R.

This paper extends the above geo-atom modeling framework in two aspects. First, the concept of a geo-object is extended to support additional properties. For instance, a geo-object can represent a ship-based survey conducted on a pre-defined transect. In addition to hydrodynamic and water quality parameters at the geo-atom level, the geo-object can have its own properties, such as a ship name, surveyors, pre-defined transect, etc. Thus, the extended geo-object is defined as

$$o_i = <Q(A, V', R), \overline{A}, \overline{V}> \tag{4}$$

where $\overline{A} = \{\bar{a}_1, ..., \bar{a}_n\}$ is a attribute scheme at the geo-object level and $\overline{V} = \{\bar{v}_1, ..., \bar{v}_n\}$ is the attribute values associated with o_i. Second, the concept of the 'geo-object-class' is further introduced to aggregate geo-objects with the same attribute scheme $\overline{A}$ as

$$C = <O(\overline{A}, A, R)> \tag{5}$$

where $O(\overline{A}, A, R) = \{o_1, ..., o_n\}$ is a set of geo-objects with the same attribute scheme $\overline{A}$. The same attribute scheme at both the geo-atom and geo-object levels is required for effective storage of the coastal information in the spatiotemporal database.

Object-oriented spatiotemporal data model

This subsection presents a new object-oriented spatiotemporal data model for modeling dynamic 3D coastal information including stationary objects, moving objects and evolving fields. The proposed data model is built on the above geo-atom concept framework.

The class diagram of the proposed spatiotemporal data model is depicted in Figure 1 in UML (Unified Modeling Language) notation. For clarity, the defined classes in the figure are distinguished by underlining from the above concept framework. In the proposed data model, GeoAtom, GeoObject, GeoObjectClass and GeoField represent the geo-atom, geo-object, geo-object-class and geo-field concepts, respectively. StationaryPoint is a sub-class (or a

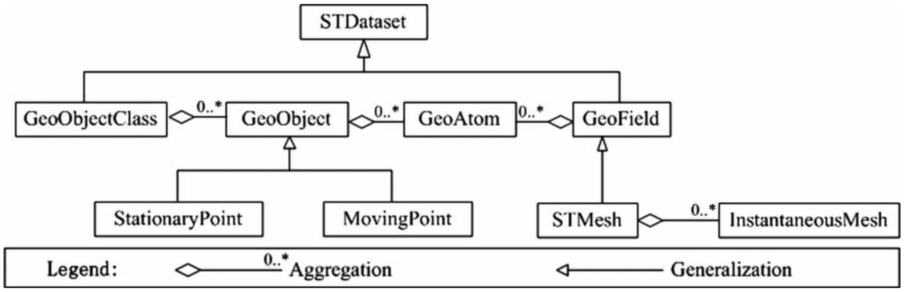


Figure 1 | Class diagram for modeling dynamic 3D coastal data.

derived class) of GeoObject, representing the category of stationary objects. MovingPoint is also a sub-class of GeoObject, representing the category of moving objects. The data in the evolving field category are represented as STMesh, a sub-class of GeoField. STMesh is an InstantaneousMesh set, and each of which represents a 2D mesh of finite elements at a given depth level and timestamp. STDataset is a super-class of GeoObjectClass and GeoField. It represents spatiotemporal datasets for all three types of dynamic 3D coastal data.

The properties and operations of defined classes are shown in Table 1. For the sake of clarity, the properties are presented in italic font without parentheses and the operations are presented in italic font with parentheses. The GeoAtom class possesses six properties. *AtomID* property is the identity of a geo-atom. *Location*, *Z*, *T*, *AtomAttributeScheme* and *AttomAttributeValues* are $<x, y>$, z, t, A and V shown in Equation (1), respectively.

The GeoObject class relates to the geo-object concept. Among its ten properties, the *ObjectID* property is the identity of the geo-object used to distinguish the geo-object from its geo-object-class (V' in Equation (4)); the *ObjAttributeSheme* and *ObjAttributeValues* properties are found in attribute scheme $\bar{A}$ and attribute values $\bar{V}$ at the geo-object level, respectively; the *Envelope* property is the minimum bounding box (MBB) of the geo-object in 2D space; *Zmin* and *Zmax* are the minimum and maximum depth value, respectively; *Tmin* and *Tmax* define the time period; and the *ObjectClass* property relates to its associated geo-object class.

StationaryPoint represents the long-term survey data collected at a fixed station over a range of depths (the category of stationary objects). This class is a sub-class of GeoObject, inheriting the properties and operations defined in GeoObject. The StationaryPoint defines four additional operations. The *GetTimeSeries()* function is used to retrieve the time series of geo-atoms at a given depth value; while the *GeDepthProfile()* function is used to retrieve the depth profile of geo-atoms at a given timestamp. *TemporalInterpolation()* is for the derivation of values at an unsampled point in time, while *ProfileInterpolation()* is for deriving values at an unknown point along a vertical water column. The details of these two interpolation operations, referred to as the 1D interpolation technique, have been described in Ng *et al.* (2007).

MovingPoint is a sub-class of GeoObject for representing the short-term survey data collected by a moving

Table 1 | Properties and operations of proposed classes

Classes	Properties	Operations
GeoAtom	AtomID, Location, Z, T, AtomAttributeScheme, AtomAttributeValues	GetAtomAttributeValue( ), SetAtomAttributeValue( )
GeoObject	ObjectID, ObjAttributeSheme, ObjAttributeValues, Envelope, Zmin, Zmax, Tmin, Tmax, AtomCount, ObjectClass	GetObjAttributeValue( ), SetObjAttributeValue( ), GetGeoAtoms( ), GetGeoAtom( ), InsertGeoAtom( ), DeleteGeoAtom( )
StationaryPoint	Location	GetTimeSeries( ), GetDepthProfile( ), TemporalInterpolation( ), ProfileInterpolation( )
MovingPoint	Transect	GetDepthProfile( ), ProfileInterpolation( ), TransectInterpolation( )
STDataset	Name, Description, Envelope, Zmin, Zmax, Tmin, Tmax, AtomAttributeScheme	
GeoObjectClass	ObjAttributeSheme, ObjectCount	GetGeoObjects( ), GetGeoObject( ), InsertGeoObject( ), DeleteGeoObject( ), SpatialInterpolation( ), TemporalSpatialInterpolation( ), ProfileSpatialInterpolation( )
GeoField		
STMesh	DepthLevelCount, TCount	GetInstantaneousMesh( ), GetTimeSeries( ), GetDepthProfile( )
InstantaneousMesh	MeshID, DepthLevel, T, STMesh	GetGeoAtom( ), SpatialInterpolation( )

sensor platform (the moving object category). In addition to the properties and operations inherited from GeoObject, MovingPoint defines one property and three operations. The *transect* property is the pre-defined route of a moving sensor platform in 2D space. *GetDepthProfile( )* and *ProfileInterpolation( )* functions are similar to those defined for StationaryPoint. The *TransectInterpolation( )* function is for estimating an unsampled point along a pre-defined transect.

STDataset is a super class of the GeoObjectClass and GeoField. It provides a set of common properties for all three types of coastal data. Among its eight properties, the *Envelope* property is the MBB of the spatiotemporal dataset in 2D space and the *AtomAttributeScheme* property is component A in Equations (2) or (5).

GeoObjectClass is a sub-class of STDataset representing the geo-object-class concept. In addition to the properties defined in STDataset, GeoObjectClass provides a set of functions to retrieve, insert and delete its associated geo-objects. GeoObjectClass also defines three interpolation operations. The *SpatialInterpolation( )* function creates a raster layer from geo-atoms at a given timestamp and depth level using traditional 2D interpolation techniques (i.e. inverse distance weight, kriging and trend). Very often the sampling times of surveys are not simultaneous and the *TemporalSpatialInterpolation()* function is defined to deal with this problem by combining the temporal and spatial interpolation techniques. Similarly, the *ProfileSpatialInterpolation()* function is for the creation of a raster layer combining profile and spatial interpolation techniques.

GeoField represents the geo-field concept. It is a sub-class of STDataset, inheriting all properties defined in the STDataset.

STMesh is a sub-class of GeoField for representing the geo-field in the category of evolving fields. In addition to the properties inherited from GeoField, STMesh provides the *GetTimeSeries( )* and *GetDepthProfile( )* functions to support time series and depth profile analysis at a given location. The *GetInstantaneousMesh( )* function is used to retrieve an instance of InstantaneousMesh at a given depth level and timestamp.

InstantaneousMesh provides a 2D finite element mesh at a given depth level and timestamp. Each InstantaneousMesh consists of a set of geo-atoms at the same depth level and timestamp. The *SpatialInterpolation()* function creates a raster layer from those geo-atoms associated with InstantaneousMesh.

Logical data model

This subsection describes a logical data model for the implementation of a spatiotemporal database. The logical data model provides for mapping between the classes defined in the object-oriented data model and tables constructed in the database. It gives a tabular view of how the dynamic 3D coastal-related data are stored in the database.

Figure 2 illustrates the logical data model. For the sake of clarity, the tables are presented in an italic font with underlining. As shown in the figure, the STDataset class is mapped onto the *STDataset* table, and the hydrodynamic and water quality parameters are stored in the *AtomAttribute* table. The *Dataset_Attribute_Rel* table is used to maintain the many-to-many relationships between the *STDataset* and *AtomAttribute* tables. To store an STDataset, two separate tables are also required for storing associated GeoObjects (or InstantaneousMesh) and GeoAtoms.

For example, a spatiotemporal dataset, namely SO, is a long-term survey of temperature and pH value at three fixed stations. To store this spatiotemporal dataset (see Figure 2), a *SO_StationaryPoint* table is used to store three geo-objects at different stations; a *SO_GeoAtom* table is used to store a set of geo-atoms collected at these three stations; a record in the *STDataset* table is created to store this geo-object-class; and two records in the *Dataset_Attribute_Rel* table are generated to store the attribute scheme of this geo-object-class (i.e. temperature and pH value). The *SO_StationaryPoint* and *SO_GeoAtom* tables are linked to the record in the *STDataset* table by storing these two table names in ObjectTableName and AtomTableName fields. Similar storage mechanisms can be applied for storing data in the other two categories. As shown in the figure, the *MO_MovingPoint* and *Mo_GeoAtom* tables store geo-objects and geo-atoms for a spatiotemporal dataset in the category of moving objects; while the *EF_InstantaneousMesh* and *EF_GeoAtom* tables maintain a InstantaneousMesh in the category of evolving fields.

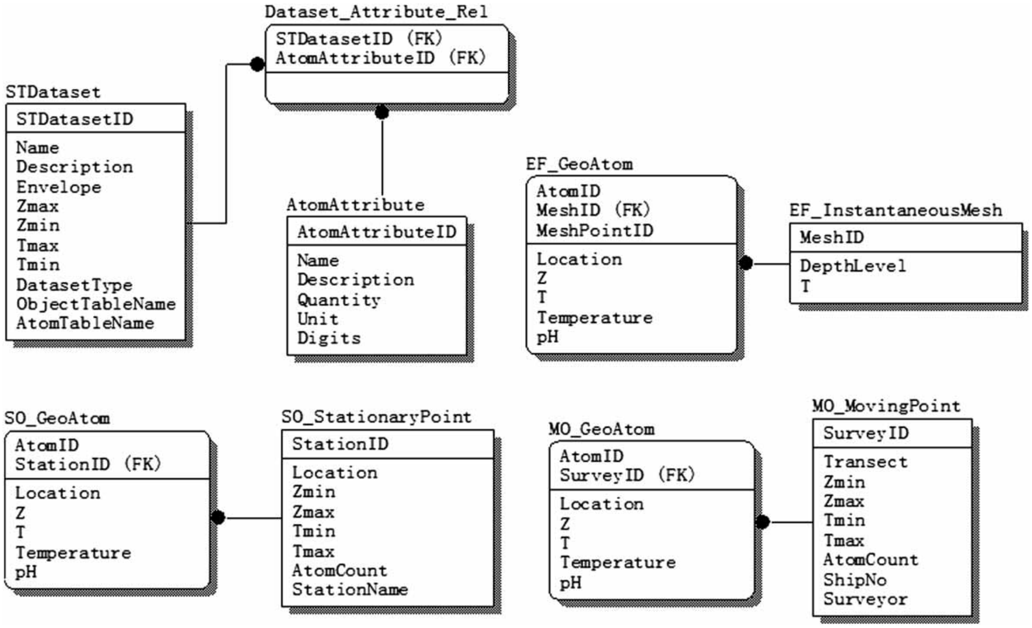


Figure 2 | Logical data model for storing dynamic 3D coastal data.

CASE STUDY AND INTERFACE DESIGN

A real-world case study in Hong Kong is presented in this section to illustrate the proposed spatiotemporal data model applications. The study area and data collection is described in the first subsection and the design of user interfaces is discussed in the following subsection.

Study area and data collection

As shown in Figure 3, Hong Kong is situated on the southern coast of China (22°09′–22°37′ N, 113°52′–114°30′ E), with a land area of 1,098 and 1,651 km^2 of marine waters (Yip *et al.* 2006). Hong Kong is on the eastern side of the Pearl River Estuary (PRE), which is a triangular-shaped estuary receiving freshwater from the Pearl River Delta (PRD) draining into the South China Sea. The estuary is about 5 km wide at its northern end and widens to about 35 km at its southern end, with a longitudinal (north–south) length of approximately 70 km (Ng 2006).

PRD has been the most economically dynamic region of China. The huge economic and industrial development in the PRD during recent decades has led to serious degradation of water quality in the PRE. As Hong Kong is located adjacent to the PRE, deteriorating water quality in the PRE also poses a threat to the marine waters of Hong Kong (Ng 2006). In this study, the area of interest is defined as the PRE including those regions of Hong Kong waters. In order to mitigate the deteriorating water quality situation in the study area, a Pearl River Estuary Coastal Information System (PRECIS) was developed.

PRECIS comprises all three types of dynamic 3D coastal-related data. The survey data were acquired from seven large-scale field projects, conducted by the Hong Kong Government, including a Civil Engineering Department (CED) Project (agreement no. CE32/96), an Enhancement of WAHMO Mathematical Models project, an Environmental Protection Department (EPD) Project (agreement no. CE42/97), an EPD on-going marine water and sediment quality monitoring project, a Pearl River Estuary Pollution Project (PREPP) and a Hong Kong Observatory (HKO) project. These collected survey data encompassed 102 physical, chemical and biological property variables, such as temperature, current velocity, pH, salinity, turbidity, dissolved oxygen, nutrients, metals, organics and coliform bacteria.

PRECIS adopted a complex three-dimensional hydrodynamic sediment and heavy metal transport numerical

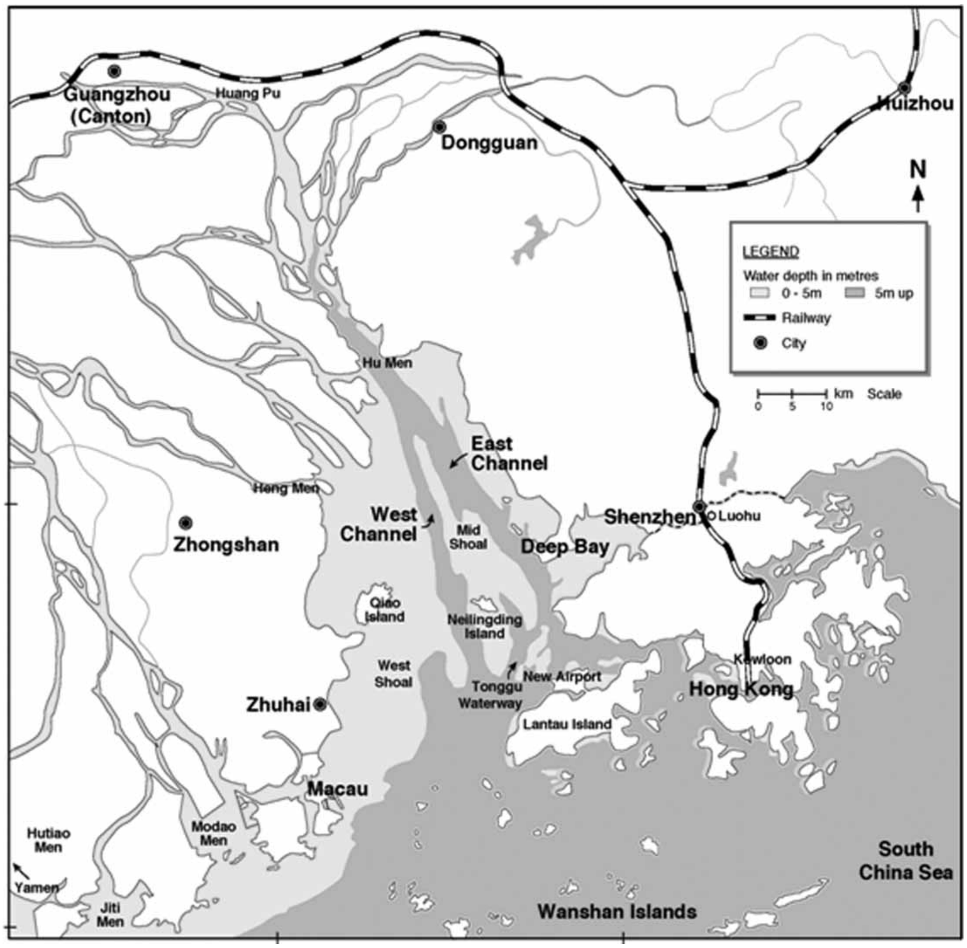


Figure 3 | Study area: Hong Kong.

model (Wai *et al.* 2003) to simulate or forecast the deterioration of water quality conditions in the PRE. This model is capable of predicting hydrodynamic patterns and sediment and heavy metal transport for the entire PRE. The model simulation was carried out for a 1 week period, 11–18 March 2008, and the model outputs were generated once every hour. The 3D mesh grid used in the study consisted of 11,342 nodes horizontally and seven layers in the vertical direction. The output of each node related to a list of 16 parameters, such as salinity, tidal level, sediment concentration, metal concentration, etc. Table 2 provides a summary of the collected survey data and model outputs. The logical model presented in the previous section was implemented to design the spatiotemporal database so as to store these collected survey data and model outputs.

Table 2 | Summary of collected data

Type	Number of spatiotemporal dataset	Number of geo-atoms
Stationary objects	116	5,130,425
Moving objects	44	1,031,038
Evolving field	1	13,338,192

System implementation

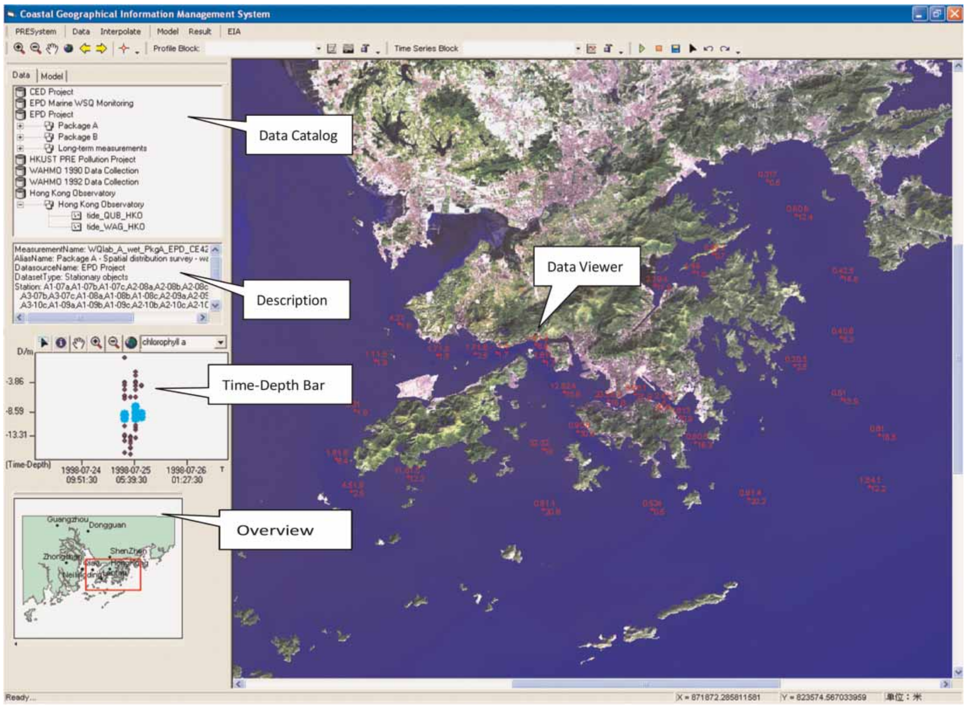
The proposed spatiotemporal data model as well as the PRECIS system was implemented through ESRI's ArcObject library using the Microsoft Visual Basic 6.0 programming language. The library enables implementation of powerful spatial data types and operations, provides a spatial data engine for supporting various relational database management systems, provides maps for displaying geographical information and offers other high-level interface controls for rapid application development.

PRECIS uses the following user interface for visualization and exploration of dynamic 3D coastal-related data, as shown in Figure 4. The main interface consists of five windows including a data catalog window, a data viewer window, a time–depth bar window, a data description window and an overview window.

The data catalog window provides an overview of coastal-related data stored in the system. In this window, the survey data including stationary objects and moving objects are listed in the Data tab, while the evolving fields generated by the hydrodynamic model are shown in the Model tab. In each tab, a three-level tree view is used to visualize the spatiotemporal dataset gathered from various sources. The first level in tree view, HydroDataSource, represents the source of data; the second level, HydroDataSet, is a group of spatiotemporal datasets aggregated by a certain rule; and the last level is the spatiotemporal dataset. The data catalog window can be used to control which spatiotemporal dataset is displaying in the data viewer window.

The data viewer window contains the main display of the active spatiotemporal dataset with geo-atoms at current time period and depth levels. In the data viewer window, the red points illustrate the locations of geo-atoms and the red labels show the values of a specific hydrodynamic or water quality parameter. The current time period and depth levels of the active spatiotemporal dataset as well as the parameter can be controlled in the time–depth bar window.

The time–depth bar is a map presenting all time–depth points of the active spatiotemporal dataset. It enables users to set the current time period and depth levels of the active spatiotemporal dataset by either drawing a rectangle or selecting a single time–depth point. Once the time period and depth levels are specified, a query will be asked of the active spatiotemporal dataset and results of the query (a set of geo-atoms) will be displayed in the data viewer window. The ComboBox control above the time–depth bar is used to specify the hydrodynamic or water quality parameter that is displayed in the data



MeasurementName: WQlab_A_wet_PkgA_EPD_CE42
AliasName: Package A - Spatial distribution survey - we
DatasourceName: EPD Project
DatasetType: Stationary objects
Station: A1-07a,A1-07b,A1-07c,A2-08a,A2-08b,A2-08c
A3-07b,A3-07c,A1-08a,A1-08b,A1-08c,A2-09a,A2-09
A3-10c,A1-09a,A1-09b,A1-09c,A2-10b,A2-10c,A2-1C

X = 871872.285811581
Y = 823574.567033959
單位：米

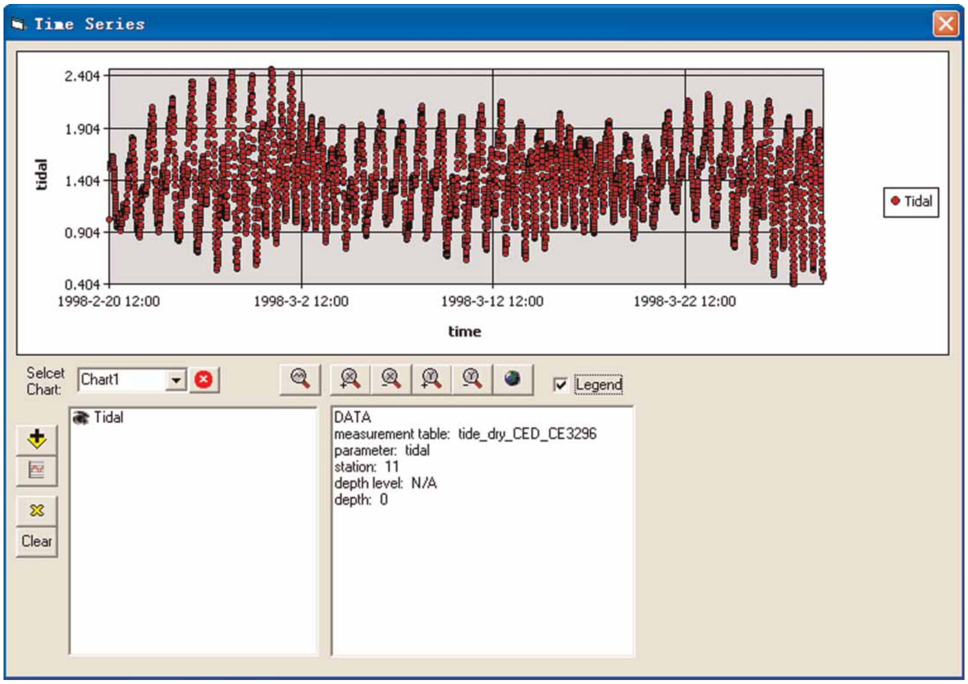
Figure 4 | Main user interface.

viewer window. When users specify different parameters, no additional query is required, as values of all parameters are already associated with the geo-atoms.

The data description window gives a brief description of the active spatiotemporal dataset. The overview window shows the full extent of the active spatiotemporal dataset. A box in the overview window represents the currently displayed area on the data viewer. Users can move this box to pan the map on the data viewer and shrink or enlarge it to zoom in or out. Figure 4 illustrates this visualization framework. In this figure, the spatiotemporal dataset 'WQlab_A_wet_PkgA_EPD_CE4297' in the HydroDataSet 'PackageA' of the HydroDataSource 'EPD Project' was set as the active spatiotemporal dataset. The current time instant was '25 July 1998 10:00:53', current depth level was from 6 to 11 m below mean sea level and the water quality parameter was chlorophyll-*a*.

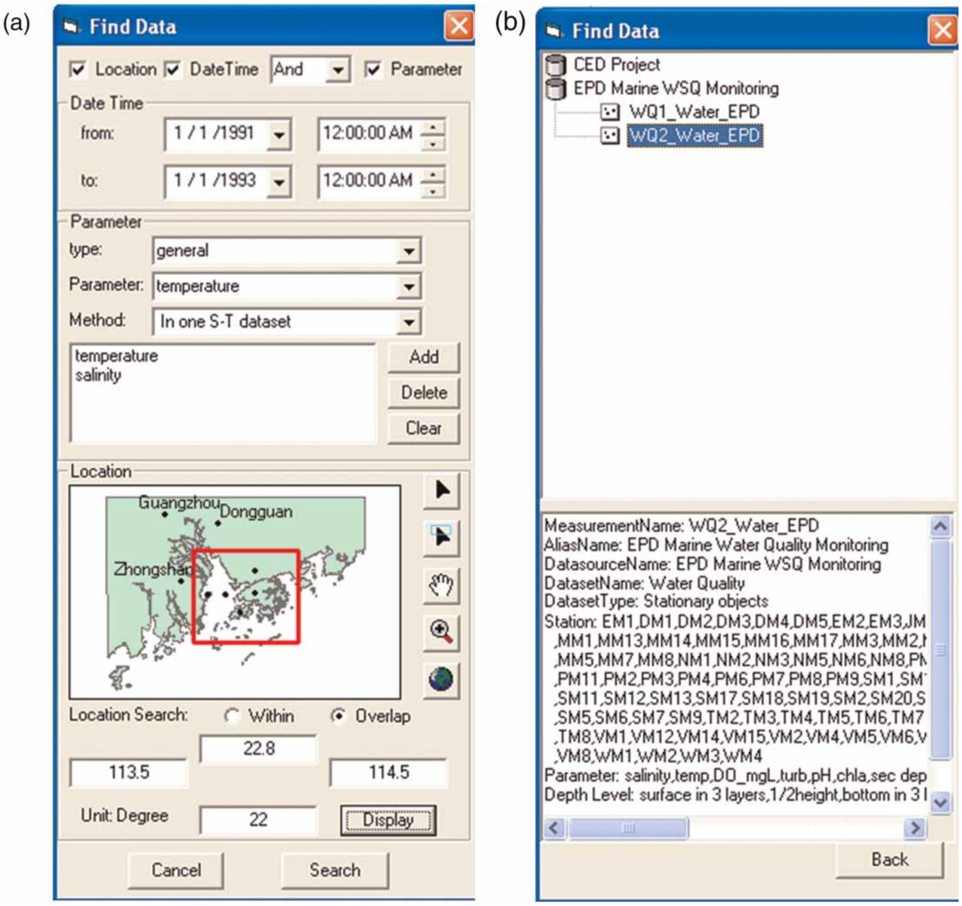
The time series plot and depth profile display of the coastal-related data are also incorporated into the PRECIS for examining temporal and depth variation. Users can explore the time series (or depth profile) of a specified parameter by clicking a location in the data viewer window. Figure 5 illustrates a simple time series plot of tidal level in PRECIS. Note that the spatiotemporal data in the categories of stationary points and evolving fields support both the time series plot and depth profile display, while the data in the category of moving objects only support the depth profile display (as in MovingObject without the *GetTimeSeries()* function).

The PRECIS system provides a spatiotemporal search function to efficiently retrieve target spatiotemporal datasets among a large volume of coastal-related data gathered from various sources. Through this function, users can search the spatiotemporal datasets by specifying their 2D spatial extent, time period and desired parameters (see Figure 6(a)). To implement this searching function, a 3D R-tree index (Guttman 1984) is constructed on all spatiotemporal datasets in RRECIS. To retrieve the target spatiotemporal datasets, a spatiotemporal query is first conducted on the 3D R-tree by specifying a spatiotemporal extent in 2D space and the 1D time domain. A further refinement is then performed on the results of the spatiotemporal query according to the input parameters. The retrieved spatiotemporal datasets are listed in the tree-view window (see Figure 6(b)), in which one spatiotemporal dataset is selected as the active spatiotemporal dataset displaying in the data viewer window.



DATA
measurement table: tide_dry_CED_CE3296
parameter: tidal
station: 11
depth level: N/A
depth: 0

Figure 5 | Time series plot.



(a)

☑ Location ☑ DateTime And ☑ Parameter

Date Time
from: 1 / 1 /1991 12:00:00 AM
to: 1 / 1 /1993 12:00:00 AM

Parameter
type: general
Parameter: temperature
Method: In one S-T dataset
temperature
salinity

Location
Location Search: ○ Within ● Overlap
22.8
113.5
114.5
Unit: Degree 22

(b)

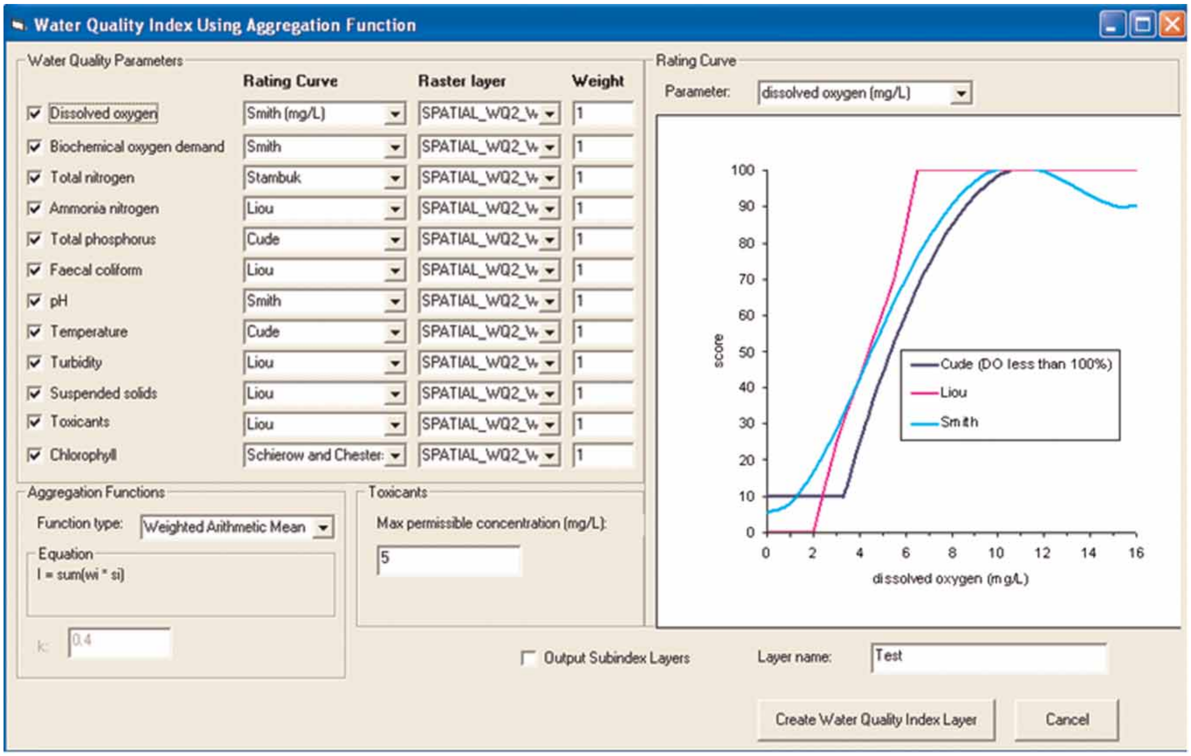
CED Project
EPD Marine WSQ Monitoring
WQ1_Water_EPD
WQ2_Water_EPD

```
MeasurementName: WQ2_Water_EPD
AliasName: EPD Marine Water Quality Monitoring
DatasourceName: EPD Marine WSQ Monitoring
DatasetName: Water Quality
DatasetType: Stationary objects
Station: EM1,DM1,DM2,DM3,DM4,DM5,EM2,EM3,JM
  ,MM1,MM13,MM14,MM15,MM16,MM17,MM3,MM2,
  ,MM5,MM7,MM8,NM1,NM2,NM3,NM5,NM6,NM8,P
  ,PM11,PM2,PM3,PM4,PM6,PM7,PM8,PM9,SM1,SM
  ,SM11,SM12,SM13,SM17,SM18,SM19,SM2,SM20,S
  ,SM5,SM6,SM7,SM9,TM2,TM3,TM4,TM5,TM6,TM7
  ,TM8,VM1,VM12,VM14,VM15,VM2,VM4,VM5,VM6,V
  ,VM8,WM1,WM2,WM3,WM4
Parameter: salinity,temp,DO_mgL,turb,pH,chla,sec dep
Depth Level: surface in 3 layers,1/2height,bottom in 3
```

Figure 6 | The spatiotemporal searching function; (a) input parameters, (b) results.

The PRECIS system also provides six interpolation functions for estimating values at points in space–time where no measurement was taken. The interpolation functions provided include 1D temporal, 1D transect, 1D profile, 2D spatial, 3D temporal–spatial and 3D profile–spatial interpolations. These six functions are implemented based on the interpolation operations defined in the proposed spatiotemporal data model (refer to the earlier subsection). With these interpolation functions, an environmental impact assessment (EIA) function is further developed for water quality evaluation.

Figures 7 and 8 illustrate a sample application of interpolation functions and the EIA function to identify the most vulnerable water region in Hong Kong. As shown in Figure 7, 12 water quality parameters collected by the selected spatiotemporal dataset were considered for water quality evaluation (including dissolved oxygen, biochemical oxygen demand, total nitrogen, ammonia nitrogen, total phosphorus, fecal coliforms, pH, temperature, turbidity, suspended solids and chlorophyll-*a*). The raster layers of these parameters were first generated using the 3D temporal–spatial function for the surface depth level at 13 March 1998 12:00:00. The raster-based water quality variables in different units were then normalized into unitless sub-index values based on user-defined rating curves (Schierow & Chesters 1988; Smith 1990; Cude 2001; Liou *et al.* 2004). These normalized sub-index values were further aggregated into a single water quality index (WQI) value using a weighted arithmetic mean aggregation function (Swamee & Tyagi 2000). The calculated WQI that represents the water



	Rating Curve	Raster layer	Weight
☑ Dissolved oxygen	Smith (mg/L)	SPATIAL_WQ2_W	1
☑ Biochemical oxygen demand	Smith	SPATIAL_WQ2_W	1
☑ Total nitrogen	Stambuk	SPATIAL_WQ2_W	1
☑ Ammonia nitrogen	Liou	SPATIAL_WQ2_W	1
☑ Total phosphorus	Cude	SPATIAL_WQ2_W	1
☑ Faecal coliform	Liou	SPATIAL_WQ2_W	1
☑ pH	Smith	SPATIAL_WQ2_W	1
☑ Temperature	Cude	SPATIAL_WQ2_W	1
☑ Turbidity	Liou	SPATIAL_WQ2_W	1
☑ Suspended solids	Liou	SPATIAL_WQ2_W	1
☑ Toxicants	Liou	SPATIAL_WQ2_W	1
☑ Chlorophyll	Schierow and Chester:	SPATIAL_WQ2_W	1

Parameter: dissolved oxygen (mg/L)

Aggregation Functions

Function type: Weighted Arithmetic Mean

Equation

I = sum(wi * si)

k: 0.4

Toxicants

Max permissible concentration (mg/L): 5

☐ Output Subindex Layers

Layer name: Test

Figure 7 | The interface of EIA function.

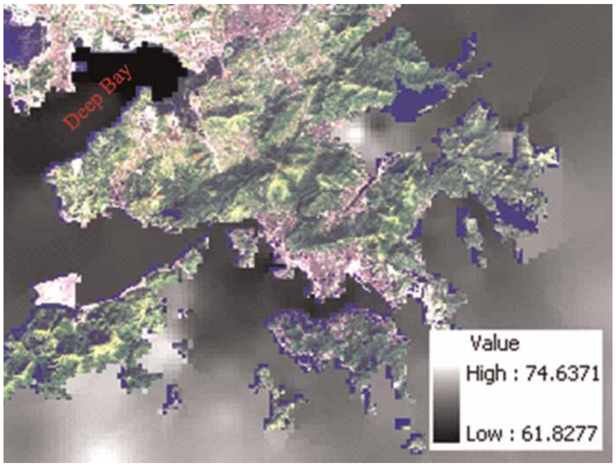


Figure 8 | The results of EIA function.

quality is shown in Figure 8. The value of WQI ranges from 0 to 100, with 0 for the worst condition and 100 for the best condition. By examining the figure, Deep Bay was identified as the most problematic water region in Hong Kong.

CONCLUSIONS

An investigation into the modeling and visualization of a dynamic 3D coastal environment has been conducted in this study. Coastal-related data are heterogeneous, dynamic and three-dimensional. According to their spatiotemporal characteristics, coastal-related data can be classified into the three categories of stationary objects, moving objects and evolving fields. To represent these three types of dynamic 3D coastal-related data, a new object-oriented spatiotemporal data model has been proposed which builds on the concepts of the geo-atom, geo-object, geo-object-class and geo-field. The proposed object-oriented spatiotemporal data model defines a set of abstract data types with suitable spatiotemporal operations to effectively manipulate the dynamic 3D coastal-related data. In addition, a logical data model was proposed to enable effective storage of coastal data. The logical data model provides mapping between the classes defined in the object-oriented data model and tables constructed in the database.

The proposed object-oriented and logical data models were implemented in a real-world coastal information management system to assist in mitigating the deteriorating water quality situation in Hong Kong. An elegant visualization framework was designed for displaying dynamic 3D coastal-related data, based on a new concept of time–depth bar. A spatiotemporal data searching function was developed to efficiently retrieve the desired spatiotemporal datasets from among a large volume of coastal-related data gathered from various sources. Six different types of interpolation functions were also provided for estimating unsampled points in space–time. Based on these interpolation functions, an EIA function was further developed for water quality evaluation in Hong Kong. The developed coastal information system provides a multifunctional hydrodynamic tool for engineers and environmentalists in Hong Kong. It can be used not only to analyze the existing water quality conditions according to the survey data, but also to predict the potential environmental impact resulting from hydrodynamic model outputs.

The proposed spatiotemporal data model only considered dynamic 3D coastal-related data based on the concepts of geo-objects and geo-fields. It may not be capable of representing certain coastal phenomena possessing both object and field characteristics (e.g. oil spill near the coast). Thus, an interesting extension of the proposed spatiotemporal model will be to consider such coastal phenomena using the concept of field objects. Another interesting extension of this study will be to develop an internet-based GIS system for sharing coastal information with the other domains.

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