Applied Ocean Research 47 (2014) 344–351

Contents lists available at ScienceDirect

Applied Ocean Research

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

Prediction of sea water levels using wind information and soft computing techniques

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ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form 15 May 2014
Accepted 7 July 2014
Available online 31 July 2014

Keywords:
Sea water levels
Sea level anomaly
Wind shear velocity
Genetic Programming
Artificial Neural Network

ABSTRACT

Large variations of sea water levels are a matter of concern for the offshore and coastal locations having shallow water depths. Safety of maritime activities, and properties, as well as human lives at such locations can be ensured by using the accurately predicted water levels. Harmonic analysis is traditionally employed for tide predictions, but often the values of predicted tides and observed (measured) water levels are not identical. The difference between them is called sea level anomaly. This can be attributed to non-inclusion of meteorological parameters as an input for tide prediction. Therefore other prediction techniques become necessary. The earlier studies on sea level predictions indicate better efficiency of alternate techniques such as Artificial Neural Network (ANN) and Genetic Programming (GP), and that most researchers have used sea level time series as model inputs. Present work predicts sea levels indirectly by predicting sea level anomalies (SLAs) using hourly local wind shear velocity components of the present time and up to the previous 12 h as inputs at four stations near the USA coastline with the techniques of GP and ANN. The error measures and graphs indicate that predictions are satisfactory.

1. Introduction

Knowledge of sea water levels and their variations is required for planning, operation, and maintenance works such as construction of jetties and harbors in the coastal and offshore locations, grounding of ships, navigation of the vessels with deep draft, installation of platforms, loading and unloading in the high tide zones. Tidal fluctuations causing large variations in the waterfront distances in low lying areas, small islands, and the lands with gentle slope are critical for the safety of properties and human lives. Working and safety of ocean based nonconventional energy power plants also depends on such fluctuations. A significant increase in the hydrometrological events such as rise of the sea water levels, frequency of occurrence of cyclones and their severity is experienced in the recent past all over the globe. This highlights reliable and accurate prediction of sea water levels as one of the major challenges for the researchers.

Variations of the sea levels are produced by combination of complex processes involving forces of attraction of the Moon and the Sun on the Earth, bathymetric characteristics as well as meteorological parameters like the atmospheric pressure, air temperature, water temperature, ocean currents, wind, etc. [1]. The observed (or measured) sea water levels consist of tidal and non-tidal portions. The tidal or astronomical portions are created by the astronomical alignment of the Sun–Earth–Moon system while the non-tidal or non-astronomical portions are caused by the combined effect of other parameters. Accuracy of traditional harmonic models depends on the number of harmonics considered, which in turn depends on the length of data used for modeling. Deo and Chaudhari [2] mentioned that in spite of considering as many as 69 harmonic constituents for tide prediction, the harmonic analysis becomes ineffective if non-periodic meteorological events such as hurricanes and cold fronts predominate. Makarynska and Makarynskyy [3] stated that the conventional harmonic analysis for sea level predictions may suffer from 30% residual errors if the hydro-meteorological effects involved in the process are neglected.

Therefore alternate modeling techniques and strategies are tried out by ocean researchers for improving sea level predictions. In the classical approach based on harmonic analysis, tides are considered as a resultant of different harmonics and their frequencies derived from astronomical observations. Other techniques such as analysis of tides as propagation of long waves, regression, and the numerical model in combination with tidal dynamic equations are also tried in sea level research. Chang and Lin [4] reported that numerical method can catch the tidal characteristics successfully even if the hydrodynamic characteristics of tides are not known but generation of the numerical grid requires a lot of time for predicting the tides.

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0141-1187/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2014.07.003

Traditionally the emphasis of knowledge discovery has been on some theory that demands appropriate data obtained through observations or experiments. In this process, a theory based model is obtained in mathematical form; which can be termed as 'theory-driven approach'. It makes an extensive use of the associated mathematical methods and the physical process or processes involved in the phenomena. On the other hand, the 'data-driven approach' utilizes input–output data sets to derive a model that fits the data optimally. It aims at providing the tools to facilitate conversion of data into a convenient form to convey a better understanding of the processes hidden in these data and a mathematical statement of the relations between various parameters in the data can be obtained [5]. Babovic and Abbott [6] explained three criteria for an evolutionary process to occur as given by Maynard-Smith [7] and three case studies of evolution of equations from the hydraulic data [8]. Hybrid techniques combining deterministic numerical model and chaos theory is tried out by Sannasiraj et al. [9], Wang et al. [10], etc. for water level predictions. Modified strategies such as data assimilation, application of error corrections through neural networks, etc. along with Singapore Regional (numerical) Model are demonstrated by Kurniawan et al. [11], Sun et al. [12], Karri et al. [13] in the Singapore Regional Waters for improving water level predictions.

Soft computing techniques such as the Artificial Neural Network (ANN) and Genetic Programming (GP) fall in the domain of data-driven techniques. Some advantages of the data-driven techniques are: (1) understanding of the underlying physical processes is not a pre-requisite, (2) modeling data need not be huge and exogenous, (3) re-calibration of the developed models can be done in comparatively less time and with less efforts, (4) a reasonable generalization is extracted from the data in spite of the complex physical processes involved in the phenomena, and (5) the developed models are more robust since they are more data tolerant.

Present work follows the suite of Cox et al. [14] and Londhe [15] in that the soft technique is employed for predicting the sea level anomaly and water level is obtained subsequently by adding the predicted anomaly to the harmonic tidal level. A series of wind shear velocity components of 1–3 years is supplied to the model as inputs and the models are developed using the techniques of GP and ANN at four stations near the USA coastline. The methodology is explained in Section 3. The innovation in the present work is the use of hourly wind shear velocity component series – the major causal parameter – as model input for predicting non-astronomical components of water levels (sea level anomaly).

The paper is organized as follows: literature review is summarized in Section 2. The study area and data are described in Section 3.The methodology adopted and model development process is detailed out in Section 4. Results are discussed in Section 5 and Section 6 gives the conclusions and scope for further research.

2. Literature review

Ample literature is available on sea level predictions using traditional as well as alternate approaches. Literature review pertaining to scope of the present work is summarized in this section.

Data-driven techniques include soft computing techniques, which are found to be more versatile for the phenomena such as ocean waves, water level variations, rainfall, changes in the meteorological parameters, etc. Such phenomena involve nonlinear and complex relationships between several variables.

An Artificial Neural Network (ANN) consists of number of artificial neurons, interconnected with connection links of different weightages, which tries to mimic the working of a human brain for reaching a reasonable solution to fit the input–output data sets. Readers are referred to the paper by the ASCE Task Committee [16] for details of ANNs. Genetic Programming (GP) searches for the best possible solution of a problem by generating new programs starting with an initial set of individuals called parents (programs). The children or offspring (new programs) are created based on the Darwinian Principle – 'survival of the fittest'. New programs are evolved in the subsequent generations through combination of the processes of crossover, mutation, and reproduction (copy) to model the data sets. More fit programs are chosen as a part of the new generation and the best program is obtained if the user defined termination criterion is satisfied. Fundamentals of tree-based GP can be understood from Koza [17]. More efficient variants of the GP are described by Babovic and Keijzer [5]. Some noteworthy research based on the ANNs and GP modeling for water level and tidal level predictions are quoted below.

In the earliest known work on sea water levels, Deo and Chaudhary [2] developed three layered feed forward neural networks to estimate sea levels at subordinate stations using the sea levels at a reference station. Tsai and Lee [18] used ANNs for forecasting diurnal and semi-diurnal tides by using the field data of diurnal and semidiurnal tides. Lee and Jeng [19] developed ANN models for tide forecasts using a short-term tidal record. All diurnal, semi-diurnal and mixed tides were considered to predict hourly tidal levels over a week's period using different lengths of tidal record at Keelung, Hsinchu and Kaohsiung harbors in Taiwan. Cox et al. [14] proved the limitations of the harmonic analysis in their work by developing ANN modes using the data at Galveston Pleasure Pier in the Gulf of Mexico in the spring and summer seasons. Time series of sea level anomaly along with barometric pressure, locally forecasted wind speed and wind direction were the inputs in a three layered ANN for forecasting the sea level anomaly and in turn the sea levels with 3–36 h lead time.

Lee et al. [20] and Lee [21] used a no-hidden layer ANNs to find five most influential harmonic constituents and used them in a three layered feed forward neural network to supplement missing tidal data as well as to predict tidal levels one year in advance with 15 days of hourly tidal observations. Makarynskyy et al. [22] used ANNs to predict hourly sea level variations for the following 24 h as well as for half-daily, daily, 5-daily and 10-daily mean sea levels at Hillarys Boat Harbor, Western Australia. In the first set of simulations, their ANNs successfully predicted hourly sea levels with lead times of 1–24 h and to correct the results of these initial simulations further, second set of simulations were implemented. In the second simulations, ANNs were implemented to forecast sea levels averaged over 12 h, 24 h, 5 days and 10 days, three time steps ahead. Good predictions were obtained over the first two time steps by them rather than over the third time interval and maximum coefficient of correlation (r) of 0.86 is reported for 24 h forecast using water levels averaged over 24 h.

Steidley et al. [23] used an ANN to improve predictions of water levels where the tide charts particularly perform poorly. Lee [24] used a three layered feed forward neural network with pressure, wind velocity, wind direction, and harmonic tides as inputs to estimate storm surge at Taichung Harbor, Taiwan during three different typhoons in a year. Alvisi et al. [25] commented that the precision of ANNs over fuzzy logic would be higher if more reliable input data are used for predicting the sea levels. Chang and Lin [4] used tide generating astronomical forces as inputs and presented multi-point tidal level predictions with an ANN for the sites with tidal characteristics similar to a reference site. Tidal forecast based on the short-term measurements was successfully done by Lee et al. [26] using harmonic analysis and ANN. Chen et al. [27] used harmonic constituents, wavelet analysis and neural networks to retrieve missing tidal data supplement for a very long period (up to 5 years) with a very short (even just 1 month of data) period of tidal record. The results of the methodology validation show that short-term sea level registrations can be efficiently employed to produce