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Application of a fuzzy inference system for the prediction of longshore sediment transport

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ABSTRACT

A fuzzy inference system (FIS) and a hybrid adaptive network-based fuzzy inference system (ANFIS), which combines a fuzzy inference system and a neural network, are used to predict and model longshore sediment transport (LST). The measurement data (field and experimental data) obtained from Kamphuis [1] and Smith et al. [2] were used to develop the model. The FIS and ANFIS models employ five inputs (breaking wave height, breaking wave angle, slope at the breaking point, peak wave period and median grain size) and one output (longshore sediment transport rate). The criteria used to measure the performances of the models include the bias, the root mean square error, the scatter index and the coefficients of determination and correlation. The results indicate that the ANFIS model is superior to the FIS model for predicting LST rates. To verify the ANFIS model, the model was applied to the Karaburun coastal region, which is located along the southwestern coast of the Black Sea. The LST rates obtained from the ANFIS model were compared with the field measurements, the CERC [3] formula, the Kamphuis [1] formula and the numerical model (LITPACK). The percentages of error between the measured rates and the calculated LST rates based on the ANFIS method, the CERC formula ($K_{sig} = 0.39$), the calibrated CERC formula ($K_{sig} = 0.08$), the Kamphuis [1] formula and the numerical model (LITPACK) are 6.5%, 413.9%, 6.9%, 15.3% and 18.1%, respectively. The comparison of the results suggests that the ANFIS model is superior to the FIS model for predicting LST rates and performs significantly better than the tested empirical formulas and the numerical model.

1. Introduction

Accurate determination of the longshore sediment transport (LST) rate in coastal zones is a critical issue for coastal engineers. The LST rate is essential for assessing the coastal morphology and changes in shoreline. LST is defined as the movement of sedimentary material in the littoral zone and is caused by the interaction of winds, waves, currents, tides, sediments and other phenomena in the littoral zone. Many different formulations for the estimation of the LST rate are presented.

Bijker [4] developed a formula to calculate the sediment transport as a function of a given wave field and a given longshore current irrespective of its origin (wave-induced current or tidal current). The Bijker transport formula consists of two components, namely, a bed load transport component and a suspended load transport component. The bed load transport formula was adopted from the Kalinske–Frijlink [5] formula (for bed load transport under river conditions). Bailard and Inman [6] derived a formula for both the suspended and the bed load transport based on the energetics approach by Bagnold [7]. The CERC formula [3], which was developed from prototype and model measurements prior to the development of longshore current theory, expresses a correlation between the longshore transport rate and the longshore component of energy flux at the outer edge of the surf zone. Van Rijn [8] presented comprehensive formulas for calculating the bed load and the suspended load. Watanabe et al. [9] proposed a power-model-type formula for the local sediment transport rate under the combined action of waves and currents that consists of the summation of the transport rate due to mean currents and the direct action of waves. Kamphuis [1] proposed a formula for the LST rate based on three-dimensional, mobile-bed hydraulic beach model experiments that were performed with both regular and irregular waves. After a detailed dimensional analysis, he expressed the LST rate as a function of wave steepness, beach slope, relative grain size and wave angle. Damgaard and Soulsby [10] derived a physics-based formula for bed load LST. Although it is primarily intended for use on shingle beaches, it is also applicable to the bed load component for sandy beaches. Bayram et al. [11] presented a new formula for calculating the LST rate. This formula is derived from the average concentration and longshore current velocity of the surf zone, in which the current may originate from breaking waves, wind or tides. However, because the LST rate is a

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highly complex littoral process, a precise prediction model of the LST rate has not been developed. These well-known empirical formulas, which are selected for their rapid and practical application, provide reasonable estimates related to the conditions in which they are employed.

Alternatively, the LST rate can be estimated using soft tools, such as fuzzy logic (FL), artificial neural networks (ANNs) and an adaptive neuro-fuzzy inference system (ANFIS). These soft tools have been extensively applied in a variety of areas, with an emphasis on diagnosis and forecasting. Recently, fuzzy inference systems (FISs) and adaptive network-based fuzzy inference systems (ANFISs) have been used to develop LST models. They are also being employed to establish a correlation between the variables and the desired phenomena that comprises a collection of "if-then" rules, which define the fuzzy relations of fuzzy variables in systems by utilizing fuzzy logic or fuzzy set theory. The use of fuzzy logic theory enables the user to achieve inevitable imprecision and uncertainty in the data. Some examples of this use include the prediction of wave parameters [12–16], the determination of the LST [17,18], the preliminary design of rubble mound breakwaters by Balas et al. [19], the prediction of runup in swash zones by [20], studies about water resource problems [21–28], studies about climatic and meteorological changes [29,30], studies about daily flow forecasting [31,32], studies about flood forecasting by Stüber et al. [33], the estimation of scour beneath spillways by Azamathulla et al. [34], the prediction of water levels by Chang and Chang [35], modeling of hydrological time series by Nayak et al. [36] and the estimation of pile group scour by Bateni and Jeng [37].

This study aims to develop a new LST model that can accurately predict the LST rate. The motivation for the study is to provide a practical and rapid determination of the LST rate and to include less uncertainty in the model by calibration against the field and experimental data. This study primarily addresses the implementation of the FIS and the ANFIS, which combines a fuzzy inference system and a neural network, to determine the LST rate. The measurement data (laboratory and field data) obtained from Kamphuis [1] and laboratory data obtained from Smith et al. [2] were used to develop the model. The ANFIS model was applied to the Karaburun coastal region, which is located along the southwestern coast of the Black Sea. The LST rate obtained from the ANFIS model was compared with the field measurements, the CERC [3] formula, the Kamphuis [1] formula and the numerical model (LITPACK).

The remainder of this paper is organized as follows: A brief review of the LST formulas (CERC and Kamphuis [1]) and the numerical model (LITPACK) is provided in Section 2. The LST rates obtained for the respective research area are also presented. The principles of the FIS and ANFIS models are described in Section 3. Modeling of the LST rates with the FIS and ANFIS models using measured field and laboratory data is detailed in Section 4. The predictions of CERC, Kamphuis [1], the numerical model (LITPACK) and the ANFIS model are compared with the field data. Conclusions are presented in Section 6.

2. Longshore sediment transport (LST) rate for the site

The field study was conducted in a coastal village (named Karaburun) located near the southwestern coast of the Black Sea at 41°21′05″ N and 28°41′01″ E, 40 km northwest of Istanbul Bosporus (Fig. 1). The study field shoreline extends approximately 4.0 km and exhibits a WNW–ESE general orientation. The accurate prediction of the longshore sediment transport rate is critical due to erosion and sedimentation problems in the Karaburun coastal area.

To determine the LST rates in this study area, long-term field surveys were performed. Sea-bottom topography, shoreline changes, sediment properties, wind, wave and current measurements were conducted. The average net annual LST rate for the research area was determined based on the differences in the morphological volumes among the surveys. The volume differences were obtained from the accretion at the secondary breakwater of the harbor located at the western end of the 4 km sandy beach. The shoreline between 1996 and 2006 was measured using a Real Time Kinematic Global Positioning System (RTK-GPS) at seasonal intervals. In addition, bathymetric surveys of the nearshore zone of the Karaburun coastal area were performed for the same time period. To determine the average net LST rate from the accretion at the harbor, which acts as a total trap, volume differences between the surveys were obtained. Consequently, the average net longshore sediment transport for the Karaburun coastal area was determined to be 72,000 m^3/y (Table 1). Table 1 depicts the net and gross LST rates for the research area, as predicted by three different methods, and the measured net LST rate for the region. The direction of the net longshore sediment transport extends from east-south-east (ESE) to west-north-west (WNW) [38].

Table 1
The net and gross longshore sediment transport rates measured and predicted by different methods [38].

	Q_{net} (m^3/y)	Q_{gross} (m^3/y)
Measured	72,000	
CERC formula (K = 0.39 (uncalibrated))	370,000	644,000
CERC formula (K = 0.08 (Calibrated))	77,000	135,000
Kamphuis [1]	83,000	170,000
Numerical model (LITPACK)	85,000	152,500

The LST rates in the respective research area were estimated with two empirical methods: Kamphuis [1] and CERC [3]. The Kamphuis [1] formula, which is based on dimensional analysis, is the most frequently used empirical equation for the LST rate. The formula considers the wave period, the beach slope and the grain size of the sediment, as well as the wave height and incident wave angle, for the longshore sediment transport.

$$Q = 6.4 \times 10^4 H_{sb}^2 T_p^{1.5} {m_b}^{0.75} D_{50}^{-0.25} \sin^{0.6}(2\alpha_b) \quad (1)$$

where Q is the longshore sediment transport rate (m^3/y), H_{sb} is the significant breaking wave height, T_p is the peak wave period, m_b is the breaking slope, D_{50} is the median grain size and α_b is the breaking wave angle.

The net longshore sediment transport for the Karaburun region was determined to be 83,000 m^3/y. The results of the calculations for the research area according to the Kamphuis [1] formula are displayed in Table 1.

The most common method for calculating the total LST rate is the CERC equation [3], which predicts the bulk (total) longshore transport rate in the cross-shore direction. Using the empirical dimensionless coefficient K, the equation reveals that the longshore sediment transport is in direct proportion to the wave energy flux evaluated at the breaker position.

$$Q = \frac{K}{16\sqrt{\gamma_b}} \rho g^{3/2} H_{sb}^{5/2} \sin(2\alpha_b) \quad (2)$$

where Q is the total immersed weight LST rate, K is an empirical coefficient that relates sediment transport to the wave energy flux, γ_b is the breaker index, ρ is the density of water, g is the acceleration due to gravity, H_{sb} is the significant wave height at breaking and α_b is the wave angle at breaking.

Numerous studies have shown that the CERC formula performs well if the value of K is calibrated [2,39–43]. The standard coefficient value K in the empirical formula was employed with and without calibration of the data sets. Values for K (uncalibrated) and γ_b of 0.39 and 0.8, respectively, were used in the equation. The K (calibrated) value was calculated to be 0.08 after the calibration and validation steps. Based on the calculations for the research area, the