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On the integrated modelling of coastal changes

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Abstract. This paper introduces a possible approach to integrated modelling of coastal change, focusing on coastal land use and cover change. Some of the most important open issues in the context of integrated modelling of coastal change are introduced. The paper focuses on methodological aspects. Specific reference is made to Physiographic Unit Modelling as an approach to better handle spatial variability and 'morphogenesis', and as a way to focus on coastal change mechanisms instead of absolute coastal dynamics for achieving an important simplification of the problem. The application is briefly discussed with reference to a 'minimal model'. The methodological structure introduced is considered particularly suitable to represent, according to a variable degree of simplification, the integrative dynamics between resources and uses of the resources.

Keywords: Coastal zone; Land use; Management; Morphogenesis; Spatial dynamics.

Abbreviations: CLUCC =Coastal Land Use and Cover Change; ICM =Integrated Coastal Management; ICZM =Integrated Coastal Zone Management;RSLR =Relative Sea Level Rise.

Introduction

The need for the evaluation of coastal changes

The coastal zone is an integrated complex of marine, coastal and terrestrial subsystems. Integrated Coastal Zone Management (ICZM), in this issue also indicated as Integrated Coastal Management (ICM), needs to anticipate the effects of current and potential natural and human-induced processes. It should respond to the various processes (and possibly anticipate them) effectively and without delay, with the overall aim of maintaining anthropogenic functions and using coastal resources in a sustainable manner. This means that practical knowledge of the mechanisms driving both the coastal zone systems as a whole and its constituent subsystems is a necessary prerequisite for effective ICZM. Models that are actually available to support planning and evaluation of ICZM strategies and activities are still mainly non-integrated mathematical models developed for sectoral purposes. Integrated assessment is made by combining often non-immediately compatible results of these models, with all the risks connected with such operation in terms of robustness of the results. We need to move further on from this stage of development

In the present paper the problem of modelling the mechanisms of land-use and land-cover change in the coastal zone is introduced. This refers primarily to the land-based part of the coastal system as it is the area most visibly subjected to structural modifications in cases of change. In principle there would be no difficulties in extending the same considerations to the marine part of the coastal system. The paper highlights the role of geomorphological and ecological processes in the evolution of land-cover as mediated by the land-use structure – which in its turn is determined by the socio-economic setting. A landscape is composed of ever-changing elements. Their spatial and temporal patterns characterize a landscape to an observer; at the same time they inform us of the complexity of dynamic processes at various scales. Many of our research questions and management issues are focused on the relationship between the changes that occur in the composition of the landscape and the spatial configuration of landscape elements.

Changes in land use result from the complex interaction of many factors including policy, management, economics, culture, human behaviour in general and the environment. Land use change, in turn, affects many components and processes in a landscape, such as the hydrologic cycle, species diversity and local economies. It is for these reasons that land use issues are central to the concerns of local and regional resource managers and local land use planners independent of whether or not they are dealing with a coastal situation.

We consider the fact that sustainable development needs to balance the use of coastal resources with the coastal resources themselves in the course of time. Looking for a 'common denominator' between uses and resources, we identify that of 'values'. The attribution of values can be made on a 'static portrait' of resource distribution and of patterns of uses of such resources; however, the implementation of sustainable management approaches in an increasingly complex situation needs the development of a ‘dynamic portrait’. For this reason, while considering the integration between resources and uses in the coastal zone, we believe it is important to look, initially, at the mechanisms driving the coastal zone system and, secondly, at the evolution in time of coastal land use and coastal land cover changes. The mechanisms make the coastal zone more or less ‘attractive’, while the changes make it more or less adaptable and able to sustain human presence.

The approach

The aim of studies of ‘Coastal Land Use and Cover Change’ (CLUCC) is to improve the understanding of the dynamics of land use and land cover change for the whole coastal system, with the focus on improving the ability to project such change. This is important because changes in land use and land cover are inputs to, and consequences of, environmental modifications. Therefore, insight in land use and cover change is important to integrated modelling and integrated assessment of environmental issues in general. Moreover, insights in CLUCC are needed to identify the likely points where human communities can intervene to change the trajectories of global land use (and thereby environmental change) according to changing needs and values.

The concepts hereby described are mainly the result of experiences from three Mediterranean deltas: the Ebro Delta (Spain), the Rhône Delta (France) and the Po Delta (Italy). A brief reference will thus be made in the paper to a simple example, a simple ‘synthetic delta’, that is helpful in highlighting the critical aspects concerning integration between different components. Deltaic areas are characterized by a highly dynamic nature and high spatial variability from both the points of view of natural and human-related aspects. They present a complex overall behaviour and are highly sensitive to both human interference and natural phenomena. The lack of information about the integral functioning of deltaic areas and the lack of understanding of the role of the constituent processes must be covered with suitable methodologies and tools to satisfy the needs of Integrated Coastal Management programs. Integrated assessment for a deltaic area at a given time and space scale requires suitable identification of the physical, ecological and socio-economic aspects and processes.

The present work originates from the problem of evaluating the impact of possible relative sea level rise (RSLR) on the above deltas. Further, the possibility of human management and intervention is an integral element in assessing possible adaptation measures to these changes highly affecting land use and cover modifications. The starting point is thus the description of land use and cover and of their changes or mechanisms of change. In order to do this we identify mechanisms of influence from the geomorphological and the ecological aspects toward the socio-economic aspects (in terms of values) and mechanisms of influence from the socio-economic aspects to the physical and ecological ones (in terms of human management and intervention activities).

This paper presents the structure of an integrated conceptual model based on the description of such links according to a variable degree of detail. The perspective is dominated by the aim of describing the land cover changes as resulting from the natural processes. The socio-economic aspects, and particularly the land use types, are thus considered to the extent they directly influence the ‘natural dynamics’ and the extent to which they are constrained by the same natural dynamics. Practically speaking, this comes down to the use of physiographic units (‘environmental’ objects). On a relatively large spatial scale (Capobianco & Otter 1996) physiographic units allow us to accommodate the characterization of the human interference and of natural forcing factors and, to a variable extent, the available knowledge about the natural environmental dynamics.

One should also be aware of the need to focus on the budgets for water, sediment and salinity as main driving factors for changes in the coastal zone. Moreover, a ‘synthetic delta’ example is introduced where changes of the vertical dimension in the deltaic plain and changes of the horizontal dimension in the fringe are considered the most relevant variables.

Generalities on coastal land use and cover changes

Subsystems in the coastal area

The study of Coastal Land Use and Cover Change (CLUCC) requires either standardized classification (or typologies) of use and cover or data provided in a manner that allows various standardized sets of classifications to be constructed. Methods of defining relevant subsystems in the coastal zone in terms of climate, topography, soils, vegetation or productive purpose have a long history. There is, however, no satisfactory and commonly accepted method of defining and classifying coastal uses; probably because this is an activity very much dependent on the local attitude towards coastal management.

CLUCC research should emphasize the development of classifications and data on three dimensions of land use (Turner et al. 1995). The first dimension involves the land characteristics: ‘how the coastal land use

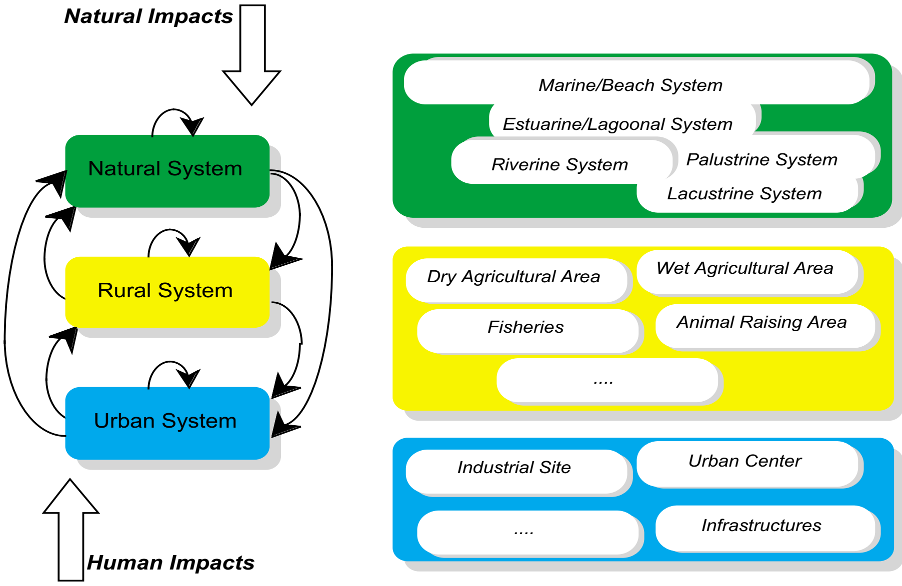

Fig. 1. Basic classification of subsystems and impacts for a coastal system. In the Rural and Urban systems subsystems are schematized geographically or economically.

and cover are used'. The uses always involve some kind of 'small-scale manipulations' of the bio-geomorphological components that can only be determined over their full sequence or time period. The second dimension refers to the land user's purposes or objectives served by the manipulation: 'why the land is used'. These objectives may vary considerably among individuals, societies and historical periods, but generally include the satisfaction of needs for income, food, fodder, fuel, products, shelter, and landscape values. The third dimension of use is the 'broader bio-geo-morphological and socio-economic circumstances or underlying conditions'. Bio-geomorphological conditions – for example climatic zone, soils, occurrence of pests and diseases- determine, in part, what type of land use and cover may be found.

The basic distinction is between natural, rural and urban systems. A natural area can be defined as an area characterized by a largely spontaneous development of the local (eco)system(s). A rural environment can be defined as characterized by cultivated soils, while the urban environment is characterized by the predominance of built-up areas. In a way this grouping represents a classification of the relative degree of influence of man and, more specifically, the relative degree of 'stabilization of the landscape' that is imposed by man.

According to Fig.1, the natural, rural and urban systems each possess a distinct number of natural elements which are characteristic of that part of the coastal zone system. Each element can be further delineated according to its composition, morphology and (internal) dynamics. Concerning the composition each of these elements can be described in a more detailed manner by focusing on its physical, ecological and socio-economic aspects. Obviously an urban system will have a larger component of socio-economic factors than the other two systems. Concerning morphology and dynamics the focus will be on the size of each morphological entity present within the elements and the possible functional links with, and within, the elements. The classification is also considered to be consistent with the requirements for a landscape description of wetland areas (Farinha et al. 1996). Eventually a refinement at the level of definition of subsystems could be considered.

The role of the spatial scale

It is well-known that changing the spatial scale of the analysis may change the quality and value of the results. Moreover, issues such as uncertainty and predictability are connected with the spatial scale. CLUCC research is confronted with two different scale effects that must be taken into account: (1) each scale has its own specific units and variables; and (2) the interrelationships between sets of variables and units change with scale. As different scales allow us to answer different questions, a better understanding of land-use drivers can only be achieved by combining observations and explanations from different levels of the scale hierarchy. A comprehensive study of CLUCC requires a nested set of scales and corresponding data.

Spatial, hierarchical and temporal scales must be understood in terms of their real world, measured (empirical) and modelled, before making an appropriate selection of scale. Scale effects exist in all land use/

cover phenomena but can only be assessed by measuring their properties. Since all such phenomena and properties cannot be measured, we are forced to make arbitrary (and subjective) choices in selecting useful scales. Similarly, models are generally only valid for given, well-defined scales. Thus, CLUCC research must pay considerable attention to the assessment of empirical and model scales on the basis of a formalized approach.

Practical difficulties are represented by the fact that scales are related in different ways to the peculiarities of the natural system, the rural system, and the urban system. From a system-theoretic perspective, we could say that the state of the natural, rural and urban systems also implies socio-economic related components. We hereby assume that the socio-economic characteristics of the three systems are related to their structural and functional characters according to the attribution of 'values':

- Values connected to the use of resources (while also considering the use of space)
- Values of non-use (considering also 'social perception' of the value of the resource)

The existence of values, with their typology and their spatial variability represent a formidable mechanism to trigger modifications and changes in the coastal zone. Any modelling framework should at least consider their existence for the evaluation of scenarios of change, by using them to define boundary conditions and/or parameters affecting the dynamics.

The relationships on a large scale

A distinction between use and cover is useful to characterize the coastal landscape according to human- and nature-related aspects. In the present approach land use is (primarily) the result of decision processes while land cover (primarily) results from geomorphological and ecological processes (Fig. 2). Land use has principally been a concern of the social scientists. It refers to the human employment of land and includes settlement, cultivation, pasture, rangeland, recreation etc. Land cover has principally been a concern of the natural scientists as it denotes the physical state of the land. It includes the quantity and type of surface vegetation, water and earth materials (Meyer & Turner 1994). Land use and land cover can be seen as the critical factors mediating between socio-economic, political and cultural behaviour and global environmental changes.

Adjacent physiographic units

The first step is an attempt to model explicit anthropogenic, as well as natural, causes to coastal land use and land cover change. To include explicit causes of land use change makes land use change models more useful for policy analysis. Integrating a multitude of factors into a model containing policy, economics, population and the environment does, however, present a problem when addressing which currency or unit of measure to consider. When such problems arise, it is useful to develop a common model currency. In our approach, we convert all variables in the model that affect change in land use by employing a relative ranking system where large values reflect a great influence on the direction of change and small values reflect little or no influence on change. Water, sediment and salinity represent the currencies we adopt. More than one currency is required in order to describe the dynamics of interest. If we followed a more static approach, other currencies would probably be more appropriate, such as vegetation type and -succession, which implicitly allow us to distinguish between river-dominated areas, sea-dominated areas, etc.

Secondly, we attempt to develop a land use change model that can be transferred to many regions. To accomplish this objective, we have focused on the development of a spatial modelling framework that allows for any number of driving variables affecting land use change to be included. The framework also has the ability to quantify the relative influence of each driving variable on the process of land use change. This latter feature is important because similar driving variables of land use change are in operation in many locations but their relative influence on land use change differs depending on the circumstances peculiar to a region.

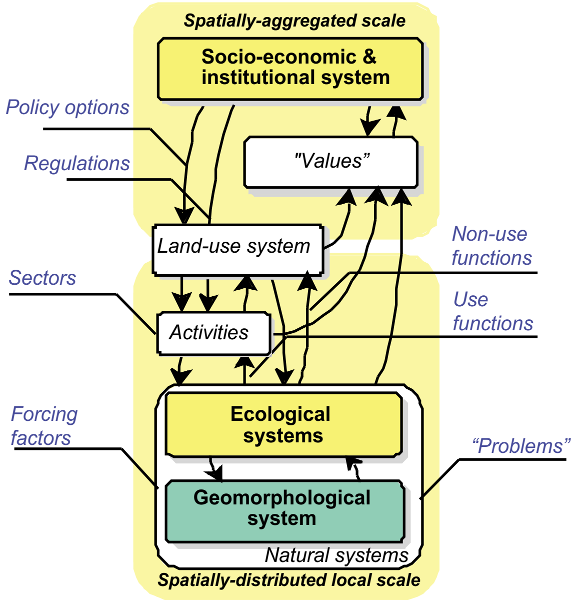

Fig. 2. A conceptual model of relationships.

Modelling land use and cover dynamics

Spatial modelling

Spatial modelling of land use change has been approached differently by various researchers in the past. There are three main approaches which can be classified as ecological, statistical and mathematical, and can be illustrated by the following three studies. Constanza et al. (1990), taking the ecological approach, developed a Coastal Ecological Landscape Spatial Simulation model which predicted habitat changes in Louisiana based on natural and anthropogenic induced changes to water and nutrient levels. This model uses a grid of cells with state equations describing the interaction of water and nutrient fluxes between adjacent cells. Vegetation succession is modelled using a set of temporal rules where the state of the plant community changes if environmental conditions (e.g. salt concentration) are altered.

Turner (1991), using a statistical approach, developed a simulation model of land-use change. She combined first-order Markov land-use transition probabilities and the influence of a cell's nearest eight neighbours on its probability of changing land use states. Probabilities were derived empirically using a land use change analysis. She found that this model performed better than land use change models that only used Markov transition probabilities.

Cellular automata are mathematical objects that have been studied extensively in mathematics, physics, computer science and artificial intelligence (Gutowitz 1991), although until recently they were best known as games (Gardner 1970). A cellular automaton consists of an array of cells in which each cell can assume one of *k* discrete states at any one time. Time progresses in discrete steps and all cells change state simultaneously as a function of their own state, together with the state of the cells in their neighbourhood, in accordance with a specified set of transition rules. Transition rules can be either qualitative, quantitative or both. Engelen et al. (1995) used a cellular automaton to model land use changes on Caribbean islands. They developed a series of historical land use change maps used to formulate a set of growth rate rules for the cells.

Four classes can be distinguished: 'spontaneous growth', 'diffusive growth', 'organic growth' and 'facility-influenced growth'. 'Spontaneous growth' models the nearest neighbour's influence on adjacent cells; 'diffusive growth' applies to areas that are suitable to allow for development; 'organic growth' allows current use locations to expand outwards; 'facility-influenced growth' is based on the general influence of existing facilities on development of the area. In practice the description of the change in land use can be further summarized by rules describing both the positive and negative effects (e.g. Engelen et al. 1993; White & Engelen 1993).

Physiographic units: The creation of diversity and the emergence of patterns

Cellular automata have the capacity to organize space at a macroscopic scale, although transition rules operate at a very local scale. Geographical clusters can be generated that are realistic in terms of their size, spatial distribution and socio-economic composition (White & Engelen 1993). The modelling approach based on physiographic units differs from the cellular automata one. In a sense it is more 'process-oriented' and instead of generating geographical clusters from the microscale, it aims to directly describe the modifications of the existing geographical clusters. Nevertheless, it has to be noted that such modifications could originate different type of clusters through mechanisms of 'morphogenesis' similar to the ones that induce the emergence of patterns in cellular automata. Another reason for looking for aggregation is that temporal evolution, in the real world, hardly continues with small and equal time steps; instead it is based on discrete events determined by the over-crossing of certain threshold values.

Based on the morphological substrate and the landscape units, a fully integrated landscape spatial model can be implemented from a 'division' of the study area obtained through the identification of uniform physiographic units. Each physiographic unit, or 'object', will contain a 'copy' of individual unit models. Unit model equations can be integrated into a variable-scale spatial grid fitted to the dynamics of each single unit. Different levels of aggregation of these unit models can be evaluated to determine an optimal compromise between accuracy and manageability. The models of the individual units can themselves be cellular automata with a variable degree of discretization (Fig. 3). The more recent initiatives in the characterization of wetland areas in the Mediterranean (Farinha et al.1996) can provide the fundamental classification schemes for the identification of the physiographic units. To them, by using the peculiarity of coastal zone systems, we add the functional characterization, i.e. the process description.

The behaviour of a physiographic unit based landscape model could be examined in theoretical terms. A possibility is to focus on classes of generic 'behaviour rules' (Table 1), which necessarily are more articulated than the ones for cellular automata. Without going into too much detail, we can look at such an approach as an intermediate solution between uniform-spatial-scale 'process-based' landscape modelling and 'cellular automata' where for each spatial cell the 'rules of transition' from

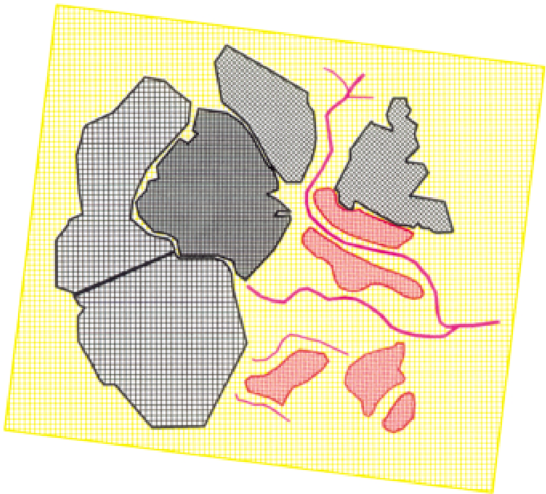

Fig. 3. Variable discretization.

one state to another are specified. In other words, in the cellular automaton higher-level aggregations are characterized by comparatively more complex behaviour. Physiographic units maintain, in themselves, both a description of the specific resources and the description of the uses of such resources.

We hereby consider the physiographic units as being spatially delimited by constraints. These constraints can change over time, sometimes quite rapidly, in relation to the occurrence of extreme natural events and in relation to human interventions. For a spatially distributed system, multiple equilibria in land cover (and land use) are possible, even in the long term, meaning that the timing and character of events and interventions determine the succession outcomes. In the context of the physiographic unit approach to modelling, we basically distinguish between natural, rural and urban systems, thus reproducing what is the result of the observation of the coastal area. A natural area can be defined as an area characterized by spontaneous development of the (eco)system. A rural environment can be defined as characterized by cultivated soils, while the urban environment is characterized by built up areas. In a way this grouping represents a classification of the human influence in the coastal zone.

A physiographic unit 'adapts' to the presence of another physiographic unit in a way similar to that of a living organism adapting to its environment. The coastal environment is assumed to consist of large numbers of physiographic units that have many states of (temporary) equilibrium. The coastal environment is thus assumed to be multistable with large numbers of possible attractors for the state variables. Whether because the primary links between the physiographic units are few by definition, or because equilibria in the physiographic units are common, the interaction between physiographic units is assumed to be weak and apparent only in the long term or during extreme events. In common with living organisms, the physiographic units will adapt to their environment by providing second-order feedbacks that veto all states of equilibrium except those that leave each defining variable within its proper limits. The defining variables are those which characterize the physiographic unit (e.g. the area of a barrier island cannot be less than zero, the elevation of a marsh could be less than zero with respect to mean sea level by not less than the minimum tide level in the long term, etc.).

Continuing with the details, we further distinguish between the structural dimension basically related to the relationships, on a geographical basis, between the various components of the coastal system and the functional dimension basically related to their internal behaviour. In other words, the structural dimension concerns the description of land use and cover while the functional dimension concerns the internal dynamics. The focus is on the size of- and the possible links with- and within the constituent elements.

Table 1. Generic behaviour rules for physiographic units.

Aspect	Description
Diversity	Mechanism to create diversity
Aggregation	The ability to form a higher level unit consisting of an ensemble of the original units, stable at each instant and also through developmental processes
Relationship	Formation of a syntactic rule from complex mutual relationship
Pattern formation	Formation of a unit to separate it from outside
Transition rule	Formation of discrete states leading to unit types, and also analogue modulation of the state
Splitting	Recursivity of a state, preserved by the reproduction
Genetics	Hierarchy of differential process, characterized in the course of time and also in the 'phenotype space', i.e. a space representing some kind of 'genetic' characteristics
Spatial character	Mechanism to map the global information to each individual unit
Multiple characters	Higher level of differentiation
Formation rule	Formation of a higher-level reproduction unit

The structural dimension is characterized by composition (where each component is characterized by: socio-economic variables, ecological variables, physical variables and chemical/biological variables) and by morphology (defined by the horizontal dimensions and by vertical dimensions, that basically follow natural dynamics induced by more or less natural forces). In the horizontal dimension shapes and patterns emerge (physical boundaries), where for the more natural physiographic units such boundaries can undertake a morphological evolution (i.e. they can shift, change, appear or disappear) and for the more artificial physiographic units they are constrained by current land uses. In the vertical dimension land elevation is determined, affected by inorganic sediment supply as well as by new soil formed by the degradation and compaction of organic soil.

The functional dimension is characterized by internal dynamics, for each one of the variables – socio-economic dynamics, ecological dynamics, physical dynamics and chemical/biological dynamics – and by the links (between the various systems) driven or affected by natural forces and human activities. The links represent the 'active' part of the spatially distributed model construction. Six main classes of 'links' between the various physiographic units have been identified in the natural, rural and urban systems based on the 'exchange' of water, sediment, salinity (Capobianco & Otter 1996). Water, sediments and salinity are chosen here as starting points for the description of the natural functioning of the coastal zone system, as they can be considered as being characteristic of the main coastal zone processes. The interactions between these three groups of processes determine the coastal zone regime, which is responsible for the vertical and horizontal distribution of interfaces. Management of the coastal zone must begin by the acknowledgement of the relative importance of the different processes controlling its geomorphology and by adjusting the objectives of the management to the foreseeable geomorphological changes at different scales of time.

An aggregated conceptual model

More specifically, water represents the main driving factor for coastal zone dynamics at all scales. Sediment constitutes the fundamental ingredient for the morphological evolution of the coastal zone, while salinity represents one of the regulating variables for the ecological components. Basically it indicates the interface between fresh-water (river) and salt-water (sea).

On a large scale we can introduce a conceptual model such as that of Fig. 4, where the most important morphological aspects are considered. In this case we can consider the fringe and the plain to be 'very large-scale physiographic units'. Such assumption is particularly justified by the fact that the horizontal boundaries of the coastal plain are, to a large extent, determined by land use considerations. In our temporal frame of interest (30-50 yr) the control on elevation of the plain area for primary (productive) activities as well as the control on extension of the fringe area for tertiary activities (e.g. tourism) are of primary importance. In other words the whole modelling problem is 'reduced' to the description of the vertical dimension in the plain area and the horizontal dimension in the fringe area.

The coastal plain is considered as being a 'river-dominated' area (i.e. the dynamics are dominated by the dynamics of the river), at least potentially given the high artificial character; the coastal fringe is considered as being a 'sea-dominated' area (i.e. the dynamics are dominated by the dynamics of the sea). Where human activities have low impact, land cover is determined by biophysical energy flows and the state characteristics that these forces influence. Geomorphological variables generally constrain and condition land use at most of the time scales over which land use changes, and this is an

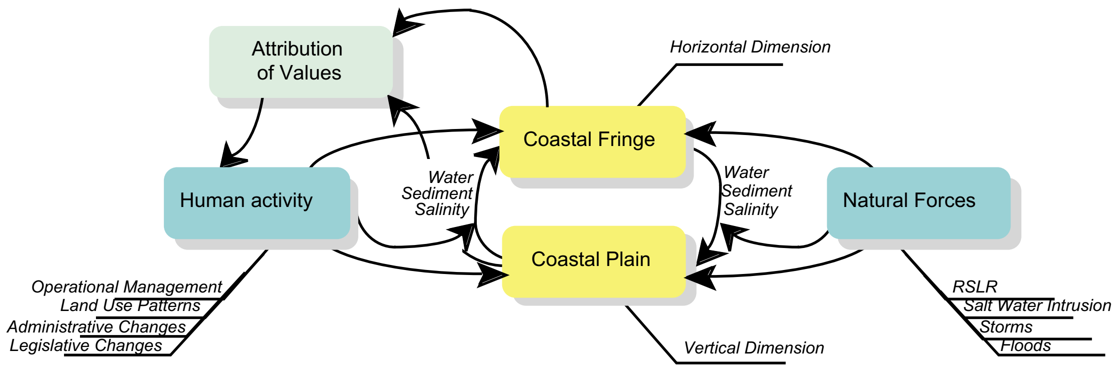

Fig. 4. Integrated conceptual model from a large-scale view.

important element to be included in models of land-use potential. While it could be considered that socio-economic conditions are probably more important in determining the land use change decisions, we should not forget that geomorphology actually determines the activities connected to the particular forms of land use.

A higher concentration of natural systems is found in the fringe area. A possible exception that can be considered, at least for the rural system, is the presence of fisheries. On the other hand, there is a predominance of rural systems in the plain. The river is considered in this scheme as one of the natural forces. Many human activities are devoted to the management of the flows of water, sediment and salinity (see Table 2).

The definition of regimes (for water, sediment and salinity) represents a simple way of summarizing the conditions to which a site is exposed during a certain period of time (e.g. a year). As far as modelling is concerned, the definition of classes allows for the formulation of models and for the formulation of the description of the forces. We distinguish classes such as (1) periodical forces, (2) random short-term, (3) random short-term periodical, (4) random seasonal, (5) random periodical; (6) periodical is understood in relation to river discharge regime, or tidal character, or wave climate or management practices. Such conditions are of fundamental importance in determining the vegetation characteristics, morphology and, in the ultimate analysis, the dynamic character of the physiographic unit.

It is of particular interest to identify those boundaries that are mainly driven by natural forcing factors (e.g. an exposed beach, or a dune) and those boundaries that are mainly driven by human activities (e.g. dike or embankment construction). Of course, the first boundaries are subject to change because of long term morphological and ecological processes, while the latter are subject to change because of human actions. Even the spatial characteristics of the two types of boundary are quite different: the natural ones are very irregular and the artificial ones much more regular – e.g. see Fig. 5, where a simple schematization of a lagoon area in the Po Delta, Italy is presented.

As an additional consideration concerning processes and boundary conditions we draw attention to the fact that human activities are regulated, or at least influenced, by planning acts. Or, where specific planning acts are missing, by the legislation and the regulatory framework. The physiographic unit approach can be useful in managing provisions of different overlapping planning acts. Eventually, in the full application of the concept, all the Acts will be characterized by their effects on the internal dynamics of each physiographic unit and by their effects on the dynamics of the 'links' (water, sediment, salinity).

Application of the modelling framework

Interventions

Land use in the coastal zone includes a number of activities and management practices that can have great consequences for the functioning of the whole coastal zone. Many human activities in the coastal zone influence, or are even focused on, the management of natural coastal zone processes which make the activities (use of the coastal resources) possible in the first place (e.g. drainage of water in low-lying areas). Some sectoral

Table 2. Intervention strategies.

Interventions	Water	Sediment	Salinity
Operational management	• Management of the irrigation system (pumping) • Management of the drainage system (pumping) • Management of the sewage system (pumping)	• Dredging • Management of upstream dams • Management of pumping systems	• Control of the salt-water intrusion according to tidal conditions
Maintenance	• Maintenance of the hydraulic network (new pumping systems)	• Beach nourishment and re-nourishment • Dredging	
Structural interventions	• Changes in the hydraulic network (new pumping patterns; new dikes)	• Wetland creation • Dune creation • Controlled distribution under flooding conditions	• Changes in the groundwater pumping/welling system
Land use changes	• Changes in the physical boundaries of natural/rural/urban systems	• Changes in the physical boundaries of natural/rural/urban systems	• Changes in the physical boundaries of natural/rural/urban systems
Administrative changes	• Changes in the boundaries of natural/rural/urban systems	• Changes in the boundaries of natural/rural/urban systems	• Changes in the boundaries of natural/rural/urban systems

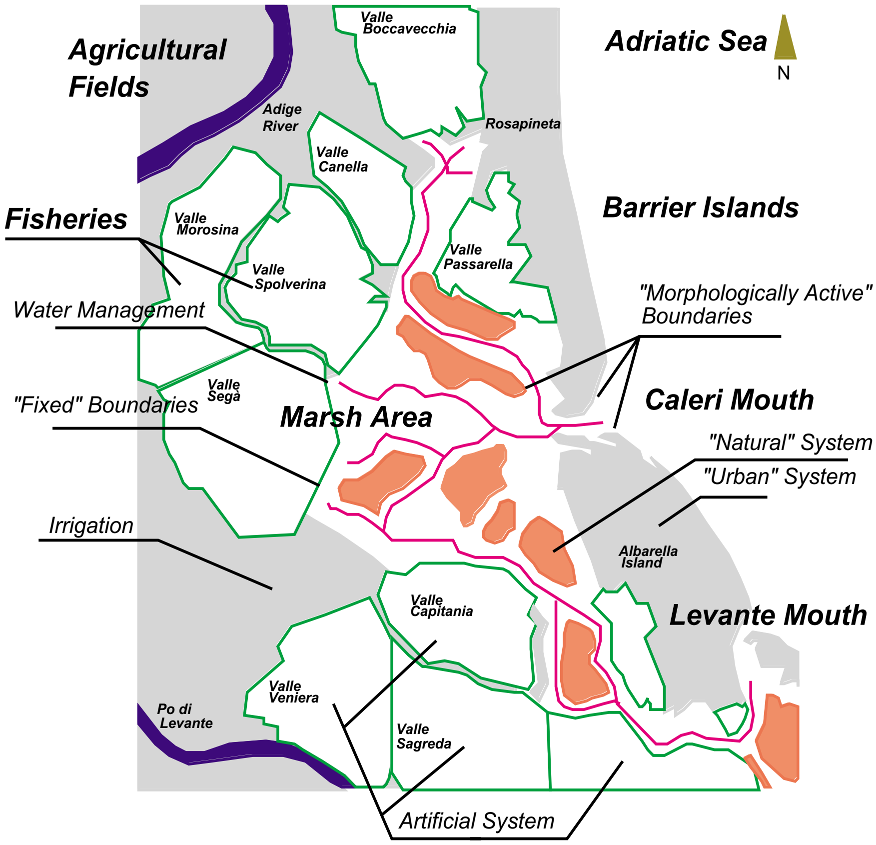

Fig. 5. A complex lagoon system in the Po Delta.

management practices may lead to a worsening of the natural (or man-induced) problems, e.g. groundwater pumping with the resulting saline intrusion. In general we can consider the external natural environment and the management tasks as being those factors that actually trigger changes.

Interventions can be defined in terms of the decision as well as the influencing factors that might affect water and sediment fluxes and salinity modifications. Practically speaking, management practices are exerted in terms of:

- control actions
- constraints
- conditioning actions

Spatial scales of intervention are from local to general and temporal scales of intervention from event-based to continuous. A classification exercise can also be attempted in this case in relation to specific coastal zone management tasks and with the extent of the area subject to management. As Table 2 suggests, we have a formidable set of processes able to drive and trigger changes in the coastal zone, even without going into details of the specific actions but simply looking at the impact of such actions on the dynamics of water, sediment and salinity. What is important to remember here is that such information must be geographically referred.

Influencing factors and decisions determine interventions on the coastal system. Such interventions affect the dynamics of sediment, water and salinity, both between and within the physiographic units. Physiographic units ‘react’ to such dynamics with their own internal dynamics which determine an evolution of the land cover, changes in the ‘values’ attributed to the natural system, to the activities and to the land-use system.

Practically, human interventions can be specified in terms of:

- List of values … (drained, diked, …)
- Areas subject to... (limits in pumping capacity, limits in dike height, limitations of use, …)
- Fluxes of … (specification of the flux of water, relationships with land use and natural events, …)

Most of such interventions will be related to the management practices. The operational management, maintenance and structural interventions can also result from the need to counteract a certain RSLR under a given management scenario, e.g. amount of water to pump and height of the dike. Legislation changes, as well as cultural modifications can themselves lead to specification of regulatory constraints for such management practices.

Basic issues and the definition of a minimal model

The net result of our conceptual effort is a set of fundamental ‘building blocks’ for the construction of models of relationships in a coastal zone environment. Using such tiles we can reshape one or more simulation models according to specific questions and/or to scenarios. The type of questions basically correspond to the investigation of the reasons that make, for example, the Po Delta attractive in spite of the fact that it is to a large extent below mean sea level. Some examples:

- Suppose we have a certain land use and a certain ongoing management practice. What are the costs of maintaining such land use structure under scenarios of relative sea level rise (RSLR)?
- Suppose there is a certain long-term objective. Which are, under various scenarios of RSLR, the modifications of land use most likely to happen?

In the simplest situation we can consider a certain scenario for the natural forces and examine the benefits following a certain land use pattern. We can contribute in such a way to the investigation of:

- the main driving forces and constraints that influence land managers to maintain or change land use over time;
- the mechanisms and processes by which land managers develop a land-use system, defined in terms of an operation sequence, and the ways their purposes are translated into action;
- the effects on land cover (e.g. the spatial appearance of the physiographic units) of the application of a land use type (e.g. agriculture) over time, and the feedback of these consequences to land uses and their driving forces.

This will allow the undertaking of comparative studies of coastal land-use/cover dynamics using common protocols and standardized terms, measures and indicators of land use and its dynamics. These will likely include:

- Transdisciplinary classification of the coastal zone; the evaluation of the multifaceted sources of the problem require a classification based on criteria with priority other than those given by one single discipline.
- Uncertainty in the recognition and definition of the ‘problem’; recognition of the existence or of the possible occurrence of a problem requires technical developments, the understanding of ongoing processes, as well as the ‘perception’ of it as being a problem.
- Uncertainty in the identification and implementation of the ‘solution’; the identification of the solution to a problem requires technical capability, as well as the acceptance of it as being a solution given a number of constraints.
- Predictability of coastal morphological changes; the degree of predictability and/or the limitations to the predictability of coastal morphological changes should be identified.

The timing of human interventions as well as the spatial distribution of human intervention, their effects and their planning should be considered.

In the simplest cases, a model, such as shown in Fig. 6, allows us to consider the integral dynamics between plain and fringe and, what is particularly important from an end-user’s point of view, allow us to take into account such processes as competition for land uses between plain-related uses and fringe-related uses. Suppose we have at our disposal a ‘synthetic delta’, basically corresponding to the structure of Fig. 4, where the most important morphological parameters are the horizontal dimension (i.e. the width of the beach) for the fringe and the vertical dimension (i.e. the soil elevation) for the plain (see Capobianco & Otter 1996). The model considers the simulation of:

- Inorganic sediment supply from the river (depending on distance from the river, physical characteristics of the site, current elevation level (the higher the elevation, the less the sediment supply). The sediment supply is described with a yearly periodical Poisson function (giving ‘pulsing’ events).
- Position of salt-water table in the soil with respect to the free surface, which means that the higher the salt-water table, the less salinity effect is felt by the vegetation. Position of the salt-water table depends, in a non-constant way, on evapotranspiration, thus increasing the salinity-induced limitation to growth during the summer period. Dynamics are related to elevation changes with respect to subsidence; the speed of salt-water intrusion is related to the distance from the sea according to a distance factor and to an ‘angle of intrusion’.
- Subsidence causes a displacement of the free surface level (of the elevation with respect to the original reference) but also induces salt-water intrusion.
- The relative accretion of the beach is obtained through the ‘unmanaged’ sediment not remaining in the coastal plain and not lost in the sea (the available sand-fraction), while erosion is very crudely computed by using a modification of a geometric rule (the so-called ‘Bruun’ rule).

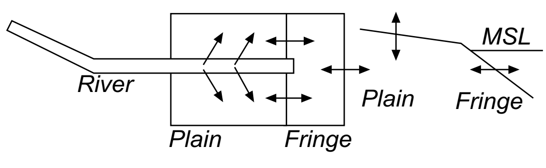

Fig. 6. ‘Synthetic delta’ model.

The width of the fringe influences the salt-water intrusion in the plain area thus introducing an important feedback mechanism.

In this example, control exerted on water fluxes can be seen as the currently undertaken management practice (e.g. irrigation practices).

As a second choice it is possible to act on the salt-water intrusion by following one of two approaches. The first approach is to use freshwater to force a lowering of the salt-water table, but the period when this is more necessary is the same period when freshwater is less available. The second approach is to use artificial means to limit salt-water intrusion during high tide along adjacent river branches. However, the best approach to keep salt-water away from the area is simply to increase the horizontal distance from the sea (e.g. by well-planned reclamation interventions and/or moving human activities areas further away). This consideration opens the link with a simplified fringe model where an increase in fringe width induces a reduction in speed of salt-water intrusion. The salt-water intrusion factor also introduces elements of spatial variability and formation of patterns.

A possible alternative management practice could consist in the modification of the type of vegetation. In a natural environment this can be the result of natural succession, whereas in a rural environment this can only follow a specific decision to rotate production. In the first case we assume that there is an autonomous adaptation to changing (salinity and elevation) conditions. In the second case such adaptation could be made artificially; while it will certainly result in being an expensive operation. It may be possible to extend in time the productive period of the area by use of these adaptations – see Fankhauser (1995) for a comprehensive discussion on the problem. In other words, it is possible to enlarge the 'sustainability window'.

Properties of the minimal model

A continuous balance between uses and resources in the coastal zone exists, affected by human activities and natural forces. The secret of success of an Integrated Coastal Zone Management program lies in an ability to sustain uses and resources under possible scenarios of natural and socio-economic change. A suitable understanding of the internal dynamics as well as an understanding of the mechanisms driving change is a necessary prerequisite.

In our minimal model of a deltaic system, on a time scale of interest of 30-50 yr, we can distinguish a variety of processes evolving differently in time. We have processes evolving continuously, processes evolving with random pulsing events (generally with a character of seasonality) and processes changing at discrete times (also with a possible seasonal character). From the point of view of the deltaic fringe the interest is that of keeping a certain minimum horizontal dimension (beach width), while from the point of view of the deltaic plain the interest is to keep a certain minimum elevation (e.g. to guarantee the necessary substratum for agriculture). However, simulations show that the net result is a system working around an unstable equilibrium between natural forces and human induced actions and constraints. Interestingly, the examination of the conditions inducing a transition of a 'dynamic regime' of the deltaic system (e.g. transition from an accreting to an eroding beach, from freshwater-dominated to salt-water dominated conditions in the plain, etc.).

The general observation we can draw here is that the decision to favour a human related direction of change with respect to natural changes may only have a limited sustainability in time according to (socio-economic) values that are also subject to continuous change in time.

Summary and Conclusion

The planning of Integrated Coastal Zone Management actions asks for spatially distributed modelling. The constituent objects on are so-called physiographic units, which are the fundamental spatial objects for the description of land cover and land use structure. For management decisions, the role of the spatial complexity should not be underestimated, because it is fundamental for the evaluation of changes on time and space scales relevant to land use planning and management. The more we aggregate in space, the less the results are useful for determining actual management actions. The progress in long-term modelling of land use and land cover change in the coastal zone, is stimulated by adopting a conceptual framework which can embrace all the data and experience concerning the coastal system of interest. Deltaic areas are a particular case here.

The approach can be structured into a model-based Decision Support System, coupled with a Geographic Information System technology which represent the state-of-the-art of decision support tools in environmental management. The modelling framework will allow for the identification of what is most likely going to happen under given scenarios of change. At same time it will allow for the verification of the impacts of possible management practices and/or policy options. Integrated modelling will eventually play an important role in characterizing the degree of sustainability of a certain management policy as well as the impact on sustainability of a specific intervention (Capobianco et al. 1999).

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References

Capobianco, M. & Otter, H. 1996. *Modelling land use and land cover changes for deltaic areas.* International workshop on the state-of-the-art of ICZM in the Mediterranean and the Black Sea. Iberotel Sarigerme Park.

Capobianco, M., DeVriend, H.J., Nicholls, R. & Stive, M.J.F. 1999. Coastal area impact and vulnerability assessment: A morphodynamic modeller's point of view. *J. Coastal Res.* 53: 701-716.

Capobianco, M., Jimenez, J.A., Sanchez-Arcilla, A. & Stive, M.J.F. 1997. Budget models for the evolution of deltas. Definition of processes and scales. *J. Coastal Conserv.* 4: 7-16.

Costanza, R., Sklar, F.H. & White, M.L. 1990. Modelling coastal landscape dynamics. *BioScience* 40: 91-107.

Engelen, G., White, R. & Uljee, I. 1993. Exploratory modelling of socio-economic impacts of climatic change. In: Maul, G.A. (ed.) *Climate change in the intra-americas sea*, pp. 306-324. Edward Arnold, London.

Engelen, G., White, R., Uljee, I. & Drazan, P. 1995. Using cellular automata for integrated modelling of socio-environmental systems. *Environ. Monit. Assessm.* 34: 203-214.

Farinha, J.C., Costa, L., Zalidis, G., Matzavelas, A., Fitoka, E., Hecher, N. & Tomàs Vives, P. 1996. *Mediterranean wetland inventory: habitat description system*. MedWet/ ICN/Wetlands International/Greek Biotope/Wetland Centre (EKBY)/ Instituto da Conservaçao de Naturaleza (ICN) Publication, Vol. 3, Athens.

Gardner, M. 1970. The fantastic combinations of John Conways new solitaire game Life. *Sci. Am.* 223: 120-123.

Gutowitz, H. 1991. *Cellular automata. Theory and experiment.* The MIT Press, Cambridge, MS.

Meyer, W.B. & Turner II, B.L. (eds.) 1994. *Changes in land use and land cover: A global perspective.* Cambridge University Press, Cambridge.

Turner II, B.L., Skole, D., Sanderson, S., Fischer, G., Fresco, L. & Leemans, R. 1995. *Land-use and land-cover change science/research plan*. IGBP Report No. 35 and HDP Report No. 7. ICSU, Stockholm.

Turner, R.K. 1991. Economics and wetland management. *Ambio* 20: 59-63.

White, R. & Engelen, G. 1993. Cellular automata and fractal urban form: A cellular modelling approach to the evolution of urban land use patterns. *Environ. Plann.* 25: 1175-1199.

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