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Spatio-temporal scaling effects on longshore sediment transport pattern along the nearshore zone

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ABSTRACT

A measure of uncertainties, entropy has been employed in such different applications as coastal engineering probability inferences. Entropy sediment transport integration theories present novel visions in coastal analyses/modeling the application and development of which are still far-reaching. Effort has been made in the present paper to propose a method that needs an entropy-power index for spatio-temporal patterns analyses. Results have shown that the index is suitable for marine/hydrological ecosystem components analyses based on a beach area case study. The method makes use of six Makran Coastal monthly data (1970–2015) and studies variables such as spatio-temporal patterns, LSTR (long-shore sediment transport rate), wind speed, and wave height all of which are time-dependent and play considerable roles in terrestrial coastal investigations; the mentioned variables show meaningful spatio-temporal variability most of the time, but explanation of their combined performance is not easy. Accordingly, the use of an entropy-power index can show considerable signals that facilitate the evaluation of water resources and will provide an insight regarding hydrological parameters' interactions at scales as large as beach areas. Results have revealed that an STDDPI (entropy based spatio-temporal disorder dynamics power index) can simulate wave, long-shore sediment transport rate, and wind when granulometry, concentration, and flow conditions vary.

1. Introduction

Coastal region vulnerability is not the result of sea level variations (assuming a static coastal morphology); contrarily, the latter is an invariable equilibration process at different timescales. Waves are commonly assumed to be the major stimulants of the evolution of coasts; however, they have a very strong nonlinear role and coast response to varying forcing is vague. Some researchers (Ranasinghe, 2016; Payo et al., 2016) believe that the understanding (let alone prediction) of coastal evolution, which is the result of interaction among numerous hydrodynamic/geologic processes at different spatio-temporal scales, is not easy at all; however, to forecast climatic changes and SLR (sea level rise), long-term (10- to 100-year time intervals), quantitative, and dependable coastal evolution predictions are issues researchers are after for adaptation planning (Ranasinghe and Stive, 2009; Nicholls et al., 2014). On the one hand, sea-level anomalies, tides, waves, fluvial discharges, storms, and currents, all known as near-shore hydrodynamic processes, play important parts in bringing about seasonal/multi-annual (short-term) coastal morphologic changes (Yan et al., 2013; Larsson et al., 2017; Slinger, 2016; Bricheno et al., 2016), and on the other hand, chronic coastal variations are often caused by such phenomena as climatic changes, land use, natural/anthropogenic sediment supply, Aeolian transport, gradients in alongshore sediment transport, and relative sea-level variations which are all referred to as decadal/centennial (long-term) processes (Kärnä and Baptista, 2016; Huang et al., 2017; Dogliotti et al., 2016). Hence, coastal evolution prediction based on 10- to 100-year time intervals usually necessitates precise hydrodynamic/geologic forcing models.

Simulation of the behavior of some scales and processes can be done using various coastal evolution models' paradigms. On the one hand, resolution of hydrodynamic forcing and morphologic responses often necessitate studies of coastal hazards/shoreline variations (due to extreme events) that depend mostly on detailed, computationally-onerous, physics-based numerical modeling

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(Bowers et al., 2017; Khorram and Ergil, 2011b) and on the other hand, prediction of chronic shoreline variations requires simplified experimental or process-based models. Nonetheless, since all models depend on approximating complicated, multi-scale systems, they can be erroneous; however, they can be practical tools to help a better understanding/predicting of the shoreline evolution (Khorram and Ergil, 2011a, 2011c).

Sediment transport processes in coastal waters are highly influenced by high-frequency waves that are generally sediment stirring agents, cause oscillatory movements that act on particles, and cause sediments to be transported by the mean current; sediment transport calculations are done using the LSTR (littoral drift) on beaches as a very common requirement.

Extensive, long-period coastal zone studies have revealed that sediments are transported offshore by storm waves while they return shoreward by fair-weather waves and swell. Onshore-directed transport processes that relate to wave-asymmetry and wave-induced streaming and dominate during conditions with low, non-breaking wave conditions, often result in accretion processes in the beach zone, but coast beach and dune zone are strongly attacked by the incoming waves during storm cycles (high-energy conditions with breaking waves) and the result is usually erosion processes.

All planning types that may be influenced by coastal dynamics are referred to as coastal planning and can include statutory, environmental, and facility planning that occur over a wide spatio-temporal scale range. Since the need to react to a mobile coastal boundary is the common factor, the interaction between a specific scale and land use sensitivity to coastal variations will affect the perspective of what forms the coastal zone; sometimes, it might also be required to consider the impact of the planned land use on coastal dynamics. Generally, land uses most sensitive to coastal variations or very long-term ones (time scales of 100 or more years for freehold land) should be known for planning; this involves the potential for important climate variations and, hence, considerable coastal dynamics.

Many different experimental formulae that relate sediment movement to currents/winds/waves' dynamic forces and also to sediments properties have been resulted from the data analyses of the coastline zone. Shore Protection Manual and other references (e.g. Southgate and Nairn, 1993; Adamowski, 2008; Chen et al., 2011b; Khorram and Ergil, 2010a,b; Dandapath et al., 2012; Xu et al., 2016) have provided solution approaches/guidelines to help coastal engineers in their design activities, but they provide only limited solutions to very special cases.

To define shoreline zone survey object, spatio-temporal scales have importance as the time interval between two consecutive sampling instances. As regards the spatial scale, surveying of the entire physiographic unit is necessary; definition of the latter is required for the definition of the limits of the area (generally variable) where the impacts of coastal dynamics need to be studied. As engineers believe, the zone where coastal variations (whether in plan or in profile) affect the adjacent coastline is defined as a physiographic unit; to put it differently, it is a closed area wherein sediments move and exchanges with neighboring beaches are either limited or nearly none. But, as regards the temporal scale, a short time-interval (daily analyses of phenomena for the observed period) is needed to study the short-term coastal dynamics; for studying long-term phenomena, a long-time interval is needed (a time step of at least 10 years for seasonal phenomena). Coastal morphology analyses can result in the characterization of physiographic units; comparing the historical charts and defining the area limits is the first step and analyzing photographs/maps found from topographic/aero-photographic surveys is the next; examining the following features will then be possible through inspecting the coastline variations: (a) cyclical fluctuations of the coastline, (b) river mouth evolution as fleches or cuspids (one-direction oriented flow or flow divergence respectively), (c) concave coastline (a place for the gradual convergence of the center sediment flow), and (d) near-coastal structures' buildings deposits/erosions.

The MIE (maximum information entropy) concept that states: "the most probable probability distribution that satisfies all known constraints on the distribution should have maximum entropy" (Jaynes, 1957a,b), can provide the required theoretical format for these types of problems. Since entropy can measure random variables' uncertainties, the maximum entropy concept has been widely applied in many hydraulics/hydrological processes in the last 20 years, and it can treat many hydraulics/hydrological variables, it is possible to find the entropy of the variables from historical/measured data and thus find the characteristics of the unexpected/inherent variability of the process. Different coastline response time scales of the entropy-power technique have been evaluated in the present research to characterize the longshore sediment transport rate (LSTR) spatio-temporal patterns on the basis of two time series variables, namely large-scale wave heights/wind speeds along the littoral line and data of wave evolution over a 45-year (1970–2015) observation period.

2. Entropy theory 'H'

Entropy theory was first proposed in 2004 by Bromiley (Bromiley et al., 2004); however, it was Shannon who strengthened the idea in 1948 by suggesting that it was possible to use it to find uncertainties, and used it to measure random variables through PDF (probability density function) to determine diversifications, disorders, dispersions, and uncertainties. Thereafter, different researchers (e.g. Mishra et al., 2009; Aravena and Luckman, 2009; Brunsell, 2010; Khorram and Ergil, 2010b; Ward et al., 2011; Davarpanah and Babaie, 2013; Singh, 2013; Chen et al., 2014; Sohoulande Djebou, 2015; Khorram and Jafari, 2010) applied the theory and used the maximum entropy value in several different fields as a measure of variability. However, many authors stated that the spatial variability affected the suggested model performance too; they applied the theory and studied the patterns that characterized the spatio-temporal variations of large-scale (coastline) wave heights, wind speeds, and long-shore sediment transport rates where every littoral zone was considered a separate functional unit. All these influential variables depend on the time scale and imply some past sequence memories of biophysical incidents meaning that when variables depend on time, they help as a source memory and indicate similar time relationships as in Markov's chain process (Haan et al., 1994; Azpurua and Ramos, 2010); the most popular authors who have applied stochastic models to wind analyses, wave analyses, and long-shore sediment transport rates in recent years are respectively Balzter (2000), and Szilagyi et al. (2006).

The objective of this research is to show that wave heights, wind speeds, and long-shore sediment transport rates have space-time and time-dependence patterns. Usher (1980) proposed a time-homogeneity statistical test and used it to statistically check the consistency of time patterns and detect the time-dependence. Likewise, clustering analyses can be used to estimate the importance of the space patterns. In the present research, the authors have applied the probabilistic k-mean clustering algorithm to combined spatio-temporal patterns of wave heights, wind speeds, and long-shore sediment transport rates (proposed in 2010 by Jain) because coastline zone is a complex system the elements of which randomly evolve spatio-temporal data sets.