Computers & Geosciences 103 (2017) 70–79

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Case study

Development of a GIS-based integrated framework for coastal seiches monitoring and forecasting: A North Jiangsu shoal case study

Rufu Qin*, Liangzhao Lin

State Key Laboratory of Marine Geology, Tongji University, Shanghai, China

ARTICLE INFO

Keywords:
Coastal seiches
GIS
Visualization
Web-based platform
In situ observations
Model predictions

ABSTRACT

Coastal seiches have become an increasingly important issue in coastal science and present many challenges, particularly when attempting to provide warning services. This paper presents the methodologies, techniques and integrated services adopted for the design and implementation of a Seiches Monitoring and Forecasting Integration Framework (SMAF-IF). The SMAF-IF is an integrated system with different types of sensors and numerical models and incorporates the Geographic Information System (GIS) and web techniques, which focuses on coastal seiche events detection and early warning in the North Jiangsu shoal, China. The in situ sensors perform automatic and continuous monitoring of the marine environment status and the numerical models provide the meteorological and physical oceanographic parameter estimates. A model outputs processing software was developed in C# language using ArcGIS Engine functions, which provides the capabilities of automatically generating visualization maps and warning information. Leveraging the ArcGIS Flex API and ASP.NET web services, a web based GIS framework was designed to facilitate quasi real-time data access, interactive visualization and analysis, and provision of early warning services for end users. The integrated framework proposed in this study enables decision-makers and the publics to quickly response to emergency coastal seiche events and allows an easy adaptation to other regional and scientific domains related to real-time monitoring and forecasting.

1. Introduction

A surface seiche is defined as a sharp water-level fluctuation that generally occurs in an enclosed or semi-enclosed basin (Macmahan, 2015). Past studies concluded that seiches are the results of tsunamis, moving or fluctuating atmospheric pressure systems, shifting of wind stresses on the water surface, or longshore-propagating edge waves (Tada et al., 1992; Vilibic et al., 2005; Gardner et al., 2006; Macmahan, 2015). The tide will rise abnormally and crest quickly when a strong coastal seiche event is triggered by various forces. Therefore, seiches may be regarded as a destructive process, which can threaten human lives and property and cause loss of lives as well as economic losses. In recent years, seiches in water present a particular problem to scientists and decision-makers and have become an important issue in the disaster prevention and risk assessment fields (Barberopoulou, 2008; Francis et al., 2011), which prompted building up the ability to detect seiche events and develop a seiche event early warning system for rapid and effective emergency responses.

It is worth noting that many applications and benefits for data integration are provided by in situ sensors and numerical model forecasts in the field of operational early warning systems (Nittis et al., 2006; Frigerio et al., 2014; Jaedicke et al., 2014; Tiranti et al., 2014; Fang et al., 2015; Liu et al., 2015; Wang et al., 2015). Coastal seiche event detection also relies strongly on both observations and short-term predictions based on numerical models (Tada et al., 1992; Drago, 2008). With the rapid advancement of in situ sensors and communication technologies, a long-term in situ monitoring system devoted to the observation of different marine environmental parameters has already been developed in the past few decades (Hotaling and Kocak, 2014). On the other hand, there has been rapid development and application of operational models as a result of the progress in oceanography, measuring and monitoring techniques, numerical methods, and computer and information technologies (Mayerle et al., 2016). Accordingly, we can conclude that integrated monitoring and forecast systems for the prediction of coastal seiches have become critical and feasible.

However, ocean model outputs and observation data are large-volume, multi-source, multi-variable, multi-dimensional, and heterogeneous, with complex spatial and temporal regimes, which are hard to understand, process, access and utilize and therefore present many

* Corresponding author.
E-mail addresses: qinrufu@tongji.edu.cn (R. Qin), 86774994@qq.com (L. Lin).

http://dx.doi.org/10.1016/j.cageo.2017.03.010
Received 14 December 2016; Received in revised form 4 March 2017; Accepted 10 March 2017
Available online 11 March 2017
0098-3004/

challenges for users to obtain useful and meaningful information (Ames et al., 2012; Wu et al., 2013; Portman, 2014). As a consequence, researchers cannot obtain enough information to meet the demands of research projects. Thus, a sophisticated information system that is capable of processing, integrating, acquiring, visualizing and analyzing various types of data constitutes an important issue in the context of monitoring and forecasting studies of coastal seiches.

Most ocean model predictions and observation data can be considered to be geospatial in nature. Ideally, these datasets need to be merged and visualized in a geospatial context for a variety of analyses and applications (Kaiser et al., 2006). Therefore, fully leveraging geospatial technologies, such as the geographic information system (GIS), for spatial data visualization and to gather different types of information from various sources into one system has become increasingly important in many geoscience fields, including coastal science, in recent years. Kulawiak et al. (2010) implements a Web-based GIS coupling with an existing oil spill monitoring and forecasting system for visualizing and publishing data from different sources. Demir and Krajewski (2013) presented the flood information system to provide easy access to real-time flood and flood forecasts, and interactive visualizations using WebGIS based techniques. Mayerle et al. (2016) developed a WebGIS based coastal information system based on operational modeling system and operational sensors for assisting decision makers in the management of Jeddah coastal waters. In our previous works, we have utilized GIS to process the ocean model predictions (Yuan et al., 2012). However, up to now, nothing in the literature has been found that describes monitoring and forecasting systems coupling with GIS for providing early warning services of coastal seiche events.

Recent developments of online technology and web-based GIS provide a great opportunity to establish an online information system for web-based managing, visualizing, analyzing, and sharing seiche-related data and information as well as improving the timeliness of warnings and preparation for coastal seiche events. In the present research, we introduce the design and implementation of a GIS-based application named Seiche Monitoring and Forecasting Integration Framework (SMAF-IF) with the aim of developing a real-time prediction system that supports early warning coastal seiche events in the North Jiangsu shoal, China. SMAF-IF is an integrated system with different types of sensors for in situ observations and numerical forecasting and incorporates advanced visualization techniques, which perform continuous monitoring of the marine environment status, provide predictions and warning services, and facilitate the dissemination of seiche-related information.

The remainder of this paper is organized as follows. Section 2 gives a general description of the study area. Section 3 outlines the design and implementation of the SMAF-IF application. Section 4 summarizes the conclusions.

2. Description of the study area

The North Jiangsu shoal, China, at a 0–20 m water depth and with more than 250 km of shoreline, is located at the junction of the Yellow Sea and East China Sea, which covers the domain of 31°50′0′′–33°20′0′′S, 122°E longitude to the west. Fig. 1 describes the topography of the coastal areas and the surrounding region. Extremely complicated coastal geomorphology, broad shallow bathymetry, long linear coastlines, quite variable time-space weather and hydrodynamic conditions, and a number of reports of historic water level fluctuations in the coastal waters promote favorable conditions for seiche events. The coastal areas are thereby subjected to regional seiche hazards. These coastal seiches, locally known as 'odd tide', have occurred more frequently in the coastal areas in recent years and have induced marine accidents and strongly affected marine transport, fisheries and aquaculture on the west shores. Considering the challenges, more work is needed to establish a real-time monitoring and forecasting system to better understand the nature and to make earlier prediction of coastal seiches in selected important regions to mitigate hazards and minimize losses.

3. Implementation

3.1. Architecture description

The general architecture of the SMAF-IF is composed of four components, as shown in Fig. 2: (1) a monitoring system for in situ observations acquired via a real-time sensor data, (2) the operational forecasting system for seiche event predictions, (3) the server-side data processing tools and multiple databases to automatically generate and manage data products, and (4) a rich web application interface for quasi real-time data access, interactive visualization and analysis, and provision of early warning services for end users. The following sections give a brief description of the specific features and services supported by the above-mentioned components.

3.2. Monitoring system

The seiche event early warning system is an application scenario in which sensor monitoring can serve an important function. Time series observation data collected from the monitoring system with high resolution can provide data for model forcing (e.g., winds), calibration, validation and assimilation and therefore improve the accuracy of forecasts. In a research-oriented effort, the East China Sea Branch of S.O.A. has initiated the construction of a multi-sensor monitoring system to provide leading-edge infrastructure for long-term sustained observations at a few selected significant sites. The approximate positions of the monitoring platforms are presented in Fig. 1. Currently, it consists of the following observation subsystems: tow surface buoys and three ocean subsurface buoys moored offshore, two high-frequency surface wave radar (HFSWR) stations and two shore-side land stations that are spatially distributed along the coastline, and three fixed observations installed in the coastal waters. These sub-systems, except for the sub-surface buoys, are provided with power and communication capabilities, ensuring 24/7 operations, a high data rate and real-time data.

The monitoring system integrates a variety of autonomous and real-time sensors that can collect data with sampling rates ranging from every one minute to several hours. The monitored parameters primarily focus on the physical processes (atmospheric conditions, waves, and hydrodynamics) of the marine environment, including the wind speed, wind direction, air pressure, air temperature and humidity, current magnitude and direction, sea level, waves, water temperature, and conductivity. The row sensor data were collected in the form of ASCII and continuously transmitted to the shore-side station or the data center at the Forecasting Center in East China Sea Branch of S.O.A. through a variety of communication modes, including Very High Frequency (VHF), Code Division Multiple Access (CDMA), Microwave Communication, or Very Small Aperture Terminal (VSAT) satellite transmission. Exceptionally, the data collected by subsurface buoys was usually not available until the moorings were recovered.

3.3. Operational modeling system

Forecasting the occurrence of seiche events has been identified as the core of the project. The modeling system included in the SMAF-IF primarily focuses on near real time forecasting waves, currents and wind velocities, and water levels in the North Jiangsu shoal. This section provides an overview of the applied numerical models. The detailed descriptions and evaluations of the forecasting skills are outside the scope of this paper.

Waves were simulated using the open source model Simulating Waves Nearshore (SWAN). SWAN is the third generation wave

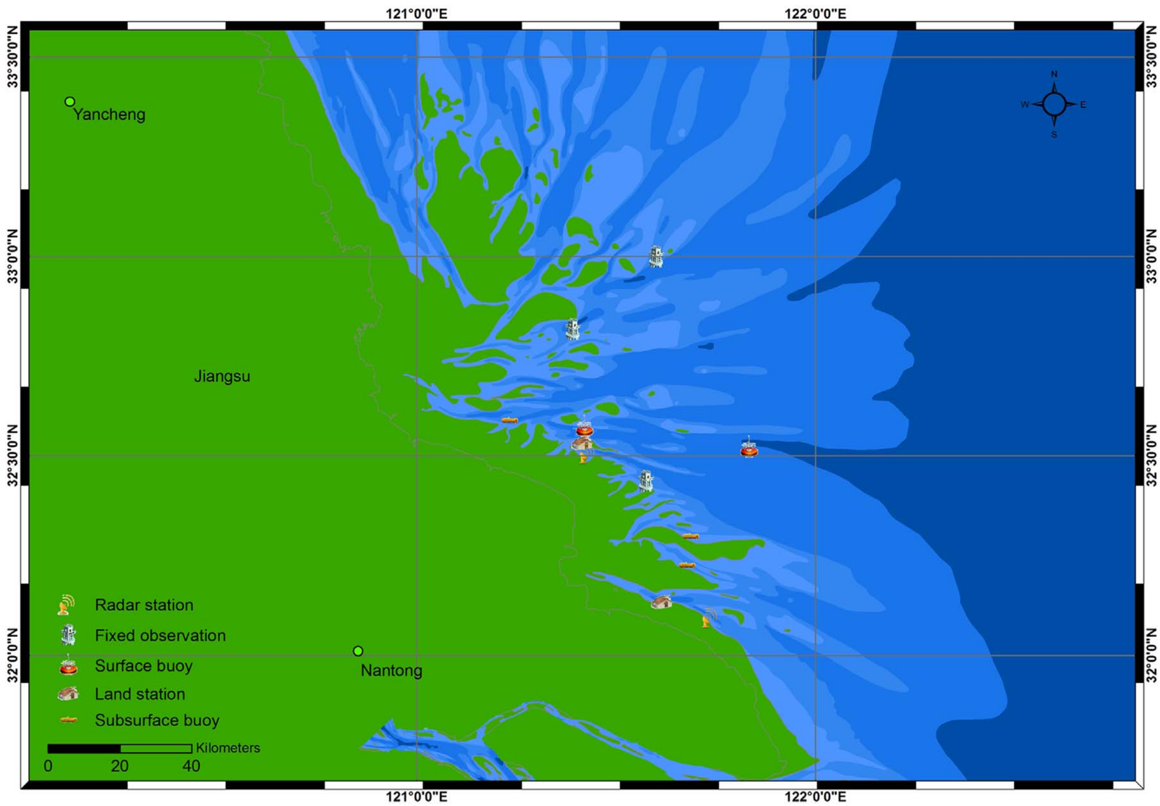

Fig. 1. The topography of the study area and the spatial distribution of in-situ coastal seiches monitoring platforms.

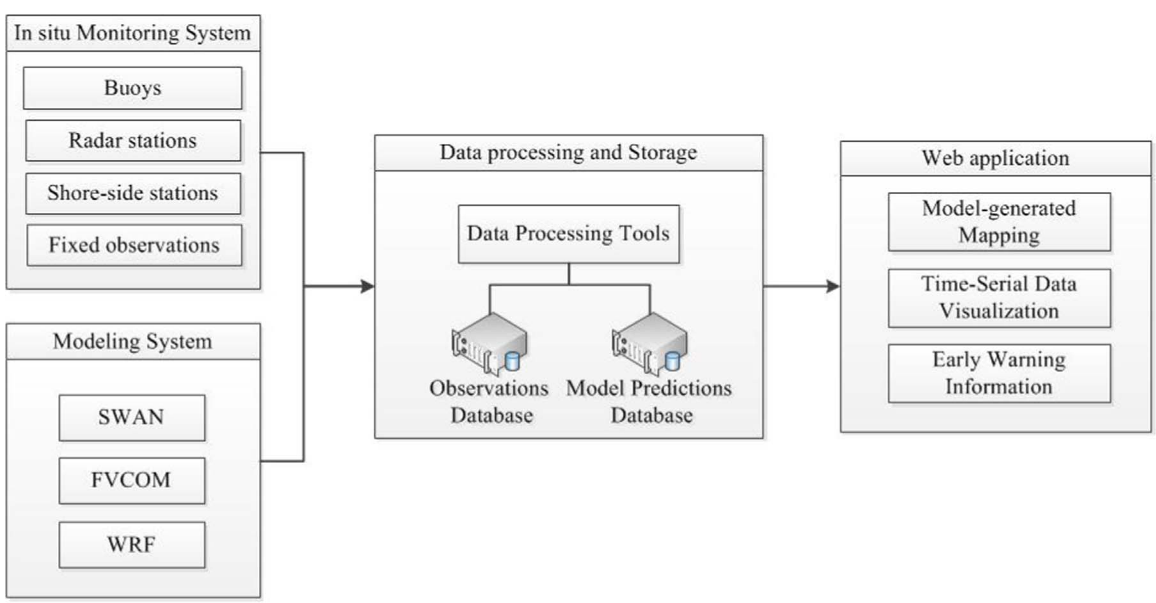

Fig. 2. Schematic showing the general architecture of SMAF-IF.

simulation model, developed at Delft University of Technology, which calculates wave parameters in coastal areas, inland waters, and open ocean. It is a finite difference model that solves the action balance equation and its solution is computationally intensive and suitable for the nearshore applications (Genseberger and Donners, 2015; Amrutha et al., 2016). In this work, wave heights, wave directions and wave periods were computed on an unstructured mesh grid with a resolution that decreased from 10 m near the coast to 200 m offshore. The 3-dimensional regional ocean model, Finite-Volume Community Ocean Model (FVCOM), was adopted to forecast water levels and current velocities. FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, 3-D primitive equation coastal ocean circulation model developed by UMASSD-WHOI joint efforts. The unstructured meshe used in the model is topological flexibility and highly advantageous for resolving dynamics in regions with complex shorelines. Moreover, the ability of FVCOM to accurately solve scalar conservation equations and the simplicity of the coding structure has make FVCOM ideally suited for many coastal and interdisciplinary scientific applications (Shore, 2009; MEDML, 2013; Wan et al., 2016). The numerical simulation was carried out with the same horizontal resolution as SWAN. For vertical discretization, 8 sigma layers were adopted. A uniform mesh grid atmospheric model, Weather Research and Forecasting Model (WRF), was used to calculate the wind velocities at 10 m above the water surface in the x and y directions, with a 5 km grid spacing. The WRF model is a new-generation mesoscale NWP system that solves the nonhydrostatic compressible Navier-Stokes equations to serve both operational forecasting and atmospheric research needs, which is suitable for a broad range of applications and widely used by both operational and research communities (Daniels et al., 2016; Mohan and Sati, 2016). Furthermore, data assimilation techniques were implemented to assimilate the observation data in these models with the objective of improving the meteorological and physical oceanographic parameter estimates.

The modeling system is computationally intensive and runs on High Performance Computing (HPC) environments at the Forecasting Center in East China Sea Branch of S.O.A., which allow the models to produce spatiotemporally high-resolution datasets. The modeling system generates 72-h forecasts with 10 min intervals on a daily basis. A common data format, netCDF (network Common Data Form), is adopted to store the model outputs. Finally, the netCDF files are pushed to a specified workspace on the database server archive via FTP, and a software tool will automatically process these datasets.

The modeling system predicts the possible seiche event occurrence beforehand by comparing the data of the model forecasts with the predefined thresholds. In this study, a potential seiche event triggering condition on a given region is set: (1) with current velocities greater than 1.8 m/s; or (2) with the amplitude of water levels increasing in an untimely fashion up to 80 cm in 30 min. The predictions, given acceptable accuracy, allow decision-makers and the public to take the necessary actions to prepare for a strong seiche event.

3.4. Data processing tools

The tools that are deployed server-side focus on data processing and data product generation. With regard to the observation data, the ODPT (Observation Data Processing Tool) was responsible for real-time reception of the continuous sensor raw data once the data from the operational sensors was transmitted to the data center, parsing the individual data files based on their particular data format and then arranging the data into a compatible format so that they could be entered into a database for further use. A software tool called MPPT (Models Post-Processing Tool) was developed to visualize the model outputs. This section focuses on the design and implementation of MPPT. The ODPT capabilities are intentionally omitted.

Visualization of model-generated netCDF files traditionally depends on third-party tools, such as Grid Analysis and Display System (GrADS), FERRET, IDL, and MATLAB. However, this presents some limitations. Generally, the specialized software is not seamlessly integrated with GIS and is limited in terms of the degree of user interaction and control, including a lack of support for the ability to zoom in/out or perform any type of highly interactive visualization processing and analysis (Xu et al., 2013). On the other hand, there is likely to be a need to develop custom scripts to implement complicated data processing so that forecasters require specialized expertise and training, which is a tedious and time-consuming process (Wu et al., 2013). In this work, we design the GIS-based software MPPT to provide the capabilities of automatically generating visualization maps and warning information.

The MPPT tool was developed in the C# language using the Microsoft Visual Studio 2010 platform, which is a standalone desktop GIS application built upon ESRI ArcGIS Engine functions. It was implemented as a multi-step procedure using several separate automated processes for visualization with a minimal investment of time and effort. The geospatial processing workflow included in the tool is illustrated in Fig. 3.

The software component was designed as an event-driven, multi-tasking and multi-threaded application, which means that the processing workflow can be concurrently invoked to process multiple files (SWAN, FVCOM, or WRF model outputs) simultaneously, as long as new outputs are available. These mechanisms enable the software to fully leverage the available hardware and allow the software to continue with other processes rather than to wait for the response of a process with a long run time. Notably, this contributes to a significant improvement of the processing efficiency. By contrast, multiple operations on a single file must be executed sequentially so that the complex, multi-step processing workflow can be launched at once because subsequent steps only start once previous steps have finished. The details of the workflow are described as follows:

(1)Files are automatically detected upon arrival of a new output to the archive, and the software conversion function is triggered to convert netCDF files to GIS layers. At first, (2) the software component identifies the model according to the netCDF file name and reads the corresponding configuration file that contains information needed to read the data values at the mesh nodes. (3) The netCDF files are then parsed and the interpreted datasets are stored in an oracle database that is accessible for further analysis. At the same time, a copy of the data is kept in memory until the file processing is completed. Initially, (4) a vector-point layer (Shapefile) is created based on the coordinates of the mesh nodes with the data values of the model forecasts as the attributes of each vector point. Once completed, (5) an inverse distance weighting (IDW) spatial interpolation is executed based on the vector point layer to generate a raster layer, such as the water level field. There are many interpolation methods, in practice, selection of a particular interpolation method should depend upon the sample data, as well take into account the calculation efficiency. We notice that some other interpolation methods such as kriging may be more exact and useful than IDW but take longer to calculate. It is important to notice that the quality of the IDW interpolation result can be acceptable, if the distribution of sample data points is even. Further, (6) an area of interest (AOI) is extracted from an interpolation map. In the next step, (7) contour layers are generated, with interest contour levels based on the AOI raster layers. Optionally and if necessary, (8) the contours can be smoothed with a given smoothing tolerance. Then, (9) all of the generated GIS layers are geographically referenced with a unified coordinate system for the purpose of overlaying on the background data. Additionally, to better represent the ocean characteristics, (10) it is necessary to design a custom GIS layer rendering style with proper symbols. In this work, the estimated current (wind, wave) direction and magnitude are symbolized with arrows, while the raster layers use classification rendering or stretch rendering with color ramps. Moreover, some features, such as wave vector points and wave contours, are labeled with specified formats. Lastly, (11) the symbolized maps will be saved as ArcMap document files (*.mxd) and published as tiled map caches using the ArcGIS Server to provide better speed and improved stability map services to the public via the internet. These map services are automatically updated when new GIS layers are generated. According to these mechanisms of converting model outputs to GIS layers, the tool automatically generates visualized data products (listed in Table 1) and publishes the map services each day.

(12) Once the conversions have been completed, an event detection program, capable of identifying the given areas at potential risk based on the aforementioned coastal seiche events triggering conditions, is ready to generate warning information. The warning information includes the date, time and location of possible seiche events, accompanied by the max values of water levels and current velocities. The information will also be stored in the database. Optionally, (13) after a review by forecasters, real-time notifications are transmitted via SMS to a preselected list of people who were appointed for each warning area and are published on a web page for the broader public, simultaneously. Accordingly, the information regarding the current status of the multiple data processing steps is indicated through progress bars and label tips and is also logged in a log file as an EXtensible Markup Language (XML) file. Fig. 4 shows the main

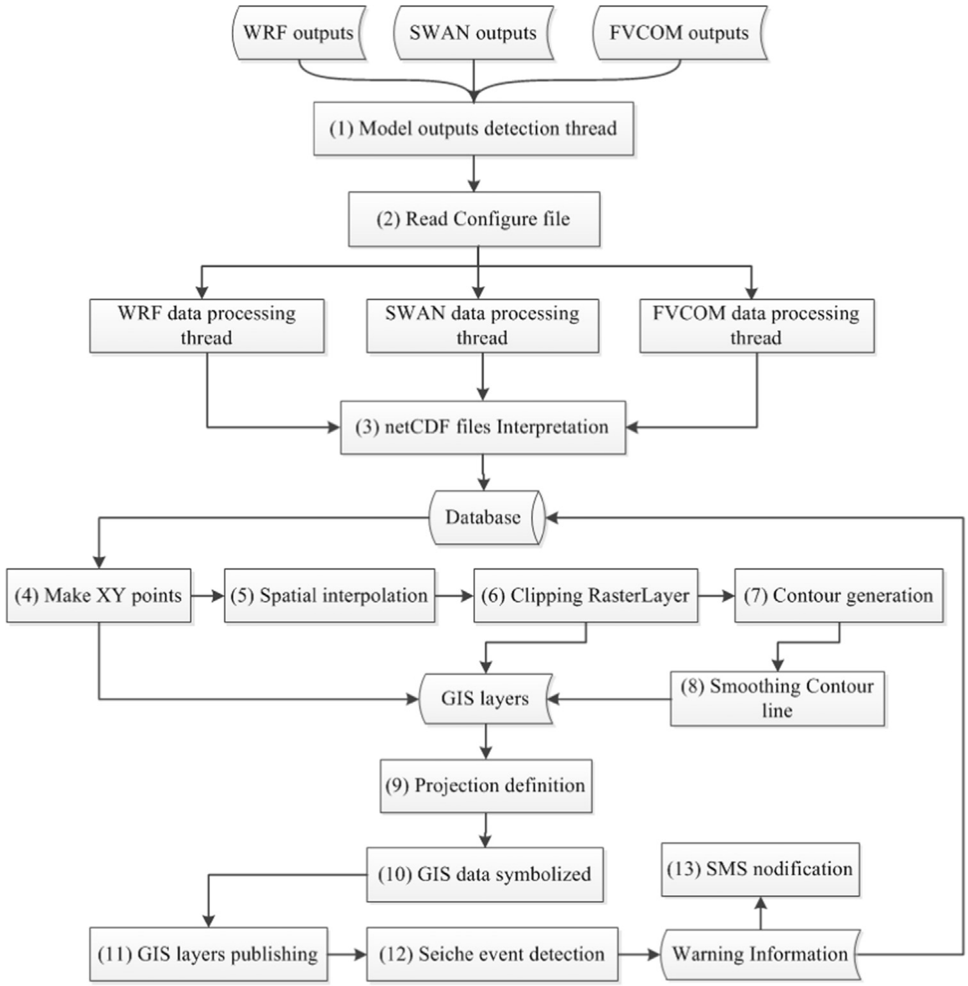

Fig. 3. Flow chart showing the geospatial processing workflow adopted in this study.

Table 1
Description of the model output files and converted GIS files produced by MPPT.

Model name	GIS layer	GIS layer format
FVCOM	Water levels field	Raster layer
	Water levels contours	Vector layer
	Current velocities filed	Raster layer
	Current velocities contours	Vector layer
	Current filed (velocities and directions)	Vector layer
SWAN	Wave heights field	Raster layer
	Wave heights contours	Vector layer
	Wave directions	Vector layer
WRF	Wind field (velocities and directions)	Vector layer

interface of the software.

In addition to the key capability of automatic processing, the software component also provides an interactive environment to perform the workflow step by step (as shown in Fig. 5), which improves the flexibility of the tool to incorporate other simulation models in future applications, if required. Moreover, a GIS editor toolset is available for users to edit the generated GIS layers. Another characteristic of this application is that users have an opportunity to configure the parameters, such as the contour levels, symbol properties (i.e., transparency, color, size), and so forth.

3.5. WebGIS application development

The development of the WebGIS based application interface, which provides a free and one-stop web-platform to aggregate time series observation data and model outputs in a user-friendly way, is an important component of the SMAF-IF application. It also incorporates map-based and time series-based interactive visualization tools using advanced web mapping techniques to facilitate both visualization and analysis of the information.

Currently, two main web system architectural styles are commonly employed to build information infrastructures: SOAP and REST (Vitolo et al., 2015; Navarro and Silva, 2016). The design of the WebGIS platform used a REST architecture model. In the REST architecture model, the resources from web servers are identified as uniform resource identifiers (URIs) and manipulated according to their representations, which can be accessed by users utilizing client-side applications (Chen et al., 2014). As a client-server model, the client makes requests to the server through a web browser, and the server receives requests and performs tasks based on user operations and transmits the results to the clients. These technologies allow distributed in situ observations and simulation model outputs to be accessed through web services, which can be integrated to support coastal seiche events monitoring and forecasting.

The graphical user interface was developed using the free, open source Adobe Flex (now Apache Flex) framework. Flex is a high-level, event-driven framework that includes robust libraries for charting, mapping and generating application frameworks; provides a rich interactive user interface; and is portable across different web browsers (Alder and Hostetler, 2015; Smith et al., 2016). We note that there is a trend towards web development under the relatively new HTML5 platform (Smith et al., 2016), and Flex may not currently be the best option available (Rajib et al., 2016). However, the Flex software

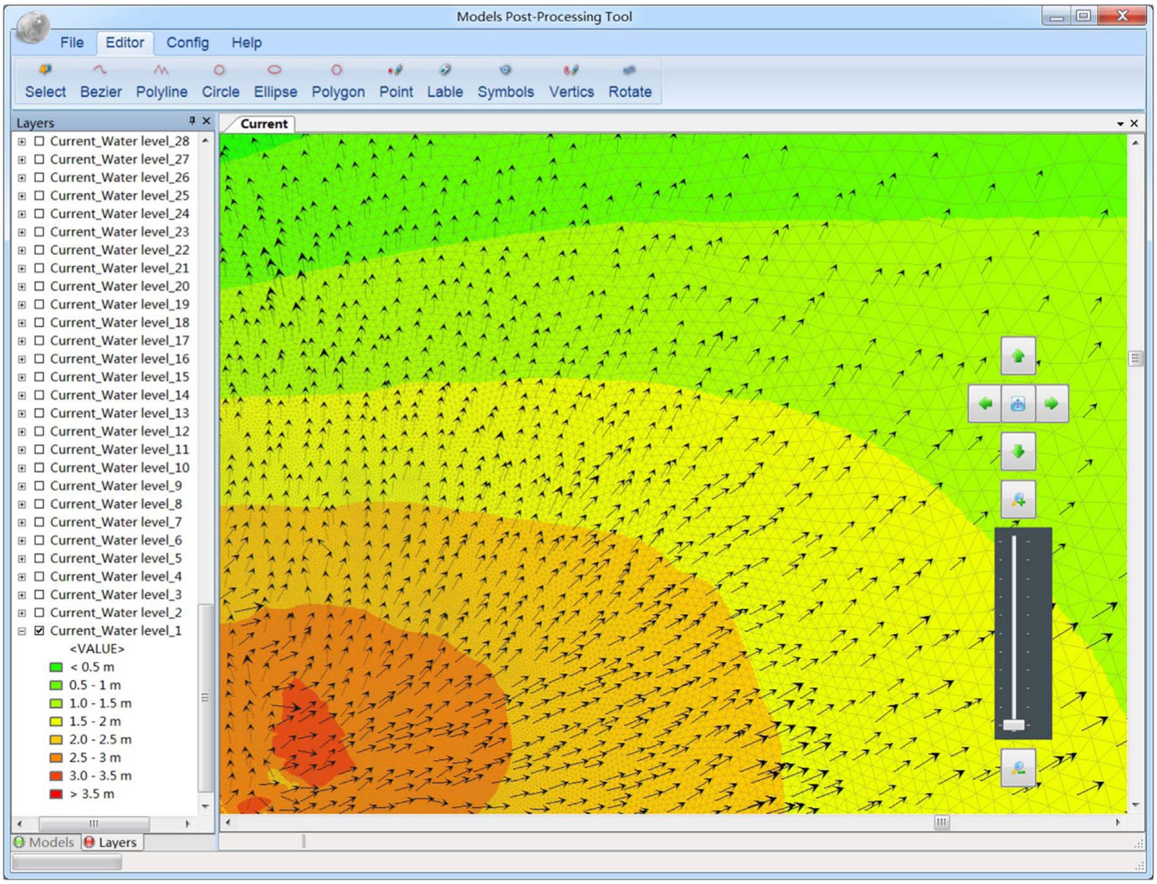

Fig. 4. Main interface of the software and visualized data products (water levels, surface current velocities and directions) previewed in a map window.

development kit was a widely used platform for developing Rich Internet Applications (RIAs) when the project started. Especially, the WebGIS application was designed with an easy-to-use point-and-click web interface to visualize and analyze data through a few clicks and drags of a computer mouse; thus, it can be easily manipulated by the public without any technical background.

Flex has difficulties systematically managing the data provided to the user because it focuses only on implementing the user screen (Kim

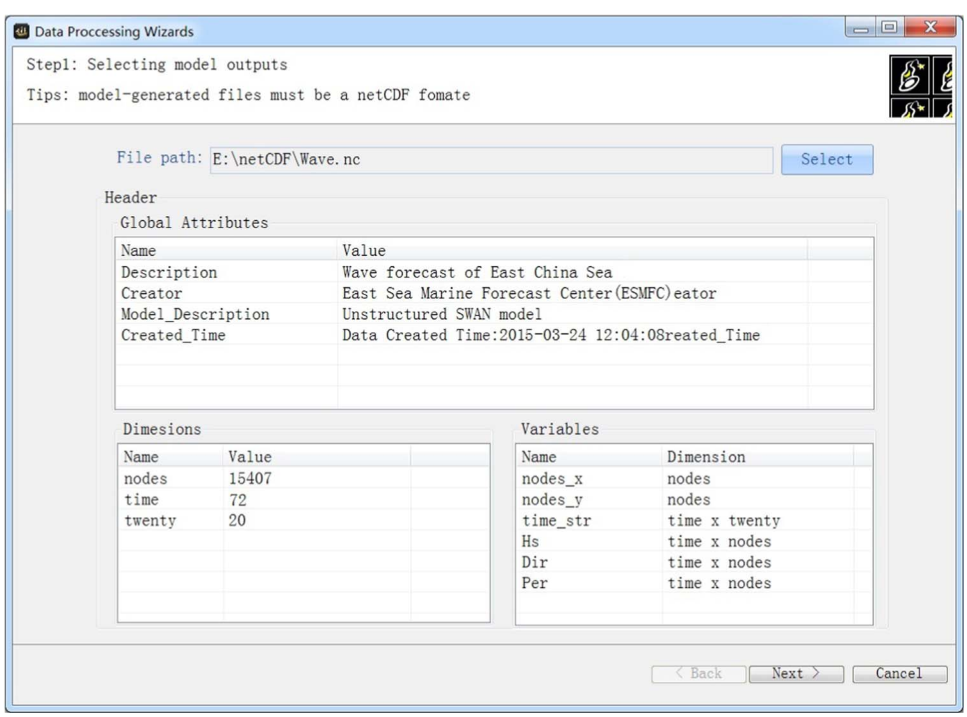

Fig. 5. A screenshot of the model outputs post-processing wizards.

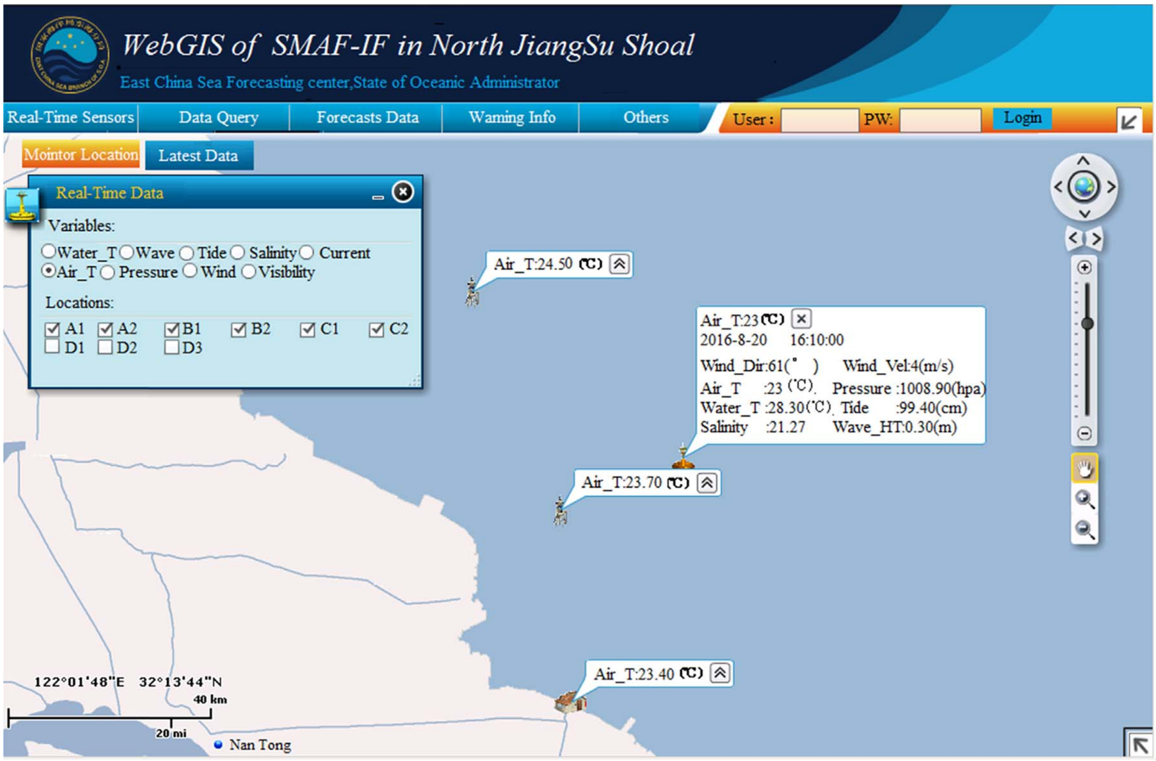

Fig. 6. Latest sensor data displayed in the map-viewer.

and Kim, 2016). However, it can manipulate a database on the server using web services. In this work, observation data access was realized through web services hosted by ASP.NET,. NET Framework and Microsoft's Internet Information Server (IIS).

The web platform has three basic models (observation data, model predictions, and warning information) in its main interface. In the time series observation data module, a map-based visualization of monitoring locations together with information (text, pictures, or videos) about the sensors and platforms are displayed in the map-viewer window. The latest sensor data of each observation location are displayed at the top of the graphic, which is updated every 5 min, or more frequently when required, as shown in Fig. 6.

In addition to displaying the latest real-time sensor data, the web platform enables users to perform specific queries on historical time series observation data through search interfaces and web services. When time series data are loaded, the visualization of the selected interesting parameters is implemented using the FusionCharts plotting libraries. The selected web plotting tool allows the time series data to be displayed in the form of a Cartesian graph, where the *x*-axis is the date-time and the y-axis can be any variable. The plot (see Fig. 7(a)) enables the user to investigate time series trends of parameters monitored on individual observation platforms. Switching between 'Plot' and 'Tabular' buttons, the selected time series data can be viewed in a simple tabular view and downloaded to a local computer directory as a text file or in CSV format.

Furthermore, it is noteworthy that enhanced time series data visualizations within the web platform include the ability to simultaneously plot multiple time series on one chart. Therefore, it is possible to make a visual comparison among multiple variable time series at the same location or a time series for a single variable taken at different points (Fig. 7(b)). It should be noted that access to the observation data is restricted to registered users only.

The capabilities of the web platform to visualize and map forecast products are provided using the Environmental Systems Research

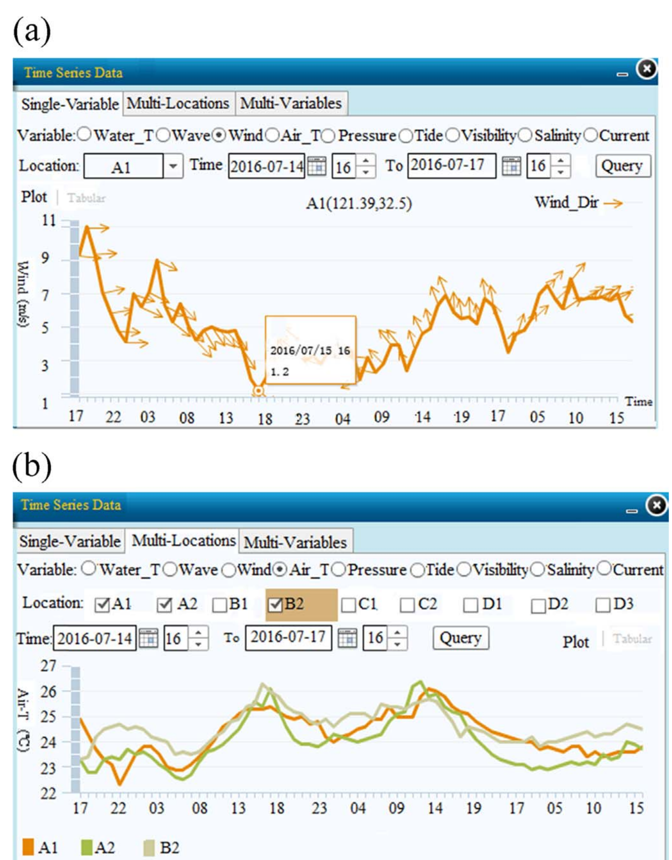

Fig. 7. Example of time series data visualizations. (a) Time series wind parameter (velocity and direction) at the same location. (b) Time series of air temperature at different locations.

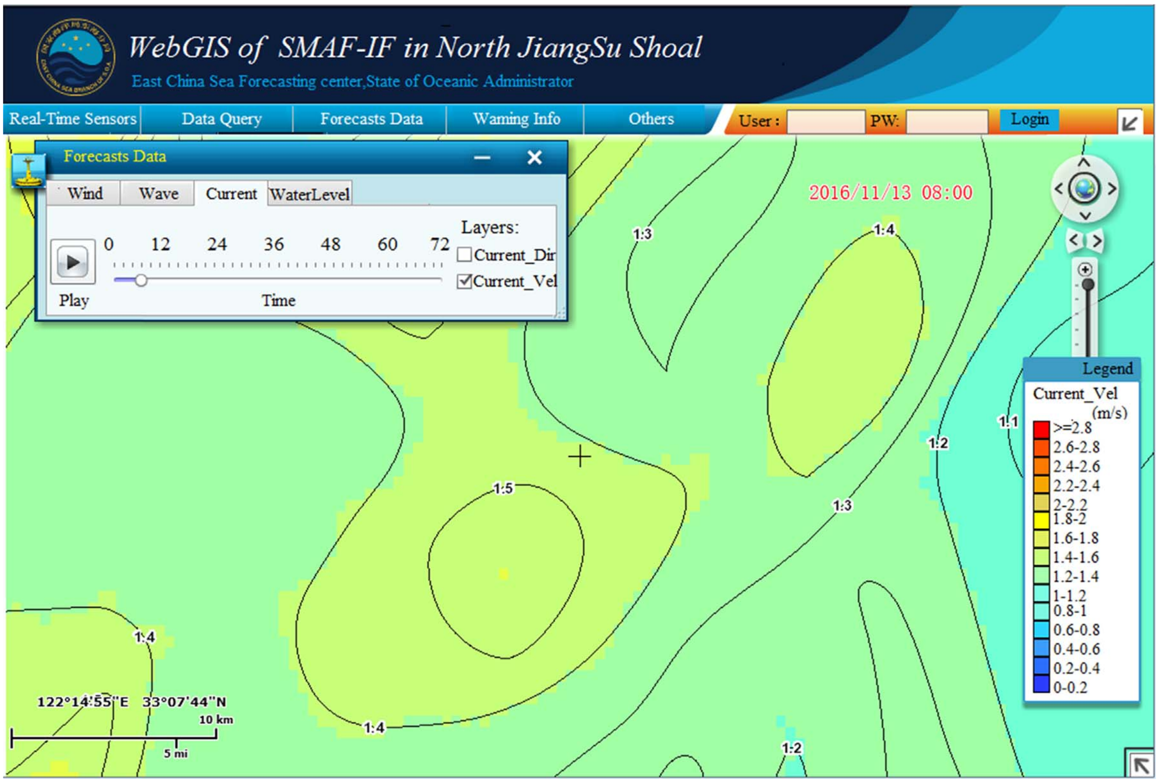

Fig. 8. Online visualization of forecasts (example of surface current velocities field and velocities contours).

Institute (ESRI) ArcGIS Flex API. Interactive geospatial data are available for users in a map-viewer with a web browser, as shown in Fig. 8. There is no need for the client to install additional GIS software other than the Adobe Flash Player, which is installed on most desktop computers connected to the internet. Semi-dynamic geographic information is also available to support interactive animations of temporal changes for specific variables, such as wind, wave and currents. The animation controller window provides functionalities to create an automatic animation at user-specified intervals with replay and pause controls as well as data layers that are activated by the user with check box controls housed within the tab. Additionally, the web platform also provides a set of basic GIS functionalities, including zoom in/zoom out, pan, and distance/area measurements.

The web platform also disseminates the seiche warning information in the form of online bulletin, as shown in Fig. 9. The highlight bulletin indicates that there are potential seiche events in some key areas of the study area. The bulletin is colored with different colors, which identify the strength level of a seiche event. In this study, the strength of seiche events is classified into four levels according the value of current velocities and water levels (Table 2).

4. Conclusions

Coastal seiches are a complex process, particularly when addressing an early warning system. This study examines an integrated real-time monitoring and forecasting system for preliminary predictions of seiche events in the North Jiangsu shoal, China. Previous to this study, no long-term in situ monitoring and model predictions of seiche events in the study area had been recorded. This work and associated proactive management can limit potential life and economic losses that can arise from the occurrence of a strong seiche event.

The SMAF-IF has been used successfully to provide early warning of coastal seiche events in several experiments. This set of simulations indicates that the high resolution models for meteorological and physical oceanographic parameter is correctly implemented and able to perform coastal seiche events predictions. Operational activities of SMAF-IF in the case study have demonstrated the value of coupling both predictive models and continuous in situ oceanography monitoring devices. Ocean and atmospheric models provide a way to understand and predict the behavior of seiches, and the real-time data from the multi-sensor monitoring system will be valuable for data assimilation, model validation, and reducing modeling errors. By taking full advantage of the GIS geoprocessing technology, we successfully implemented a server-side model outputs processing software, which was able to automatically perform complex geoprocessing and routinely obtain cartographic products at the time of post-processing. It eliminates the need to download, process, and store large volumes of data on local computers and therefore leads to simpler client-side software and increases the speed of data visualization (speeds up client-side operations). The geoprocessing workflow discussed here is an optional solution for performing model output processing, which can be valuable for the development of other model post-processing tools. Making use of ArcGIS Flex API and ASP.NET web services, the WebGIS based application allow the observation data and model outputs to be published, shared, visualized, and analyzed through a web application interface. The dynamic web data visualization platform is flexible, expandable, platform-independent, cost-effective, and also easily integrates to other systems, which contributes to the improvement of the overall SMAF-IF performance and enables decision-makers and the public to implement proactive seiche hazard respond strategies.

Although the SMAF-IF application is currently applied exclusively to North Jiangsu shoal datasets in our case study, it is believed that the structure and modular design of the SMAF-IF allows easy adaptation to other regional and scientific domains related to real-time monitoring and forecasting. Likewise, the availability of the web service allows data within the SMAF-IF to be accessible from other information systems and applications. Accordingly, in future work, it will be interesting to improve the functionalities of SMAF-IF through the development of new web services. Moreover, to meet the requirement of mobile

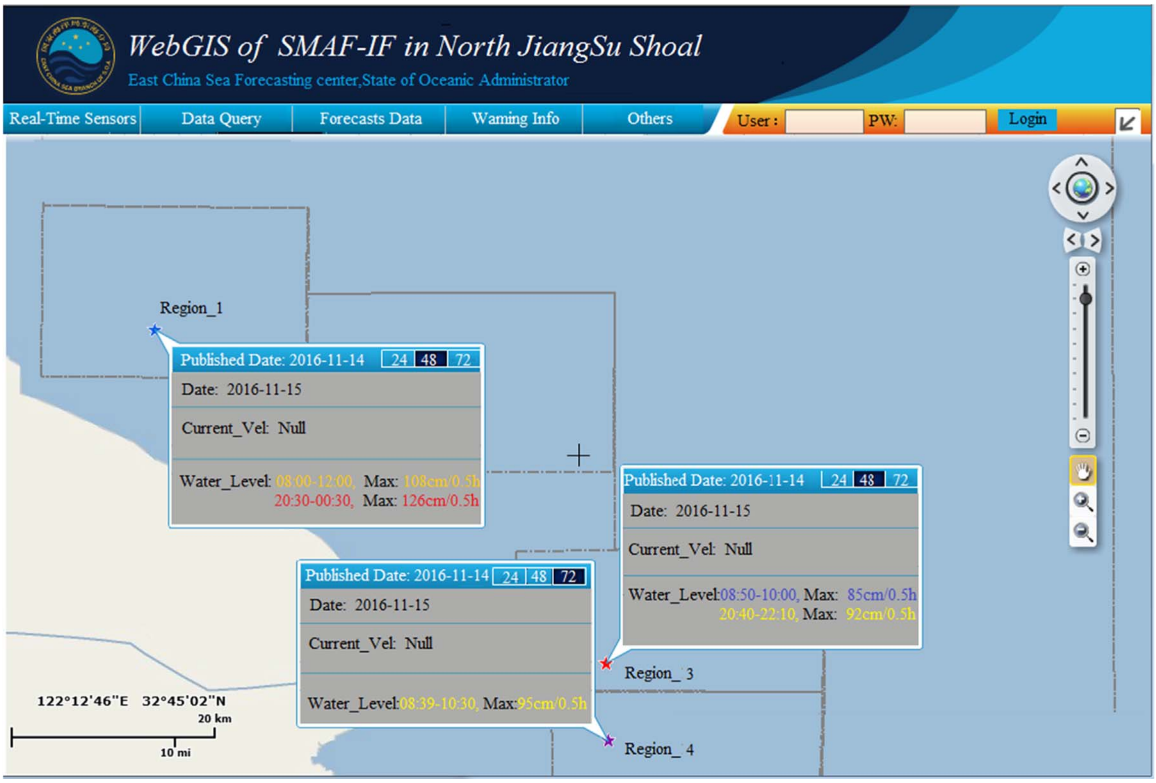

Fig. 9. Early warning information of potential seiche events in some given areas.

Table 2
Four levels of information to be used in seiche events warning.

Levels	Current velocities (m/s)	Water levels increases (cm/0.5 h)	Colors
IV	[1.8, 2.0)	[80, 90)	Blue
III	[2.0, 2.2)	[90, 105)	Yellow
II	[2.2, 2.4)	[105, 120)	Orange
I	≥2.4	≥120	Red

platform adoption, we are going to develop a new version of the web application via the HTML5 platform, which can be packaged into android or IOS apps.

Acknowledgments

This work was supported by the Marine Industry Research Special Funds for Public Welfare Projects (Nos. 200905014, 201405022). The authors acknowledge the Forecasting Center in East China Sea Branch of S.O.A. for providing information about coastal seiches.

References

Alder, J.R., Hostetler, S.W., 2015. Web based visualization of large climate data sets. Model. Softw. 68, 175–180.
Ames, D.P., Horsburgh, J.S., Cao, Y., Kadlec, J., Whiteaker, T., Valentine, D., 2012. HydroDesktop: web services-based software for hydrologic data discovery, download, visualization, and analysis. Model. Softw. 37, 146–156.
Amrutha, M.M., Kumar, V.S., Sandhya, K.G., Nair, T.M.B., Rathod, J.L., 2016. Wave hindcast studies using SWAN nested in WAVEWATCH III - comparison with measured nearshore buoy data off Karwar, eastern Arabian Sea. Ocean Eng. 119, 114–124.
Barberopoulou, A., 2008. A Seiche hazard study for Lake Union, Seattle, Washington. B. Seismol. Soc. Am. 98, 1837–1848.
Chen, X.N., Ye, X.Y., Carroll, M.C., Li, Y.R., 2014. Online flood information system: REST-Based web service. Int. J. Appl. Geosp. Res. 5, 1–10.
Daniels, M.H., Lundquist, K.A., Mirocha, J.D., Wiersema, D.J., Chow, F.K., 2016. A new vertical grid nesting capability in the weather research and forecasting (WRF) model. Mon. Weather Rev. 144, 3725–3747.
Demir, I., Krajewski, W.F., 2013. Towards an integrated flood information system: centralized data access, analysis, and visualization. Model. Softw. 50, 77–84.
Drago, A., 2008. Numerical modelling of coastal seiches in Malta. Phys. Chem. Earth 33, 260–275.
Francis, M., Yeh, H., Dinter, D., Hong, K., Thio, H.K., Olig, S., 2011. Solutions to Coastal Disasters. In: Proceedings of the 2011 Solutions to Coastal Disasters Conference, Alaska, pp. 376–395.
Fang, S.F., Xu, L.D., Zhu, Y.Q., Liu, Y.Q., Liu, Z.H., Pei, H., Yan, J.W., Zhang, H.F., 2015. An integrated information system for snowmelt flood early-warning based on internet of things. Inform. Syst. Front. 17, 321–335.
Frigerio, S., Schenato, L., Bossi, G., Cavalli, M., Mantovani, M., Marcato, G., Pasuto, A., 2014. A web-based platform for automatic and continuous landslide monitoring: the Rotolon (eastern Italian Alps) case study. Comput. Geosci. 63, 96–105.
Gardner, J.T., English, M.C., Prowse, T.D., 2006. Wind-forced seiche events on Great Slave Lake: hydrologic implications for the Slave River Delta, NWT, Canada. Hydro. Process 20, 4051–4072.
Genseberger, M., Donners, J., 2015. A hybrid SWAN version for fast and efficient practical wave modelling. Procedia Comput. Sci. 51, 1524–1533.
Hotaling, L., Kocak, D., 2014. Sensors for long-term ocean observation-evaluation of the state of technology. In: Oceans 2014, St. John's. September 14-19.
Jaedicke, C., Syre, E., Sverdrup-Thygeson, K., 2014. GIS-aided avalanche warning in Norway. Comput. Geosci. 66, 31–40.
Kaiser, H., MacLaren, J., Perrie, W., Stone, G., Zhang, X.P., 2006. GIS and integrated coastal ocean forecasting. Concurr. Comput. Pract. Exp. 8, 1–16.
Kim, J.Y., Kim, Y.H., 2016. Intelligent data management framework for advanced Web service. J. Supercomput. 72, 3455–3467.
Kulawiak, M., Prospathopoulos, A., Perivoliotis, L., 2010. Interactive visualization of marine pollution monitoring and forecasting data via a web-based GIS. Comput. Geosci. 36, 1069–1080.
Liu, Y., Hu, J.M., Snell-Feikema, I., VanBemmel, M.S., Lamsal, A., Wimberly, M.C., 2015. Software to facilitate remote sensing data access for disease early warning systems. Model. Softw. 74, 247–257.
Macmahan, J., 2015. Low-Frequency Seiche in a Large Bay. J. Phys. Oceanogr. 45, 716–723.
Mayerle, R., Al-Subhi, A., Ferna´ndez Jaramillo, J., Salama, A., Bruss, G., Zubier, K., Runte, K., Turki, A., Hesse, K., Jastania, H., Ladwig, N., Mudarris, M., 2016. Development of a coastal information system for the management of Jeddah coastal waters in Saudi Arabia. Comput. Geosci. 89, 71–78.
MEDML, 2013. The Unstructured Grid Finite Volume Community Ocean Model (FVCOM). ⟨http://fvcom.smast.umassd.edu/fvcom/⟩ (accessed 02.02.17).
Mohan, M., Sati, A.P., 2016. WRF model performance analysis for a suite of simulation design. Atmos. Res. 169, 280–291.
Navarro, A., Silva, A.D., 2016. A meta model-based definition of a conversion mechanism between SOAP and RESTful web services. Comput. Stand. Interfaces 48, 49–70.
Nittis, K., Perivoliotis, L., Korres, G., Tziavos, C., Thanos, I., 2006. Operational monitoring and forecasting for marine environmental applications in the Aegean Sea. Model. Softw. 21, 243–257.

Portman, M.E., 2014. Visualization for planning and management of oceans and coasts. Ocean Coast. Manag. 98, 176–185.
Rajib, M.A., Merwade, V., Kim, I.L., Zhao, L., Song, C., Zhe, S.D., 2016. SWATShare - A web platform for collaborative research and education through online sharing, simulation and visualization of SWAT models. Model. Softw. 73, 498–512.
Shore, J.A., 2009. Modelling the circulation and exchange of Kingston Basin and Lake Ontario with FVCOM. Ocean Model. 30, 106–114.
Smith, J.P., Hunter, T.S., Clites, A.H., Stow, C.A., Slawecki, T., Muhr, G.C., Gronewold, A.D., 2016. An expandable web-based platform for visually analyzing basin-scale hydro-climate time series data. Model. Softw. 78, 97–105.
Tada, T., Tsuji, Y., Tsukamoto, M., Ueno, Y., Kawashima, M., Egawa, T., Yamazaki, Y., 1992. Comparison of observed and theoretically calculated seiches of Heda Bay Japan. Pure Appl. Geophys. 138, 309–322.
Tiranti, D., Cremonini, R., Marco, F., Gaeta, A.R., Barbero, S., 2014. The defense (debris flows triggered by storms - nowcasting system): an early warning system for torrential processes by radar storm tracking using a Geographic Information System (GIS). Comput. Geosci. 70, 96–109.
Vilibic, I., Domijan, N., Cupic, S., 2005. Wind versus air pressure seiche triggering in the Middle Adriatic coastal waters. J. Mar. Syst. 57, 189–200.
Vitolo, C., Elkhatib, Y., Reusser, D., Macleod, C.J.A., Buytaert, W., 2015. Web technologies for environmental Big data. Model. Softw. 63, 185–198.
Wan, Z.H., Ren, Z.F., Wang, X.C., Zheng, H.H., 2016. Application of unstructured grid finite-volume coastal ocean model (FVCOM) to the Yangtze River hypoxic zone. Int. J. Numer. Method H. 26, 2410–2418.
Wang, Y.G., Zhang, W.S., Engel, B.A., Peng, H., Theller, L., Shi, Y.Y., Hu, S., 2015. A fast mobile early warning system for water quality emergency risk in ungauged river basins. Model. Softw. Model. Softw. 73, 76–89.
Wu, H.P., Zhong, G.C., Tang, W., Luo, B., Lv, Z.L., 2013. Weather services products generation system based on GIS geoprocessing. Comput. Geosci. 51, 16–21.
Xu, B.L., Lin, H., Gong, J., Tang, S., Hu, Y., Nasser, I., Jing, T, 2013. Integration of a computational grid and virtual geographic environment to facilitate air pollution simulation. Comput. Geosci. 54, 184–195.
Yuan, B.L., Qin, R.F., Lin, L.Z., Pan, Z.D., 2012. Study on visualization of FVCOM model data based on the integration of GIS and FVCOM. In: Oceans 2012, Yeosu, South Korea, 5 pp.