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Combining deterministic modelling with artificial neural networks for suspended sediment estimates

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ABSTRACT

Estimates of suspended sediment concentrations and transport are an important part of any marine environment assessment study because these factors have a direct impact on the life cycle and survival of marine ecosystems. This paper proposes to implement a combined methodology to tackle these estimates. The first component of the methodology comprised two numerical current and wave models, while the second component was based on the artificial intelligence technique of neural networks (ANNs) used to reproduce values of sediment concentrations observed at two sites. The ANNs were fed with modelled currents and waves and trained to produce area-specific concentration estimates. The trained ANNs were then applied to predict sediment concentrations over an independent period of observations. The use of a data set that merged together observations from both the mentioned sites provided the best ANN testing results in terms of both the normalised root mean square error (0.13) and the mean relative error (0.02).

1. Introduction

Concentrations and transport of suspended sediments in seawater environments have a direct impact onto the life cycle and survival of marine ecosystems. This is due to the fact that suspended sediment concentrations (SSCs) determine seawater turbidity and thus light penetration. Fine particles in suspended sediments are also recognised as a carrier of nutrients as well as contaminants (e.g. [1]). Elevated levels of SSC and turbidity can drastically affect an ecosystems' functionality. Therefore, estimates of suspended sediment concentrations and their transport have become an important part of any marine environment assessment study associated with such disturbing marine sediment activities as dredging, drilling, coastal and offshore construction, as well as nearshore navigation.

Practical sediment transport and concentration estimates have historically been obtained using empirically derived expressions based on either physical insights and/or experimental measurements collected in laboratory and field experiments (e.g. [2,3]). Such experiments are frequently conducted in idealised physical conditions and are sediment type- and site-specific. Many empirical models for estimating SSC rely on bottom stress induced by waves and currents, and the physical properties of the sediment including grain size distribution and cohesiveness. It is often difficult or impossible to obtain decent temporal and spatial coverage of these parameters therefore limiting the applicability of such empirical expressions.

An alternative case- and site-specific approach can be provided by a data-driven artificial intelligence technique of neural networks. Applicability of artificial neural networks (ANNs) to obtain approximations of nonlinear mathematical functions was proven by Hornik [4]. It has also been demonstrated in a number of environmental and ocean and coastal engineering applications that ANNs are able to reproduce behaviours of complex water systems without any preceding knowledge of the internal relations among the system's components. Some examples of such applications include simulations of environmental parameters (e.g. [5]), wind waves (e.g. [6,7]), sea level (e.g. [8,9]), as well as solving the tasks of metocean data interpolation (e.g. [10,11]) and assimilation (e.g. [12–14]). Comparisons between outcomes of ANNs and conventional modelling techniques (e.g. hydrodynamic and/or statistical models) demonstrated that in the same or similar marine environments the neural methodology provides more accurate site-specific estimates.

Recently, thanks to their universal applicability, ANNs found wide spread application in simulations of suspended sediment transport and flux in rivers (e.g. [15–18,43]). Flume and field observations of the streamflow and antecedent sediment data were used as input parameters in these simulations.

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Several recent riverine studies (e.g. [19–21]) demonstrated applicability of data/measurement-based artificial intelligence techniques to suspended sediment and bed loads estimates.

Compared to the above, novelty of the present study consists in tackling the task of SSC estimates in the marine environments and by combining a deterministic numerical modelling approach with artificial neural network simulations.

The reason for the methodology development was as follows. Currents and waves are usually measured by a different type (or types) of equipment from the one measuring sediments. Frequently these different instruments are being deployed at different times, or a field study is conducted that concentrates on measuring only one or two of the mentioned parameters. For instance, defining sediment thresholds for environmental assessments might be done by measuring and analysing variations in ambient sediment concentrations only, without taking into account ambient currents and waves. After the measurements are finished, however, questions usually arise about the driving forces determining SSC variations. In such cases, an absence of simultaneous observations for currents, waves and SSC can be addressed by applying deterministic numerical models to hindcast the currents and wind waves in the area of interest, and then the technique of ANN to relate the model outcomes with the observed SSC.

The current study implements such an ANN application for obtaining of site-specific SSC estimates. The proposed methodology is based on current and wave model results and SSC observations. The used ANNs were trained and tested on data sets from two different sites within the study area.

Site-specific data imposes limits on the generalisation of the relationships developed by the ANN technique over wider areas. To overcome this shortcoming, the available site-specific data sets were merged together, and new ANNs were trained and tested on this new longer data set. The test outcomes demonstrated that ANNs were capable of generalisations within the study area.

It should be noted that this paper did not consciously aim at inter-comparing different artificial intelligence techniques, as this was proven many times that in such inter-comparison studies the techniques produces only marginally different results (e.g. [22–26] among many others).

The paper is structured as follows. Section 2 describes the observations while Section 3 presents the hydrodynamic and wave models, the technique of neural networks, and implemented sediment data pre-processing procedures used in this study. Discussion is given in Section 4 of the suspended sediment concentrations estimated using the proposed methodology in Mermaid Sound, Western Australia. Some conclusions are given in Section 5.

2. Suspended sediment data

Field observations of SSC were collected from two sites within Mermaid Sound which is part of the Dampier Archipelago in Western Australia. SAS instruments [27] were deployed at locations near Angel Island (ANGI hereafter) and Tidepole Island (TDPL hereafter) to observe variations of turbidity over time. The ANGI site was representative of SSC conditions in the outer, more open part of Mermaid Sound, while the TDPL site was representative of well sheltered conditions of the inner sound (Fig. 1). The observations were collected over a period 14/11/2006–06/02/2007 at ANGI and 16/11/2006–08/02/2007 at TDPL (Fig. 2). There were neither current nor wave measurements available for a comparative analysis over the same period of time.

Sediment meters used in Mermaid Sound were SAS meters developed at James Cook University, Australia. The meters collected optical backscatter data from a horizontal sensor and converted them to SSC (mg/L) via an internal calibration. The conversion procedure was empirically calibrated using sediments collected from sites adjacent to the instruments before the observations. All recordings were logged on a 10 min interval.

3. Methodology

The methodology proposed in the present study consists of two major components. The first component includes hydrodynamic and wave modelling to hindcast the conditions present at the time of the suspended sediment measurements. This was necessary as no observations for waves or currents were available from the sites. The second component involves developing and training artificial neural networks along with input of the modelled wave and current data and observed SSC data to determine a relationship between the former two and the latter and to use the relationship for predictions of SSC at other sites.

3.1. Deterministic numerical modelling

The deterministic model component was composed of two numerical models, HYDROMAP and SWAN. It is firmly believed though that this component may have been completed using any well developed and thoroughly validated hydrodynamic and wind wave models, including open source and publically available ones (e.g. ADCIRC, Delf3D, etc.).

HYDROMAP is a three dimensional barotropic ocean and coastal circulation model that simulates the flow of ocean currents due to forcing by astronomical tides, wind stress and bottom friction. The model follows the finite-difference solution for regular grids (e.g. [28,29]) further developed to employ a space-staggered gridding strategy to support two-way nesting over sub-areas (e.g. [30]). In this application, spatial resolution at the outer boundaries was set at 1000 m and spatial nesting was applied to increase spatial resolution to 500 m, 250 m and 125 m over sub-areas of interest. The three-dimensional shape of the grid was defined using a composite of bathymetric data derived from different sources. These included detailed soundings from bathymetric surveys over the area, digitised depths from the most recent navigation chart (AUS 57) and corrections for more recent modifications within the area.

The extent of the model domain is shown in Fig. 1. Forcing due to astronomical tidal variations was specified at all open boundaries from tidal constituent values that define the wavelength and amplitude of individual tidal constituents. The model was configured to interpolate tidal constituent values from the global inverse tidal model, TPXOv6.2 (e.g. [31]) and to generate vertically-varying currents with a parabolic distribution on the forcing by wind and seabed drag. Winds were sourced from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis (e.g. [32]), which is a global surface hindcast model that uses atmospheric observations from the world's array of observation stations, inclusive of stations surrounding the study area. The NCEP/NCAR model assimilates measurements of meteorological variables and represents synoptic-scale winds, therefore some local wind variability may be non- or under-represented.

Based on the above, it is clear that HYDROMAP was not configured for precise time-step and site-specific predictions of currents but rather for hindcasts of the most statistically significant hydrodynamic features affecting sedimentation in the area.

HYDROMAP validations were performed targeting representation of tides as well as trends and variability of circulation patterns over long periods of time (several months), rather than predications of site-specific, short-term events. Based on the validation results [33], it was concluded that the model represents well tide and current variability in the region.