Observations and ecogeomorphological modelling of tidal environments

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ABSTRACT. The dynamics characterizing tidal environments are dictated by a complex of geomorphological and ecological processes, whose close interaction makes a holistic and interdisciplinary approach necessary for their understanding and quantitative description. Only an interdisciplinary approach may, for example, recognise the importance of feedback mechanisms linking salt marsh soil topography and vegetation. The latter is, in fact, a crucial factor in determining sediment transport, stabilisation and resuspension and its development is, in turn, influenced by soil topography and characteristics, which determine its aeration conditions. The present note summarizes some of the main results obtained through an interdisciplinary approach within the European research project TIDE (Tidal Inlets Dynamics and Environment). The research groups participating in the project have produced a large body of quantitative observations of ecological (salt marsh vegetation and benthos) and morphological (topography and channel network geometry) properties, through remote sensing (from satellite and airborne sensors) and field observations and are developing, on the basis of such observations, mathematical models of ecogeomorphologic co-evolution in tidal environments. In particular, the note describes i) the accurate quantitative maps of salt marsh vegetation (and their statistical analyses) obtained by means of suitable classification procedures applied to multi- and hyper-spectral data or through airborne laser altimetry; ii) the relationships which may be inferred on the basis of the data gathered linking ecological (e.g. biodiversity) and morphological (e.g. topography and network characteristics) properties; iii) the field characterization of the benthic component (e.g. field measurements of sediment critical shear stress depending on the presence of biofilms released by diatoms); iv) conceptual and quantitative ecogeomorphic models, which may be developed and validated by use of remote-sensing and field observations

1 INTRODUCTION

Tidal areas, such as lagoons and estuaries, are complex and delicate environments subject to rapid morphological and ecological change, often in response to strong human interference. Beside their evident ecological importance (e.g. recognised by the International Ramsar Convention on Wetlands), coastal wetland areas are often the location of important human settlements and the centre of relevant social/cultural interests (Venice being a very representative example). It is thus very important, from an environmental, economic and social point of view, to be able to accurately and quantitatively monitor and predict the evolution of tidal environments. The present note refers about the research activities of the TIDE European project, whose main objective is the development and validation of comprehensive dynamical models of intertidal systems, explicitly incorporating both physical and ecological processes. Useful models of tidal systems, in fact, cannot separately describe their biology and physics without failing to predict the overall system behaviour. The richness of the interactions between ecological components and the physical processes occurring in tidal environments requires a holistic approach to the study of the system as a whole rather than as a collection of parts. The morphological evolution of tidal environments, in fact, may not just be broken down into a few constitutive physical processes, such as sediment dynamics induced by hydrodynamic patterns and residual circulation, because it is also crucially dependent on ecological dynamics, such as the development of vegetation and the biological status of the sediments (e.g. Marani et al., 2004). The intertidal zone is characterized by the presence of sediment microbial assemblages (microphytobenthos, mainly composed by cyanobacteria and microalgae) and of halophytic vegetation (i.e. macrophytes which have adapted to a very large soil salinity), playing an important role in the dynamic equilibrium of the system. The very transformation of tidal flats (areas lying below mean sea level and periodically exposed by tidal fluctuations) into salt marshes (vegetated areas above mean sea level but periodically flooded by the tide) is the result of a local increase of deposition rates (e.g. Allen, 2000; Friedrichs and Perry, 2001) and of the colonisation, first by microbiota (Aspden et al., 2004), and then by pioneer vascular plants (e.g. Silvestri et al., 2000) of the resulting more elevated area. Once established, microphytobenthos increases the sediment critical erosion shear stress by depositing polymeric biofilms (Yallop et al., 2000), which stabilize the mud surface. Pioneer vegetation also stabilizes the sediment and has a key role in favoring soil accretion, by enhancing organic deposition and suspended sediment trapping and by damping sediment resuspension induced by wind waves (e.g. Friedrichs and Perry, 2001). The developing marsh is subsequently colonized by other vegetation species, through a positive ecological feedback (Ursino et al., 2004), which further stabilize it, but its continued existence depends on the subtle equilibrium and interplay between sediment transport processes, possible subsidence and biotic dynamics.

2 REMOTE SENSING AND FIELD OBSERVATIONS

The presence and characteristics of microbiota and halophytes depend on a number of physiological needs (e.g. light, water, oxygen, salt, etc.) and the spatially complex distribution of these controlling factors induces a high variability of biota in the intertidal zone. The presence of halophytic vegetation over salt marshes, for example, is not random nor spatially uncorrelated but is, on the contrary, organised in ‘patchy’ distributions (*zonation*, Adam, 1990; Silvestri et al., 2000), whose dynamic explanation is crucial to the comprehension of the overall ecogeomorphological evolution of tidal environments. The morphology of the intertidal zone is also quite complex in terms, for example, of its topography and of the geometry of the network of channels dissecting it. The observed characteristics of this complex system must form the basis of any model and are necessary for its validation. The development of the models proposed hence imposes important requirements on observations, which must be performed on scales ranging, spatially, from the order of tens of centimetres to the order of kilometres, and temporally from the daily to the annual time scale. This range of temporal and spatial scales can only be achieved by integrating field observations with remote sensing techniques.

The observational activities performed under the TIDE project at three study sites (Venice lagoon; the Eden Estuary, Scotland; and Morecambe Bay, England, please see http://www.tideproject.org for more details) have included geomorphologic, hydrodynamic and ecological field measurements, together with ad hoc airborne and satellite remote sensing observations. The remote sensing campaigns performed under the TIDE project included: i) CASI flights (1.3 m ground resolution, 15 spectral bands in the visible and near infrared part of the spectrum; four surveys in the Eden Estuary and two in the Venice Lagoon); ii) MIVIS flights (2.2 m resolution, 102 bands in the visible, near and thermal infrared; four campaigns in the lagoon of Venice); iii) LiDar flights (0.5 m or 1.0 m resolution depending on the sensor, accuracy of 15 cm; three flights over the Eden estuary, one in Morecambe Bay and two in the Venice lagoon); iv) conventional photogrammetric flights (three over the Eden estuary, one over Morecambe Bay and one over the Venice lagoon); v) acquisition of multispectral data from the QuickBird satellite (2.8 m resolution, four spectral bands in the visible and near infrared, four acquisitions over the Venice Lagoon); vi) digital images acquisitions from a tethered helium balloon (2 cm resolutions, two bands in the visible and near infrared, several acquisitions in the Venice Lagoon).

Figure 1 shows a grey-scale representation of a LiDar acquisition performed within TIDE over the

Venice lagoon. The different shades of grey represent elevations with respect to mean sea level for the San Felice salt marsh, one of the project study sites. This salt marsh is located in the northern part of the Venice lagoon (semi-diurnal tidal regime with maximum tidal excursion of ±0.70 m a.m.s.l.) has an average elevation of about 0.30 m a.m.s.l. and is mainly colonized by four halophytes: *Spartina maritima*, *Limonium narbonense*, *Sarcocornia fruticosa* and *Juncus maritimus*.

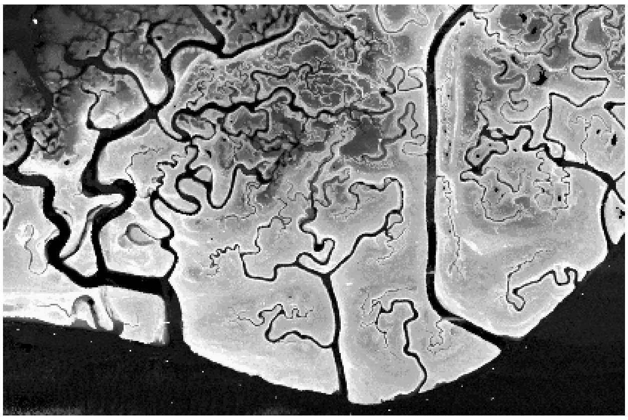

Figure 1. Gray-scale representation of a LiDar survey over the San Felice salt marsh within the Venice lagoon.

The complex channel network elaborated by tidal action is evident and it may already be anticipated that also the spatial distribution of vegetation retrieved from multispectral and hyperspectral data exhibits, as will be illustrated in the following, a high spatial complexity, partly induced by the morphology but with entirely different statistical properties.

TIDE remote sensing data acquisitions were accompanied by extensive field campaigns to provide adequate ground ancillary information and direct observations of ecological parameters. Ancillary information for the quantitative interpretation of remote sensing data were collected at a large number of locations (for example about 50 areas were surveyed in the Venice lagoon for each overflight), whose boundaries were accurately determined through DGPS observations. Within each region, vegetation presence and abundance was estimated both by direct inspection and from photographs taken from a 2.5 m high pole. This procedure was adopted for all the remote sensing acquisitions and the data were used to train and validate the classification procedures described in the following.

The suite of observations performed during field campaigns (usually during corresponding remote sensing acquisitions) were: critical erosion shear stress using a Cohesive Strength Meter (CSM); contact cores for the measurement of bulk density, water content, pigment signatures, chlorophyll a content, total organic carbon, sediment grain size and colloidal carbohydrate concentration; cryolanders to investigate pigment depth profiles; surface scrapes to investigate surface structure; lens tissues to determine the motile fraction of the microphytobenthos; fluorescence measurements to investigate biomass distribution and vitality; fluorescence measurements on higher plants; topographic measurements, vegetation height and relative abundance, ground spectral signatures (of vegetation types and reference targets), vegetation PAR, sun-photometric observations. Details regarding the results may be found in Marani (2003; 2004), while selected results will be presented and discussed here.

The characterization of benthic assemblages and sediment properties was performed at the nodes of a 5 x 5 point grid set up within each study area, with a distance of 2 meters between each node and a fixed orientation with respect to North.

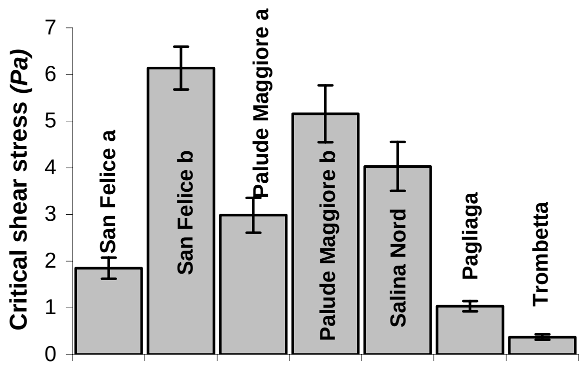

Figure 2. Critical shear stresses observed at different study sites within the Venice lagoon.

Critical shear stress for erosion is a fundamental piece of information for understanding and modelling geomorphic dynamics of intertidal areas. The shear stress corresponding to the first erosion of sediment induced by a jet of water directed toward the surface was measured with a CSM (Tolhurst et al., 2000) at all study sites. As an example, Figure 2 shows average values and standard deviations (computed over a large number of samples) obtained in salt marshes within the Venice lagoon, characterized by marked differences in average elevation, microbiota and macrophytes. The variability may be partly due to differences in the inorganic properties of the sediment (a sandy loam in all cases), but it is more likely linked to its biotic characteristics. Significant differences in total organic content were found between the sites and correlations with observed microphytobenthos properties are currently being studied.

3 ANALYSES OF REMOTE SENSING DATA

A passive remote sensor, such as those used in the TIDE project, acquires the radiation reflected by the earth surface and discretizes it into a number of spectral channels. After suitable processing of the data (e.g. see Mather, 1999, for a general introduction and Silvestri et al., 2003 for sample applications to halophytic vegetation), these may be used to determine the nature of the earth surface cover. Each surface type (e.g. halophytic vegetation types), in fact, exhibits a characteristic *spectral signature*, expressing, for each wavelength, the fraction (*reflectance*) of the electromagnetic energy received which is reflected by that specific surface type. By applying suitable classification procedures, which implicitly or explicitly identify such spectral signatures, each pixel from a remote sensing dataset can be attributed to one of the *classes*, or surface types, of interest, thus allowing the study of their spatial distribution.

Firstly, class separability was evaluated on the TIDE remote sensing data, by selectively removing spectral channels and thus identifying the channels containing information useful to discriminate the salt marsh vegetation species of interest (Menenti and Wang, in Marani, 2003; 2004). Standard classification methods (e.g. Maximum Likelihood and Spectral Angle Mapper, Mather, 1999) and several new approaches were then applied and their results compared. New methods developed within TIDE include Neural-Network-based classification procedures (Menenti and Wang, in Marani, 2004), the Multi Strategical Images Classifier, which makes use of hybrid unsupervised classification systems combined with a conceptual classification method (Korczak and Quirin, in Marani, 2003) and an evolutionary classifier system, which integrates symbolic learning and genetic, evolution-based, computing (Korczak and Quirin, 2003).

An example of the result of a classification procedure is shown in Figure 3, where a map of the dominant halophytes produced by a Neural Network algorithm applied to CASI data is represented (Menenti and Wang, in Marani, 2004). The spatial distributions of vegetation retrieved from both multi- and hyper- spectral data were found to be consistent with qualitative direct observations and with quantitative ground truthing information, showing that satellite and airborne remote sensing are reliable analysis and monitoring tools in tidal environments.

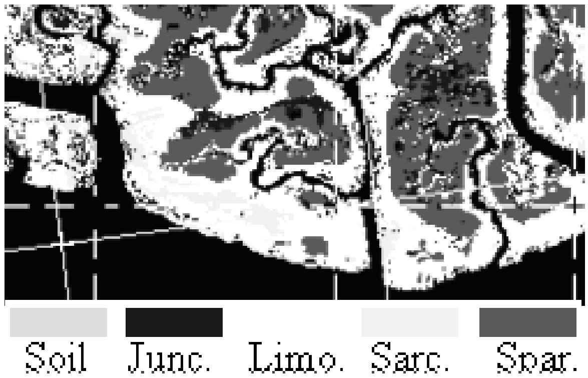

Figure 3. Map of dominant species obtained using a Neural Network classification on CASI September 22 2002 flight over the San Felice marsh in the Venice Lagoon.

Several classification procedures and analyses on TIDE data are described in Belluco et al. (2004), who, for example, study the statistical properties of connected clusters of conspecific vegetation, such as those shown in Figure 4 for Limonium narbonense (based on a Spectral Angle Mapper classification of satellite Quickbird data). In particular, they find that the probability distributions of vegetation clusters exhibit a power-law form and thus lack a characteristic scale, revealing the hidden structure of vegetation spatial organisation.

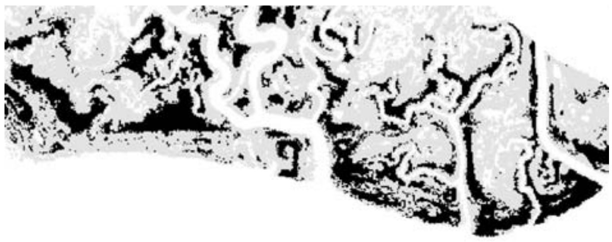

Figure 4. Connected clusters of Limonium narbonense obtained by the spectral angle mapper scheme from QuickBird data from the San Felice marsh.

Remote sensing observations may also be used to objectively retrieve and analyse the connected structure of tidal channel networks. An important activity within the TIDE project is the development of a semi-automatic channel extraction algorithm from LiDar data. The algorithm uses a multi-level knowledge-based approach. Low-level processing extracts channel fragments based on image properties, and then high-level processing improves the network using domain-based knowledge (Mason and Scott, 2004). Figure 5 illustrates an example of the results of the procedures developed, applied to the LiDar data of Figure 1. Quantitative validations of such results indicate that, even though the extraction must be supervised by an operator, the procedure proposed constitutes a useful tool for the objective analysis of the channel network structure.

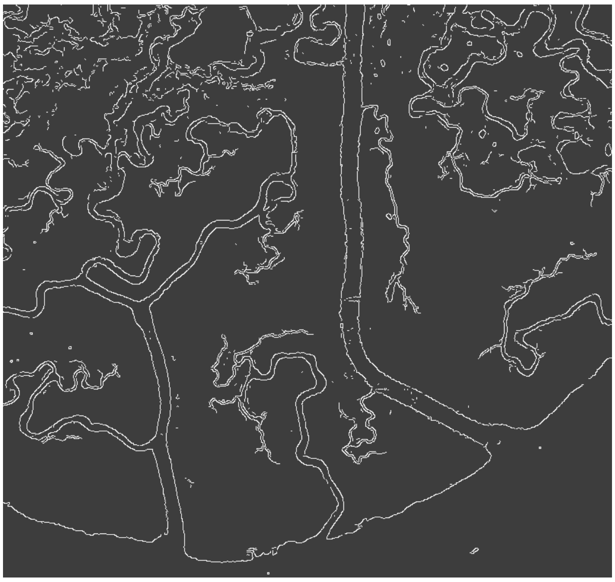

Figure 5. Results of automatic channel extraction procedures applied to the LiDar data of Figure 1.

The extracted channel network may then be used for several geomorphologic analyses such as those discussed by Marani et al (2003), who apply a simplified hydrodynamic model to describe the drainage patterns induced by the observed network structure.

4 MATHEMATICAL MODELS IN TIDAL ENVIRONMENTS

The modelling activities performed within TIDE are, on one hand, aimed at the description of the coupled evolution of intertidal biota and geomorphology, and, on the other, on the implementation of continuous hydrologic models suitable for application in watersheds draining into tidal environments, which can provide reliable estimates of fresh water fluxes into such systems.

The digitized channel structure obtained from remote sensing data using the algorithms introduced above, may be used as boundary conditions for a simplified model of water circulation (Rinaldo et al., 1999) which, by neglecting higher order effects, equates the gradients of the water surface to the (linearized) friction terms and reduces the shallow-water equations to:

$$\nabla^2 \eta = K \qquad (1)$$

where η is the water elevation above a local reference and K summarizes the forcing (tidal fluctuations) and friction terms. The solution of (1), obtained by imposing a constant water level throughout the channel network (corresponding to assuming tidal propagation to be much faster in the channels than over the salt marshes), yields a reference distribution of water elevation (Figure 6), which may be used to compute flow directions on the basis of the steepest descent (i.e. by implicitly assuming that the energy surface is coincident with the water surface).

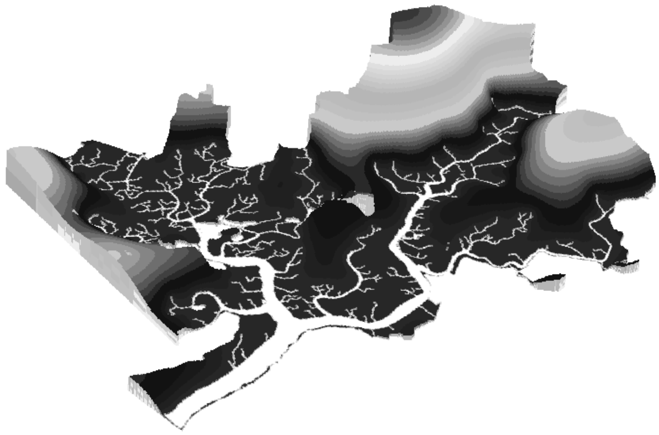

Figure 6. Solution to eq. (1) in the northern part of the Venice lagoon.

Equation (1) has been shown, by comparisons to observations and finite element modelling results, to accurately predict drainage directions and, through the use of the continuity equation, to allow a reliable evaluation of the maximum (land-forming) values of discharge occurring within the network (Marani et al., 2003).

D’Alpaos et al. (2004a; b) use solutions like the one depicted in Figure 6 to evaluate bottom shear stresses as $\tau(\mathbf{x})=\gamma[\eta(\mathbf{x})-z(\mathbf{x})]\cdot\nabla\eta(\mathbf{x})$ at every point **x** within an intertidal area, thus identifying the sites subject to erosion.

They then construct a physically based network evolution model, which, leaving details aside, assumes that, at every time step, the unchanneled sites where $\tau(\mathbf{x})$ exceeds a critical shear stress are eroded and become part of the channel network (Figure 7). The detailed structure of the model may be found in D’Alpaos et al. (2004a; b), but it is here worth pointing out that the model in the form described may easily incorporate the effects of biota on sediment stability (i.e. critical erosional shear stress) and its characterizations described in section 2 (e.g. see Figure 2).

A comprehensive model of tidal ecogeomorphic evolution also requires the development of mathematical descriptions of biotic evolution. The activities of the project, in this respect, have been developed in two directions. Field observations (e.g. soil elevation, salinity, availability of oxygen, species abundance and biomass, etc., Camuffo and Belluco, in Marani 2003; 2004) and modelling experiments (subsurface saturated/unsaturated flow modelling, Ursino et al., 2004, and shallow water flow modelling, Silvestri et al., 2004) have been performed in order to link vegetation species occurence and well-defined physical parameters.

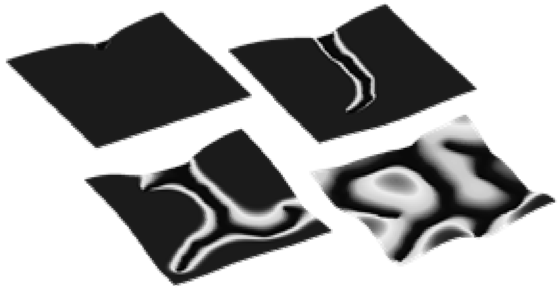

Figure 7. Time evolution of a synthetic network according to the model by D'Alpaos et al. (2004a;b).

The information obtained through the combined use of observations and models is now being used to develop a vegetation model based on stochastic contact processes (e.g. Durrett and Levine, 1994).

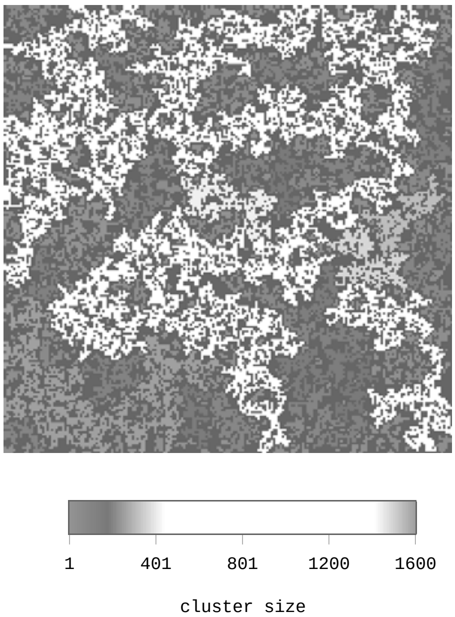

Figure 8. Steady state configuration produced by a stochastic contact process simulating salt marsh vegetation dynamics

Such models, applied to salt marsh vegetation for the first time, describe the dynamics of a vegetation species through a set of evolution rules. According to the model adopted, the simulation domain is initialized with a random (spatially uncorrelated) distribution of plants: each site is either occupied or empty (only a single vegetation species is currently considered). At each time step each plant dies with probability γ, while empty sites neighboring surviving plants are colonised by new propagules with probability λ.

Repeated applications of the rules produce a spatial distribution of plants of the type shown in Figure 8 (Marani, 2004), which represents through grey-sacale values the size of the connected vegetation clusters produced by the model. Interestingly, for some parameters values, modelled distributions reproduce observed vegetation cluster statistics (see section 3), thus showing that remote sensing observations provide a useful constraint for ecological modelling assumptions.

Another important modelling activity within TIDE is related to the description of the hydrologic balance in coastal watersheds, with specific applications to the lagoon of Venice. Fresh water inputs are, in fact, an important factor in the ecogeomorphological dynamics of tidal environments, with particular reference to effects on water salinity and sediment supply and to the assessment of possible effects of river floods. The model developed within TIDE, GEO_{TOP}, is a terrain-based distributed model of the mass and energy balance. It explicitly describes runoff generation processes, by integrating Richards' equation, it uses a detailed SVATS model to describe energy fluxes exchanged between the atmosphere and the soil and includes an explicit description of horizontal water redistribution fluxes, to capture the contribution of subsurface flow to total discharge, which, in planar coastal catchments, may be quite relevant. The model has been applied to the river Dese catchment, closed at an outlet subject to tidal fluctuations (area of about 90 km^2), which drains into the Venice lagoon. The comparison with observed discharges is quite encouraging even though the validation of the model is still in progress (Rigon, in Marani, 2004). Particular attention is being devoted to the validation of the detailed energy balance, which will also be performed in a distributed fashion, on the basis of surface temperatures derived from Landsat and Aster satellite observations.

5 SOCIO-ECONOMIC IMPACTS

There typically is a conflict between the ecological health of a natural system and human activities. Such activities are on the other hand very important from a social and economical point of view and a sustainable development must be sought. The TIDE project also aims to address how changes in resource exploitation (e.g. agriculture or tourist exploitation) of a tidal system can be developed with the consent of all user groups. End user groups, farmers, tourists and agencies in the Eden Estuary have thus been involved in semi-structured interviews to assess their level of understanding about the system. A selected sub-set of candidates is now being informed about potential environmental management strategies and consequences for the estuary. A subsequent comparison with the uninformed control group (the naïve group), will allow the determination of the influence of adequate scientific and policy information on the way candidates perceive the health and future of the coastal environment.

6 FUTURE DEVELOPMENTS

An interdisciplinary approach to the study of tidal environments, involving biology, hydrodynamics, geomorphology, hydrology, remote sensing and sociology has been presented. The work carried out under this framework is intended to produce comprehensive models describing the ecogeomorphic dynamics of a tidal environment and their possible impacts on the decision-making process. Clearly, only a summary of the activities carried out under the TIDE project could be presented, in an attempt to describe the general approach, details may be found in the appropriate literature. The description provided here indicates that the project has reached the crucial point in which results from different fields (e.g. geomorphic and ecological models) are being further integrated to provide a truly interdisciplinary predictive description of a tidal system. In particular, the integration of models of microphytobenthos, vegetation and geomorphology will be the key to a successful representation of intertidal processes and will have to rely on simplified formulations of the relevant interactions (e.g. Silvestri et al., 2004; Ursino et al., 2004) yet retaining their essential dynamics.

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