Coastal Flood Hazard Mapping at two scales. Application to the Ebro delta

Doctoral Thesis

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6. Discussion

Always be ready to explain the hows and whys.
Fallout 3

6.1 Introduction

This thesis proposes a methodologic approach for Flood Hazard Mapping at two working scales. Firstly on a long-term scale related to events of Relative Sea-Level Rise, and secondly at an episodic/extreme scale related to storm events. These two scales were proposed, considering that they are the most representative for coastlines changes (erosion, accretion, flood etc).

On the long term scale the Relative Sea-Level Rise is the most important components of current studies of assessment of climate change and evaluation of their effects in the coastal zone. The understanding of the changes in sea-level, will help us to prevent or minimize damage as well as improve the response of the Ebro Delta (a low-lying coast), in future conditions.

The episodic scale has an important role since the episodic or extreme events can cause large damage to the coastal zone and backbeach areas, particularly when poor planning or preparation to this kind of events has taken place. For this reason it is necessary to know the potential damage presented by an event of this nature. The knowledge of probability, the impact of the coastal storms and the associated damage can serve as a base for the design of strategies for the protection and management, and also set priorities and levels of protection.

The establishment of working and management scales, and to know in advance the damages of the study area, allows us to set priorities, assess efforts to adapt to environmental changes and in turn minimize the damage in the economic and social component.

Regardless the flooding scale or source, an important input of this work was the DEM. Since the quality, accuracy and resolution, report directly to the final values to determine potential flood areas. The studio area has a low-lying profile, with a lot of small canals and dykes (that in a High resolution DEM can be observed in detail). This configuration can generate big variations on the calculation of flood-prone areas. In this case, the DEM has a high resolution, allowing us to obtain very detailed results, but with a high computational cost, so a discrete resample of the DEM was necessary, in the areas of interest in order to not loose accuracy.

6.2 Flooding due to Relative Sea Level Rise

As we mentioned in chapter 5.3, the potential flood areas with a RSLR in the Ebro Delta have been estimated between 9916 ha for the lower scenario (35 cm), to 18,837 ha for the higher scenario (75 cm). This corresponds to 32% and 70% of the Delta area.

In the development of this work, a number of assumptions and considerations (eustatic sea level rise, subsidence of delta plain, Bruun's rule-like response for the beaches, and no response for the backbeach) were made. These assumptions allowed us to work in a structured and less variable environment, but it must be take into account that these could cause uncertainty problems.

The main variable in this analysis is the eustatic sea level rise, and because to the calculation methodology, it is also the component that shows the biggest uncertainty.

The value of SLR is obtained from mathematical models which involve a large number of variables and assumptions. For that reason the final value of SLR is contained within a range. To limit the uncertainties due to the above, we selected the values for maximum and minimum in the range and a mean value. Therefore, our final map of flood areas, shows the limits of flooding associated with the range of variation of the SLR.

The other important point that might cause problems is the one associated with the coastal response. Since we assumed have considered the coast as a dyke, where the beaches will respond based on the Bruun´s law. This consideration implies that there is enough sediment in the coastal area, and the coastal behavior does not vary in time. So the coast can rise in conjunct with sea level and maintain its role as a levee.

Based on our results, we corroborate that the Ebro Delta is highly sensitive to changes in sea level as expected. Most of the flooded areas that actually are occupied by rice pads normally correspond to ancient coastal lagoons, canals and river courses. These areas are located in the lower areas of the topography of the delta. These areas identified as potential flood areas by RSLR, match with those established as vulnerable by Sanchez-Arcilla *et al*., (1998).

The main flooded areas of the delta are those located in the surrounding of the bays, and connected by channels that normally are used to drain rice fields. In case of a SLR they could serve as entree channels for the water. If the channels are closed it is more feasible to stop the flood associated to direct communication with the sea. The variation in the flooded area for that action can reach up to 30%.

Sea level rise will have a strong impact on ecosystems in the Ebro Delta and could lead to the "drowning" of most low-elevation habitats and a further salinisation of freshwater and brackish habitats, resulting in a strong increase of unvegetated, shallowly flooded areas (Jimenez *et al*., 2009).It is necessary to consider that areas below the targeted water level, but not directly connected to the sea could be affected by other processes such as an increase in salt content in the soil and water.

Based on the previous discussion we believe that the biggest losses will be attributed to the economic part. Because there is no plan to adapt the current form of exploitation to future changes in the environment. The losses due to the diminishing of agricultural growth area will be irreversible. On the environmental side, some habitats are lost but others that now have a smaller presence could increase or regain their dominance in the delta (lagoons, brackish areas), therefore this will not be considered a loss, but an ecological profit.

The ability to determine the flood-prone areas in a long-term, gives us the tool to prevent, or take the necessary actions to reduce the impact of sea level rise.

According to Klein *et al*., (1999) some actions can be undertaken in coastal management faced to sea level rise, the first "classical" is the Total Protection (Hold the line), at all costs trying to keep the current use. The second would be to turn to a more sustainable approach: "Adaptation" that considers the gradual adaptation to the new profile of the coast. The third action corresponds to not taking any actions.

In this case there are economical and ecological considerations to be taken into account before conduct any of the two possible actions. At first “Hold the line” represent the almost total change of the coast profile of the Ebro delta, for its protection and almost a total isolation of the delta because, as we see before, if we close the channels, the floods are reduced or controlled. This implies a loss of the natural function of the costal lagoons and therefore a drastic change in the delta area. Besides that have to be consider a pumping system or similar that allows the output of the water from rice fields.

“Hold the line” for the Ebro delta area represents a strong investment in dykes and pumping systems that end making the delta in an artificial area dependent entirely of the artificial systems. The idea of Hold the Line is associated with the conservation of large areas of production of rice in the delta area and the way of life associated. But the rice crops will eventually suffer from high salt stress and the cost-benefit of maintenance using this method will not positive. Therefore costs of maintaining the Delta without flooding (construction of dykes, pumping systems, etc.) will be greater than the economic benefits of rice.

We consider that the “Adaptation” is the most plausible option to this area, trying to adjust and protect the delta. But not by holding the line, but by promoting the regeneration of old lagoons, and looking for a new sediment supply that will help the delta alleviate the natural subsidence. This means the loss of cropland and the increase of brackish creeks (lagoons, riparian buffer). But this loss, will allow long-term management and preparation of the delta and a gradual “Adaptation”. Also the control of channels by dams and pumps, not allowing the entry of water, would be another approach. The recovery of natural areas, could lead to changes in which the delta is exploited, migrating from a high impact productive use to a low-impact use.

From an economic point of view, the losses due to rising sea levels will be big due to the loss of large areas of cultivation, given that the delta presents high cultivation exploitation which has been the main economical axis on the zone. These losses range from 23% of the area, equivalent to losing an average production of 34,000 tons/year to 52% of cultivated area (77,000 tons/year). Unless a proper strategy for ‘Hold the line’ is implemented on the long term, the cost associated to maintain the Delta without flooding with a good level of rice production, could be excessive as this would involve the construction and maintenance of construction of dykes and pumping systems to maintain the flood under control.

From an ecological point of view, we can not consider the flood areas as losses as it would increase the marsh area and coastal lagoons, this coupled with the decline in cultivation, would improve the surrounding environment. Vegetation in coastal lagoons and freshwater inland wetlands will be primarily influenced by increased frequency of flooding by the sea (due to higher salinity levels, Valdemoro *et al*., 2007). Of the submerged lagoon vegetations, freshwater types may disappear and the brackish (Ruppia-dominated) vegetation type may expand in coverage (Menendez *et al*., 2002). Coops & van Geest (200?) conclude that even a low rise of sea level, can result in "the drowning" of the most low-elevation habitats and a further salinisation of the lagoons. So we could speak of an ecological benefit, when a scarce habitat in the Catalan coast would recover or increase.

It is important to note that in either case, due to the reduction in the contribution of the river water, the saltwater intrusion has increased. This is mainly due to the reduction of the water volume that supplies the delta, as the water level decreases increases the salt intrusion in the terrestrial area and the salt wedge at the river side. This problem in addition with the increased frequency of flooding by the sea could increase even more the levels of salinity of the soil, leading to rice farming to become economically unfeasible.

6.3 Flooding due to Storms

In chapter 5.4 a FHM framework for coastal storms was described and potential flooding areas for the La Marquesa in Delta Ebro were calculated. These areas shows a variation between 17 ha for a 10 years of return storm, to 475 ha for a 500 year storm. It is necessary to take into account some consideration in the methodologies that we used in this framework.

In this work for the statistical analysis in the determination of return times, the Response Based Approach was selected. We believe that this is the most objective statistical approach since any joint probability of events assumptions and simplifications are not made. Considering the Response Based Approach we select a value that associates the runup and the coastal erosion which is proportional to the overtopping. Overtopping corresponds to the final response of the behavior in which we are interested. The only problem associated with this selection, is that we can not directly obtain the values of wave height and wave period required for internal calculations, as well as for the construction of the simulated storm climate. This problem was solved by associating the final values of the analysis with storms databases.

The coastal response to storms is an important part of the framework for FHM at this scale, so the right selection of a beach profile or how to evaluate the beach response is a basic part in the final results. In this work three approaches to evaluate this element of the framework were tested.

We can say that including the behavior of the beach in subsequent calculations as runup and overtopping is basic; the use of a model of this response allows us to work more accurately. In our case we use the SBEACH, which does not exclude the use of newer models or more detailed, for instance XBEACH (Roelvink *et al*., 2008). In case the user has no access to a model, the use of an envelope of the beach can be selected alternatively. Thus give as result a range of possible floods, from which areas of risk associated with a range of uncertainty may be identified. Finally the use of an average beach profile could be proposed. Variations between this methodology and the first are about 3.5 times in overtopping volume and 1.8 in flooded areas.

The results show that the uncertainty introduced in the analysis due to the use of a single profile to represent the entire coastal stretch should be much lower than the associated to the selection of the configuration profile of such. Moreover, it also has to be stressed that for the same conditions, the uncertainty in overtopping rates will be larger than in the period of exceedence for overtopping.

The inclusion of the beach response during the event, results in an increase of overtopping rates. So the volume of floodwater entering the coastal plain would be significantly underestimated (almost 4 times). Based on the above the coastal manager could select the best choice inputs and know the expected variability.

It is important to consider that changes in the profile due to coastal storms do not occur only in the visible part of the beach. In some small storms, the major changes take place in the submerged part of the beach (inshore). These changes, in the inshore which may be considered minimal, can induce changes in the slope, which would affect the attack of waves and this change the range of the runup (this calculation is sensible to variation in the slope) and therefore cause variations in the final overtopping.

When the flooded area was determined by the mathematical model, a principal part for the final results (as mentioned above in the RSLR discussion) is the selection of the grid resolution of the DEM. We selected a high resolution grid, to avoid hide or erase the trace of the large number of existing channels and small dykes in our study area. Also a very small time step was selected, to avoid instability problems in the mathematical model. Bates

(2000, 2003, and 2005), recommends the use of grids of 50 to 100 meters which allow a high-speed and low computational cost. Considering the type of terrain where Bates has worked, these resolutions are allowed, but in our case the grid size can cause changes in three times the flood area.

As mentioned in chapter 5.4.3, the highest affectation for floods are in the habitats such as croplands, dunes, lagoons and ripparian buffer. Most of those areas are located near to the coast.

This is a usual phenomenon, so the flood in lagoons and ripparian buffer do not produce long-term problems for these habitats. As these habitats can resist, or need for their natural cycles, a periodic flood.

The cropland is the most affected habitat by the flood given the broad extension. As an artificial habitat that depends entirely from man for its maintenance, the resilience which can provide to storms is minimal, but also the actions that can take for recovery area could be faster (Thus, rice producers wash the rice fields affected by overwash after the storm passed with a large amount of fresh water to decrease the salinity of the soil. With this, the land is ready again to be used for rice production, (Jimenez *et al*., 2009)).

The final result is a range map of flood hazard areas for a given return time. This information allows management and planning for the delta area on safety levels, which depends of the return time considered.

The possibility of conducting a cross between scenarios of RSLR and storms was raised, but because the area presents a very low-lying coast as seen in chapter 5.3, only considering RSLR this area was flooded for any RSLR exceeding 35 cm, so the storms would not affect the area. The only possible variation is that in a scenario of permanent inundation, the storms can impact more inward and affect also the flooded area.

When using ecological values or ecological services, it must be considered that the values are related to the provision given by the environment. Only if a total loss of the habitat exist, could be the proposed value considered as a loss. However, this scale was used for measurement since we consider necessary to give a less abstract view of the damage.

If we can account the “losses” in an economy mode, we can give weight to the potential damage to the environment, as well as having a way of making comparisons with other places. We could compare with the losses in the Ebro Delta by RSLR and say if they are very high compared with those given to example in the Mississippi or the Nile. On the other hand, if we can apply these weights to the losses by storms, this will help us to compare the values that are trying to preserve with the possible actions to prevent their loss (Cost-Benefit). Also, these values give us the chance to calculate an annual average damage curve that indicates the potential damage expected over a year, and is also a useful mean to compare the damages between the different scenarios or return periods.

The cropland is leading by a wide margin the list of economic losses. This is mainly due to the high intervention and reliance on the human hand and their low levels of resilience. Moreover, habitats in the area, being “native” are able to withstand the storms with a low level of damage. The losses due to flooding of the cropland could be considered as tangible losses, because its damage or loss is directly associated with losses in rice production.

There is a need to emphasize that the biggest loss would occur only in the case that the storm impact on the coast during a period in which the rice is planted (at present, storms usually occur out of the rice season).

The development of a vulnerability indicator to coastal erosion, help us to establish areas along the coast, where erosion due to storms will be able to remove the protection given by the beach.

The loss of the beach protection can result in coastal areas that serve as entry or initiation of flooding in backbeach. These areas would be identified by a high or very high level of VuCEES.

The inclusion of variation over time within VuCEES gives us the possibility to identify areas that can easily lose their protection (for the erosion), and to show more changes in their morphology. This information helps us to select the areas that have to be taken into account because they can influence the long-term flooding (increase of entry points or starting areas of flooding, and therefore an increase in the flooded area).

Determining how the flood varies over time affected by beach erosion is not part of this study hence it has been recommended for future works.

We can establish an approximate relationship between the kilometer of beaches with high vulnerability and the total area flooded, thereby increasing the beaches with high to very high vulnerability to erosion (this one given in principle by the measured storm), will increase the flooded area in the backbeach. When the protection of the coast is reduced there are more entry points for overwash, and then more area could be flooded.

6.4 Proposed Management on the Delta

The Spanish Ministry of Environment aims to undertake actions to minimize flooding in the coastal zone of the Ebro Delta. It plans the construction of a dyke-wall along the coastal zone of the Alfacs Bay, which seeks to prevent or reduce the effects of climate change in the area. This barrier does not close completely the communication between the delta and bays, because the gateways and channels allow the exchange of water. The proposed dike-wall would be locate in the shoreline delta and would be six meters wide by two meters high, with a pedestrian lane and a bicycle lane.

The analysis done in this thesis help us to assess the behavior of this area under different scenarios and the identification of problems and responses of the coast. First we can understand these actions based on the statements of those in charge, as a Hold the line ("These works will allow us to preserve the Delta as we know it today," Jordi Galofre in El Pais 2009), that allow continuation of the activities within the delta unchanged. (See also figure 6.1)

In an analysis of the proposal plan, we can say that the construction of a dyke-wall cannot serve to prevent flooding in the crop areas surrounding the lagoons, if the channels which link the lagoons with the Bays (Alfacs and Fangar) remain open. The flood water does not come only from the Bay areas, but also from the channels connected with the sea, for that reason it will be advisable to have them under control or closed (figure 6.2).

Hold the line implies to close the coast and the complete blockade of channels to ensure the conservation of the delta as it is known today, and stop the floods by RSLR or storm surge, but based on the baselines mentioned above, this is the action which would less recommend.

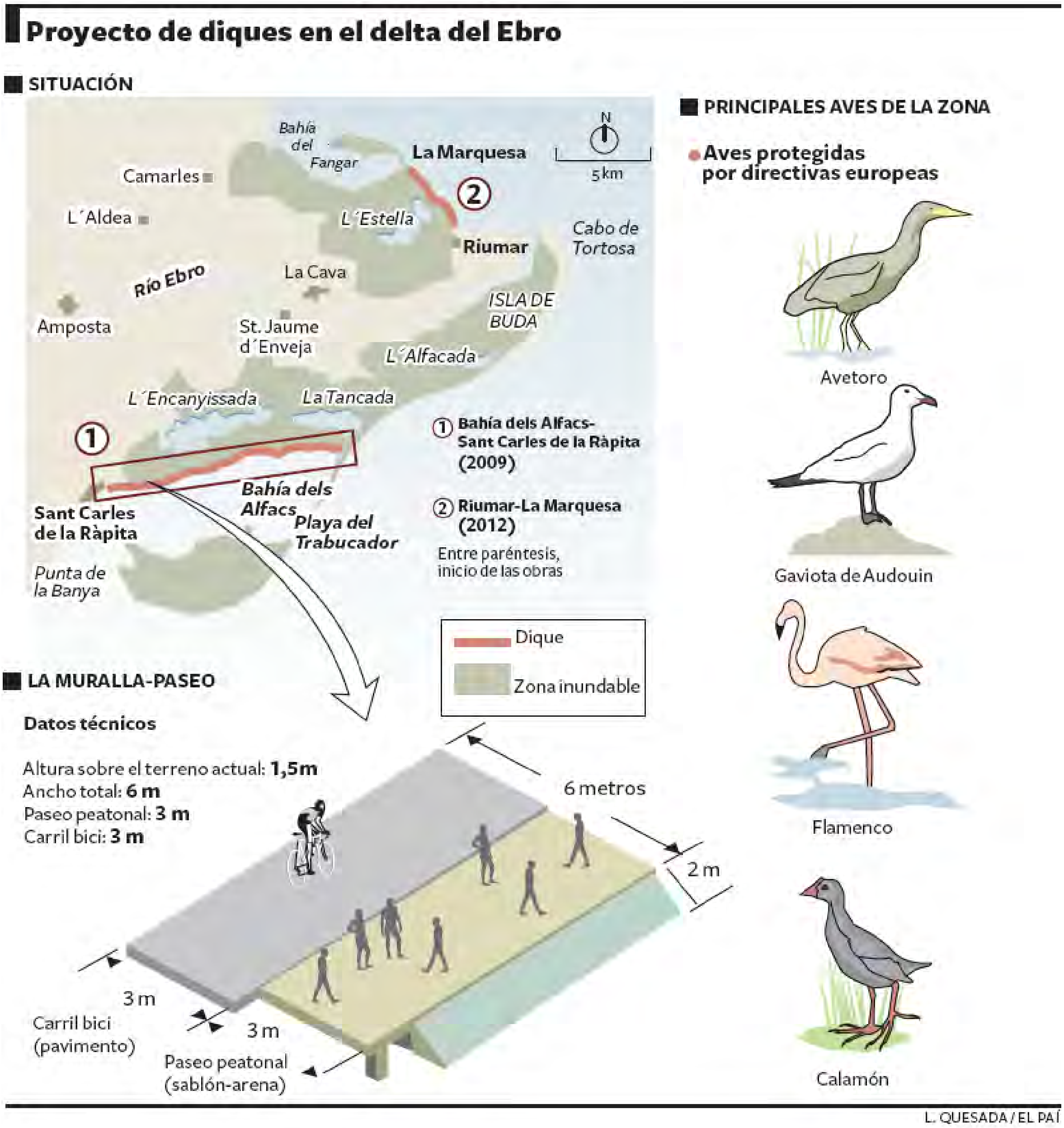

Figure 6.1 Dykes project for the Ebro delta.
From El Pais edition of 27/07/2009

Figure 6.2. Figure 6.2. Flooded areas in a 55cm RSLR scenario, with the dykes schematized in the figure above. Changes in the beaches and Trabucador, look increased due to the scale of the figure. Flooded areas within the delta are due to the existence of channels that connect with the bays.

Within this line of thinking, could be recommend the construction of a dyke-wall around the lagoons, which allows the communication with the sea, and consequently a healthy ecosystem. This kind of dyke allows the coexistence of the lagoons with the cropland and would prevent the water to pass in these growing areas (figure 6.3). This plan could keep from the flood about 7000 ha of the delta. But can control the salinisation of the delta by salt water intrusion, and the rice farming will be eventually become economically unfeasible.

Figure 6.3. Flooded areas in a 55cm RSLR scenario, with the dykes around the contour of the lagoons, and the edge of the delta, as recommended in this work.

For the Marquesa area, the proposed dyke would meet its goal to eliminate or reduce flood damages. The construction of the dyke should involve a change in the landuse, changing the croplands in front of the dyke for natural areas. That means no more losses associated to cropland in the backbeach in case of flood. The flood in the backbeach could be confined in a more controlled area without risk of damage. As the dyke would prevent flooding of the land located at the back, the losses associated with flood would be eliminated (Figure 6.4).

Figure 6.4. Flood in La Marquesa, for a 500 year return period storm, considering the dykes proposed.

7. Conclusions

We have the duty of formulating, of summarizing, and of communicating our conclusions, in intelligible form, in recognition of the right of other free minds to utilize them in making their own decisions.

Ronald Fisher

A methodological framework for Flood Hazard Mapping and Damage Assessment to Coastal Storms was proposed in this thesis in two working scales: A long-term scale related to Relative Sea-Level Rise, and an episodic/extreme scale related to storm events. The incorporation of coastal response to storm events in this framework is a basic part of this proposal. This methodological framework was applied on the Delta Ebro.

Below the main conclusions are outlined into two groups, those relating to the proposed methodology and those associated with their application in the study area.

Methodological conclusions

The morphodynamic response of the coast to storms is a basic component in the Flood Hazard Mapping for sandy coasts, or those in which there are no hard protections. Including the behavior of the beach is essential for the subsequent calculations such as runup and overtopping, enabling a more precise calculation of overwash volumes that can flood the backbeach. Taking into account this feature, the calculated flooded area could be larger when compared to the one obtained by using other methodologies that consider a static beach.

In the cases where this approach cannot be applied, it is suggested then to use an envelope beach, knowing in advance that this approach give as result, a range of potential flood areas. Alternatively, applying the classical methodology, consisting in the use of an average beach profile and considering a non response beach, is also plausible. Anyway the variations in the results due to the selected approach have to be taken into account, and also their associated uncertainty.

When working in an area such as the Ebro Delta a high resolution Digital Elevation Model is essential, regardless of the scale of the work. A lower-resolution Digital Elevation Model would hide or erase details, which could lead to variations in several orders of magnitude in the flood area. As an example, our study area presents a large number of small dykes and canals which are associated with agriculture, coupled with the extremely flat topography, which could be easily hidden when applying a low resolution DEM.

The use of Response Approach to define the Extreme Climate is recommended. Because its formulation minimizes the variations associated with the processes, and generates more conservative results towards safety. If an Event method (Joint Probability) is used, it is advisable to know the variation associated to the process within these elements, since the results produce significant variations.

The use of ecological services help us to evaluate the damage of the coastal flooding. These values allow us to give an assessment weight for further evaluation. Is necessary the development of the damage curves for the study area.

Ebro Delta Conclusions

A low-lying topography makes the Ebro delta a highly sensitive area to Sea Level Rise and flooding associated with coastal storms.

In the case of a Relative Sea Level Rise, a rise of 35 cm in the sea-level can cause a flooding of 30% (9,916 ha) of the delta area, and in the most serious case of 75 cm, which could be translated in up to 70% (18,837 ha).

Inundated areas by coastal storms (for the north area of the delta) have variations from 17 ha for 10 years of return period storm to 475 ha for a 500-year extreme event. These zones are usually connected with coastal areas where the protection for the beach is very low or zero. These regions are the most affected for the flood by storms but on the other hand it is assumed that almost all habitats (due to its location and characteristics), can deal with the flood without problems.

For the two proposed scales, the habitat with major susceptibility to floods is the cropland (from 23% to 53% of their area on RSLR, and more than 400 ha on storm case). In the case of Relative Sea Level Rise scenario, this is due to their large extension along the delta whereas in the storm floods scenario, this is mainly due to their low resistance compared to other habitats, and also to its location near the coast.

The economic losses in the Ebro Delta are associated with crop fields, which may affect directly the local economy. Damage to the environment was not taken into account due to the fact that the coastal environment can have a high resilience in response to coastal events. Due to the lack of damage curves (as it is implemented in other countries) we can not make a directly linkage of economic value with the ecological loss.

'Adaptation' is considered the best alternative for the delta adjustment. Assuming that there is an absence of a contribution of sediment, which helps to alleviate subsidence and sea level rise, the Delta Adaptation to future changes has to admit losses in area or changes in land use.

There is a need to emphasize that the closing of channels that connect the delta with the open sea or bays, reduces significantly the flooded area (more than 30%, in some cases). This implies the loss of connectivity of the lagoons and consequently we consider that there would be changes in physical and ecological levels, which discourage this type of action.

As a final step, we give the "How to" approach of our framework for Flood Hazard Mapping as a DIY (Do it yourself) one.

- Define the origin of your flood (RSLR, storms)
- Obtain sea level corresponding to the selected scale.
  In the case of RSLR: Relative sea level rise over time.
  In the case of storm: storm climate defined based on sea levels (swell, storm surge, tides, etc)
- In the case of a storm event, determine the morphodynamic response of the beach to the selected events
- Calculate the water volumes that can flood your area (storm case).
- Select a DEM with high resolution.
- Map the floods in the area with the help of GIS or numerical models
- Calculate losses and damages
- Elaborate flood maps
- Have a feedback of the information with the stakeholders

8. References

I libri si rispettano usandoli,
non lasciandoli stare.

Umberto Eco

Alvarado-Aguilar, D. & Jiménez, J.A. 2007. A pseudo-dynamic approach to Coastal Flood Hazard Mapping. Proc. CoastGIS 2007, Santander.

Altaba, C.R., 1990. The last known population of the freshwaters mussel Margaritifera auricularia (Bivalvia, Unionoida): a conservation priority. Biol. Conserv. 52, 271–286.

Aparicio, E., Vargas, M.J., Olmo, J.P., Sostoa, A., 2000. Decline of native freshwater fishes in a Mediterranenan watershed on the Iberian Peninsula: a quantitative assessment. Environ. Biol. Fishes 59, 11–19

Araujo, R., Ramos, M.A., 2000. Status and conservation of the giant European freshwater pearl mussel Margaritifera auricularia. Biol. Conserv. 96 (2), 233–239.

Bates, P.D. & De Roo, A.P.J. 2000. A simple raster-based model for floodplain inundation. Journal of Hydrology 236: 54-77.

Bates, P.D., Horritt, M.S., Aronica, G., Beven, K., 2004. Bayesian updating of flood inundation likelihoods conditioned on inundation extent data. Hydrological Processes 18, 3347–3370

Bates, P.D., Dawson, R.J., Hall, J.W., Horritt, M.S., Nicholls, R.J., Wicks, J. & Hassan, M.A.A.M. 2005. Simplified two-dimensional numerical modeling of coastal flooding and example applications. Coastal Engineering 52: 793-810.

Battjes, J.A., Gerritsen, J.A., 2002. Coastal modelling for flood defence. Philosophical Transactions of the Royal Society of London Series A, Mathematical and Physical Sciences 360, 1461–1475.

Bakkes J.A., G.J. Van den Born, J.C. Helder, R.J. Swart, C.W. Hope, J.D.E. Parker .1994. An Overview of Environmental Indicators: State of the Art and Perspectives.

Benavente, J., Del Río, L., Gracia, F. J., & Martínez-del-Pozo, J. A. 2006 Coastal flooding hazard related to storms and coastal evolution in Valdelagrana spit (Cadiz Bay Natural Park, SW Spain). Continental Shelf Research, 26, 1061-1076.

Berghan, T. and S. Westlake. 2001. Floodplain Management Planning Guidelines: Current Thinking and Practice in New Zealand. Opus Consulting in conjunction with the Sustainable Management Fund, Ministry for the Environment, Wellington.

Besley, P. 1999. “Overtopping of Seawalls: Design and Assessment Manual”, R&D Technical Report W178, HR Wallingford.

Boruff, B. J., Emrich, C., Cutter, S. L., 2005. Erosion hazard vulnerability of US coastal counties. Journal of Coastal Research. 21, 932-942.

Bradbrook K. 2006. JFLOW: a multiscale two-dimensional dynamic flood model.Water and Environment Journal 20, 79–86.

Brenner, J. 2007. Valuation of ecosystem services in the Catalan coastal zone. Ph D. Thesis. Universitat Politécnica de Catalunya, Barcelona 186 pp.

British Standards Institution, 1981. BS3680: Methods of Measurement of Liquid Flow in Open Channels, Weirs and Flumes. BSI, London.

Bruun, P., 1962. Sea-level rise as a cause of shore erosion. Journal of Waterways and Harbours, Division WW1, 117-130.

Callaghan, D.P., Nielsen, P., Short, A., and Ranasinghe, R., 2008, Statistical simulation of wave climate and extreme beach erosion: Coastal Engineering, v. 55, p. 375-390.

Camp, J., Romero, J., Pérez, M., Vidal, M., Delgado, M., Martinez, A., 1991. Production–consumption budget in an estuarine bay: how anoxia is prevented in a forced system. Oecol. Aquat. 10, 145–152.

Cañizares, R. & Irish, J.L. 2008. Simulation of storm-induced barrier island morphodynamics and flooding. Coastal Engineering, doi:10.1016/j.coastaleng. 2008.04.006.

Cendrero -Uceda A., D.W. Fischer.1997. A procedure for Assessing the Environmental Quality of Coastal Areas for Planning and Management. Journal of Coastal Research, 13(3), 723-744.

Comín, F.A., Menéndez, M., Lucena, J.R., 1990. Proposals for macrophyte recovery in eutrophic coastal lagoons. Hydrobiologia 200/201, 427–436

CoastView Consortium. 2002. CoastView Work Programme

Cheung, K.F., Phadke, A.C., Wei, Y., Rojas, R., Douyere, Y.J.M., Martino, C.D., Houston, S.H., Liu, P.L.F., Lynett, P.J., Dodd, N., Liao, S., Nakazaki, E., 2003. Modeling of storm-induced coastal flooding for emergency management. Ocean Engineering 30, 1353–1386.

Chow, Tzee Kiu Edwin, 2005. The Role of Scale and Spatial Heterogeneity in Modeling Hydrologic Response, Ph.D Dissertation, University of South Carolina.

Clarke, K. C., 1997, Getting Started With Geographic Information Systems (Upper Saddle River, NJ: Prentice Hall).

Colby, J. D., Mulcahy, K. A., and Wang, Y.: 2000, Modelling flooding extent from Hurricane Floyd in the coastal plains of North Carolina, Environmental Hazards 2, 157–168

Cowell P.J., T.Q. Zeng, 2003. Integrating Uncertainty Theories with GIS for Modeling Coastal Hazards of Climate Change. Marine Geodesy, 26:5–18,

Day, J.W., Pont, D., Hensel, P., Ibáñez, C., 1995. Impacts of sea level rise on deltas in the Gulf of Mexico and the Mediterranean: the importance of pulsing events to sustainability. Estuaries 18, 636–647.

Day, J. W., Maltby, E., Ibáñez, C. 2006. River basin management and delta sustainability: A commentary on the Ebro Delta and the Spanish National Hydrological Plan. Ecological Engineering, 26, 85-99.

Divoky, D., McDougal, W. G 2006. Response-Based Coastal Flood Analysis. . Proceedings 30th international Conference Coastal Engineering, ASCE 5291-5301

Elvira, B., 1995. Conservation status of endemic freshwater fish in Spain. Biol. Conserv. 72, 129–136.

ESRI, 1999. ArcView (ver. 3.2). Environmental Systems Research Institute, Inc., Redlands, California

EUROSION 2004.Living with coastal erosion in Europe: Sediment and Space for Sustainability Part VII –Guidance document for quick hazard assessment of coastal erosion and associated flooding

Eykhoff P. System identification: parameter and state estimation. Chichester, England:

Fassardi, C. 2006. The Definition of Wave Setup and Runup Using a Response Based Approach. Proceedings 30th international Conference Coastal Engineering, ASCE. 1800-1811

Federal Emergency Management Agency (FEMA). 2003 (April). Guidelines and Specifications for Flood Hazard Mapping Partners. Appendix D: Guidance for Coastal Flooding Analyses and Mapping.

Federal Emergency Management Agency (FEMA). 2005. Wave runup and Overtopping. FEMA Coastal Flood Hazard Analysis and Mapping Guidelines Focused Study Report. http://www.fema.gov/pdf/fhm/frm_p1wave2.pdf.

Flather R.A. 1994. A Storm Surge Prediction Model for the Northern Bay of Bengal with Application to the Cyclone Disaster In April 1991. Journal of Physical Oceanography, Vol 24 172-190.

Flood Risk Directive. Directive 2007/60/EC of the European Parliament and of the Council 23 October 2007 on the assessment and management of flood risks

Forés, E., 1989. Ricefields as filters. Arch. Hydrobiol. 116, 517–527.

Forés, E., 1992. Nutrient loading and drainage channel response in a ricefield system. Hydrobiologia 230, 193–200.

Gallopín, G.C. 1997. Indicators and their use: information for decision-making. In: Moldan, B. and Billharz, D. (eds.), Sustainability indicators. Report of the project on indicators of sustainable development. SCOPE, Wiley.

Galofré, J. A. Sánchez-Arcilla, J. Jiménez, and M. Garcia. A note on fans conclusions: from research analyses to management implications. Continental Shelf Research, 22:379–385, 2002.

Galy, G.M., and Sanders, S.A., 2000, Using SAR imagery for flood modeling, RGS-IBG Annual Conference: University of Sussex.

Gambolati G, Teatini P, Gonella M 2002. GIS simulations of the inundation risk in the coastal lowlands of the Northern Adriatic Sea. Mathematical and Computer Modeling 35(9–10):963–972

Generalitat de Catalunya. 2004. Programa de actuaciones urgentes en las zonas costeras del Delta del Ebro afectadas por los temporales. Departament de Medi Ambient i Habitatge, Barcelona.

Goda, Y. 1971. Expected rate of Irregular wave overtopping of seawalls. Coastal Engineering in Japan, Vol. 14, 1971.

Goda, Y. 1985. Random Seas and Design of Maritime Structures. University of Tokyo Press. Tokyo, Japan.

Guedes-Soares C, Carretero JC, Weisse R, Alvarez E .2002. A 40 years hindcast of wind, sea-level and waves in European waters. Proceedings of OMAE 2002: 21st international conference on offshore mechanics and arctic engineering. Oslo, Norway

Guillén, J., Palanques, A., 1992. Sediment dynamics and hydrodynamics in the lower course of a river highly regulated by dams: the Ebro River. Sedimentology 39, 567–579.

Gutiérrez-Espeleta, E.E. 1998. Designing environmental indicators for decision makers. In: Statistics for Economic and Social Developments, INIEGI, México.

Guza, R.T., Thornton, E.B., 1982. Swash oscillations on a natural beach. Journal of Geophysical Research 87 (C1), 483–491

Holman, R.A., Bowen, A.J., 1984. Longshore structure of infragravity wave motions. Journal of Geophysical Research 89 (C4), 6446–6452.

Horritt, M.S. and Bates, P.D., 2001b. Effects of spatial resolution on a raster based model of flood flow. Journal of Hydrology, 253, 239-249.

Howd, P.A., Oltman-Shay, J., Holman, R.A., 1991. Wave variance partitioning in the trough of a barred beach. Journal of Geophysical Research 96 (C7), 12781–12795.

Hubbert G.D. & McInnes K.L. 1999. A storm surge model for coastal planning and impact studies. Journal of Coastal Research, 15 (1), 168-185.

Hunter, N.M., Horritt, M.S., Bates, P.D., Wilson, M.D., Werner, M.G.F., 2005. An adaptive time step solution for raster-based storage cell modeling of floodplain inundation. Advances in Water Resources 28, 975–991.

Ibáñez, C., 2000. Integrated management in the Special Protection Area of the Ebro Delta: implications of rice cultivation for birds. In: Proceedings of the Conference on the Council Directive on the Conservation of Wild Birds, Comisión Europea, pp. 98–103.

Ibáñez, C., Canicio, A., Day, J.W., Curcó, A., 1997a. Morphologic development, relative sea level rise and sustainible management of water and sediment in the Ebre Delta, Spain. J. Coastal Conserv. 3, 191–202.

Ibáñez, C., Curcó, A., Day, J.W., Prat, N., 2000. Structure and productivity of microtidal Mediterranean coastal marshes. In:Weinstein, M.P., Kreeger, D.A. (Eds.), Concepts and Controversies in Tidal Marsh Ecology. Dordrecht, Kluwer.

Ibáñez, C., Pont, D., Prat, N., 1997b. Characterization of the Ebre and Rhone estuaries: a basis for defining and classifying salt-wedge estuaries. Limnol. Oceanogr. 42 (1), 89–101.

Ibáñez, C., Prat, N., 2003. The Environmenal Impact of the Spanish National Hydrological Plan on the Lower Ebro River and Delta. Water Res. Dev. 19 (3), 485–500

Ibáñez, C., Prat, N., Canicio, A., 1996. Changes in the hydrology and sediment transport produced by large dams on the lower Ebro river and its estuary. Regul. Rivers 12, 51–62.

Ibáñez, C., Prat, N., Canicio, A., Curcó, A., 1999a. El Delta del Ebro, un sistema amenazado. Editorial Bakeaz, Bilbao.

Ibáñez, C., Rodrigues-Capitulo, A., Prat, N., 1995. The combined impacts of river regulation and eutrophication on the dynamics of the salt wedge and the ecology of the lower Ebro River. In: Fergursony, A., Harper, D. (Eds.), Ecological Basis for River Management. John Wiley & Sons, pp. 105–114.

Ibáñez, C., Saldaña, J., Prat, N., 1999b. A model to determine the advective circulation in a three layer, sat-wedge estuary: application to the Ebre River Estuary. Estuarine, Coastal, Shelf Sci. 48, 271–279.

IPCC, 2001. Climate change 2001 : synthesis report. A contribution of working groups I, II and III to the Third Assesment Report of the Intergovernmental Panel on Climate Change.

IPCC. 2007a. Summary for Policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL. (eds) Climate change 2007: The Physical Science Basis.Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK and New York. 996 p. Available from: www.ipcc.ch/ipccreports/ar4-wg1.htm (30 June 2008).

IPCC. 2007b. Summary for Policymakers. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE. (eds.) Climate change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. . Cambridge University Press: Cambridge, UK. 976 p. Available from: www.ipcc.ch/ipccreports/ar4-wg2.htm (30 June 2008).

IPCC. 2007c. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp. Available from: www.ipcc.ch/ipccreports/ar4-wg1.htm (30 June 2008).

Jiménez, J.A., Sánchez-Arcilla, A., 1993. Medium-term coastal response at the Ebro delta, Spain. Mar. Geol. 114, 105–118.

Jiménez J.A., Sánchez-Arcilla, A., Valdemoro, H.I., Gracia, V. & Nieto, F. 1997. Processes reshaping the Ebro delta. Marine Geology 144: 59-79.

Jiménez J. A. & M. van Koningsveld. 2002. Coastal State Indicators a Bridge between Science and Coastal Management. Coastal indicators Report. Technical Report. Coast View

Jiménez, J.A. 2005. Effects of storm impacts in the Ebro delta coast. FLOODSite Integrated Flood Risk Analysis and Management Methodologies. www.floodsite.net

Jiménez, J.A., Sallenger, A. and Fauver, L. (2006). Sediment transport and barrier island changes during massive overwash events. Proc. 30th ICCE, ASCE, 2870-2879.

Jiménez, J.A. 2008. Contributing to European flood hazard atlas. Executive Summary. FLOODSite Integrated Flood Risk Analysis and Management Methodologies. www.floodsite.net

Jiménez, J.A., Valdemoro, H.I., Bosom, E., Gracia, V. and Galofré, J. 2009. Decadal-scale variations in storminess and coastal hazards in the Ebro delta. Marine Geology, (in review).

Klein R. J.T., R.J. Nicholls, N. Mimura. 1999. Coastal Adaptation to Climate Change: Can the IPCC Technical Guidelines be applied? Journal Mitigation and Adaptation Strategies for Global Change. V3 N3-4, 1573-1596

Kobayashi N., Tega Y. and Hancock M.W. 1996. Wave reflection and overwash of dunes. Journal of Waterway, Port, Coastal and Ocean Engineering. ASCE, 122(3), 150-153.

Kraus, N.C. & Hayashi, K. 2005. Numerical morphological model of barrier island breaching. Proc. 29th ICCE, ASCE, 2120–2132.

Kurtz, J.C., Jackson, L.E. and Fisher, W.S. 2001. Strategies for evaluating indicators based on guidelines from the Environmental Protection Agency's Office of Research and Development. Ecological Indicators, 1, 49-60.

Larson M. & Kraus N.C. 1989. SBEACH: Numerical Model for Simulating Storm-Induced Beach Change, CERC-89-9, US Army Corps of Engineers, Vicksburg.

Martin K St. 1995.Applications in Coastal Zone Research and Management. Explorations in Geographical Information Systems Technology. Volume 3. United Nations Institute for Training and Research. Switzerland.

Martínez-Vilalta, A., 1995. The rice fields of the Ebro Delta. In: Morillo, C., González, J.L. (Eds.), Management of Mediterranean Wetlands. Ministerio de Medio Ambiente, Madrid.

Martínez-Vilalta, A., Giró, F., 1996. Case Study 3: Spain. The Ebro Delta. In: Hails, A.J. (Ed.),Wetlands, Biodiversity and the Ramsar Convention. Ramsar Convention Bureau and Ministry of Environment and Forests, India, pp. 103–106.

McFadden, L., Nicholls, R.J., Penning-Rowsell, E. (Eds.), 2006. Managing coastal vulnerability. Elsevier Science.

Mendoza Ponce E.T. 2008. Coastal vulnerability to Storms in the Catalan Coast. Ph D. Thesis. Universitat Politécnica de Catalunya, Barcelona 190 pp.

Menéndez, M., Comín, F.A., 2000. Spring and summer proliferation of floating macroalgae in a Mediterranean coastal lagoon (Tancada lagoon, Ebro Delta, NE Spain). Estuarine, Coastal, Shelf Sci. 51, 215–226.

Menéndez, M., O. Hernández & F. A. Comín, 2002. Spatial distribution and ecophysiological characteristics of macrophytes in a Mediterranean Coastal Lagoon. Estuarine, Coastal and Shelf Science 55: 403–413.

Meehl, G. A., et al. 2007. Global climate projections, in Climate Change 2007: The Physical Science Basis, edited by S. Solomon et al., pp. 747–845, Cambridge Univ. Press, Cambridge, U.K.

Messner F., E. Penning-Rowsell, C. Green, V.Meyer, S. Tunstall, A. van der Veen 2006. Guidelines for Socio-economic Flood Damage Evaluation. FLOODSite Integrated Flood Risk Analysis and Management Methodologies. www.floodsite.net

Minson 2006. Flood Damage Assessment. Whangarei CBD Flood Management Study. Whangarei District Council. New Zealand.

Morton R.A. 2002. Factor Controlling Storm Impacts on Coastal Barriers and Beaches – A preliminary Basis for Near Real-time Forecasting. Journal of Coastal Research 18: 486-501.

Muñoz, I., Prat, N., 1989. The effects of regulation on the lower Ebro River (N.E. Spain). Regul. Rivers 3, 345–354.

Nielsen O, Roberts S, Gray D, McPherson A & Hitchman A. 2005. Hydrodynamic modeling of coastal inundation. MODSIM 2005 International Congress on Modeling and Simulation, Modelling and Simulation Society of Australian and New Zealand, 518–523. www.mssanz.org.au/modsim05/papers/nielsen.pdf

Nicholls, R. J., and J. Branson. 1998. Coastal resilience and planning for an uncertain future: An introduction. The Geographical Journal 164(3):255–258.

Norse E.A. (1994). Global Marine Biological Diversity. Island Press, Washington, D.C.

OECD (Organization for Economic Co-operation and Development) (1994). Environmental Indicators - Indicateurs D'environnement. Head of Publications Service OECD. Paris Francia.

Orellana A. Estudi de l'afluéncia turistica al delta de l'ebre. Soldó – informatiu del parc natural del delta de l'Ebre, 25:38, 2005.

Ott, W.R. (1978). Environmental Indices Theory and Practice (Ann Arbor, MI, Ann Arbor Science).

Owen M.W. 1980. Desing of seawalls allowing for wave overtopping. HR Wallingford, Report EX 924.

Parson E, Burkett V, Fisher-Vanden K, Keith D, Mearns L, Pitcher H, Rosenzweig C, Webster M (2007) Global change scenarios: their development and use. A report by the U.S. climate change science program and the subcommittee on global change science research. Department of energy, Office of Biological Environmental Research, p 102

M. Peng, L. Xie and L.J. Pietrafesa 2004. A numerical study of storm surge and inundation in the Croatan–Albemarle–Pamlico Estuary System. Estuarine, Coastal Shelf Sci. 59 pp. 121–137

Prat, N., Muñoz, I., Camp, J., Comin, F.A., Lucena, J.R., Romero, J., Vidal, M., 1988. Seasonal changes in particulate organic carbon and nitrogen in the river and drainage channels of the Ebro Delta (N.E. Spain). Verh. Int. Verein. Limnol. 23, 1344–1349.

Postel, S.L., Morrison, J.I., Gleick, P.H., 1998. Allocating freshwater to aquatic ecosystems: the case of the Colorado River Delta. Water Int. 23, 119–125.

Raubenheimer, B., Guza, R.T., 1996. Observations and predictions of run-up. Journal of Geophysical Research 101 (C10), 25575–25587.

Sánchez-Arcilla, A., Jiménez, J.A. and Valdemoro, H.I. 1998. The Ebro delta: morphodynamics and vulnerability. Journal of Coastal Research, 14, 3, 754-772

Santalla R. Eurosion case study: Ebro delta (spain). Technical report, Escuela Superior de Ciencias Experimentales y Tecnología, 2002.

Sanyal, J. & Lu, X. 2004. Application of remote sensing in flood management with special reference to monsoon Asia: a review, Natural Hazards, 33, pp. 283–301.

Scarton, F., Day, J.W., Rismondo, A., 2002. Primary production and decomposition of Sarcocornia fruticosium (L.) and Phragmites australis (Trin. Ex Steudel) in the Po delta, Italy. Estuaries 25, 325–336.

SEO/Birdlife, 1997. Pla Delta XXI. Directrices para la conservación y desarrollo sostenible en el Delta del Ebro, SEO/BirdLife, Madrid, p. 100.

Sostoa, A., Lobón, J., 1989. Fish and fisheries in the river Ebro: actual state and recent history. Historical Changes of Large Alluvial Rivers in Western Europe. John Wiley & Sons, London, pp. 233–247.

Sostoa, A., Sostoa, F.J., 1985. The fish community of the Ebro Delta (Northeast Spain): a model of Mediterranean estuarine ecosystem. In: Yanez-Arancibia, Y. (Ed.), Fish Community Ecology in Estuaries and Coastal Lagoons: Towards an Ecosystem Integration. UNAM Press Mexico, Mexico, pp. 654–694.

Shell International (2003) Scenarios: an explorer's guide. Global business environment. at: http://www.static.shell.com/static/ royal-en/downloads/scenarios_explorersguide.pdf

Somoza L., Barnolas A., Arasa A., Maestro A., Rees J.G. y Hernández-Molina F.J. 1998. Architectural stacking patterns of the Ebro delta controlled by Holocene high-frequency eustatic fluctuations delta-lobe switching and subsidence processes. Sedimentary Geology 117: 11-32.

Sorensen R.M.,1997.Basic Coastal Engineering. ISBN 0387233326. 324 pages

Stockdon, H.F., Holman, R.A., Howd, P.A. and Sallenger, A.H., 2006. Empirical parameterization of setup, swash, and runup. Coastal Engineering, 53(7): 573-588

Stanley, D.J., Warner, A.G., 1993. Nile Delta: geological evolution and human impact. Science 260, 628–634.

Thumerer T, Jones AP, Brown D 2000. A GIS based coastal management system for climate change associated flood risk assessment on the east coast of England. Int J Geogr Inf Sci 14(3):265–281

Tuan, T.Q., Stive, M.J.F., Verhagen, H.J. & Visser, P.J. 2008. Process-based modeling of the overflow-induced growth of erosional channels. Coastal Engineering 55: 468-483.

Valdemoro, H.I., Sanchez-Arcilla, A., Jimenez, J.A. 2007. Coastal dynamics and wetlands stability. The Ebro delta case. Hydrobiologia, 577 : 17-29. ISSN: 0018-8158

Water Framework Directive. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.

Webster, T.L. Forbes, D.L., Dickie, S., and Shreenan, R. 2004. Using topographic lidar to map flood risk from storm-surge events for Charlottetown, Prince Edward Island, Canada. Canadian Journal of Remote Sensing, Vol. 30, No. 1, pp. 54-76.

Weggel J.R. (1976) Wave Overtopping Equation. Proceedings Coastal Engineering Conference Hawaii

Xie L., L.J. Pietrafesa and M. Peng, 2004. Incorporation of a mass-conserving inundation scheme into a three-dimensional storm surge model, J. Coastal Res. 20 (), pp. 1209–1223

Zerger A, Wealands S 2004. Beyond modelling: linking models with GIS for flood risk management. Natural Hazards 33:191–208

9. Annexes

"This book is an agglomeration of lean-tos and annexes and there is no knowing how big the next addition will be, or where it will be put. At any point, I can call the book finished or unfinished."

Aleksandr Solzhenitsyn

Publications.

- J.A. Jiménez, D. Alvarado-Aguilar, H. Coop, J. Krywkow, M. Larson, G. van Geest, R. Raaijmakers, A. Sánchez-Arcilla (2009). Chapter 9: The Ebro River Delta Coast in Samuels et al. (eds). Pilot Sites of FLOODSite Proyect. En prensa

- Alvarado-Aguilar D. & J. A. Jiménez (2009).Flood Hazard Mapping for Coastal Storms in the Delta Ebro, in Flood Risk Management: Research and Practice, Samuels et al. (eds). 2009 Taylor & Francis Group, London, ISBN 978-0-415-48507-4.

- Alvarado-Aguilar, D. & Jiménez, J.A. 2007. A pseudo-dynamic approach to Coastal Flood Hazard Mapping. Proceedings of Coast GIS07, Volume II, 111-120, Santander.

A PSEUDO-DYNAMIC APPROACH TO COASTAL FLOOD HAZARD MAPPING

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ABSTRACT

The main aim of this work is to present a methodology developed to take into account the intrinsic dynamic nature of coastal sedimentary areas in flood hazard mapping. It consists in incorporating morphodynamics into the hazard assessment and how this hazard varies with time, i.e. coastal response during the flood event. The methodology is applied to the Ebro delta to estimate the range of water volumes potentially able to inundate the hinterland during the impact of a storm. In addition to this, flood hazard areas due to RSLR are also delineated.

FLOOD HAZARD MAPPING, INUNDATION, DIGITAL ELEVATION MODEL, COASTAL HAZARDS.

INTRODUCTION

Flood risk management is a critical issue for public security and quality of life in coastal low-lying areas. Due to this, most of nations have launched programmes for identifying flood prone areas and, following well-defined procedures produce hazard maps (e.g. DEFRA, 2001; FEMA, 2003). This is used to define protection needs and to take decisions and it serves to facilitate planning and prevention efforts as well as to reduce loss of life and property.

Flooding in coastal areas can be analysed at different time scales. At the long-term scale, coastal flooding should be mainly driven by sea level rise and the delineation of hazard areas is simply done by identifying areas connected with the sea below the targeted water level.

At the short-term scale, coastal flooding will result from the action of a transient driving agent, "*the storm*" normally defined in terms of a storm surge plus storm waves on a coastal stretch defined in terms of elevation. In coastal sedimentary environments, the impact of the storm will induce a significant coastal response that will interact with the storm in such a way that the intensity of the flooding could be affected (enhanced or reducing). Under these conditions, not only the flooding is relevant for the manager but also the storm-induced response due to its intrinsic associated damage (coastal erosion hazard) and its potential synergic effect with coastal flooding.

The main aim of this work is to present a methodology developed to take into account the intrinsic dynamic nature of coastal sedimentary areas in flood hazard mapping. It consists in incorporating morphodynamics into the hazard assessment and how this hazard varies with time, i.e. coastal response during the flood event. Thus, in some cases, this morphodynamic response will "enhance" the susceptibility of the area, and in other cases, it should mitigate the damages, in comparison with fixed coastal dikes and revetments for long-term flood hazard estimations.

Different methods for incorporating the coastal response associated to impact of storms will be analysed and compared by applying them to one low-lying stretch of the Catalan coast where a high-precision DEM exists and where the coastal morphodynamic response is well characterised.

AREA OF STUDY

The Ebro delta is located on the Spanish Mediterranean coast about 200 km southward of Barcelona. It has an approximate subaerial surface of 320 km^2 and a coastline length of about 50 km including the inner coast in the two main lagoons (Figure 1). It includes a Natural Park of 7,802 ha giving administrative protection to the areas of highest environmental value, including habitats like freshwater, brackish and saline lagoons, salt marshes and coastal and small dune sandy areas. At the same time, it is actively exploited by means of agriculture, mainly for rice production (about 66% of the total subaerial surface is devoted to rice production). The population is about 50,000 inhabitants, including people living in the delta itself and people with a direct economic dependence on it.

At the long-term scale, the Ebro delta has been identified as a highly vulnerable environment (e.g. Sánchez-Arcilla et al., 1998). Although pristine deltas (without any human interference) can cope with RSLR because the deltaic plain should be able to vertically accrete, deltas where human action has led to a decrease of riverine sediment supplies cannot as it is the case of the Ebro delta (Jiménez and Sánchez-Arcilla, 1993; Guillén and Palanques, 1998).

Medium-term coastal processes are associated with changes at a temporal scale of several years and a spatial scale of several km. At this scale, most of the observed changes have been related with the net longshore sediment transport processes and correspond to a coastal reshaping in which eroding stretches are feeding accreting ones (Jiménez and Sánchez-Arcilla, 1993).

Finally, episodic events are associated with hydrodynamic processes with a long return period, unknown periodicity and a spatial scale defined by the length of the coastal response. The main "driving" agent for these events is the presence of very energetic sea states, generally characterised by the coexistence of storm surges and storm waves, which in the Ebro delta coast usually occur due to the passage of low pressure systems off the delta inducing eastern wave storms (Jimenez *et al*. 1997). Although the entire deltaic coast is subjected to the action of such events, the more vulnerable stretches are those with a narrow emerged beach and fronted by a “low-crested” bar or bar system. The most vulnerable areas are: (i) Illa de Buda at the central lobe; (ii) Trabucador beach at the Southern hemidelta and (iii) Marquesa beach at the Northern hemidelta (see e.g. Sánchez-Arcilla et al., 1998).

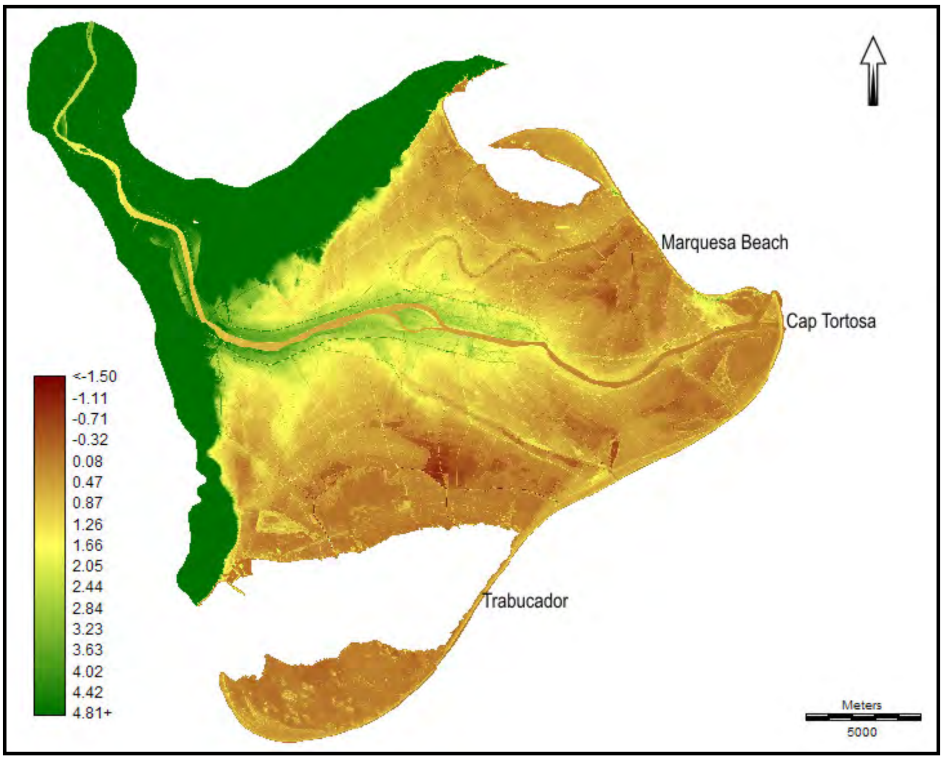

Figure 1. The Ebro delta.

Main data used in this study consisted in a DEM of the Ebro delta build from topography obtained with an airborne scanning lidar by the Institut Cartogràfic de Catalunya. In addition to this, a set of coastal profiles taken along the delta during a period of four years were used to characterize beach profile temporal variability. Finally, data to characterize storm action were obtained by a directional wave buoy off the Ebro delta at 50 m depth.

EVALUATION OF INUNDATED AREAS

Two different inundation scenarios are considered in this analysis. The first scenario is given by a steady increase in the water level. This should correspond to flooding due to relative sea level rise and it will verify for a water level surged with respect to the actual one with time enough to inundate all the areas directly connected to the sea below that level. Within this scenario we have to consider that sandy coastlines exposed to wave action will response following a Bruun's rule-like response, i.e. the will move upwards and landwards following sea level. As a consequence of this, if the main barrier protecting the hinterland is given by the beach, its elevation will be the same with respect to the mean water level although it will be landward of the actual position after sea level rise. This will only occur in dynamically active (sandy rich) areas where no fixed inner boundaries (seawall, levees, etc) do exist.

The second scenario is given by the inundation produced by the temporary increase of the water level during the impact of a storm. Here, the water level will vary with time because it will be controlled by the storm surge plus the induced wave run-up during the storm duration. Thus, to estimate the induced coastal inundation a different approach must be followed. In this case, first we evaluate the water discharge above the beach during the storm duration. After that, the so-estimated "flooding" water volume has to be distributed in the hinterland taking into account the actual topography and considering existing barriers (levees, roads, etc.).

INUNDATION DUE TO RSLR

As it was previously mentioned, processes acting at the long-term scale will mainly affect to the deltaic dynamics in the vertical dimension, i.e. the relative elevation of the deltaic body with respect to the sea level. This has very important implications for a low-lying coastal environment, especially in a scenario of rising sea level because the only way to avoid direct inundation by the sea is the vertical accretion of the deltaic plain.

Due to the absence of sediment supplies to the deltaic plain, no vertical accretion is taking place and, as a consequence, RSLR (due to the combined action of subsidence and eustatic sea level rise) will increase the probability of flooding of low-lying areas, specially those directly connected to the sea or where a "passive" coastal fringe exists. In the Ebro delta, "passive" stretches are the inner coasts in the two main lagoons where no energetic driving agents are acting nor there is any significant sand stock (and the available one has a large percentage in very fine sediment).

To give an idea of the potential vulnerability of the Ebro delta to RSLR, figure 2 shows the hazard areas to inundation for two scenarios, 0.25 m and 0.50 m. The areas potentially able to be inundated for such levels were estimated taking into account the role of hinterland structures - such as levees, dikes and roads- in preventing flooding in impounded areas. Areas below the targeted water levels but not directly connected to the sea have not been considered as hazard zones. In some cases, some of these areas could be classified as potentially vulnerable to inundation if we include the response to storms, specially in those cases where the coast has been previously breached.

Thus, the flood hazard area to a RSLR of 0.25 m has been estimated in 6,600 ha, that increases up to 14000 ha for a RSLR of 0.5 m. These two scenarios correspond to approximately 21 % and 44 % of the deltaic surface. This only includes areas to be inundated because they are directly connected to the sea. Other deltaic areas below targeted water level but not directly connected to the sae will be affected by other processes such as an increase in salt content in the soil and water.

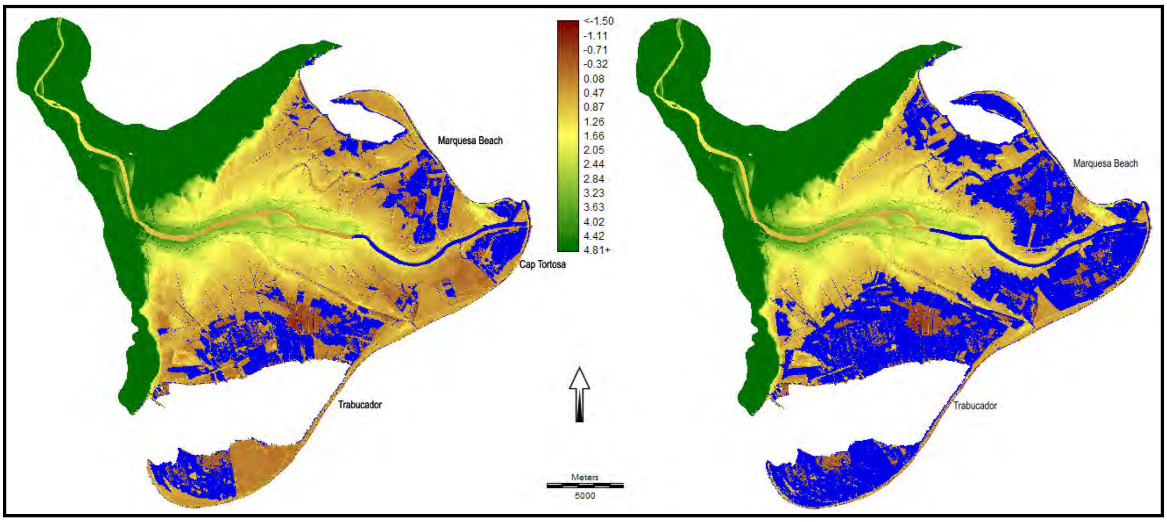

Figure 2. Flood hazard areas (blue) to RSLR of 0.25 m (left) and 0.5 m (right) at the Ebro delta.

INUNDATION DURING STORMS

As it was previously mentioned, during the impact of a storm in low-lying coastal areas, the hinterland will be inundated if water level during storm exceeds the elevation of the beach or dune crest protecting it. To properly evaluate the inundation under this scenario we have to consider that the system will respond to storm action in such a way that not only water level will change during the storm but also the beach morphology.

The induced change in beach morphology, i.e. beach lowering (decrease in the beach or dune height) and profile flattening (decrease in the beach slope) will affect the magnitude of the inundation in opposite terms when they are separately considered (see e.g. Jiménez et al., 2006). Thus, beach lowering will tend to increase the water discharge towards the hinterland because for a given water level the lowering of the beach/dune height will increase the freeboard. On the other hand, profile flattening will tend to reduce inundation because for given wave characteristics during the induced run-up will decrease due to the decrease in beach slope. The dominant effect (inundation increase or decrease) will depend on the type and magnitude of beach changes during the storm.

To take into account these effects on the potential inundation we consider three different approaches:

- no beach response,
- known beach variability,
- simulation of storm-induced beach profile response.

The first approach is the simplest one and the coastal inundation due to the impact of a storm is calculated by using the existing pre-storm beach morphology. In the most usual case, the used beach morphology does not necessarily correspond to real pre-storm conditions but should correspond to the existing one (whenever they have been obtained). Once the beach morphology is fixed, wave run-up is estimated and added to the storm surge (if any) to define the maximum total water level during the storm. From this, the water discharge is calculated for the period during which water level exceeds the beach/dune height.

The second approach introduces part of the natural beach variability. It can be used only when information about past beach morphology changes in the area do exist. First, for each profile or location along the coast, the envelope of changes at seasonal/yearly scale is obtained. From this, minimum and maximum beach elevations and associated local beach slope changes are obtained. These values are finally used to calculate the range of induced runups (determined by the slope changes) and water discharges towards the hinterland (determined by water levels and beach heights). As a consequence, the final result following this approach should be a range of potential discharges instead of a unique value as in the previous case. This approach is useful when we do not know the actual pre-storm topography but we have older beach data.

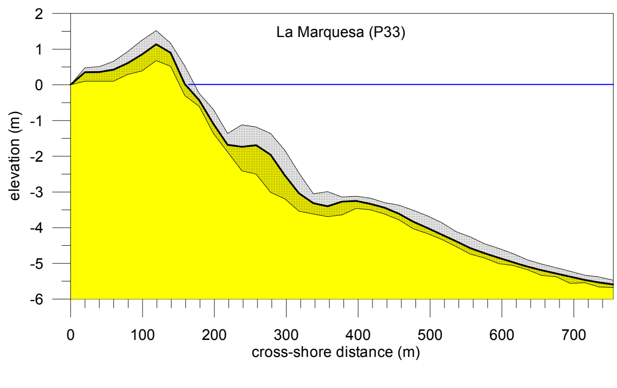

Figure 3. Beach profile envelope showing the temporal variability in a 4 years-period in the Marquesa beach.

As an example, Figure 3 shows the observed variability in one profile in the Marquesa beach (see location in Figure 1) during a period of four years. The beach height obtained from data varies between 0.7 m and 1.5 m without considering breaching events during storms and, this means that the estimated freeboard during a given storm could vary up to 0.8 m only due to the "natural variability of the profile". This difference will have important consequences in the estimation of the volume of water flooding the hinterland during the storm duration as well as in the frequency of inundation. Figure 4 shows the return period associated to the wave-induced inundation (given by the exceedence of the beach level by the wave run-up) for beach profile shown in figure 3 for the case of considering as the pre-storm beach the maximum or the mean recorded profiles. As it can be seen, for the same wave climate, the inundation return period can vary between 8.5 and 2.5 years depending on the used pre-storm conditions.

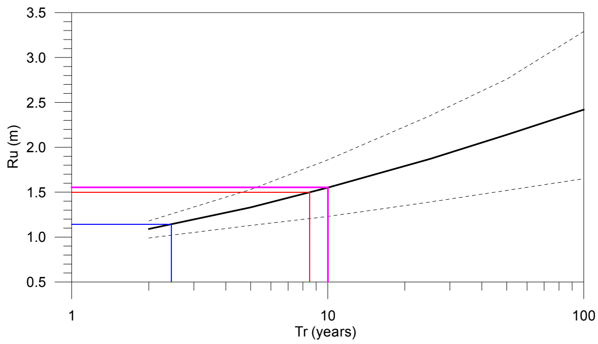

Figure 4. Estimated variability in wave-induced inundation return period for maximum (red line) and mean (blue line) beach profiles in the Marquesa beach (Figure 3).

Finally, the third approach consists in simulate the beach profile response during the storm and to update the induced run-up and water discharge following calculated changes in beach slope and height. This has been done using the Sbeach model to simulate storm-induced beach profile changes (Larson and Kraus, 1989; Wise et al., 1996). As an example, figure 5 shows the simulated changes for a profile in La Marquesa beach, where a significant lowering of the beach is observed. However, beach slope during the storm did not change too much to affect wave run-up. The consequences of taking into consideration these changes can be seen in figure 6. Thus, when the induced beach changes during the storm are incorporated, the time period during which the beach is overwashed increased and, as a consequence, the volume of water discharging in the hinterland also significantly increases.

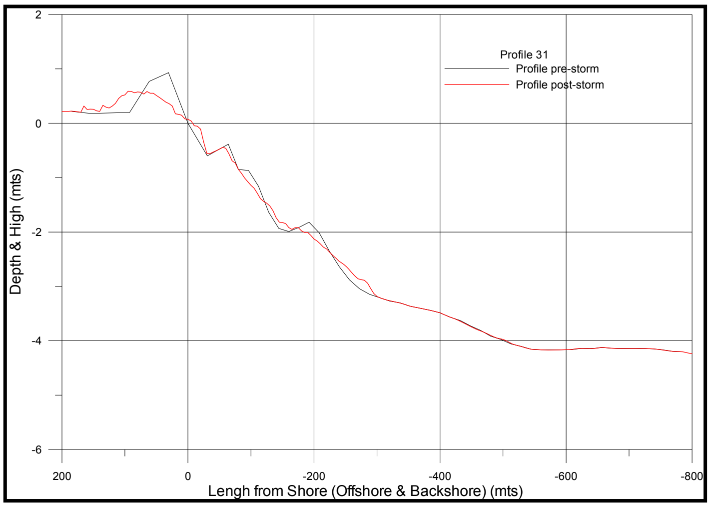

Figure 5. Simulated beach profile changes under storm impact in the Marquesa beach.

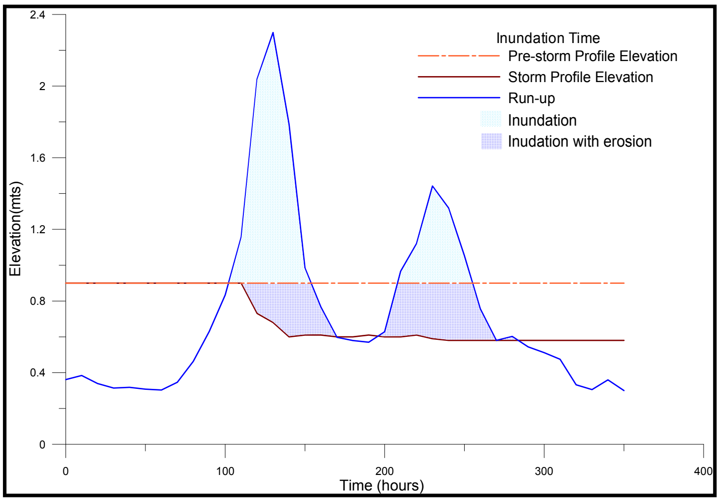

Figure 6. Periods with water level exceeding local beach elevation during a storm for fixed (left) and evolving (right) beach profiles.

To analyse the importance of storm-induced inundation, the three methodologies were applied to calculate the flooding induced by the largest recorded storm (November 2001) along the Marquesa beach (Figure 7). Results are summarised in Table 1 where the estimated water flow towards the hinterland has been calculated by estimating the induced wave runup during the storm by using the Stockdon et al. (2006) formula and the overtopping rates (water volumes towards the hinterland) are calculated following the method proposed by Fema (2005).

Figure 7. Overwash deposits along the Marquesa beach after the storm of November 2001.

Table 1. Calculated overtopping rates during the storm of November 2001 along the Marquesa beach (*peak*: at the storm peak, *mean*: storm-averaged, *in*t: integrated during the storm duration).

Profile 31	Q peak ($m^3/m/s$)	Q mean ($m^3/m/s$)	Q int (m^3/m)
Method 1 No response	0.199	0.005	127.14
Method 2 Known Beach variability	0.034 (min prof) 0.199 (max prof)	0.109 (min prof) 0.005 (max prof)	280.04 (min prof) 127.14 (max prof)
Method 3			
Simulated response	0.34	0.0109	280.052

Profile 33	Q peak ($m^3/m/s$)	Q mean ($m^3/m/s$)	Q int (m^3/m)
Method 1 No response	0.005	0.00037	9.38
Method 2 Known Beach variability	0.01 (min prof) 0.05(max prof)	0.00092 (min prof) 0.00035 (max prof)	23.7 (min prof) 8.99 (max prof)
Method 3			
Simulated response	0.005	0.00035	8.99

It has to be stressed that results showed in table 1 are affected not only by the variability introduced by considering the response of a given stretch to the storm but also by the spatial variability in the response along the coast. Integrated water volumes have been calculated by estimating the beach freeboard variation during the storm (due to changes in wave conditions and beach elevation, when applicable) and applying it to the 2 % of the time because run-up estimates are $R_{2\%}$. These water volumes will mainly inundate the areas closest to the shoreline and constrained by levees or roads delineating the outer row of rice fields.

As it can be seen in table 1 the aplication of the different methods result in overtopping rates varing in one order of magnitude. When integrated during the storm duration this results in water volumes that can vary abot 40%. Moreover when this is applied to different areas (profile 31 and 33 in table 1 are separated about 3 km.) they are able to cath the spatial variability in the response to storms and associated inundation

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REFERENCES

DEFRA (2001). *National Appraisal of Assets at Risk from Flooding and Coastal Erosion, including the potential impact of climate change. Final Report*. Flood Management Division. Department for Environment, Food and Rural Affairs, London, UK.

FEMA (2003). *Guidelines and specifications for Flood Hazard Mapping Partners*.

Guillén, J. and Palanques A. (1997). A historical perspective of the morphological evolution in the lower Ebro river. *Environmental Geology*, 30, pp. 174-180.

Jiménez J.A. and Sánchez-Arcilla, A. (1993). Medium-term coastal response at the Ebro delta, Spain. *Marine Geology*, 114, 105-118.

Jiménez, J.A., Sallenger, A. and Fauver, L. (2006). Sediment transport and barrier island changes during massive overwash events. *Proc. 30th ICCE,* ASCE, 2870-2879.

Jiménez, J.A., Sánchez-Arcilla, A., Valdemoro, H.I., Gracia, V. and Nieto, F. (1997). Processes reshaping the Ebro delta. *Marine Geology*, 144, 59-79.

Larson M. and Kraus N.C. (1989), "*SBEACH: Numerical Model for Simulating Storm-Induced Beach Change",* CERC-89-9, US Army Corps of Engineers, Vicksburg.

Sánchez-Arcilla, A., Jiménez, J.A. and Valdemoro, H.I. (1998). The Ebro delta: morphodynamics and vulnerability. *Journal of Coastal Research*, 14, 754-772.

Stockdon, H.F., Holman, R.A., Howd, P.A. and Sallenger Jr A.H. (2006), Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, 53, 573–588.

Wise, R.S., Smith, S.J. and Larson, M. (1996), "*SBEACH: Numerical model for simulating storm-induced beach change",* CERC, US Army Corps of Engineers, Vicksburg.

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Flood hazard mapping for coastal storms in the Delta Ebro

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ABSTRACT: Flood hazard mapping is a critical issue in coastal low-lying areas due to its intrinsic sensitivity to the impact of extreme storms. The estimation of the beach response during the event is a key point, not only to calculate the induced erosion, but to properly evaluate flood hazard areas since the magnitude of the flooding can be affected by a morphodynamic feedback. Here, we present a methodology to delimit the uncertainty in flood hazard mapping associated to natural beach morphodynamics. This methodology has been tested in the Ebro delta coast for the impact of a storm with a *Tr* of about 100 years. Results showed that the selection of a given initial beach profile, from the different recorded ones, can result in variations of durations of overtopping events of about 300%, which area amplified for overtopping rates. Along the study area, the uncertainty introduced due to the use of a single representative profile for the entire coast is much lower than the associated to the selection of the beach profile shape. Finally, when the beach evolution during the storm is included, the volume of floodwater entering the coastal plain is significantly larger than for any of the tested static scenarios. This means that any flood hazard mapping in sedimentary coastal environments without including the beach response will significantly underestimate the hazard area.

1 INTRODUCTION

Flooding in coastal areas will result from the combination of a driving agent, *the storm*, normally defined in terms of a water level -storm surge plus wave induced runup- acting on a receptor, the coast, which is mainly defined in terms of elevation. However, in sedimentary environments, the impact of the storm will produce a significant morphodynamic response that will interact with the storm and should affect the intensity of the flooding (enhancing or reducing).

When this is applied to low-lying areas, as deltaic coasts are, the estimation of this interaction is crucial due to the expected magnitude of the induced impacts in these environments. Thus, these areas are characterized by a very low relief, and consequently easily to be flooded, and "protected" from the sea by sandy beaches and barriers which freely respond to storm action and, in consequence, easily to be modified.

A review of the potential factors influencing the response of low-lying coasts to storms can be seen in Morton (2002). Although the number of factors is relatively large, a conclusion of such study is that the most important variables controlling the coastal response are the difference in elevation between the water level during the storm and the beach/barrier/dune crest and the duration of the flooding. This is common in most of studies of the response of low-lying coasts to extreme storms and, in fact, Sallenger (2000) proposed a hazard scale for barrier islands (that can be considered a paradigm of sensitive low-lying coasts) based in the ratio of run-up to barrier height. This has also been included in most of the existing studies in overwash and breaching under storms (e.g. Larson et al., 2005; Donnelly et al., 2006; Jiménez et al., 2006).

During these events, main induced changes in the beach profile morphology –without considering the retreat itself- can be simplified in terms of *lowering* (decrease in the beach height) and *flattening* (decrease in the beach slope). These two morphological changes will induce a morphodynamic feedback with acting processes. As an example, the magnitude of the induced inundation should be affected in opposite terms when they are separately considered (see e.g. Jiménez et al., 2006). On the one hand, beach lowering will tend to increase the water discharge towards the hinterland because for a given water level the lowering of the beach/dune height will increase the freeboard. On the other hand, the profile flattening will tend to reduce inundation because for a given set of wave characteristics, the induced run-up will decrease due to the decrease in the beach slope. The resulting effect (inundation increase or decrease) will depend on the type and magnitude of beach changes during the storm.

With these antecedents, it is clear that the estimation of the beach morphodynamic response during the storm is a key point not only to calculate the induced erosion, but to properly evaluate flood hazard areas.

This is especially relevant in non-protected coasts where the main barrier to flooding is the beach itself which can hardly be considered as a rigid boundary. Thus, if we are going to predict the flood hazard area in a costal stretch associated to the impact of a given storm, one of the key points we have to face off is to select which should be the pre-storm coastal morphology. Moreover, once we have solved this question, the next question is what will happen during the event.

Within this context, the main aim of this paper is to analyze the influence of the inclusion of the natural variability of beach morphology in coastal flood hazard mapping in non-protected areas. First we present the developed methodology to bound the uncertainty in the extension of the flooded area induced by the definition of the beach, which should be the element protecting the hinterland from floodwaters. Second, the methodology is applied to map flood hazard areas in the Ebro delta under the impact of extreme coastal storm.

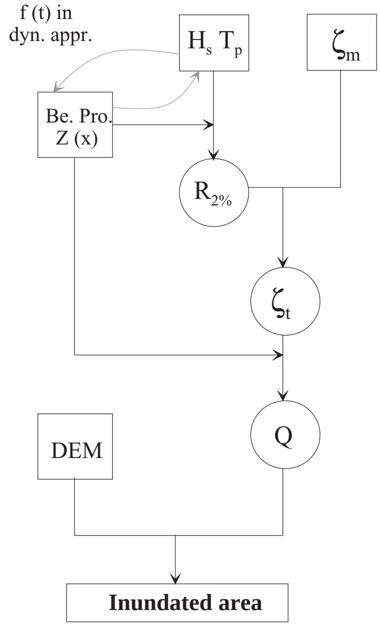

Figure 1. Outline of used methodology for coastal flood hazard mapping.

2 METHODOLOGY

The methodology used in this work is outlined in figure 1.

2.1 *Forcing*

The first step consists in the estimation of a total water level at the shoreline. This is done by using the response-method approach, which is based directly on measured or simulated water levels and waves as they occurred in nature and, the water level of interest (associated to a given probability or return period) is directly calculated from a probability distribution of total water levels. This method is specially recommended when variables determining the flood level are partially correlated, i.e. when surge and large waves are uncoupled and, for areas where wave height and periods during storms (both will determine the wave run-up) are poorly correlated (see e.g. Divoky and McDougal, 2006; Fassardi, 2006).

Since our analysis is done in a coast without any protection but natural beaches, the run-up model proposed by Stockdon et al (2006) has been selected. This was due to the fact that this formula was derived by using run-up data obtained in field and large scale experiments in beaches. The run-up ($R_{2\%}$) is calculated for each beach profile scenario (according to each beach profile definition method, see below), with differences in run-up magnitude being controlled by the use of a different beach slope since wave conditions are the same in all the cases. Obtained values are then added to simultaneous water level data (ζ_m) to build the total water level time series (ζ_t).

Total water level data are then fitted to an extreme distribution to estimate the water level associated to given probabilities or return periods.

Once the target total water level has been estimated, the following step is to calculate overtopping rates (Q) for those cases where the run-up exceeds the beach/barrier crest. This will determine the volume of floodwater penetrating to the hinterland and, in consequence, determining the extension of the flood hazard area. The overtopping volume has been calculated following the method used by Fema (2003) to estimate the inundation in low-lying coasts. In essence the method estimates the mean overtopping rate for smooth slopes based on the former works of Owen (1980).

2.2 *Beach configuration*

A critical issue to map coastal areas prone to be inundated during storms is how to properly characterize the beach configuration. Beach configuration takes part in the process by controlling the magnitude of the run-up (via beach slope) and, by controlling the overtopping (via beach/dune crest height). Thus, in contrary to the quasi-static case of dikes, beaches are continuously reacting to coastal dynamics and, especially during the impact of storms, they are significantly modified. This means that to properly map coastal flood hazard areas beach dynamics have to be incorporated to the analysis.

In this work, we have tested three different approaches to define the beach configuration during the storm impact on the inundation of the hinterland already outlined in Alvarado and Jiménez (2007).

The first approach uses a fixed beach profile. This should be equivalent to the case in which the only data available should be a pre-storm coastal configuration (taken at any moment and not necessarily just before the impact). This beach morphology is used throughout the analysis and this means that run-up will be controlled by the corresponding beach slope and the overtopping by the beach/dune crest which are maintained fixed during the storm duration. This type of the approach is equivalent to consider the beach as fixed protecting structure.

The second approach introduces some information on the natural beach variability. In essence in this approach the beach is characterized by an envelope of the possible configurations instead of a single value. It can only be used when information about past beach morphologies are available. Thus, for each representative transect along the coast, the morphology is represented by the envelope of all the existing data (ideally covering a period of several climatic periods and, thus, showing the natural changes in the beach morphology to wave action). This will permit to estimate all the relevant variables (run-up and overtopping) for the different configurations—bounded by the maximum and minimum profiles –. This should be equivalent to add some kind of confidence band to the calculated floodwater and, in consequence, to the potentially flooded surface.

Figure 2 shows an example of beach profile envelope used in this study obtained from 4 years of beach profile data where a significant variation in the beach configuration is observed.

The third approach to describe the beach morphology consists in simulating the beach profile response during the storm action recovering all the intermediate configurations from the pre-storm situation to the post-storm one. These intermediate configurations will permit to update the wave-induced run-up and overtopping rates according to the time-dependent beach slope and crest height.

Beach profile evolution during the storm has been calculated by using the SBEACH model (Larson and Kraus, 1989; Wise et al., 1996). This model has been previously used to simulate the dune lowering before the inundation of the hinterland during the impact of extreme storms (see e.g. Cañizares and Irish, 2008).

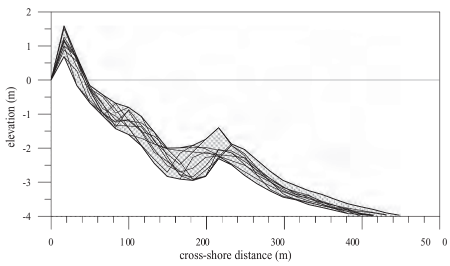

Figure 2. Envelope of beach profiles taken during a 4 years period in the Northern part of the Ebro delta.

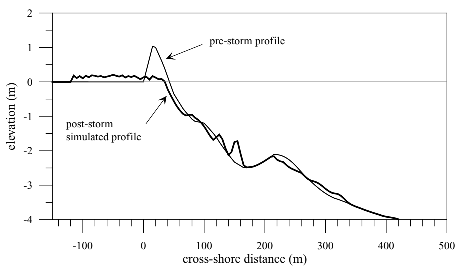

Figure 3. Beach profile evolution during the impact of a storm simulated by using Sbeach.

The model is applied to selected profiles taken a long the outer coast of the Ebro delta and, it is assumed that they are representative of the coastal response along a given stretch (alongshore uniform stretches).

The model simulates the beach profile response due to storm wave action by assuming sediment transport is due to cross-shore processes only.

An example of the application of the model to simulate beach profile changes is shown in figure 3. As it can be seen, if the beach evolution during the storm is incorporated, there is a significant difference in beach morphology –a decrease in beach height of about 1 m-. If this knowledge is incorporated to the flood mapping, results significantly vary with respect to those obtained for the initial configuration.

2.3 *Inundation*

Finally, once water levels and beach configurations are known, the last step is to determine which part of the coastal plain is flooded.

To calculate the potential flood zone we used the LISFLOOD-FP inundation model (Bates and de Roo, 2000). This is a raster grid based model that has been successfully employed to simulate the inundation in fluvial and coastal areas (see e.g. Bates and De Roo, 2000; Bates et al., 2005). The model predicts water depths in each grid cell at each time step, and hence can simulate the dynamic propagation of flood waves over fluvial, coastal and estuarine floodplains. In our analysis we specify the data input as a time series of water flow at the shoreline bordering the deltaic plain (calculated through the overtopping rates).

3 AREA OF STUDY AND DATA

The Ebro delta is located in the Spanish Mediterranean coast about 200 km southward of Barcelona. It has an approximate sub-aerial surface of 320 km^2 and a coastline length of about 50 km excluding the inner coast in the two semi-enclosed bays (Figure 4). It is microtidal environment with astronomical tidal range of about 25 cm although storm surges clearly exceeding such magnitude are not infrequent in the area (Jiménez et al., 1997). As many other deltas, it is an ecologically rich environment, with areas of highest interest habitats being composed by freshwater, brackish and saline lagoons, salt marshes and coastal and small dune sandy areas. At the same time, it is actively exploited by means of agriculture; mainly for rice production (about 66% of the total sub-aerial surface is devoted to rice production).

This is a very low-lying area with a maximum elevation above the MSL of about 4 m. Table 1 shows the percentage of the delta surface below given elevations. These data clearly show that the system is potentially highly vulnerable to floods since about 49% is below an elevation of +0.5 m.

These figures were calculated from a DEM of the Ebro delta derived from LIDAR data obtained by the Institut Cartogràfic de Catalunya. The data used in this study has a spatial resolution of 1 m and a vertical accuracy of 15 cm acquired the year 2004.

To simulate the inundation of the delta at a reasonable computational cost, the DEM was aggregated to 10 m resolution. This size was selected after testing the effects of the cell size in masking the effects of the presence of canals and small dikes separating rice pads.

In addition to this, a database of beach profiles was also available. It is composed by a series of profiles taken during 4 years at a spatial interval of 1–1.5 km along the coast. Although beach profiles were not taken simultaneously to the DEM, they can be used to characterize the beach profile temporal variability along the coast. Moreover, since the deltaic plain dynamics is much slower than beach dynamics (and especially in this case because it is highly regulated by human action) both datasets were integrated to get a "dynamic boundary" of the Ebro delta. Thus, the DEM is used to characterize all the elevations along the deltaic surface and the beach profiles are used to estimate the flooding of the area as it is described in the methodology.

Finally, to characterize the forcing, different data sets have been used: (i) a 17 years long wave time series recorded by a directional wave buoy at 50 m depth off Cap Tortosa since 1990; (ii) a 43 years (1958–2001) long time series of hindcasted wave conditions

Figure 4. The Ebro delta. The rectangle indicates the area for flood hazard mapping and points indicate profile locations (see figure 9).

Table 1. Distribution of deltaic surface per elevations.

Elevation (m ab MSL)	Surface (ha)	Surface (%)
<0.5	16,296	49.09
0.5–1.0	7,539	22.71
1.0–2.0	5,968	17.98
2.0–3.0	2,495	7.52
3.0–4.0	754	2.27
>4.0	141	0.42

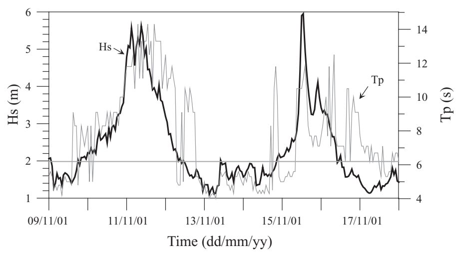

Figure 5. Wave conditions during the target storm recorded by a wave buoy off the Ebro delta (adapted from Jiménez et al., 2005).

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obtained within the framework of the Hipocas project (Guedes Soares et al., 2002).

The selected event to test the described methodology was the one associated to a return period of about 100 years. This was selected because it is extreme enough to produce a significant flooding on the one hand and, because we have a detailed record of a storm of such characteristics on the other hand. This storm was recorded in November 2001 (figure 5) and produced a significant erosion and inundation along the Ebro delta coast (see Jiménez et al. 2005; 2008).

4 RESULTS AND DISCUSSION

4.1 *Scenarios for the analysis*

Here, we have restricted the analysis to the simulation of flooding of the northern part of the Ebro delta, which is one of the most sensitive areas to the impact of storms and that "frequently" experiences temporary inundation of the deltaic plain (Jiménez et al, 2005; 2008). Also, since the main objective of the paper is to test the methodology, we have spatially restricted the analysis to reduce the computational cost and we have concentrated in an area where we observed significant overwash during the simulated storm (Jiménez et al. 2005, 2008) (see figure 6).

Along this coastal stretch we have information on the natural variability of four representative beach profiles. The available data cover the evolution of these four profiles (named as 31 to 34 from south to north, see locations in figure 4) during four years during which a "significant storm (return period of about 10 years) impacted the coast.

The first task was to obtain for each beach profile three representative states: mean, maximum and minimum. These states will be hereinafter called as *profile scenarios* and they have been obtained by statistical analysis of all the existing data for each profile. Thus,

Figure 6. Northern part of the Ebro delta coast (La Marquesa beach) just after the impact of the storm of November, 2001.

the *mean* corresponds to a simple averaging of all the existing data of a given profile; the *maximum* is a hypothetical configuration given by the upper limit of the envelope of all the data of the corresponding profile and *minimum* is the hypothetical configuration given by the lower limit of the envelope. These three scenarios will be used to test the influence of the beach morphology on the different parameters controlling flooding.

4.2 *Floodwater*

Once we have the different scenarios defined in terms of beach profile configurations, first we estimate the variation in the period of beach overtopping during the storm due to the definition of pre-storm beach morphology. Table 2 shows the obtained exceedence times along the coast defined as the storm time period during which the total water level (here limited to the wave run-up, $R_{2\%}$) exceeded the beach height.

The first aspect to be highlighted is that, for all locations along the coast (specified by profile names), there is a very significant variation in the duration of overtopping conditions.

Thus, by measuring the differences in overtopping conditions in terms of a pseudo-coefficient of variation ([*Tmax-Tmin*]*100/Tmean*), we find that the uncertainty introduced in the flood analysis (only referred to the duration of overtopping conditions) should vary from a minimum value of 117% (profile 33) up to maximum of 395% (profile 31). Taking into account that this time duration is a critical issue to calculate the total volume of water entering to the hinterland, it is evident the impact that the proper selection of the pre-storm profile will have in the final results.

These calculated variations are strongly dependent on the natural profile variability, decreasing in importance for low- response coasts. However, low-lying sandy coasts, as the one studied here, are highly dynamic environments and, in consequence, although obtained values are strictly valid for analyzed conditions; they can be used as an order-of-magnitude of the expected variations.

Table 2. Periods of effective beach overtopping ($R_{2\%}$ > beach height) for the different profile scenarios along the Northern part of the Ebro delta coast.

Profile	Max (hours)	Min (hours)	Mean (hours)
31	10	160	38
32	29	114	69
33	29	111	70
34	29	160	100

Finally, with respect to the spatial variations along the studied coastal stretch, obtained results show a relatively low variability. Thus, obtained coefficients of variation for each scenario range from a minimum value of 20.1% for the worst scenario (profiles defined with the minimum shape) to 39.2 % for the safest one (profiles defined with the maximum shape). This should indicate that the morphological consequences of coastal dynamics on beach configuration are relatively alongshore uniform, especially when high energetic events (those determining the minimum profile scenario) are considered.

Moreover, these results should also indicate that the uncertainty introduced in the analysis due to the use of a single profile to represent the entire coastal stretch should be much lower than the associated to the selection of the configuration of such profile.

Once the duration of overtopping events was determined, the next step was to compare the magnitude of such events. Table 3 and figure 7 show calculated mean overtopping rates (averaged during the duration of the storm) for each profile scenario.

Obtained results show a similar behavior to the calculated for the overtopping periods. Thus, when different profile scenarios are compared, a large variability is again detected, with the pseudo coefficient of variation ranging from a minimum value of 115% (profile 33) to a maximum of 1,355% (profile 31). This huge increase in the variation for profile 31 is due to the dependence of the overtopping formula on the beach height (freeboard). Because the worst scenario (minimum configuration) for profile 31 corresponds to a really eroded and low profile, overtopping rates dramatically increase.

Table 3. Mean overtopping rates (averaged along the storm duration) estimated for the three beach profile configurations in the Northern part of the Ebro delta coast.

Profile	Max Q (10^{-3} m³/m/s)	Min Q (10^{-3} m³/m/s)	Mean Q (10^{-3} m³/m/s)
31	0.292	14.356	1.038
32	0.733	3.947	1.978
33	0.853	2.918	1.796
34	0.811	5.345	2.506

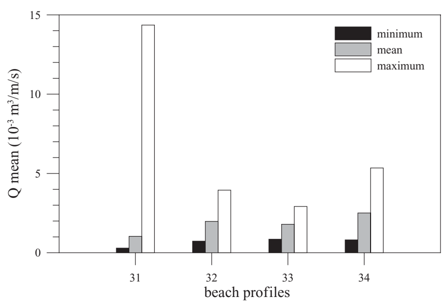

Figure 7. Mean overtopping rates (averaged along the storm duration) estimated for the three beach profile configurations in the Northern part of the Ebro delta coast.

This should indicate that the above estimated uncertainty for the overtopping period could be amplified when converted to volume of floodwaters.

When mean overtopping rates are compared along the coast for a given scenario, they also show a similar behavior than the observed for overtopping periods, i.e. a much lower variability than the observed as a function of the profile configuration. Thus, calculated coefficients of variation are of the same order of magnitude with a minimum value of 33.31% to a maximum one of 78.86%. Again, there is an increase for the worst scenario (minimum profile) due to the already mentioned sensitivity of the overtopping formula to beach height.

In practical terms, these results show that, similarly to the case of overtopping periods, the uncertainty introduced in the analysis due to the use of a single representative profile for the entire coast will be much lower than the associated to the selection of the beach profile shape. Moreover, it has also to be stressed than for the same conditions, the uncertainty in overtopping rates will be larger than in the period of exceedence for overtopping.

Once we have determined the range of variation for the different scenarios, a remaining question is what beach morphology must be used throughout in the flooding analysis?

Although previous results serve to delimit the uncertainty of the analysis, it is clear that whatever the selected beach configuration should be, it will change during the event.

As a final test, we have evaluated the previous two variables (period of exceedence for overtopping and overtopping rates) for one location along the coast (profile 32) including the simulated beach response during the event (table 4). In addition to the mean overtopping rates (averaged during the event), we have included also the peak discharge during the event.

As it can be seen and as it was expected, the inclusion of the beach evolution during the event results in an increase of overtopping rates. The magnitude of the calculated increase is about 1.7 times the calculated for the previously defined as the worst scenario (minimum configuration). This means that even selecting the worst scenario for static-oriented (fixed beach profile) flood hazard mapping in low-lying coasts, the volume of floodwater entering the

Table 4. Calculated overtopping rates during the storm of November 2001 along the Marquesa beach for the different scenarios (*peak*: at the storm peak; *mean*: storm-averaged; *Flooded area*: after 10 hours of continuous overtopping).

Profile scenario	Q peak (10^{-3} m³/m/s)	Q mean (10^{-3} m³/m/s)	Flooded area (ha)
Mean	16.811	1.978	78
Maximum	6.653	0.073	36
Minimum	32.717	3.947	110
Evolving Beach response	55.736	7.403	155

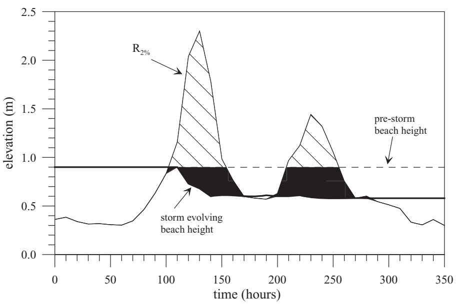

Figure 8. Run-up vs beach elevation during the target storm for static and dynamic beach configurations.

coastal plain would be significantly underestimated. This is illustrated in figure 8 through the comparison of the run-up during the storm (assuming beach slope changes are small enough to modify it) with the beach height for the static approach (a given profile maintained fixed throughout the analysis) and the dynamic one (simulated beach evolution).

4.3 *Inundation*

Once floodwater at the shoreline was estimated for the different scenarios, the remaining step was to delineate the part of the deltaic plain prone to be flooded during the event.

The first practical task was to extend along the coast the calculations done for representative profiles. To do this and according to the existing information, we have assumed the existence of an alongshore uniformity in morphology and response. Thus, each profile is considered to be representative of a coastal stretch of about 1 km. With this assumption, the total floodwater entering the hinterland across the beach will be the overtopping rates estimated for a given profile extended along the corresponding stretch. Although there are morphological evidences of alongshore uniform response of the study area under the impact of extreme storms (Jiménez et al., 2008), this introduces some uncertainty in the final extension of the flooded area. This is inherent to coastal flood analysis in sedimentary environments (coasts naturally protected by natural beaches/barriers) since (accurate) morphodynamic modeling of overwash and breaching processes is still an open question (e.g. Kraus and Hayashi, 2005; Tuan et al., 2008; Cañizares and Irish, 2008).

These spatially-integrated overtopping rates need to be also time-integrated over the duration of the storm. When the main source to induce flooding is the wave-induced run-up, there is some uncertainty about how to extend this pulsating process during a large period. Since the main objective of this paper is to analyze the effects of the morphodynamic interaction in relative terms we have just extended the overtopping rates to a total duration of 10 hours. The resulting integrated water flow was introduced as boundary conditions in LISFLOOD-FP in 100 seaward edge cells (1 km along the delta coastline).

The potentially flooded areas for each scenario are shown in figure 9 whereas the corresponding calculated flooded surface can be seen in table 4.

The first aspect to be highlighted is that when a static approach is followed, i.e. the beach is represented by a constant profile throughout the duration of the event, very significant differences are found. Thus, the estimated inundated area with a protecting beach represented by the mean profile (figure 9a) is 78 ha. However, when the beach is represented by the “extreme profiles”, i.e. the recorded minimum and maximum profiles, this surface will vary between 110 ha and 36 ha respectively (figures 9c and 9b).

These calculated values stress on the one hand the influence of the pre-existing morphology on the extension of the area to be inundated and, on the other hand, the influence of the selection of the initial configuration. This last point is especially critical since in most of the occasions the use of a “just-in-time” pre-storm morphology is just a matter of (very good) luck. The normal situation should be to have a given beach morphology taken in any moment that will not necessarily reflect the real beach morphology subjected to the impact of the storm.

With respect to the topography plain –data included in the DEM-, this issue is not too relevant provided major features controlling the extension of the flood have not changed (e.g. canals network, dikes, etc.).

The range of calculated values should serve to estimate the uncertainty in the calculations associated to the selection of the pre-storm morphology. In this case, where we were fortunate enough to have a collection of beach profiles representing their natural variability, the flood hazard area for the target storm is delineated not as a single surface but as an

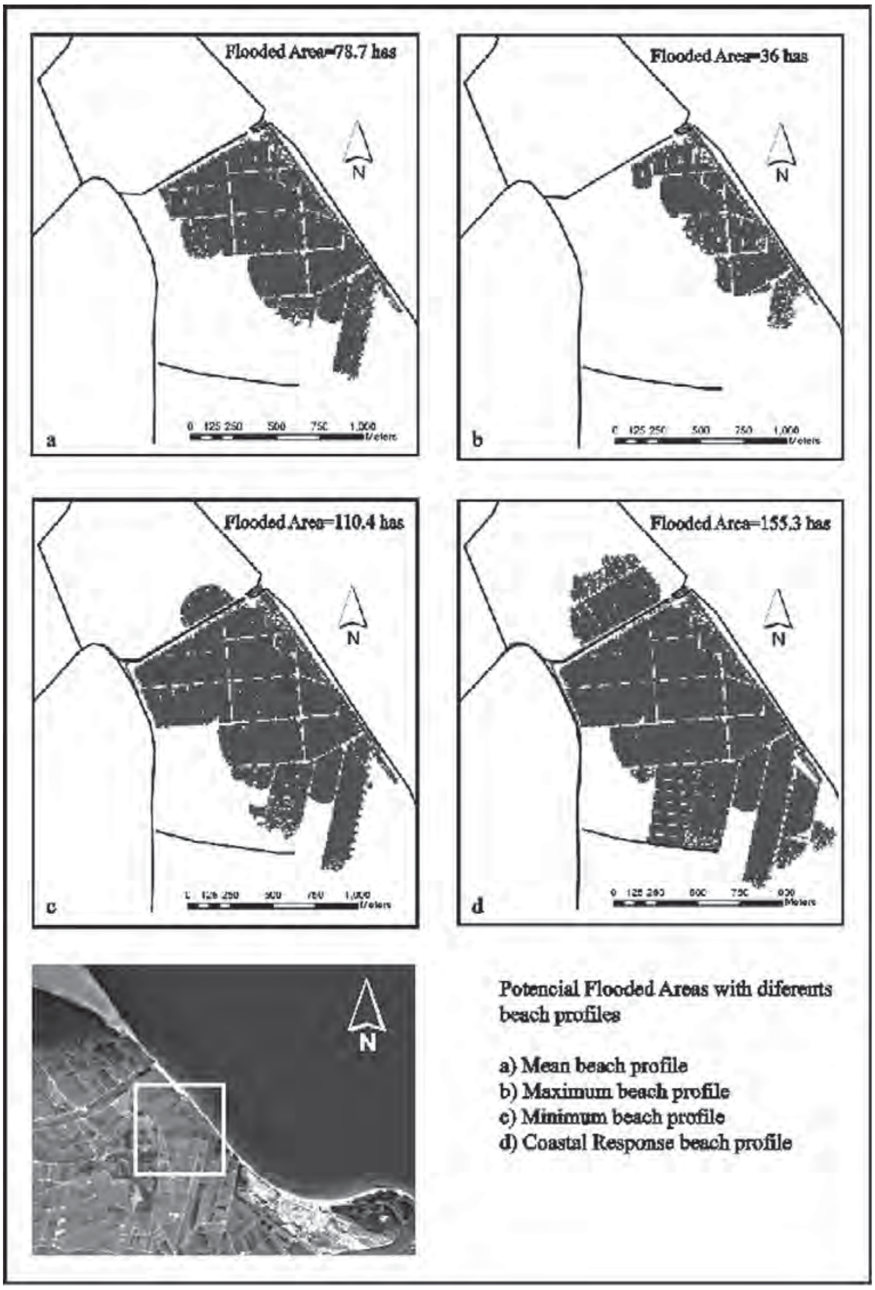

Figure 9. Delineation of flood hazard areas in the northern part of the Ebro delta as a function of the definition of the beach morphology.

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area with a confidence band, i.e. an "average" value given by figure 9a that could vary between a minimum value given by figure 9b and a maximum one given by figure 9c. The decision on what surface has to be selected would depend on the purposes of the analysis and in the level of "safety" to be imposed. As an example, if we want to be in the conservative side, the situation associated to the minimum beach profile (maximum affected surface) should be selected.

Even including this "statistical beach evolution", the extension of the flood has been calculated assuming the beach is not modified during the storm impact. When this response is incorporated as described in section 2, the surface of the flood hazard area increases up to 155 ha (figure 9d and table 4). If the previous calculated values showed the importance of the proper selection of the pre-storm morphology, this result stresses the importance of including the morphodynamic feedback in coastal flood hazard mapping. In this case, the inclusion of the coastal response during the vent determined a significant increase in the volume of water entering to the deltaic plain and, in consequence, the potentially affected surface also increased with respect to the previous calculated worst scenario.

5 CONCLUSIONS

This paper has presented an analysis of the influence of the definition of the beach morphology on flood hazard mapping in sedimentary coastal environments. To do this, a methodology to delimit the uncertainty associated to the beach natural dynamic variability was introduced.

Results showed that the selection of a given initial beach profile from the ones recorded during 4 years, can result in durations of overtopping events varying more than 300%. Regarding overtopping rates, the estimated variation is even larger due to dependence of their magnitude on the freeboard, i.e. the uncertainty is amplified for the volume of floodwaters (we found a peak variation of 1,355%).

With regards to the spatial variability, results showed (for the study area) that the uncertainty introduced in the analysis due to the use of a single representative profile for the entire coast is much lower than the associated to the selection of the beach profile shape.

When the beach evolution during the storm is included, the volume of floodwater entering the coastal plain is significantly larger than for any of the tested static scenarios. This means that any flood hazard mapping in sedimentary coastal environments without including the beach response will significantly underestimate the hazard area. Thus, for the tested case, the extension of the flood hazard area will vary between 36 ha and 110 ha for the static case and, will increase up to 155 ha when considering beach erosion during the storm.

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REFERENCES

Alvarado-Aguilar, D. & Jiménez, J.A. 2007. A pseudo-dynamic approach to Coastal Flood Hazard Mapping. *Proc. CoastGIS 2007*, Santander.

Bates, P.D. & De Roo, A.P.J. 2000. A simple raster-based model for floodplain inundation. *Journal of Hydrology* 236: 54–77.

Bates, P.D., Dawson, R.J., Hall, J.W., Horritt, M.S., Nicholls, R.J., Wicks, J. & Hassan, M.A.A.M. 2005. Simplified two-dimensional numerical modeling of coastal flooding and example applications. *Coastal Engineering* 52: 793–810.

Cañizares, R. & Irish, J.L. 2008. Simulation of storm-induced barrier island morphodynamics and flooding. *Coastal Engineering*, doi:10.1016/j.coastaleng.2008.04.006.

Divoky D. & McDougal, W.G. 2006 Response-based coastal flood analysis. *Proc. 30th ICCE*, ASCE 5291–5301.

Donnelly, C., Kraus, N.C. & Larson, M. 2006. State of knowledge on measurement and modelling of coastal overwash. *Journal of Coastal Research* 22: 965–991.

Fassardi, C. 2006. The definition of wave setup and runup using a response based approach. *Proc. 30th ICCE*, ASCE. 1800–1811.

FEMA. 2003. *Guidelines and specifications for Flood Hazard Mapping Partners.*

Guedes-Soares, C., Weisse, R., Carretero, J.C. & Alvarez, E. 2002. A 40 years hindcast of wind, sea level, and waves in European waters. *21st Int. Conf. OMAE*, Oslo, 1–7.

Jiménez, J.A., Sallenger, A. & Fauver, L. 2006. Sediment transport and barrier island changes during massive overwash events. *Proc. 30th ICCE*, ASCE, 2870–2879.

Jiménez J.A., Sánchez-Arcilla, A. & Valdemoro, H.I. 2005. Storm impacts on the Ebro delta coast. *FLOODsite Research Report.*

Jiménez, J.A., Gracia, V. & Valdemoro, H.I. 2008. The Ebro delta coastal response during 2001–2004: a proxy of the potential effects of an increase in storminess? *Int Symposium on Effects of Climate Change on the World's Oceans*. PICES, Gijon.

Jiménez J.A., Sánchez-Arcilla, A., Valdemoro, H.I., Gracia, V. & Nieto, F. 1997. Processes reshaping the Ebro delta. *Marine Geology* 144: 59–79.

Kraus, N.C. & Hayashi, K. 2005. Numerical morpholotical model of barrier island breaching. *Proc. 29th ICCE*, ASCE, 2120–2132.

Larson M. & Kraus N.C. 1989. *SBEACH: Numerical Model for Simulating Storm-Induced Beach Change*, CERC-89-9, US Army Corps of Engineers, Vicksburg.

Larson, M., Donnelly, C. & Hanson, H. 2005. Analytical modeling of dune response due to wave impact and overwash. *Coastal Dynamics 2005*, ASCE.

Morton R.A. 2002. Factor Controlling Storm Impacts on Coastal Barriers and Beaches—A preliminary Basis for Near Real-time Forecasting. *Journal of Coastal Research* 18: 486–501.

Owen M.W. 1980. *Design of seawalls allowing for wave overtopping.* HR Wallingford, Report EX 924.

Sallenger, A. 2000. Storm impact scale for barrier islands. *Journal of Coastal Research* 16: 890-895.

Stockdon, H.F., Holman, R.A., Howd, P.A. & Sallenger, A.H. 2006. Empirical parameterization of setup, swash, and runup. *Coastal Engineering* 53: 573–588.

Tuan, T.Q., Stive, M.J.F., Verhagen, H.J. & Visser, P.J. 2008. Process-based modeling of the overflow-induced growth of erosional channels. *Coastal Engineering* 55: 468–483.

Wise, R.S., Smith, S.J. & Larson, M. 1996. *SBEACH: Numerical model for simulating storm-induced beach change*, CERC, US Army Corps of Engineers, Vicksburg.

Chapter 9: The Ebro River Delta Coast

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1. Introduction

The Ebro delta is located on the Spanish Mediterranean coast about 200 km southward of Barcelona. It has an approximate subaerial surface of 320 km^2 and a coastline length of about 50 km (Figure 1). It is an ecologically rich environment and it includes a Natural Park of 7,800 ha giving administrative protection to areas of high environmental value, including habitats like freshwater, brackish and saline lagoons, salt marshes and coastal and small dune sandy areas. At the same time, it is actively exploited by means of agriculture, mainly for rice production (about 66% of the total subaerial surface is devoted to rice production and between 10% and 15% to other crops) and it provides support for a significant percentage of the fishing and aquaculture activities in Catalonia. The population is about 50.000 inhabitants, including people living in the delta itself and people with a direct economic dependence on it.

The extensive damming in the Ebro catchment basin has reduced the overall sedimentary supply to the deltaic system during the second half of the 20^{th} century. As a result of this, the delta has evolved from accretion to stability in terms of subaerial surface, although experiencing strong reshaping processes (e.g. Jiménez and Sánchez-

Arcilla, 1993; Jiménez et al. 1997; Guillén and Palanques, 1997). Moreover, this sediment supply cut-off should produce a decrease in the relative land elevation due to the inexistence of river floods able to distribute sediments along the deltaic plain to compensate relative sea level rise in the area.

Figure 1. The Ebro delta. Red polygons indicate most vulnerable areas to storm impacts.

Although many studies have been done in the Ebro delta related to coastal evolution from different standpoints, none of them specifically deals with the impact of flood events. Taking into account that about the 50% of the subaerial deltaic surface is comprised between the mean sea level and the height +0.5 m above MWL, it seems clear that the area should be extremely vulnerable to this forcing.

Coastal floods in the Ebro delta are mainly originated by two main agents: RSLR and the impact of storms. The first one is a long-term process in which the difference between projected sea level and deltaic elevation will drive the inundation of low-lying areas in a permanent manner. The second one is a transient process integrating the result of beach and dune erosion and overwash. A first estimation of the vulnerability to these processes was done by Sánchez-Arcilla et al. (1998; 2007) who identified the main areas along the coast prone to be affected and also made a first estimation of the expected physical impacts. However, these authors did not quantitatively estimated storms-induced flood hazards and, their study did not directly consider environmental and/or societal impacts.

Storm impacts on the Ebro delta coast usually occur under the coexistence of surged water levels due to the passage of low pressure systems off the delta coast and eastern wave storms (e.g. Jiménez et al. 1997). Although the entire deltaic coast is subjected to the action of these events, most vulnerable stretches are those subject to relatively large long-term erosion rates, resulting in a beach configuration characterised by a narrow and low emerged beach with a "low-crested" bar or bar system in front. The most sensitive areas are (figure 1): (i) Illa de Buda at the central lobe; (ii) Trabucador beach at the Southern hemidelta and (iii) Marquesa beach at the Northern hemidelta. These areas have been identified taking into account the magnitude of their morphodynamic response (Jiménez et al. 2005) and the frequency of reported damages due to storm impacts during the last decade (Generalitat de Catalunya, 2004).

The induced "coastal damages" occurred in situations characterized by (i) affectation of agriculture lands by inundation (local owners being the receptor of the damage), (ii) affectation of natural values due to storm impacts – wave exposure or inundation - (Natural Park being the receptor of the damage), (iii) impulsive coastal

erosion of very large magnitude. Figure 2 illustrates the potential affectation of agriculture lands after the impact of extreme storms, when overwash deposits are observed in the rice pads closest to the shoreline.

Figure 2. Overwash deposits in rice pads along the Marquesa beach after the impact of a storm on November 2001.

Taking into account the above mentioned expected physical vulnerability of the Ebro delta to floods and the existence of important natural values and a high level of human pressure exerted on the system, it become evident the need to assess the impact of coastal floods on the Ebro delta coast taking into account not only physical terms but also environmental and socio-economic ones. Thus, the main objective of this work is to examine vulnerability, risk and defence needs against flooding of marine origin at the Ebro delta coast.

2. Methodology

General approach

To achieve the objectives of this work, the general methodology developed within the FLOOD*site* project was adapted to specific characteristic of the study area. Figure 3 shows the FLOOD*site* source-pathway-receptor approach applied to delineation of flood hazard areas in coastal sedimentary environments due to the impact of extreme events.

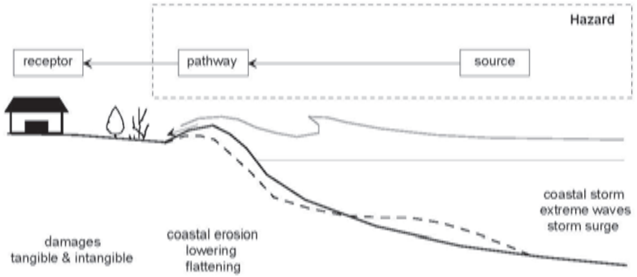

Figure 3. Source-Pathway-Receptor model for Coastal Flood Hazard Mapping (Jiménez et al. 2008).

Sources refer to marine forcings inducing the flood event. In this work we have selected two flood risk sources, one associated to long-term processes which is given by RSLR and, other one associated to episodic/extreme events which is given by storm impacts.

Pathways refer to processes leading to coastal flooding induced by the agents mentioned before. Since the Ebro delta coast is a dynamic sedimentary environment, here we consider two processes: inundation and erosion.

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The characterization of the *Receptor* refers to the estimation of the flooding effects in the territory. Due to the high natural values of the Ebro delta we have specifically included the assessment of the ecological impact of coastal floods. In addition to this, the local perception of stakeholders to flood risks was also investigated.

In what follows the main methodological aspects used in the different parts of this study are outlined.

Flooding due to RSLR

At the long-term scale, flood hazard areas in the Ebro delta induced by RSLR have been delineated by estimating the deltaic surface lying below a given projected water level with a direct connection to the sea. Although theoretically, deltaic environments are able to cope to SLR this will only occur for deltaic plains able to vertically accrete mainly due to river sediment supplies (see e.g. Day et al., 1997). However, this is not the case of the Ebro delta since the entire plain is occupied by humans (settlements and economic activities such as agriculture) and this forces the water authorities to fully prevent inundation by regulating river flows.

Due to this, the delta is assumed to behave as a passive floodplain separated from the sea by a fringe which is active along the outer coast (which is formed by sand and able to attain a long-term equilibrium profile) and passive along the inner coast in the bays (where is composed by fine materials and sands sheltered from wave action).

The topography of the entire Ebro delta used in this work consists of a DEM derived from LIDAR data obtained by the Institut Cartogràfic de Catalunya. The original DEM has a resolution of 1 m x 1m and it was re-sampled to a grid of 5 m x 5m.

To delineate the floodplain areas to be inundated we took into account the different behaviour of outer and inner coastlines. Passive inner coastlines will maintain

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their absolute elevation and, thus, sites with an original elevation lower than the RSLR scenario will be inundated. On the other hand, active outer coastlines will maintain their relative elevation because we assume they will react to RSLR as predicted by Bruun's rule, i.e. maintaining constant their elevation with respect to sea level. Along these coastlines we also take into account the possibility to be temporarily connected to the sea due to the impact of extreme events. This is done by estimating the long-term distribution of beach erosion and overwash events in different stretches along the deltaic coast by using a dune erosion-overwash analytical model (Larson et al., 2009).

The RSLR scenario used in this work was +0.50 m which should include the contribution of the climate-change eustatic component and a local component due to subsidence (see e.g. Sánchez-Arcilla et al. 2008).

Flooding due to storm events

At the episodic scale, flood hazard areas in the Ebro delta due to the impact of coastal storms were delineated by estimating the deltaic surface temporarily affected by overwash (landward) flows over the beach during a storm. To do this, a specific methodology to map flood hazard coastal areas taking into account their morphodynamic response to storm action was developed (see Alvarado and Jiménez, 2008) which is outlined in figure 4.

The first step consists in the estimation of a total water level at the shoreline. This is done by using the response-method approach, which is based directly on measured or simulated water levels and waves as they occur in Nature and, the water level of interest (associated to a given probability or return period) being directly calculated from a probability distribution of total water levels (see e.g. Divoky and McDougal, 2006). In this analysis the model proposed by Stockdon et al (2006) is used

to estimate the wave-induced runup in beaches. The obtained values are then added to simultaneous water level data (ζ_m) to build the total water level time series (ζ_t) which is then fitted to an extreme distribution to estimate water levels associated to given probabilities or return periods.

Figure 4. Methodology to generate a coastal flood hazard map for sandy coasts.

Once we have estimated the total water level, the following step is to calculate overtopping rates (Q) for those cases where water level exceeds the beach/barrier crest. This will determine the volume of floodwater penetrating the hinterland and, in consequence, determining the extension of the flood hazard area. The overtopping volume has been calculated following the method used by Fema (2003) to estimate the inundation in low-lying coasts.

A critical issue of mapping coastal areas prone to be inundated during storms is the inclusion of beach morphodynamics. Beach configuration controls the magnitude of the run-up (via beach slope) and overtopping (via beach/dune crest height). Because beaches are continuously reacting to driving factors, especially during storm impacts, to properly map coastal flood hazard areas beach dynamics have to be incorporated to the analysis (see e.g. Alvarado and Jiménez, 2008).

This is here included by simulating the beach profile response during the storm action by using the SBEACH model (Larson and Kraus, 1989; Wise et al., 1996) which has successfully been used to simulate the dune lowering before the inundation of the hinterland during the impact of extreme storms (see e.g. Cañizares and Irish, 2008). Once the beach profile evolution during the event is calculated, intermediate configurations from the pre-storm situation to the post-storm one are used to update the wave-induced run-up and overtopping rates according to the time-dependent beach slope and crest height.

Finally, once water levels and beach configurations are known, the last step is to determine which part of the coastal plain is flooded. This is done by using the LISFLOOD-FP inundation model (see model description in Bates et al., 2005). The model predicts water depths in each grid cell at each time step, and hence can simulate the dynamic propagation of flood waves over fluvial, coastal and estuarine floodplains. In our analysis we specify the data input as a time series of water flow at the shoreline bordering the deltaic plain (calculated through the overtopping rates).

In this work, we analyze deltaic flooding due to the impact of an extreme storm with a return period of about 100 years. This storm impacted the coast in November 2001, and it was fully recorded by a wave buoy off the delta, being the most energetic storm ever recorded at the Ebro delta coast. It was a double peaked storm from the E

with Hs values of 5.6 and 5.95 m at the two peaks and durations (above a Hs threshold of 2 m) of 63 and 38 hours and with Tp values of 13.3 and 11.1 s. Due to this, in this work we used the actual wave and water level data recorded during the storm to illustrate episodic flood risks.

Ecological impact

To determine the effects of sea flooding on vegetation composition in wetlands of the Ebro Delta, the following steps have been carried out (see details in Coops et al., 2007):

- Selection of representative areas in the Ebro Delta.
- Selection of relevant habitat types and species.
- Determination of dose-effect chain: environmental variables - vegetation type.
- Assessment of habitat changes.

In this study, two areas have been selected to analyse the effects of coastal flooding on natural values of the Ebro delta: Illa de Buda and Punta de la Banya (see Figure 1). These areas were chosen because of their expected differences in response to storm floods and sea level rise, respectively and, because they can be considered representative of the main biotopes along the Ebro delta coast. The Illa de Buda features a large coastal lagoon, that is bordered by low lying dunes at the sea side. Consequently, this area is sensitive for an increased occurrence of storm floods. These floods will result in episodic inflow of sea water, which may disrupt the spatial gradient of salinity in the lagoon. In addition, a progressive erosion of the coastal line is taking place at Illa de Buda, which makes this area particularly vulnerable for breaches during storms. La Banya consists of an extensive low-lying salt marsh system. The southern most tip of this area has no embankments, and in the absence of storms, is also regularly flooded by the sea. Because of the low soil elevation of La Banya (60% of the area is lower than 0.2 m above sea level) and the absence of levees at the most southern tip, this area is highly sensitive to the effects of sea level rise.

The Ebro Delta has a large number of habitat types and species according to the Habitat and Bird Directive (Natura 2000) for which certain goals have to be met according to the Natura 2000 EU Directive. Therefore, we have focussed on the effects of sea level rise and storm floods for the Natura 2000 habitat types which occur in the selected areas in the Ebro Delta (existing habitat types in Illa de Buda and La Banya can be found in Coops et al., 2007). As an example, Figure 5 shows the distribution of habitats in La Banya spit.

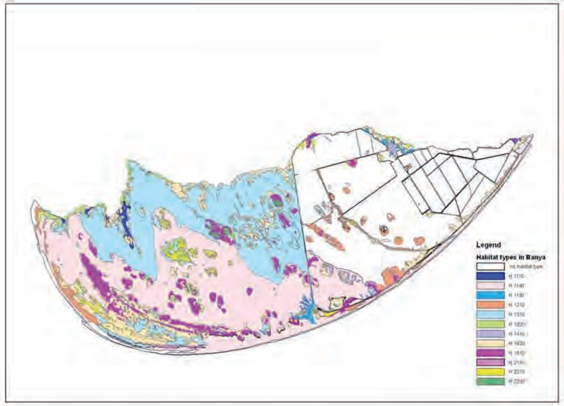

Figure 5. Map of Natura 2000 habitat types at Banya - H1110 Sandbanks permanent covered by sea water; H1140 Mudflats and sandflats intertidal; H1150 Coastal lagoons; H1210 Annual vegetation drift lines; H1310 *Salicornia* and other annuals; H1320 *Spartina* swards; H1410 *Juncus maritimus* salt meadows; H1420 Halophilous scrub (Sarcocornetea); H1510 Salt steppes (Limonietalia); H2110 Embryonic shifting dunes; H2210 Crucianellion maritimae dunes; H2230 Malcolmietalia dune grasslands.

The effects of environmental variables on vegetation composition can be visualized by a "dose-effect" chain. A dose-effect chain describes the relationships between conditional variables, operational variables and their influence on plant distribution patterns. According to this information, predictions can be made how increased flooding frequency and global sea level rise will change the distributions of habitat and/or vegetation types. For the Ebro Delta wetlands, separate dose-effect chains can be produced for:

- terrestrial plants of salt marshes and dunes;
- (semi-)aquatic plants in coastal lagoons.

Alvarez-Rogel et al (2006) presented relationships between plant species dominance and gradients in soil salinity and hydrological conditions for salt marshes and dune systems along the SE Spanish Mediterranean coast.

The identified main factors controlling the environment for plant growth were the depth of the groundwater table and salinity. A shallow water table will result in anaerobic conditions in the root zone that, in combination with extreme salinities, creates an inhospitable environment for plant growth. Furthermore, differences in flooding frequency will play a role, as salinity levels may rise because of increased flooding by the sea. Additionally, the vegetation composition may be affected by salt spray (Barbour, 1978) and sand movement (Morenocasasola, 1986), especially at sites close to the sea.

The preferential zoning of each habitat type was derived separately for Buda Island and La Banya, because the response of vegetation composition to soil elevation differed significantly between these areas. The 'preference' for salinity was based on literature data (Alvarez-Rogel *et al.*, 2006; Phleger, 1971; Haines & Dunn, 1976).

For coastal lagoons, the conceptual framework for macrophyte, phytoplankton, and macro-algae occurrence developed by Menendez et al. (2002) for the Buda lagoon was used. In this study, the spatial distribution of phytoplankton, filamentous macro-algae, and macrophyte species were related to (variations in) salinity and nitrogen content. The two extremes of the salinity gradient were represented by the aquatic macrophyte species *P. pectinatus* (6 – 15 ppt) and *Z. noltii* (12 – 26 ppt), while *R. cirrhosa* grew optimal at intermediate values (range: 10 – 26 ppt). For vegetation stands of *Phragmites australis* (reed beds), soil elevation was derived from overlaying the habitat map and elevation map, while preference for salinity was derived from literature (Mauchamp and Mesléard, 2001).

Risk Assessment

Risk assessment can be defined as the understanding, evaluating and interpreting the perceptions of risk and societal tolerances of risk to inform decisions and actions in the flood management process (Samuels and Gouldby, 2007). In this work, the methodology selected for flood risk assessment combines three different methods: the quantifiable conventional approach to risk, the taxonomic analysis of perceived risk and the analytical framework of a spatial multi-criteria analysis (see Raaijmakers et al. 2008).

First, a typology for flood hazards was developed based on individual and/or stakeholders' judgements. Awareness, worry and preparedness are the three characteristics that typify a community to reflect various levels of ignorance, perceived security, perceived control or desired risk reduction. Applying 'worry' as the central characteristic, a trade-off is hypothesized between "worry" and the benefits that various

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societal groups receive from a risky situation. The four types of risk characteristics are depicted in Figure 6.

This trade-off of characteristics was applied in a Spatial Multi-Criteria Analysis (SMCA) where risk perception-scores were used as weights in a standard MCA procedure. Finally, local risk perception in the Ebro delta was characterized by an on-site survey to stakeholders who were selected to represent the main economic activities and functions in the delta. Seven individuals representing the following groups of stakeholders have been interviewed:

- The rice producers *Agrupation* (RP), a co-operative of rice farmers established in 1985 with about 2000 associates.
- The water distribution co-operative *Communidad Regantes* (WD) , which is responsible for the fair distribution of fresh water of the river Ebro to rice farmers, including local water policy and water planning.
- The salt manufacturer (SM) who extracts salt on the Trinidad Salt pans on the La Banya spit. This salt extraction is vital for the pink flamingo population in the wildlife park. The extracted salt is transported by lorries along the Trabucador barrier, which is vulnerable to breaching during storm events.
- The restaurant at the Marquesa beach (RM). During the last years, the building is frequently damaged by the impact of storms.
- The local tourism organisation (TO) is prevailingly aimed at eco-tourists attracted by the Ebro delta Natural Park and beaches.
- The town council of Sant Jaume d'Enveja (TC), one of the coastal communities in the delta, being one of the centres of fishery and aquaculture in the region.
- The Department of Coasts (CE) of the Ministry of Environment which is responsible for coastal zone management.

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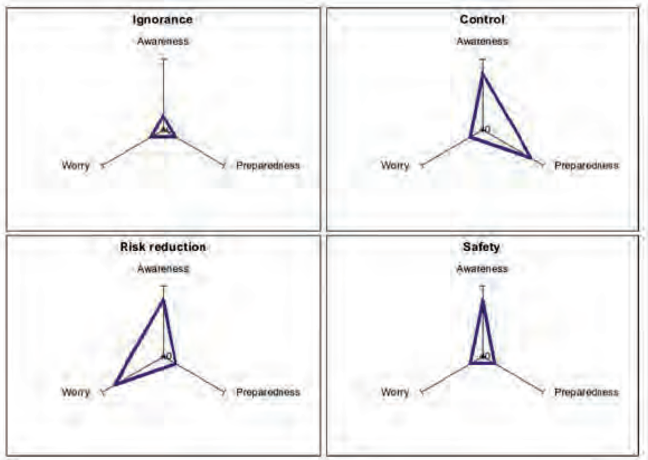

Figure 6. Typologies of risk characteristics (Raaijmakers et al. 2008).

3. Results

Deltaic inundation due to RSLR

Figure 7 shows the deltaic area subject to flood hazards due to a RSLR of +0.50 m. The calculated hazard surface was about 13000 ha, which corresponds to approximately 44 % of the deltaic surface. Figure 7 also classified the delineated hazard areas in different levels taking into account their "connectivity" to the sea.

Risk level 1 refers to areas with a direct connection to the sea and fronted by a passive coast, i.e. a coastal fringe not able to respond to RSLR (mainly the coastal fringe along the N and S bays). The consequence of this static behavior is that they will be "instantaneously" inundated.

Risk level 2 corresponds to areas presently protected by an active beach (able to respond to RSLR and, in consequence, maintaining their relative height with respect to MWL) but fronted by a coastal stretch subject to erosive processes and having suffered significant overwash events during the last decade. This is illustrated in Figure 8 where the calculated empirical long-term distribution function for the overwash volume in the Marquesa beach (Northern hemidelta coast) is presented. Results show that due to the low dune elevation at the back of the beach, frequent overwash is predicted to occur at this site. For the analyzed long-term wave climate (1957-2001), calculations identified the November 2001 storm as the most erosive event, leading to an erosion of more than 90% of beach volume and producing a significant beach breaching.

Risk level 3 areas are "isolated" from the other ones by the barrier effects of structures such as levees and roads. They could be efficient in the short term (e.g. temporary floods) but their role in controlling inundation will not be efficient in the long-term (e.g. climate change–induced) unless protected areas are converted to polders.

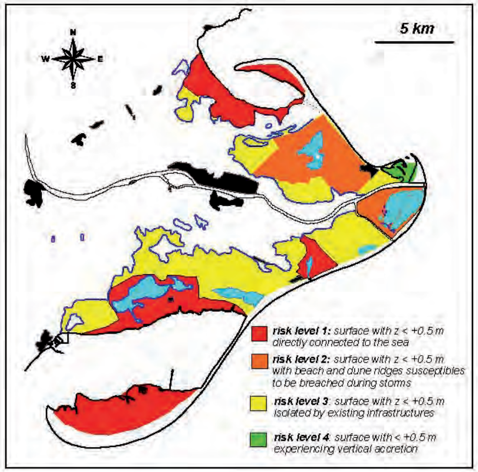

Figure 7. Top: Flood hazard map of the Ebro delta for a RSLR of +0.50 m (blue areas within the delta). Bottom: Classification of hazard areas in function of their connectivity.

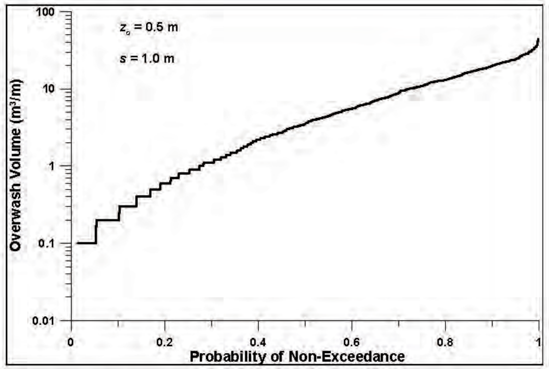

Figure 8. Empirical distribution function describing the probability of non-exceedance for a specific overwash volume during a storm event attacking La Marquesa beach.

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One of the implications of the obtained hazard areas is that, most of the "official" highly valued natural areas will be affected by this long-term scale inundation. This is due to the fact that the Natural Park extends along the entire deltaic coast (including both semi-enclosed bays) and, in consequence, one of the most affected values will be the natural one. Thus, it is expected that the 90 % of the wetland surface will potentially be affected by RSLR. In a next section, the ecological impact will be detailed assessed for two representative areas.

Deltaic inundation due to the impact of coastal storms

Figure 9 shows the flood hazard area delineated for the impact of the target storm along the Northern part of the Ebro delta. This area is selected because it is where rice pads are closest to the shoreline resulting in narrow beaches backed by the (rigid) contour of rice pads. As it can be seen, the inundated area is not continuous along the coast but it concentrates along the narrowest parts of the beach. In these areas, the impact of this storm led to significant beach and dune erosion resulting in massive local overwash events (figure 2) driving floodwaters towards the hinterland.

The shape of the hazard areas is controlled by the existing networks of channels and dikes (which will distribute the floodwater across the plain) delineating the rice pads. Here we have not considered the possibility to close some of the channels to avoid inundation which would also reduce its extension.

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Figure 9. Flood hazard map for 100 years return period storm in the northern part of the Ebro delta (blue areas within the delta).

The estimated total extension of the flood hazard area is 252 ha from which a non negligible part will be inundated by a very small volume of floodwater resulting in a few cm water level. The inclusion of the beach evolution during the event resulted in a significant increase of overtopping rates with respect to the case of representing the coastal fringe by a static beach. Alvarado and Jiménez (2008) estimated an increase in overtopping rates up to 70% when compared to the ones calculated for the beach characterized by the minimum recorded elevation. This means that even when selecting the worst scenario for static-oriented (minimum elevation) flood hazard analysis in low-lying coasts, the volume of floodwater entering the coastal plain would be significantly underestimated.

As it can be seen in figure 9, the main value to be potentially affected by this temporary inundation is economic, since hazard areas consist of agriculture lands. In spite of this, it has to be considered that most of extreme storm impacts in the Ebro delta

have been recorded in late autumn, later than the end of the collection of the crop. In consequence, the direct affectation of crops by floodwaters is not likely to occur. However, the impact of earlier extreme storms could affect the area during the last stages of crop collection (September) and, under those conditions the economic damage could be very high.

Ecological impact

Both flooding scenarios were analyzed to assess the ecological impact in the identified hazard deltaic areas. This was done by using information extracted from existing maps of vegetation types in Illa de Buda and La Banya areas. From here we derived a vegetation – elevation model which was used to predict the spatial distribution of vegetation under the new (flooded) conditions.

From the two analyzed scales, it appears that in the long-term case RSLR will have the strongest impact on ecosystems in the Ebro Delta. A sea-level rise of 50 cm will lead to the "drowning" of most low-elevation habitats and a further salinisation of freshwater and brackish habitats, resulting in a strong increase of non vegetated, shallow flooded areas.

In addition, the increased frequency of flooding by the sea may also affect vegetation composition, especially if this results in increased salinity levels of the soil. Vegetation in coastal lagoons and freshwater inland wetlands will be primarily influenced by increased frequency of flooding by the sea (due to higher salinity levels, Valdemoro et al. 2007). Of the submerged lagoon vegetations, freshwater types may disappear and the brackish (*Ruppia*-dominated) vegetation type may expand in cover (Menendez et al., 2002). Reedbeds may further decline when inundation with saltwater becomes more frequent. Increase in sea water level will probably not affect the average water level in wetlands when there is active water management (pumping water in and out). If not managed actively, water depth will increase at the expense of submerged and emergent vegetation density.

The changes in vegetation pattern due to sea-level rise will imply severe habitat loss for many characteristic bird species of salt marshes and freshwater habitats, because many of these species are highly dependent on habitat types at low elevations. Table 1 shows an example of estimated habitat changes due to sea level rise in the delta.

		zone	La Banya	Buda	Ebro Delta (national Park)
H1110	Sandbanks perm. covered by sea water	-0.2 – 0	--	+	0
H1140	Mudflats and sandflats intertidal	-0.2 – 0.2	--		-
H1150	Coastal lagoons	< -0.2	0	-	-
H1210	Annual vegetation drift lines	0 – 0.2	-		-
H1310	*Salicornia* and other annuals	0 – 0.2	--		--
H1320	*Spartina* swards	0.2 – 0.5	--	--	--
H1410	*Juncus maritimus* salt meadows	0.5 – 0.7	--	--	--
H1420	Halophilous scrub (Sarcocornetea)	0.2 – 0.5	--	--	--
H1510	Salt steppes (Limonietalia)	0.5 – 0.7	--	-	--
H2110	Embryonic shifting dunes	> 0.5	-	0	--
H2210	Crucianellion maritimae dunes	> 0.5	--		--
H2230	Malcolmietalia dune grasslands	> 0.7	--		--
H92D0	Riparian galleries and thickets	--			0
53.111	aquatic reed beds	-0.2 – 0.2		--	--

+ increase, 0 stable (± 10%), - decline (10-50%), -- strong decline (> 50%)

Table 1. Qualitative changes in surface area of elevation height classes and corresponding Natura2000 habitat types (inclusive aquatic reed beds) as a result of 0.50 m SLR.

Temporary inundation due to the impact of storms will have a minor impact on deltaic ecosystems since coastal habitats are usually able to cope with these pulsing events. The only exception would be in the case when the probability of occurrence of these flood events increases in the future in such a way that the volume of (sea) floodwater entering coastal lagoons significantly increases leading to a change in water salinity.

Flood risk perception

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Figure 10 shows the flood risk perception of the different stakeholders in the Ebro delta. From the performed interviews one of the main differences detected between public and private stakeholders is their level of worry. In general, private stakeholders are generally more worried than public ones. From the interviews it was concluded that the common population was relatively unaware about what to do in case of a flooding. On the other hand, individuals from authorities who were involved in the development of land use plans were highly aware of such risks. To find an expression for the awareness of flood risk, the respondents were questioned about their current knowledge of the November 2001 flood event and to judge the current hazard of flooding for the coastal zone. Answers to both questions indicated no difference in comparison to the awareness of flooding experts. For preparedness, a similar approach was taken and, again, only public authorities declared to be prepared.

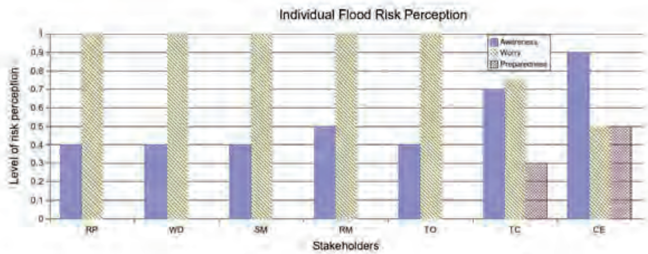

Figure 10. Individual scores on risk perception of stakeholders in the Ebro delta. Stakeholders corresponding to acronyms are described in the methodology section.

Figure 11 shows the average score of all stakeholders to risk characteristics in the Ebro delta. This served as an input into the MCA computations. Non-governmental stakeholders indicated a strong demand for risk reduction expressed in high levels of worry and awareness concerning the threat of flooding. This is reflected in the

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difference in "level of worry" between experts (CE) and local policy makers (TC) (score 0.5 and 0.75 respectively) on the one hand, and lay people on the other one (score 1) (figure 10).

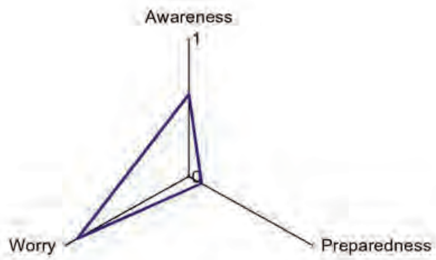

Figure 11. Average risk characteristics in the Ebro delta.

This methodology was applied to two land use scenarios for the Ebro Delta and compared with the "base" year. The two alternatives are the Business As Usual scenario and the Natural Development scenario. This last scenario is built by assuming that a strip of about 500 m wide along the coast is "re-naturalized" by abandoning the agriculture lands closest to the coastal fringe which are the presently affected by temporary floods. The combination of different methods of standardizing (maximum and interval) and weighting (risk perception and pairwise comparison) with ranking by weighted summation leads to the conclusion that the Natural Development scenario appears to be the most favorable as a sustainable flood risk management alternative (see Raaijmakers et al., 2008). This result is of course dependent on the weighting and combination methodologies, the assumed climatic scenarios and the considered time scales.

4. Implications for Flood Risk Management

The obtained results in the Ebro delta have a series of implications for managing the territory in the future. The first implication is that short-term flood hazards are limited to some locations along the coast where narrow beaches are present. This is due to the proximity of agriculture lands to the shoreline. Because these areas are also subject to long-term erosion, it is expected that the frequency of events producing temporary floods will increase without considering any climate-induced change simply due to the decrease of beach widths.

Their ecological impact can be considered as negligible since existing coastal ecosystems are able to withstand these pulsating events. However, if the frequency of these events significantly increases, freshwater and brackish wetlands could be affected by a salinity increase due to an increase in the volume of floodwater. In such a case, a habitat succession should be expected towards species more resistant/adapted to higher salinity values.

One of the main values to be affected by these episodic flood events is agriculture. Rice pads located in areas close to the coastal fringe, in zones subject to overwash during extreme storms, will be temporarily inundated. The time lag between the occurrence of extreme storms and cultivation of rice pads makes the direct economic damages to crops to be relatively low. In spite of this, private stakeholders strongly demand a flood risk reduction which was detected in their high levels of worry and awareness concerning the threat of flooding.

Taking into account this perception and the relatively small spatial scale of the problem, an adaptation strategy to inundation is being considered by coastal managers.

This consists of creating a 500 m wide buffer area shoreward of the actual beach along the Northern hemidelta to permit the inundation of the area during storms without affecting agriculture. This fringe will be bought to rice producers and incorporated to the public coastal domain. In addition to this, the innermost boundary of this fringe will be adapted to act as a barrier for inundation of the hinterland by constructing a dune and or sand bank. This strategy is also consistent with the expected impact of long-term flooding scenarios in the Ebro delta since the storm prone areas will be also affected by RSLR. Thus, specific investments in harder measurements to prevent local floods under extreme events could become ineffective in the long-term.

In this long-term scale, flood hazards in the Ebro delta will potentially affect about 40% of the deltaic surface. In this case, both natural an economic values will be modified. The first estimations of the inundation impact in the Ebro Delta due to RSLR predict "catastrophic effects" on coastal wetlands with about 90 % of their surface directly affected by a RSLR of +0.5 m. These catastrophic effects must be understood as a change or shift in the existing habitats along the Ebro delta coast that, consequently, will have to be managed in a different way. Parts of the delta where floodwater can be discharged actively may be protected from drowning as long as the incidence of floods (through levee breaching or overflow) remains within limits. However, the levees (sand ridges) along the delta are presently rather low, so that even a modest increase in sea level may lead to frequent overwash.

This flooding scenario is also indicating that to maintain the cultivation function in the Ebro delta in the long-term scale, it is necessary to have a proactive policy to compensate for the sea-level rise effects, or , alternatively, to accept a move towards polders. Otherwise this activity will eventually become economically unfeasible due to

increased salt water intrusion associated to the sinking of much of the delta plain below sea level.

In addition to this, and regarding the economic implications, it would be also necessary to consider, in a long-term analysis, the maintenance of subsidies which artificially keep the benefits of rice production at present levels. Also, the role of rice fields to supply food for bird living or hibernating in the delta has to be considered to assess the full implications of this potential affectation.

5. Concluding remarks

At the core of this work lies the challenge of assessing flood risks at different scales in a low-lying coast of high natural values which also supports an intensive use by humans. The modification of the system characteristics due to this use is largely responsible for its high vulnerability to flood hazards and its low resilience to cope with floods, especially in the long-term scale.

In spite of the fact that flood induced natural and economic damages can be calculated for different scenarios, one of the remaining problems to be solved is how to compare/integrate them in a "fair" manner. Although stakeholders' perception can be used to determine weights for such integration and also to show preferences for a given management option, the ones considered here can be biased due to the profile of the selected stakeholders. This can be improved by carefully identifying (formal) more representative stakeholders and/or launching an extensive questionnaire in the affected population. In addition to this, another option would be to obtain the right value for the ecosystem goods and services provided by the habitats affected by flood scenarios.

The analyzed Ebro Delta pilot site demonstrates that there is a difference between the demand for risk reduction on the one hand, and the "living with risk while striving for benefits" on the other. In a world with increasing flood risks decision makers have to cope with that paradox if they want to implement an effective land use policy in flood prone areas.

Finally, to put the obtained results in the proper context, it has to be considered that some of the tools used in this assessment are still being improved to more realistically deal with the analyzed problems. Thus, although morphodynamic changes and storm water levels have been coupled, some responses such as breaching are not sufficiently covered.

Moreover, the influence of the morphodynamic response in the long-term scale is only considered in a rough manner. In addition, the uncertainty in the morphodynamic response should be formalised in a similar manner to a fault tree and included in the analysis. Likewise, the methodology developed to assess flood hazard taking into account the social perception has also to be "refined". Moreover, no data to build a damage curve due to inundation exist in the Ebro delta. It is necessary to derive such curve to make a meaningful damage analysis. This can be extended to other part of the analysis such as the ecological impact because some parameters involved in different parts of the methodology have been adjusted or selected by using a limited amount of information.

6. Acknowledgements

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7. References

Alvarado, D. and Jiménez, J.A. 2008. Flood Hazard Mapping for Coastal Storms in the Delta Ebro. *Proc. FloodRisk 2008,* Oxford.

Alvarez-Rogel J, Martínez-Sánchez J J, Blázquez L C, Semitiel C M M. 2006. A conceptual model of salt marsh plant distribution in coastal dunes of southeastern Spain. *Wetlands*, 26, 703-717.

Bates, P.D., Dawson, R.J., Hall, J.W., Horritt, M.S., Nicholls, R.J., Wicks, J. and Hassan, M.A.A.M. 2005. Simplified two-dimensional numerical modeling of coastal flooding and example applications. *Coastal Engineering*, 52, 793-810.

Cañizares, R. and Irish, J.L. 2008. Simulation of storm-induced barrier island morphodynamics and flooding. *Coastal Engineering*, 55, 1089-1101.

Coops, H. , van Geest, G., Jiménez, J.A., Gracia, V. and van Buren, R. 2007. *Case study Floodsite. Sea-level rise and wetland habitats in the Ebro delta.* FLOOD*site* Report T26-07-02.

Day, J.W.Jr., Martin, J.F., Cardoch, L. and Templet, P.H. 1997. System functioning as a basis for sustainable management of delatic ecosystems. *Coastal Management*, 25, 115-153.

Divoky D. qnd McDougal, W.G. 2006 Response-based coastal flood analysis. *Proc. 30th ICCE*, ASCE 5291-5301.

FEMA. 2003. *Guidelines and specifications for Flood Hazard Mapping Partners.*

Generalitat de Catalunya. 2004. *Programa de actuaciones urgentes en las zonas costeras del Delta del Ebro afectadas por los temporales.* Departament de Medi Ambient i Habitatge, Barcelona.

Guillén, J. and Palanques, A. 1997. A historical perspective of the morphological evolution in the lower Ebro river. *Environmental Geology*, 30, 174-180.

Haines, B.L. and Dunn, E.L. 1976. Growth and resource allocation responses of *Spartina alterniflora Loisel.* to three levels of NH4, Fe and NaCl in solution culture. *Botanical Gazette*, 137, 224-230.

Jiménez, J.A. and Sánchez-Arcilla, A. 1993. Medium-term coastal response at the Ebro delta, Spain. *Marine Geology*, 114, 105-118.

Jiménez, J.A., Sánchez-Arcilla, A., Valdemoro, H.I., Gracia, V. and Nieto, F. 1997. Processes reshaping the Ebro delta. *Marine Geology*, 144, 59-79.

Jiménez, J.A., Sánchez-Arcilla, A. and Valdemoro, H.I. 2005. *Effects of storm impacts in the Ebro delta coast.* FLOOD*site* Report T26-05-01.

Jiménez, J.A., Kortenhaus, A., Anhalt, M., Plogmeier, C., Prinos, P. and Sulisz, W. 2008. *Guidelines on Coastal Flood Hazard Mapping*. FLOOD*site* Report T03-08-02.

Larson M. and Kraus N.C. 1989. *SBEACH: Numerical Model for Simulating Storm-Induced Beach Change*, CERC-89-9, US Army Corps of Engineers, Vicksburg.

Larson, M., Donnelly, C., Jimenez, J., and Hanson, H. 2009. Analytical Model of Beach Erosion and Overwash During Storms. *Maritime Engineering*, (in press).

Mauchamp A. and Mesléard, F. 2001. Salt tolerance in *Phragmites australis* populations from coastal Mediterranean marshes. *Aquatic Botany* , 70, 39-52.

Menéndez, M., Hernández, O. and Comín, F.A. 2002. Spatial Distribution and Ecophysiological Characteristics of Macrophytes in a Mediterranean Coastal Lagoon. *Estuarine, Coastal and Shelf Science*, 55, 403-413.

Morenocasasola, P. 1986. Sand movement as a factor in the distribution of plantcommunities in a coastal dune system. *Vegetatio*, 65, 2, 67-76.

Phleger, C.F. 1971. Effect of salinity on growth of a salt marsh grass. *Ecology*, 52, 908-911.

Raaijmakers, R., Krywkow, J. and van der Veen, A. 2008. Flood risk perceptions and spatial multi-criteria analysis: an exploratory research for hazard mitigation. *Natural Hazards*, 46, 307-322.

Gouldby, B. and Samuels, P. 2007. *Language of Risk. Project definitions.* FLOOD*site* Report T32-04-01 (www.floodsite.net).

Sánchez-Arcilla, A., Jiménez, J.A. and Valdemoro, H.I. 1998. The vulnerability and The Ebro delta: morphodynamics and vulnerability. *Journal of Coastal Research*, 14, 754-772.

Sánchez-Arcilla, A., Jiménez, J.A. and Valdemoro, H.I. 2007. The vulnerability and sustainability of deltaic coasts. The case of the Ebro delta, Spain. In: McFadden, L., Nicholls, R. Penning-Rowsell, E. (Eds), *Managing Coastal Vulnerability*, 79-94, Elsevier.

Sánchez-Arcilla, A., Jiménez, J.A., Valdemoro, H.I. and Gracia, V. 2008. Implications of climatic change on Spanish Mediterranean low-lying coasts: The Ebro Delta case. *Journal of Coastal Research*, 24, 306-316.

Stockdon, H.F., Holman, R.A., Howd, P.A. and Sallenger, A.H. 2006. Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, 53, 573–588.

Valdemoro, H.I., Sánchez-Arcilla, A. and Jiménez, J.A. 2007. Coastal dynamics and wetlands stability. The Ebro delta case. *Hydrobiologia*, 577, 17-29.

Wise, R.S., Smith, S.J. and Larson, M. 1994. *SBEACH: Numerical model for simulating storm-induced beach change*, CERC, US Army Corps of Engineers, Vicksburg.

Participation in symposia

- FLOODRisk 2008. The European Conference on Flood Risk Management. Research in to Practice. 30 September – 2 October 2008. Oxford UK. Short presentation and poster “Flood Hazard Mapping for Coastal Storms in the Delta Ebro”.
- Grenoble Workshop. Young Floodsite Meeting. Presentation of: An Approach to Coastal Hazard Mapping. Grenoble France 13 February 2008.
- 5th FLOODsite Project Workshop 2008. Grenoble Workshop - Review of Pilot Studies. Grenoble, France 12-14 February 2008
- ECO-IMAGINE (European Conferences and forum for Integrated coastal Management and Geo-INformation rEsearch). Final Conference: “Future Perspectives of GI for ICM”. Presentation of: “An Approach to Coastal Hazard Mapping”. 21 - 23 November 2007.
- COASTGIS07. 8th International Symposium on GIS and Computer Mapping for Coastal Zone Management. Santander, España, 8-10 October 2007. Presentation of: “A pseudo-dynamic approach to Coastal Flood Hazard Mapping”.
- BEACHMED. BEACHMED-e INTERREG IIIC. 6th Steering Committee/Components Phase B Conference Components 3 & 4. Barcelona 29 Junio 2007.
- European Symposium on Flood Risk Management Research. Poster: ‘Evaluation of Risk and Vulnerability to Floods in the Coastal Zone’ in Dresden Germany 6 & 7 February 2007. Poster en anexo
- 4th FLOODsite Project Workshop 2007 en Dresden Alemania.(5 y 8 de febrero 2007)
- ECO-IMAGINE (European Conferences and forum for Integrated coastal Management and Geo-INformation rEsearch). Thematic Conference: THE WATERFRONT MANAGEMENT AND GI. Genoa (IT) y presentation: ‘Evaluation of the Risk and Vulnerability to Floods in the Coastal Zone’., 14 - 18 November 2006.
- ECO-IMAGINE (European Conferences and forum for Integrated coastal Management and Geo-Information rEsearch). Thematic Conference: BUILDING COASTAL KNOWLEDGE AND GI. Cork (IE). Poster ‘Evaluation of the Risk and Vulnerability to Floods in the Coastal Zone’. 13–17 June 2006.

EVALUATION OF THE RISK AND VULNERABILITY TO FLOODS IN THE COASTAL ZONE

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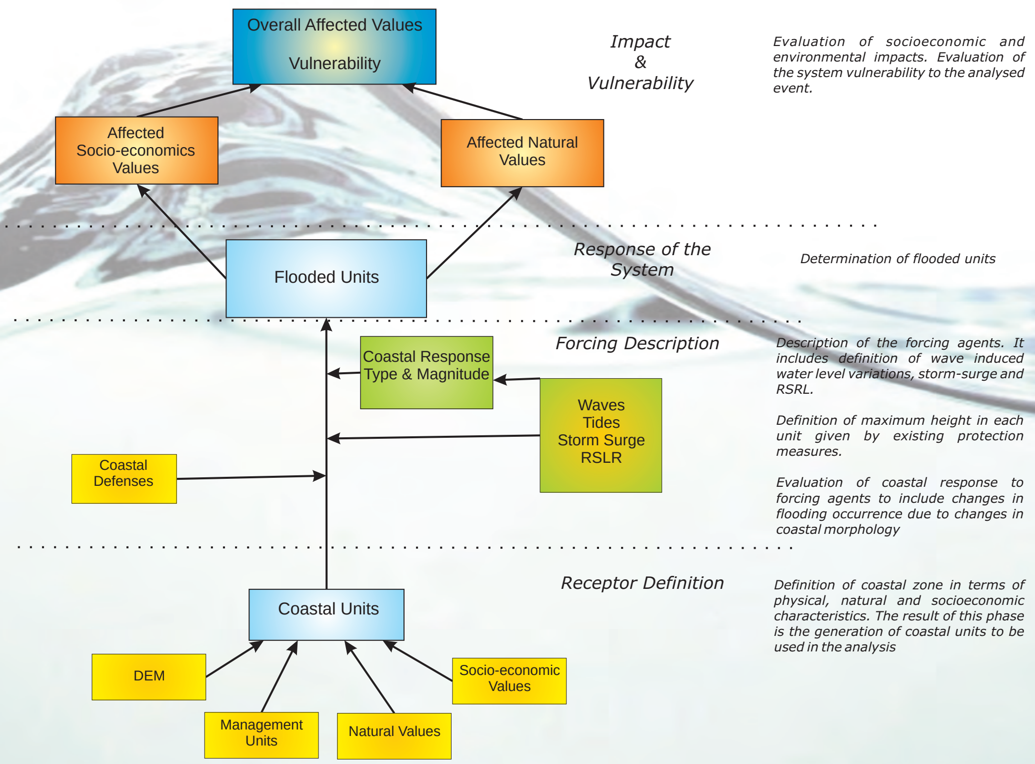
Flood Hazard mapping is a worldwide need for all the nations with low-lying areas subjected to the impact of flood events. Flood management agencies usually have to build and maintain coastal and flood defences and associated infrastructures such as barriers and gates to protect the hinterland. Due to this, most of nations have launched programmes for identifying flood prone areas and, in the best of the cases they have also defined procedures to be followed to produce hazard maps in order to define protection needs and to take decisions. However, there is not a standard approach and, in fact, many countries have not implemented any specific programme. Due to this lack of harmonization, the EC is preparing a new directive on the assessment and management of floods where flood risk mapping is one of the main tools to be developed.

The main aim of this work is to develop and test a general methodology to evaluate the vulnerability of low-lyins coastal areas to floods of marine origin. One of the main improvements of this work with respect to the existing ones is the inclusion of the dynamic behaviour of the coastal fringe. Figure 1 shows an outline of the methodology to be developed.



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Laboratori d'Enginyeria Marítima
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FLOODsite

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Flood Hazard mapping is a worldwide need for all the nations with low-lying areas subjected to the impact of flood events. Flood management agencies usually have to build and maintain coastal and flood defences and associated infrastructures such as barriers and gates to protect the hinterland. Due to this, most nations have launched programmes for identifying flood prone areas and, in the best case they have also defined procedures to be followed to produce hazard maps in order to define protection needs and to make decisions. However, there is not a standard approach and, in fact, many countries have not implemented any specific programme. Due to this lack of harmonization, the EC is preparing a new directive on the assessment and management of floods where flood risk mapping is one of the main tools needed to

Objetive

The main aim of this work is to develop and test a general methodology to evaluate the vulnerability of low-lying coastal areas to floods of marine origin.

Risk Sources

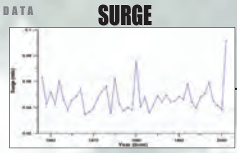
This part of the work is the identification and characterisation of risk sources causing adverse effects (flooding) in the coastal zone, and the probability of occurrence.

The working variable is the total water level at shoreline. This is the sum of two main components, mean water level (tide +storm surge) and wave induced water level.

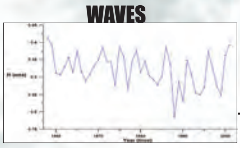
Driving Forces

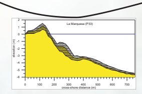
DATA

SURGE

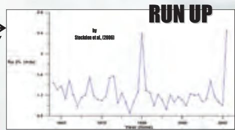


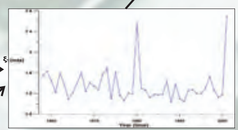
WAVES





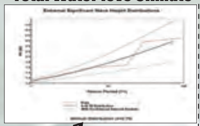
RUN UP





Total Water level

Total Water leve Climate



Risk Pathways

In this part of the work the emphasis is to put on the evaluation of the physical consequences of the coastal storm, i.e. erosion and flooding.

The first step is to evaluate the flooding probability of the area taking into account the existing morphology. Although this is a static approach is posible to introduce some kind of dynamics by including the existing knowledge in local coastal response (e.g. observed variability in beach profiles protecting the hinterland).

The second step should be to evaluate the beach response to the selected storm and to estimate the inundation of the area after considering the beach modification(Beach lowering & flatening & coastal retreat). This part will be included by parametric modelling of involved processes.

Coastal Response

Coastal Inundation

Modification of the "natural defence /barrier to flooding)

Coastal Lowering

Δx

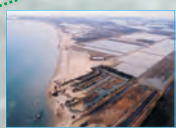
Overwash induced transport dune & beach lowering (parametric, Jimenez et al 2006)

Coastal Response Modelling

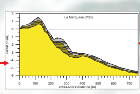
Coastal Retreat

Δz

Beach erosion induced by cross-shore transport (Sbeach)



Beach Profile Modelling



Max elevation Beach profile	T_R RunUp 2%	T_R RunUp 2%+Surge
Zmin=0.7 m	-------	-------
Zmed=1.14 m	2 years	-------
Zmax=1.5 m	7 year	5 years

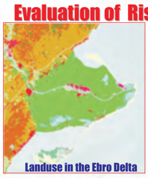
Return periods of the ocurrence of overtopping beach in the Marquesa area due to coastal storms
[without including profile response]

Risk Receptors

This step is to make the quantitative or semi-quantitative estimate of the risk and vulnerability, including attendant uncertainties, and severity of adverse events in a given population under defined exposure conditions based on hazard identification, hazard characterisation and exposure assessment

Evaluation of Risk

Evaluation of Risk and Vulnerability



Landuse in the Ebro Delta

Definition of physical, natural & socio-economic vulnerability Indexes

Idem for Risk
(evaluation of damage functions for natural values)

Mapping

Dagoberto Alvarado-Aguilar was supported by doctoral studies grant of the National Science and Technology Council of México (CONACyt)

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FLOODrisk 2008

FLOOD HAZARD MAPPING FOR COASTAL STORMS IN THE DELTA EBRO

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Flooding in coastal areas results from the combination of a **driving agent**, the storm, acting on a **receptor**, the coast. In sedimentary environments, the induced (significant) morphodynamic response will interact with the storm in such a way that the intensity of the flooding could be affected (enhanced or reduced).

The resulting effect (inundation increase or decrease) will depend on the type and magnitude of beach changes during the storm. So the estimation of the beach morphodynamic response during the storm is a key point not only to calculate the induced erosion, but to properly evaluate flood hazard areas.

Objetive

Propose a methodology to analyze the influence of the inclusion of the beach morphology response in coastal flood hazard mapping (in non-protected areas).

Ebro Delta

Surface: 320 km^2 Coastline: 50 km %Surface <+0.5 m = 50%

Methodology

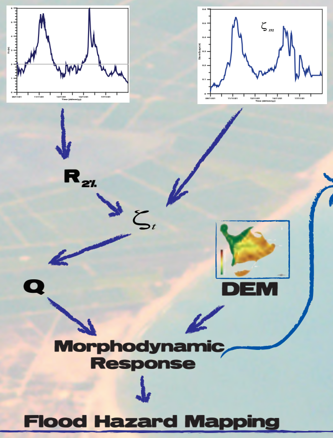
Data:
Waves / Storm Surge

Wave Runup
Stockdon *et al.* (2006)

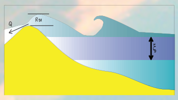
Total water level

Overtopping rates (Q)
FEMA (2003)

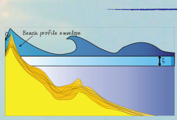
LISFLOOD-FP
(Bates & De Roo, 2000)



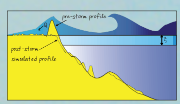
Introducing the coastal morphodynamics



Fixed Beach: The beach is considered as a fixed protecting structure, without any morphodynamic response.



Beach Envelope: it introduces the natural beach variability by considering an envelope of all the existing beach profile data. This should permit to add some kind of confidence band to the calculated floodwater.



Beach Response: by simulating the beach profile evolution during the storm (SBEACH model). The beach response during the storm is used to update the floodwater in selected time steps.

Maximum beach profile

Mean beach profile

Minimum beach profile

Evolving beach profile

Calculated overtopping rates during the storm of November 2001 along the Marquesa beach for different scenarios (peak: at the storm peak; mean: storm-averaged; Flooded area: after 10 hours of continuous overtopping).

Profile scenario	Q peak ($10^{-3}m^{-3}/m/s$)	Q mean ($10^{-3}m^{-3}/m/s$)	Flooded Area (ha)
Mean	16.811	1.978	78
Maximum	6.653	0.073	36
Minimum	32.717	3.947	110
Evolving Beach response	55.736	7.403	155

The inclusion of the beach evolution results in an increase of overtopping rates (about 1.7 times).This means that if the morphodynamic response is neglected the volume of floodwater entering to the coastal plain could be significantly underestimated.

Once the floodwater was estimated for the different scenarios, the delineation of flood hazard areas is done by distributing the water throught the deltaic plain according existing topography.

Conclusions

A methodology to bound the uncertainly in flood hazard mapping in coastal sedimentary environments is proposed.

The selection of an initial beach profile can result in changes in the duration of overtopping events more than 300%. The use of a single representative profile for the entire coast induce less uncertainty than the associated to the selection of the beach profile shape. The volume of floodwater that enters to the coastal plain is significantly larger if we take into account the beach evolution, in comparison to the static scenarios.

Any flood hazard mapping in sedimentary coastal enviroments without including the beach response will significantly underestimate the flood hazard area.

Further reading: D. Alvarado-Aguilar & J. A. Jimènez (2008). Flood Hazard Mapping for Coastal Storms in the Delta Ebro. Proc. FloodRisk 2008

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