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Hybrid harmonic analysis and wavelet network model for sea water level prediction

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ABSTRACT

Accurate sea water level prediction is required for safe marine navigation in shallow waters as well as for other marine operations. Traditionally, tide prediction is commonly carried out using only the harmonic analysis (HA-only) model or only a wavelet network (WN-only) model. The harmonic analysis method is the most reliable model for long term sea water level prediction when long data records are available and in contrast the wavelet network method is the most reliable model used for short term sea water level prediction when short data records are available. This paper developed a hybrid harmonic analysis and wavelet network (HA-and-WN) model for accurate sea water level prediction. To validate the hybrid HA-and-WN model, sea water level data from four tide gauges are employed to investigate the performance of the developed hybrid model. It is shown that the majority of error values at 95% confidence level fall within ±14.77 cm, ±2.65 cm and ±2.08 cm range in average with maximum error of 36.84 cm, 9.21 cm and 7.00 cm in average for HA-only model, WN-only model and hybrid HA-and-WN model, respectively. Also, it is found that the root-mean-squared (RMS) errors are about 9.75 cm, 1.85 cm and 1.49 cm for HA-only, WN-only and hybrid HA-and-WN models, respectively, based on the overall performance from the four tide gauges under implementation. Therefore, it is concluded that the developed hybrid HA-and-WN model is superior to the HA-only model by about 85% and outperforms the WN-only model by about 20%, based on the overall RMS errors.

1. Introduction

Accurate current and predicted sea water level information is a key element for safe marine navigation in shallow waters as well as for other marine operation. Sea water level prediction was conventionally carried out using various methods such as harmonic analysis method [1], artificial neural network model El-Diasty and El-Rabbany, 2003 and most recently by wavelet network model [2]. With the harmonic method (so called HA-only in this paper), the sea water level data series collected at a tide gauge is analysed to provide the amplitudes and the phases of all the embedded harmonic tidal constituents. These tidal constituents are employed to predict the sea water level [3]. Based on the number of constituent amplitudes and phases considered in the prediction model, different levels of accuracies can be expected. Ideally spanning a period of more than 18.6 years of tide gauge data records are required to obtain the ideal accuracy, however in practice one year of data records are used to develop the harmonic analysis model [4,5]. Long tide gauge data records are not always available, which may lead to either large errors using harmonic analysis method [1]. The harmonic analysis model can be considered as the most reliable model for long term sea water level prediction when very long data records are available.

To overcome the above limitations of the above-mentioned traditional least-squares-based harmonic analysis approach, the neural network method for sequential water levels prediction was proposed during the last decade. The use of the neural network approach was proposed by several authors. Mandl [6] and Deo and Chaudhar [7] used backpropagation neural networks to predict the hourly water levels. Lee and Jeng [8] and Lee [9] proposed artificial neural network (ANN) based model to predict long-term water levels using short-term water level measurements. El-Rabbany and El-Diasty [10] replaced the traditional least-squares-based harmonic analysis method with an ANN-based modular model for

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predicting the water levels in sequential mode using water level measurements from four different tide gauges with high accuracy.

The current-state of-the-art for sea water level prediction is the wavelet network (so called WN-only in this paper) model that recently developed by El-DiastyEl-Diasty and Al-Harbi and Al-Harbi [2]. The WN-only model is a highly nonlinear model that proved to be an accurate prediction model for many applications. It was shown that the WN-only model is superior to the HA-only model and the ANN model [2]. The WN-only model can be considered as the most reliable model for short term sea water level prediction when short data records are available.

This paper investigates a hybrid harmonic analysis and wavelet network (HA-and-WN) model for accurate sea water level prediction. Sea water level data from four different tide gauges are used to develop and validate the proposed hybrid (HA-and-WN) model. Then, to further validate the proposed model, a comparison is made between the proposed hybrid HA-and-WN model for accurate sea water level prediction, and the current-state-of-art traditional methods such as HA-only model [4,5] and WN-only model [2]. In practice, most maritime applications require an accurate prediction model for about one month ahead. To implement the performance of proposed wavelet network method, one month water level measurements, from four different tide gauges, are employed to develop a hybrid HA-and-WN model and validate the model performance accuracy by predicting one month of water levels and compare the predicted value against the measured water levels. It is worth noting that, the reason behind integrating HA model with WN model in this paper and not the existing numerical models is that the HA model is developed based on the same sea water level measurements that employed with the proposed hybrid model and therefore was considered as the best conventional method to integrate with WN-model to guarantee high correlation between the input and output during the modeling (training) stage and consequently improve the prediction accuracy of sea water level during the prediction stage.

2. Methods description

In this section, the HA-only method, the WN-only method and the HA-and-WN method are described.

2.1. Traditional least-squares-based harmonic analysis (HA-only) method

Water levels prediction is traditionally performed using least-squares-based HA-only approach based on the estimation of the tide constituents embedded in the water level measurements. The tide mathematical model is [11,1]:

$$h(t_i) = h_0 + \sum_{j=1}^{n} C_j \cos(\omega_j t) + D_j \sin(\omega_j t) \quad (1)$$

where $h(t_i)$ is the measured water levels, t_i is the time (i ranges from *1* to *N* number of water levels measurements), h_0 is the mean water level (unknown), n is the number of the expected constituents, C_j is the cosine parameters (unknown), D_j is the sine parameter (unknown), ω_j is the frequency of the expected constituent. Eqn. (1) can be written in a matrix form as:

$$h = Ax \quad (2)$$

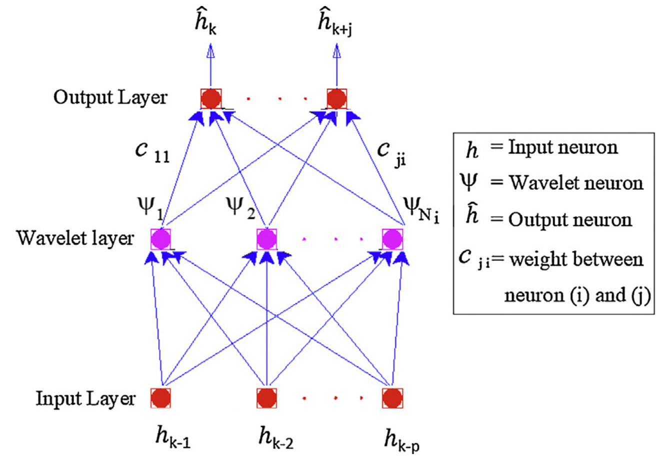

Fig. 1. General WN-only model structure (N_p-input, N_i-wavelons, and N_j-outputs).

where $h = [h(t_1), h(t_2), \ldots, h(t_N)]^T$ is the N × 1 vector of the measured tide heights, $\boldsymbol{x} = [h_0, C_1, D_1, \ldots, C_n, D_n]^T$ is the (2n + 1) × 1 vector of the unknown parameters, and $\boldsymbol{A}$ is the design matrix written as:

$$\mathbf{A} = \begin{bmatrix} 1 & cos(\omega_1 t_1) & \cdots & sin(\omega_n t_1) \\ 1 & cos(\omega_1 t_2) & \cdots & sin(\omega_n t_2) \\ \vdots & \vdots & \cdots & \vdots \\ 1 & cos(\omega_1 t_N) & \cdots & sin(\omega_n t_N) \end{bmatrix} \quad (3)$$

The unknown parameters $\boldsymbol{x}$ can be estimated when weight matrix $\boldsymbol{W}$ is known using least-squares solution as follows [12,13]:

$$\hat{\boldsymbol{x}} = (\mathbf{A}^T\mathbf{W}\mathbf{A})^{-1}\mathbf{A}^T\mathbf{W}\mathbf{h} \quad (4)$$

The associated variance-covariance matrix of the estimated parameters $\hat{\boldsymbol{x}}$ can also be estimated using propagation law for Eq. (4). Once $\boldsymbol{x}$ is estimated, the predicted water levels $\hat{h}(t_i)$ can be estimated at any time t_i from Eq. (1). It is worth noting that the current traditional HA-only method is a linear mathematical model.

2.2. Current state-of-the-art wavelet network (WN-only) method

The current-state-of-the-art for sea water level prediction is the wavelet network (so called WN-only in this paper) model that recently developed by [2]. The WN-only model is a highly nonlinear model that proved to be an accurate prediction model for many applications. The water level prediction model is developed using WN model with an output $\hat{h}_k$ computed as [2]:

$$\hat{h}_k = \sum_{i=1}^{p} c_{k-i}\Psi(a_i(h_{k-i} - b_i)) + w. \quad (5)$$

where, c_{k-i} are coefficient variables, a_i are dilation variables, b_i are translation variables, and Ψ is a wavelet function. Fig. 1 shows the wavelet network structure. The wavelet network consists of an input vector of N_p values, a layer of N_i weighted wavelets and an output vector of N_j output neurons. The wavelet network parameters (c_{k-i},$a_i$and b_i) can be estimated by a backpropagation-learning method. If N_k is the number of outputs, h_k^d is the desired output values and is the network output estimated from Eq. (5), then, the wavelet network training objective is to minimize the error function, E [14]:

$$E = \frac{1}{2}\sum_{k=1}^{N_k}(h_k^d - \hat{h}_k)\hat{h}_k \quad (6)$$