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Impacts of sea-level rise on the Ebro Delta: a first approach

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ABSTRACT

Global climatic change is taking place and it will likely affect Mediterranean deltas and other low-lying coastal regions in terms of sea-level rise, salinity increase and changes in temperature and weather patterns. This will have serious implications because these deltas are very valuable in terms of natural resources and related economic activities. This study focuses on one of the northwestern Mediterranean deltas, namely that of the Ebro river. There is an enormous lack of information about and understanding of the integral functioning of this type of system. The objective of this ongoing study is to determine the vulnerability and response of this deltaic system to climate change, such that informed decision-making can be made. In order to do this it is proposed to make combined use of existing and new field measurements (sedimentation, soil formation and coastal fringe response) and an integrated (physical/ecological) conceptual model of deltaic behaviour. Using these tools, organized in relation to the interaction with socio-economic components, a number of intervention scenarios, aiming to cope with the effects of climate change, will be examined in a later stage of the research project. It is expected that these results will provide valuable information for integrated, comprehensive approaches to determine whether management plans are sustainable. Copyright © 1996 Elsevier Science Ltd.

1. INTRODUCTION

1.1. Problem presentation

All of the available studies addressing the vulnerability of the western Mediterranean deltas to climatic change[1] are of a qualitative nature when it concerns their integral (basically physical–ecological) response including socio-economic aspects and feed-backs. To a large degree this is due to the absence of reliable monitoring data, and to a somewhat lesser extent due to the absence of integral response models.

Both for the ecological and physical systems, significant modelling progress has been made in the last decade, but what lacks is their integration and the feeding of these models with boundary conditions derived from global climatic change, management policies and field measurements. This requires the adaptation of the physical–ecological models to long-term predictions, which is a true research task (processes acting on a short time scale may act as 'noise' on a longer time scale, at which latter scale other processes, negligible in the shorter term, may play a dominant role). At the same time it may be possible to improve the description of interactions allowing for more quantitative assessments.

The use of long-term integrated, conceptual models in combination with field studies is new in its application to global change issues in the Mediterranean. A state-of-the-art comprehensive modelling approach will thus be developed and applied to try to arrive at a coupled system description of the Ebro Delta (Fig. 1), with quantitative development scenarios.

The general starting hypothesis is that deltas can be managed to function under significant rates of sea-level rise and to accommodate changes by making suitable use of natural processes and, in particular, enhancing natural ecosystem functioning. With this principle as a basis, it is considered feasible to provide advice on the potential for socio-economic developments, making sustainable use of natural resources.

1.2. Study area

The Ebro Delta coast is a 50 km long sandy shoreline developed during the last five centuries (the emerged deltaic body) with the sediment supplied by the Ebro River (Fig. 1). The total subaerial delta is about 320 km^2 (Fig. 1). The main morphological features are two spits which

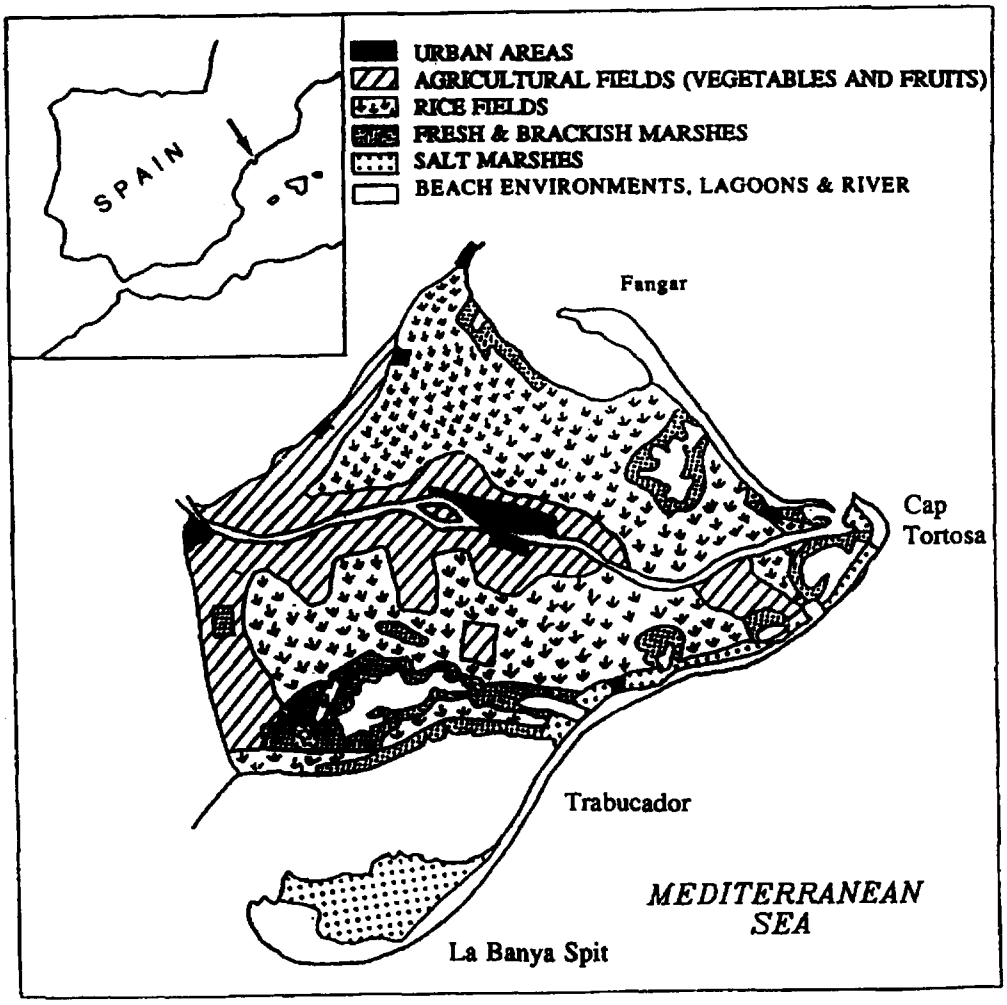

Fig. 1. The Ebro Delta.

partially close two adjacent lagoons. The delta is biologically rich in waterfowl, fisheries and vegetation and supports important economic activities associated with tourism, hunting, fishing and aquaculture. A majority of the surface area, however, is devoted to agriculture. Wetlands were drastically reduced until the creation of the Natural Park in 1983, and are nowadays only present in small areas near the beach and coastal lagoons.

After several centuries of growth, the deltaic evolutive trend changed a few decades ago in such a way that the present delta is now a wave-dominated coast.[2] This is mainly due to the nearly total reduction of solid river discharge (sand fraction at least), due to the construction of several large dams in the course of the river. The initial status of dynamic equilibrium between river discharges and wave transport capacity has evolved to a situation where the second factor is clearly dominant. Under these conditions, waves began to erode deltaic

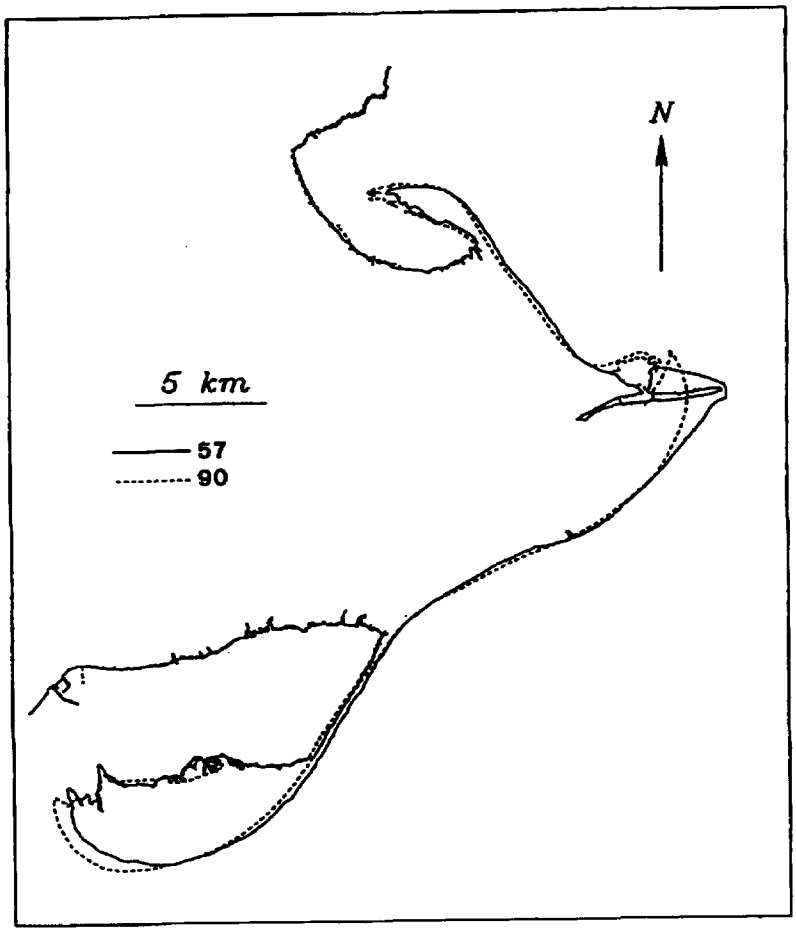

Fig. 2. Evolution of the Ebro Delta coastline from 1957 to 1990.

beaches becuase the sediment removed was not replenished and a very intense reshaping of the delta coastline began to take place. To illustrate these processes, Fig. 2 shows the deltaic evolution from 1957 to 1973 and from 1973 to 1990. A shoreline retreat of more than 1500 m in 30 years has been registered at Cap Tortosa, while the two spits have experienced significant accretion during this period. The southern spit has prograded about 700 m towards the southwest, while the northern spit has advanced about 1000 m towards the mainland coast.

2. PROJECT APPROACH

2.1. Background

Deltas are particularly sensitive to climate change induced effects. Large-scale changes (on a time scale of the order of decades) in river discharge (liquid and solid), marine climate (storminess) and sea-level

rise (both eustatic and subsidence induced) will produce a change in their present evolutive trend and status.

Deltas are, in particular, good places to study the effects of sea-level rise. Most deltas are subsiding and this, in addition to eustatic sea-level rise, leads to a 'relative sea-level rise' (RSLR) rate which is often much greater than eustatic rise. Because of high RSLR, deltaic wetlands will be affected earlier by an acceleration in eustatic sea-level rise, and they serve as models for the effects of sea-level rise in other coastal systems. Furthermore, rising sea-level will first affect regions with low tidal range, such as the Mediterranean, because the location (elevation) of coastal vegetation is related to the tidal range.

Sea-level rise, salinity increase and changes in weather patterns and temperature will therefore have serious implications on northwestern Mediterranean deltas in terms of agriculture, natural resources, tourism, etc. These deltas are extremely vulnerable because they are already sediment starved (mainly due to river regulation) so that coastal fringes have become fragile and the direct hinterland is very near the present sea-level. Consequently, slight increases in sea or storm surge levels have the potential to flood and breach large areas. In addition, the vertical growth range of coastal marsh vegetation is small because of the low tidal range. This means that slight increases in mean sea level will relatively quickly lead to inundation, deterioration and displacement of significant areas of wetland vegetation. Additionally, and because of Mediterranean weather characteristics, any change of weather pattern may dramatically affect the ocurrence of episodic events, such as storm surges.

A starting hypothesis is that these systems can continue to exist in the face of rising water levels and weather changes if there is sufficient vertical accretion of inorganic sediments and/or organic matter and sufficient supply of appropiate enough sediments to the near-shore zone. To help achieve this objective, deltas need to be managed to withstand climate change impacts by enhancing the natural functioning of coastal fringes (e.g. promoting natural dune formation, uniformity of longshore transport, etc.) and ecosystems (e.g. primary productivity, material processing, interaction among subsystems, etc). This implies for the Ebro delta to deliver to the deltaic system sediments trapped by dams and to regulate river flow not only as a function of the liquid discharge but the river solid discharge.

There is, however, an enormous lack of monitoring and, therefore, information about the integral (physico–ecological) long-term functioning of these systems. An objective of this study is to develop information on which informed decision-making can be made. More

specifically, the main objective is to assess the vulnerability and response of the Ebro deltaic coastal system to climate change. In order to do this, measurements will be taken of:

(1) vertical accretion and sedimentation rates in inner deltaic areas;
(2) organic component of soil formation in inner deltaic areas;
(3) response of and changes in the outer deltaic coastal fringe; and
(4) coastal (marine) climate and river discharges.

This information will be used in the development of a coupled physico–ecological conceptual model (system description incorporating quantitative sub-models for particular aspects or sub-systems which allow such a description). With the help of these tools, a number of intervention scenarios will be examined using an integrated, comprehensive approach to determine if management plans are sustainable.

2.2. Conceptual approach

The precise quantitative functioning of deltaic systems and their response to climate change is not well-known, largely because of a lack of long-term observations of their behaviour and response. Using field observations as an input to the conceptual model development (and eventual validation of quantitative sub-modules) is therefore crucial. Three parts can thus be distinguished in the development of this research project:

(1) A first part in which the deltaic system is analysed from physical and ecological standpoints in concert with field data analysis and on-going measurements to fill existing gaps. The aims are to gain insight in the magnitude of processes which control the deltaic behaviour and to obtain long-term data series to estimate conditions and trends defining the long-term evolution.
(2) A second part in which a conceptual model general enough to be valid for this type of delta will be developed.
(3) A third part where the conceptual model will evolve into various numerical sub-models able to simulate the functioning and future response of the deltaic system. The degree of quantitativeness will decrease as the multidisciplinarity and time-scale increase.

For operational purposes a distinction will be made between the deltaic fringe and the deltaic plane as two (obviously linked but with

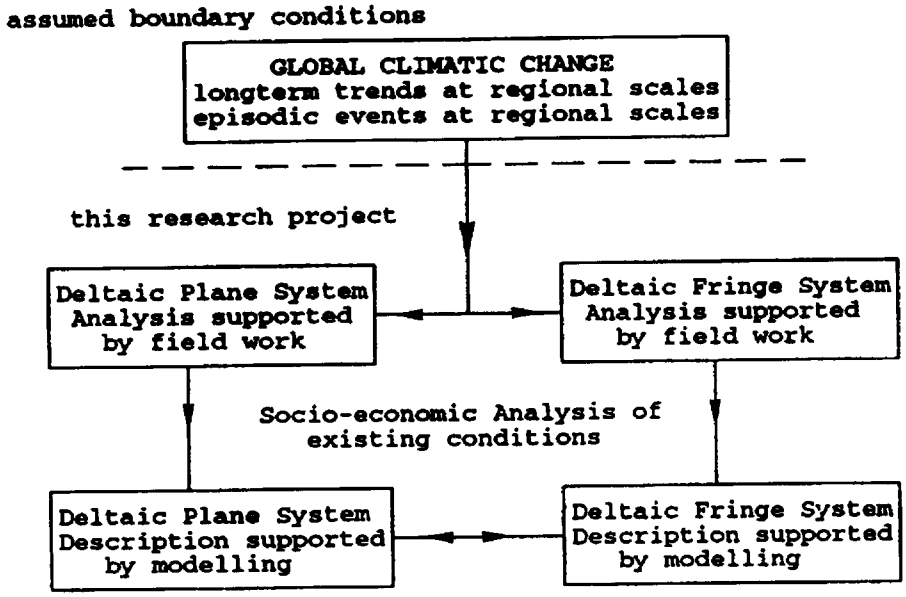

Fig. 3. Block diagram schematizing the proposed conceptual approach to model the deltaic system.

significantly different scales and energy levels) physical and ecological entities. The socio-economic component in the project refers to the assessment of intervention plans and the establishment of management scenarios to cope with climatic change effects and to allow for a sustainable development of the deltaic system. Schematically, the proposed conceptual approach is depicted in Fig. 3.

2.3. System analysis and collection of field data

The objective of this part of the research is to further the understanding of the functioning of deltaic systems by firstly analysing existing field data and identifying vital information gaps, and secondly, based on this, carrying out carefully identified field measurement campaigns to fill the most important gaps within the constraints of the project possibilities.

Some of the measurements conducted at the two sites (deltaic fringe and deltaic plane) will be integrated to obtain an improved estimation of the measured variable (e.g. determination of RSLR).

2.4. Field data in the deltaic fringe

Due to the small tidal amplitudes in the Mediterranean and low river discharge rates, at present deltaic fringes are primarily wave-dominated, i.e. the evolution of these deltaic fringes is strongly controlled by the hydrodynamic forcing due to incident waves and by the rate of relative

sea-level rise (RSLR). In almost all cases their evolution has significantly changed during the second half of this century due to sediment starvation as a result of dam construction and the associated river regulation. Both sediment availability and compaction of Holocene depositions, aggravated by groundwater and natural resources extraction, are essential factors for the coastal fringe evolution. Sampling of these data together with data on the coastal fringe hydro-dynamic forcing and evolution is of fundamental importance for understanding the physical system.

Due to the highly dynamic behaviour and multiple time scales involved in the coastal fringe, it will not be useful to consider only measurements taken in the framework of this project (with an estimated duration of two years). Thus, in the case of deltaic fringes, a significant part of the field data effort will be dedicated to the compilation and analysis of previous data in order to achieve data series long enough to be considered as representative at the working time scale (in the range of years to a few decades).

2.4.1. *Coastal evolution*

The recent and present coastal evolution will be determined to establish the 'reference level'. To estimate evolution rates, existing shoreline data from several sources (historical maps, aerial photographs, beach surveys, etc.) will be collected. These data will be completed (if possible) with bathymetric surveys, in such a way that both the emerged and submerged coasts can be analysed jointly. All these data will be analysed to estimate coastal evolution trends at the proper scale (large and medium) and to identify short-term variations as well as episodic events.

To estimate large and medium evolution scales, maps and aerial photographs will be used. Due to the nature of these data (they usually present a large time span between measurements), they are hardly influenced by short-term changes.[3] Depending on the number of available data sets, end-point-rate (EPR) methods or regression models will be used to estimate the deltaic evolution trend.[3,4]

To estimate short-term variability ranges (seasonal changes), beach profile surveys will be used, in which the increased sampling density (short time span between measurements) provides a measure of the short-term variability and a way of distinguishing this from longer-term trends. In this case, regression models will be used, where the two components (short and large) can be isolated.[2]

To estimate the role of episodic events in the coastal evolution, measurements before and after storm events will be used. In this case,

the coastal response to the storm action will be quantified as well as the post-storm recovery.[5]

2.4.2. *Determination of RSLR*

The 'eustatic' component of RSLR in the northwestern part of the Mediterranean needs better assessment, because of the lack of reliable tide gauge data and long-term cores.[6,7] Data from existing tide gauges will be evaluated critically, with an emphasis on the stability of the strata on which they are based. Through geodetic levelling (using stable land-based benchmarks), the compaction and subsidence components of existing benchmarks in the Ebro Delta will be assessed.

This estimation will be complemented with assessments of RSLR obtained from sediment budget considerations. Once the coastal evolution for a certain period (with the corresponding sediment balance) has been determined, the sediment sources (rivers and cross-shore feeding) and losses (dune formation transport and offshore losses) will be evaluated. Applying the sediment balance concept, averaged volume changes due to RSLR can be estimated, and from this, applying a model of coastal response,[8] averaged RSLR rates can also be calculated.[9] The accuarcy of this method depends on the accuracy of the estimation of each component of the sediment budget and, generally, it gives an order of magnitude of the averaged RSLR and not an exact rate.

2.4.3. *Long-term shoreface wave, surge and current climate*

To analyse/predict the long-term evolution of the coastal fringe, long-term wave, storm surge and current climates are required in order to build up representative long-term driving term scenarios.

Long-term series of wave data will be analysed, in order to estimate temporal variations in wave characteristics along the deltaic coast.[10] This analysis will be done applying regression models to obtain trends in wave parameters as well as the variability of directional wave distributions.[11] During the period of the project, the offshore wave climate will also be monitored using wave buoys and visual observations.

Available current data will be analysed in the same manner, to estimate temporal changes in current intensity and direction.

Storm surges will be identified from sea-level records in the area. The annual distribution of storm surges will be calculated in order to estimate its temporal variability. Moreover, a yearly joint distribution of storm surges and storm waves will be calculated to estimate the storminess of the area and its possible long-term variation. This point is

important since deltas, as most low-lying coasts, are sensitive environments to storm-induced impacts. During the period of the project, water levels will also be monitored using tidal gauges. This will be completed with measurements of meteorological conditions (wind and atmospheric pressure) to estimate the meteorological contribution to the actual water level.

From all these data the variability of factors contributing to the sediment budget will be assessed. Based on this, it will be possible to formulate a dynamic system description (see next sections) which will allow for predictions of the deltaic fringe response to changing 'boundary conditions' (RSLR, wave characteristics, storminess and circulation).

2.4.4. *Riverine sediment input*

Sediment input from the Ebro River will be determined in two ways. Long-term series of river flows will be used to estimate the sediment input through sediment transport formulas.[12,13] These estimations will be completed and calibrated with the existing sediment transport measurements. From this, the contribution of the river to the deltaic evolution will be determined as well as its temporal variability. During the period of study, river flow records will be collected to update data series.

These estimates are important as an additional source component in the sediment balance of the delta. The analysis of these series will allow identification of man-induced effects in the sediment balance and to estimate the limits in sediment availability regarding deltaic processes (e.g. construction of dams, which not only retain sediment but regulate the river flow).

2.5. Field data in the deltaic plane

2.5.1. *Accretion methods*

Vertical accretion will be measured using several different techniques. To measure long-term accretion rates, the Cesium 137 method will be employed. Short-term, seasonal and annual rates will be measured using a combination of short-term sedimentation on filter paper, marker horizons, and sedimentation–erosion table measurements.

Short-term sedimentation will be determined by measuring the accumulation of material on filter papers placed at different areas in the wetlands.[14] Measurements will be carried out approximately every

2–3 weeks. Since measurements are made on a short-term basis, the effect of particular types of events (such as storms, high river flow, rainfall, etc.) can, in principle, be determined.

Marker horizons will be established according to the method described by Cahoon and Turner.[15] Cores will be taken from the marker horizons once or twice a year and vertical accretion will be determined. Cores will also be taken from several areas and analysed for Cesium 137.[16] This will provide a longer-term average rate of accretion over the past 30–40 years. A sediment erosion table (SET) will also be used to measure elevation directly. SET measurements will be done four times a year. The method was developed for measuring erosion and accretion on intertidal wetlands and mud flats and shallow subtidal areas and has proved to be very accurate and non-destructive.[17,18] Because the accuracy of the SET is about ±2mm, it can measure small changes in surface elevation. The SET measurements will be compared to the sedimentation data obtained using marker horizons and Cesium cores. An advantage of the SET is that once a station is established, it can be measured for many years.

The vertical accretion rates obtained from the above measurements will be compared with the rate of RSLR for the area to determine if accretion is less than RSLR. The rate of RSLR can be estimated from regression analysis of tide gage data, long-term cores and dating of historical markers. The obtained estimate should be compatible with the one derived for the coastal fringe. If there is a vertical accretion deficit (vertical accretion <RSLR), then estimates will be made of the effect of rising water level on wetland vegetation. Because coastal wetland vegetation grows only within a given elevation range, it can be calculated when the elevation will fall below that range, given the vertical accretion deficit.[19] With this it will be possible to estimate when different wetland areas will likely become stressed and begin to deteriorate.

2.5.2. *Primary production and decomposition–organic soil formation*

The type of marshes to be studied will include the most representative in the Mediterranean. For the salt marshes, the Salicornia type species are dominant (*Salicornia fructicosa, Arthrocnemum glaucum*, etc.) and for the brackish–freshwater marshes, depending on the salinity and flooding, there may be a dominance of the Juncus or reed type species (*Juncus maritimus, Scirpus lacustris, Phragmites australis, Typha angustifolia*, etc.). The inorganic and organic matter requirements in different marsh types to maintain the land elevation as a function of

present and future trends of relative sea-level rise will be determined.[20] Aboveground and belowground production and decomposition of marsh vegetation will be measured over two growing seasons, corresponding to the two years project duration.

For annual species with a high spatial homogeneity, the method of Wiegert and Evans[21] will be used for aboveground production, whereas for those with a low homogeneity the method of Williams–Murdoch[22] will be employed. These methods are two of the most accurate available for estimating net production.[23] There is, nevertheless, an enormous lack of data concerning perennial Salicornia type species, due to the difficulty in estimating production. To obtain production estimates as accurately as possible, the method of peak biomass will be complemented with information from tagged individual stems and decomposition experiments, in order to estimate the disappearance of standing biomass.[24] Specific modifications will be designed for each species and preliminary sampling will be carried out to determine the optimum size for the samples and replicates.

Measurement of the belowground production, although difficult and time-consuming,[24] is important for estimating organic accretion in the soil. The classical method of invasion cores will be used.[25] All available methods underestimate the true production because they do not fully account for death and decomposition losses during the growing season.

The estimate of organic matter decomposition from plant production (above- and belowground) is crucial to determining the amount of plant material which remains in the soil and contributes to organic accretion. The litter bag decomposition method will be used for this.[24] Organic soil formation will be determined as described by Nyman *et al.*[20]

2.6. System description and modelling

The objective of this part of the research project is to develop linked physical (e.g. morphodynamic) and ecological system descriptions to:

- increase the understanding of deltaic dynamics (behaviour), particularly at long time scales and from an integrated, multidisciplinary standpoint;
- build up a conceptual model to simulate the functioning (i.e. impact on and response) of deltaic systems;
- analyse the effectiveness of a number of intervention or management scenarios.

The proposed effort will build on an extensive history of conceptual

and quantitative modelling approaches developed for two deltas, the Rhine (i.e. the Netherlands, lato sensu) and the Mississippi.

This part of the research will proceed in several steps. Roughly speaking, a distinction can be made between physical system oriented and ecological system oriented efforts. The physical components include hydrodynamics, sediment dynamics and morphodynamics, whereas the ecological components concern the dynamics of wetlands, aquatic habitats and agriculture. Both components will be developed in parallel efforts and then the output from the physical system functioning will be used as input forcing the ecological system functioning.

Using the current knowledge of deltaic behaviour as a basis, a conceptual model of the deltaic system dynamics (functioning) will be formulated, making proper use of the field information collected during the project. This conceptual model will evolve as much as possible into various numerical sub-models using existing generic (state-of-the-art) models of coastal fringe and deltaic plane response to changing boundary conditions on large spatial and temporal scales. The so developed suite of models will be used to address questions about the functioning of the system and impacts of different intervention and management scenarios. The kind of changes addressed in this manner will include climate variations (sea-level rise, storminess and temperature), freshwater input variations (both increase and decrease and diversions in riverine discharges), increases in nutrient input from riverine and other sources, different proportions of habitats, the effect of wetland impoundment and different schemes for the nourishment and protection of the coastal fringe. Emphasis will be on mutual interaction effects and long-term prognosis.

During a possible next phase of the project, these system decriptions would be incorporated into a fully quantitative spatial landscape model also described briefly in what follows for the sake of perspective.

2.7. Physical system oriented modelling

Physical modelling will firstly concern marine hydrodynamics and river hydraulics and hydrology. The results will provide boundary conditions for morphodynamic and ecosystem modelling. Present and future marine hydrodynamics, as determined by RSLR and changing weather patterns and temperature, will be derived by adapting (long-term generalizations are a research task far from trivial considering the very different roles played by one specific process depending on the time and space scales) and using state-of-the-art models.[26] Specific attention will be paid to aspects like vertical distribution of horizontal current

patterns (three-dimensionality due to wave breaking, interfaces, etc.), density effects and flooding. River hydraulics and hydrology, based on present and future scenarios of discharge, will be derived through state-of-the-art river modelling. Specific attention will be given to salinity intrusion. Hypotheses to be tested include the effects of river discharge, wind, mean water-level, tide, waves and bottom sediment types on the resulting circulation (with emphasis on stratification and mixing) and wave regime around the delta.

These sea and river induced conditions will provide boundary specifications for the ecologic modelling (e.g. spatial and temporal variability of advective currents), and at the same time will be used in the morphodynamic modelling of coastal fringes response, including subaquaous deltas. The morphodynamic modelling will build upon earlier model development applied, amongst others, to the Rhine delta (Dutch coastal system) in an attempt to predict its large-scale evolution in the light of an acceleration of sea-level rise.[27,8] It will be the first time that such an approach is developed and applied to a Mediterranean deltaic system.

In summary, the objectives of the physical system oriented modelling are:

(1) to develop hydrodynamic and morphodynamic model concepts for a Mediterranean deltaic system and large time and space scales;
(2) to verify and calibrate these dynamic models by comparison with data collected in the past and as part of this project;
(3) to utilize these models to gain insight into the deltaic system response for different 'forcing' situations;
(4) to provide hydrodynamic inputs for the ecological models.

2.8. Ecological system oriented modelling

Output of the deltaic fringe modelling will be used as 'physical forcing' for the deltaic plain model. The principal question which will be addressed is what will happen when the integrity of the beach/dune system is degraded. An example of this for the Ebro Delta occurred at Cap Tortosa zone, where the coastal fringe has retreated more than 1500 m in the last 35 years and, at the same time, a inner marsh area has also experienced a landward displacement (its seaward boundary). A suite of models will be used to address questions about the functioning of the system and impacts of different management scenarios as outlined in the preceding sections.

Modelling will serve as a tool for formulating and testing complex ecosystem hypotheses, directing future research efforts, making specific predictions about the impacts of major changes in the system (natural and management induced), and, in the process, advance the state of the art of ecosystem modelling. There will be a close interaction between the delta fringe and delta plain modelling efforts. The latter research is centred on hypotheses concerning both the natural system functioning and the impact of natural and human-induced changes. Because these processes are complex, interdependent, and scale dependent, a suite of models capable of simulating the various processes and their interdependencies in both space and time and at several different spatial and temporal scales is ideally necessary.

The development of these physical and ecosystem models will be based on earlier model development in both Europe and North America. Spatial landscape models have been developed for the Mississippi delta for the last two decades,[28–30] but this is the first time that such a spatial landscape approach will be applied to the Mediterranean. The development of spatial ecosystem simulation models for the Mississippi delta was aimed at predicting long-term habitat succession and horizontal water and material fluxes.[28,29] This type of model has been quite successful in reproducing historical data and predicting impacts for various long-term scenarios (ie. sea-level rise and river switching, basically).

Ecosystem simulation models will be developed and tested at two levels of spatial scale: (1) individual habitats in the delta (aquatic, wetland, agriculture, beach/dune, etc); and (in the second phase of the project) (2) full spatial model consisting of a grid of cells (between 0.25–1.0 km^2) covering the whole delta. For the habitat level models, the results of the delta fringe modelling will be used as input to the delta plain models. For the spatial model, the fringe and plain models will be combined. One major research question involves how to handle this coupling to minimize the loss of information and whether a more interactive coupling is necessary.

With respect to the first level of approach, individual habitat models will be developed for different habitats of the delta. The actual unit models will be determined during the project based on results of previous studies of the area as well as results of the project. These models will be ecosystem simulation models[31] constructed and tested using the STELLA simulation package. The major advantage of this package is that it easily and rapidly allows model construction, testing, and reconstruction so that the focus of the effort can be the structure and performance of the models and not the mechanics of

programming.[32] This allows the modelling component to more effectively serve its function of hypothesis refinement and testing.

2.9. Socio-economic management

This component of the research project will assist in the selection and interpretation of the intervention and management scenarios which will be proposed to cope with changing boundary conditions (sea-level rise, climatic change, human interference, etc.).

In the socio-economic module a framework of analysis will be developed, in which the time-evolution of the delta (as predicted by the physical and ecological models) is compared with a preferred evolution. If the predicted evolution deviates too much from the preferred one, a policy (i.e. a set of technical and non-technical measures) is developed in order to influence the system. The effects of these measures are expressed in terms of e.g. costs, area of accreted land, habitat improvement, space for recreation, or area for industrial development.

This framework of analysis will be implemented in a decision support system (DSS) for delta management. Initially, this DSS will be based upon existing models of and information on the physical, ecological, social and economical systems of the delta. Note that the DSS as such will not lead to management decisions. These depend on the judgement of the policy makers, who attribute a weight to each of the aspects. Of course, these weights can be put into the DSS, but their values have to be given by the policy makers.

The project will address both the fringe and plane of the delta. The theory of decision support systems will provide a one-dimensional approach for the fringe and a two-dimensional approach for the plane. In the first phase, the requirements for the DSS will be formulated and the need for information will be specified. Next, a modular prototype will be built, such that the modules can be replaced by new ones which contain the latest results. Inversely, this approach makes it possible to formulate requirements for information which is needed to achieve internal consistency of the DSS, and to collect this information during the project. The DSS will thus become a structuring element in the project.

In summary, the objectives of the socio-economic component of the project are:

(1) to define a strategy and framework of analysis for the delta management;

(2) to collect the required socio-economic data (e.g. land use, population, infrastructure, etc.);
(3) to define the 'reference situation' for the delta;
(4) to build up future scenarios as a function of the modelling results;
(5) to begin to define feed-back loops (such as change of land-use for a given SLR, etc.) to be included in the global model.

3. SUMMARY

The main objective of this ongoing study is to determine the vulnerability and response of the Ebro deltaic system to climate change, such that informed decision making can be made. In order to do this, it is proposed to make combined use of existing and new field measurements (accretion, sedimentation, soil formation and coastal fringe response) and an integrated (physical/ecological) conceptual model of deltaic behaviour. Using these tools, organized in relation to the interaction with socio-economic components, a number of intervention scenarios, aimed at coping with the effects of climate change, will be examined. It is expected that these results will provide valuable information for integrated, comprehensive approaches to determine whether management plans are sustainable.

Both for the ecological and physical systems, significant modelling progress has been made in the last decade, but what lacks is their integration and the feeding of these models with boundary conditions derived from global climatic change, management policies and field measurements. This requires the adaptation of the physical–ecological models to long-term predictions, which is a true research task (processes acting on a short time scale may act as 'noise' on a long-time scale, at which latter scale other processes, negligible in the shorter term, may play a dominant role). At the same time it may be possible to improve the description of interactions allowing for more quantitative assessments.

The use of long-term integrated, conceptual models in combination with field studies is new in its application to global change issues in the Mediterranean. A state-of-the-art comprehensive modelling approach will thus be developed and applied to try to arrive at a coupled system description of Ebro Delta.

The general starting hypothesis is that deltas can be managed to function under significant rates of sea-level rise and to accommodate changes by making suitable use of natural processes. With this

principle as a basis, it is considered feasible to provide advice on the potential for socio-economic developments, making sustainable use of natural resources.

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