Ocean & Coastal Management 116 (2015) 396–403

Contents lists available at ScienceDirect

Ocean & Coastal Management

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

Capacity-building paper

Mathematical modeling of coastal marine environments using observational data for coastal management

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ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form
8 August 2015
Accepted 13 August 2015
Available online xxx

Keywords:
Coastal marine environments
Probabilistic graphical model
Probabilistic inference
Coastal water quality
Coastal management
Sustainable coastal development

ABSTRACT

Coastal development affects human life and economic activity. Given a necessity to develop coastal areas, there is a need for a method by which to understand and quantitatively assess and predict changes to coastal marine environments. In this paper, we propose a mathematical modeling for coastal marine environments using observational data. In particular, we establish probabilistic graphical model based on the data-driven statistical model for Saemangeum coast of Korea, where land reclamation work has been taking place. The derived model consists of latent and observation variables and their causal relationships. Ocean currents occurred by water exchange appear to be the key factor influencing the coastal marine environments in the artificial lake of Saemangeum coast. Hence, coastal water quality in the coastal management is the major concern by stakeholders. Using the proposed model we were able to compute the followings to demonstrate the usage of our proposed model: First, if the lake were to be entirely cut off from sea water exchange (which takes place through sluice gates in the sea dyke to the open sea), coastal water quality may deteriorated to approximately 37.5% of its current quality. Secondly, in order to maintain a minimum acceptable coastal water quality in the artificial lake, permitting its use in industrial supply and agriculture, currents of about 0.6 m/s are required for sea water exchange. This approach will assist in coastal management by supporting decision-making, policy planning, and the establishment of strategies for sustainable coastal development and conservation of coastal marine environments.

1. Introduction

In spite of the fact that large scale coastal development inevitably disturbs and destroys the marine environments, coastal development is often conducted for economic growth. Hence, development of a tool or method for coastal management that facilitates conservation of coastal marine environments while allowing coastal development is necessary. To achieve sustainable coastal development, the marine environments and the changes in them should be quantitatively understood, assessed, and predicted.

Numerical oceanic models have been widely used in ocean science, both independently and in conjunction with other models or empirical methods, as a means of understanding, assessing and predicting coastal marine environments. In general, coastal marine environments constitutes four specific fields of study: ocean physics and circulation, marine water quality, marine ecosystems, and marine geology. Examples of models used in ocean physics and circulation are the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2009), Modular Ocean Model (MOM) (Griffies, 2012), and the Finite-Volume Coastal Ocean Model (FVCOM) (Chen et al., 2006). The CE-QUAL-ICM (Integrated Compartment Model) Eutrophication model is used for marine water quality and marine ecosystems (Cerco et al., 2010), and DELFT 3D (Roelvink and Van Banning, 1994) for marine geology.

Although the same laws of physics, chemistry, and fluid and hydro-static dynamics based on mass conservation and momentum equations are used to solve the governing equations, the various models formulations and parameters are differ, and they therefore, yield different projections. Furthermore, in order to identify the complex relationships between the four fields of study, coupling between models have been researched and implemented (Qiao et al., 2010; Sullivan and McWilliams, 2010; Cerco et al., 2010; Warner et al., 2008; Moon, 2005). However, the coupling methods are sometimes of sufficient computational complexity to require

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http://dx.doi.org/10.1016/j.ocecoaman.2015.08.007

the use of a supercomputer according to target accuracy, region of interesting modeling area, model resolution, and variables solved in the model.

In recent years, the interdisciplinary study field known as data science has progressed towards the defining of unknown systems or phenomena in environmental science, as the development of computer and network technology facilitates the acquisition of more valuable and greater amount of data. Data science is the study of the generalizable extraction of knowledge from data. It incorporates varying elements and builds on techniques and theories from many fields, including mathematics, statistics, pattern recognition, data mining, machine learning, artificial intelligence and data visualization, with the goal of extracting meaning from data, and creating data products (Gomes, 2009). In data science, the model is driven by data, not by numerical computer simulations.

For example, data science has been effectively and efficiently applied to climatological research for climate change, to risk assessment for coastal disaster and marine environmental pollution, and to vulnerability assessments for coastal and offshore structures and marine environments (Cho and Lee, 2011; Dietterich et al., 2012; Sheldon et al., 2013).

Similarly, in ocean science, spatio-temporal observational data accumulate constantly due to advancements in the technology of observation sensors, including satellites equipped with ocean color sensors, as well as improvements in battery capacity, submarine cables, and data storage. Hence, there are more opportunities to apply data science to define coastal marine environments. In aspect of data science, coastal marine environments can be described by establishing a data-driven mathematical model consisting of observation variables and their relationships using observational data. In Kolovoyiannis and Tsirtsis (2013) and Arhonditsis et al. (2002), a marine ecosystem model was proposed. It consists of a three-dimensional hydrodynamic numerical Princeton Ocean Model (POM) coupled to a simple ecological mode of five variables: phytoplankton, nitrate, ammonia, phosphate, and dissolved organic carbon concentrations. In order to establish and determine an ecological submodel and its parameters and evaluate the model performance, observational data analysis for the derivation of empirical equations, optimization, and skill assessment by computing basic statistics are conducted and applied. Tian et al. (2011) developed a grey dynamic modeling system which synthesized the analytic hierarchy process, grey target theory and grey forecasting modeling approaches, in order to evaluate biology and pollution indicators of the marine environments in coastal areas by hierarchical modeling, and identified relationships between variables using observational data.

In this paper we propose a mathematical modeling to quantitatively understand and assess and predict the coastal marine environments. The model identifies latent variables and forms probabilistic inferences by establishing a probabilistic graphical model (PGM). To derive an optimal model, observational data is used to estimate a computational model and to determine the coefficients using the maximum likelihood (ML) estimation. Depending on the derived model, a PGM is established and prior probabilities are calculated. Consequently, we were able to employ probabilistic inference to predict marine environmental changes.

We applied our method to the Saemangeum coast of Korea, which has undergone coastal development for land reclamation purposes, with the construction of a sea dyke. Using the resulting mathematical modeling, the coastal marine environments at Saemangeum could be quantitatively understood and assessed. Predictions for sustainable coastal development were conducted with a focus on maintaining coastal water quality and preserving coastal marine environments. This approach can be applied to any coastal area for which there is accumulated observational data, being a useful tool for coastal management when utilizing it to support decision-making.

2. Study area

Saemangeum is on the western coast of the Korean Peninsula. The area has undergone coastal development with the objective of land reclamation since 1991. The development involved the construction of a sea dyke 33.9 km long and with two sluice gates, yielding 40,100 ha of reclaimed land, and with an artificial lake on the landward side of the dyke (Fig. 1).

The dyke was completed in 2006, and land reclamation is currently underway on its landward side of the dyke. The artificial lake receives terrigenous effluents from the surrounding area, and exchanges with coastal waters via the opened sluice gates. However, for the land reclamation, water exchange is conducted only when essential, such as upon degradation of water quality in the lake.

Saemangeum's complex coastal system comprises a well-developed tidal flat with a large tidal range, the estuaries of the Mangeong and Dongjin rivers, and a chain of small islands in the outer sea area beyond the dyke. A large change in water movement and a reduction of currents occurred following construction of the dyke. The dyke has a complex effect on the already complicated relationships within the physical oceanographic environment, as well as on the marine water quality, marine ecosystems, and marine geology (Chun, 2003; Cho, 2007; Kim, 2010).

Saemangeum is one of the major distribution centers of marine transport, tourism, and fishery in north-east Asia. However, adverse effects on the surrounding marine environment are a potentially serious issue due to the polluted marine water resulting from the land reclamation project. Thus, improvements to and maintenance of marine water quality is of concern during development, in addition to the recovery of marine ecosystems and marine geology for healthy inter-tidal wetland ecosystems, fisheries, the marine tourism industry, and the provision of a pleasant residential environment around the coast.

3. The observational data

To monitor the marine environments, integrated ocean observation has been performed since 2002 (see Table 1) from the spatially distributed observation stations shown in Fig. 1. Observation buoys and towers with oceanographic and meteorological sensors have been deployed and installed. Surveys from ship and water sampling are conducted periodically.

Data pre-processing was performed by applying regression and time-series analysis for noise, anomalies, outliers, missing values, and any incorrect data (Chandola et al., 2009; Cho et al., 2013). The 15 observed variables in Table 2 were selected from over 30 observed variables listed in Table 1 under their fields of study. A total of 108 samples were obtained for each of the observed variables by taking the monthly means averages of the raw data collected from 2002 to 2010.

For computational efficiency in model estimation, dimension reduction was performed by applying principal component analysis (PCA) which aims to capture the data in terms of linearly uncorrelated set of variables (Abdi and Williams, 2010). In structural equation model (SEM) identification, it also recommends that 3 to 5 observed variables are suitable for one latent variable (Hoyle, 2014).

While there is no doubt that all of observation variables are important and necessary to describe each fields of study based on oceanographic theory, we can also carefully select only those relevant to the study subject. For example, in marine ecosystems, it is theoretically explained by three parts such as pelagic organisms,