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1.   Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) has defined climate change as "*a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods*".

Climate change is widely recognised as a serious threat to the world's environment. In 1995, the Intergovernmental Panel on Climate Change [IPCC 1996a, pp. 4-5] came to this conclusion: "*the balance of evidence suggests that there is a discernible human influence on climate change*" and asserted that Earth's climate is expected to continue to change in the future. There is also common agreement on the fact that these changes are likely to occur at a faster rate than any that have occurred during mankind's recorded history. Tett *et al.* [1999] have recently demonstrated that the increase in the Earth's temperature observed between 1946 and 1996 can be almost totally ascribed to human influences.

Global warming and the consequent variations in climatic conditions and sea level will not be uniform on the planet, but will assume specific regional or local characteristics. Regional or local variations in the relative sea level will depend on various and non-uniform factors, such as natural and human induced subsidence, erosion, sediment supply, glacial rebound, marine circulation and changes in regional and local meteorological conditions. The intensity and distribution of the impacts of climate change will therefore vary from region to region. Even when future changes in climatic conditions are similar, the intensity of the generated impacts may vary from region to region because of the different characteristics and vulnerability of the affected area.

According to the IPCC [1996b, pp. 23-24], vulnerability to climate change can be defined as the "*extent to which climate change may damage or harm a system*". Vulnerability of coastal zones has also been described as "*the degree of incapability to cope with the consequences of climate change and accelerated sea level rise*" [IPCC 1996b, pp. 289-234]. This multi-dimensional concept is directly related to the system's sensitivity and to its capability to adapt to changed conditions. The most vulnerable systems are those with a great sensitivity to climate change and a low adaptability. Sensitivity is "*the degree to which a system will respond to a change in climatic conditions*", for example the extent of the variation in the

composition, structure and functioning of an ecosystem undergoing a temperature or precipitation change. Adaptability refers to "*the degree to which adjustments are possible in practices, processes or structures of systems to projected or actual changes of climate*". Adjustments can be spontaneous or planned, reactive or anticipatory, even if planned and anticipatory options are not possible for all systems. Adaptations may reduce negative impacts and in some cases can even enable some systems to take advantage of the new conditions induced by climate changes. Adaptability depends on resilience and resistance which can be respectively defined as "the ability of a system affected by external forcing factors to return to its previous conditions" and "the ability of a system to avoid perturbation". The definition of the system's vulnerability must necessarily adopt an integrated approach. Vulnerability is, in fact, influenced by many natural and human factors which are not necessarily linked to climate change. Problems such as deforestation or desertification can enhance the sensitivity of a system while poverty, land mismanagement or poor financial and technological resource availability can limit its adaptability. In the assessment of climate change impacts it is, therefore, necessary to take into consideration the future trends of all relevant environmental and socio-economic variables such as those regarding pollution, population, economic development, consumption patterns, land use, and technological advancement [Klein and Nicholls 1998]. This is particularly important when the assessment concerns the socio-economic impact of climate changes which are generally more difficult to predict and model. Some parameters are climate-related and will therefore be influenced by changes in climatic conditions.

In order to obtain information which can be useful for the planning of defensive and mitigating measures in response to climate change impacts it is important that the assessment of a system's vulnerability is performed at a regional or local scale. However, it must be borne in mind that some problems generally affect studies conducted at these scales: limited availability of reliable climate change and sea level rise projections; greater natural variability of climatic conditions; non-uniform distribution of atmospheric aerosol and of its 'cooling' effect; and influence on the climate system exerted by variations in local characteristics such as those concerning land use. Various international research centres (such as the Climatic Research Unit of the University of East Anglia or the Hadley Centre) are attempting to solve these problems and, in particular, to develop advanced techniques for the elaboration of reliable regional and sub-regional climate change scenarios [Goodess and Palutikof 1999].

It is generally accepted that some regions of the world are more vulnerable to climate change than others. The Mediterranean basin is included among these regions [Jeftic *et al*. 1992; Hoozemans *et al*. 1993; Nicholls and Hoozemans 1996; Jeftic *et al*. 1996a]. Its high vulnerability is due to its high sensitivity and to the limited capacity of some Mediterranean regions to adopt defensive and mitigating measures. Furthermore, some areas are already affected by serious problems such as coastal and soil erosion, loss in soil fertility, fire risk, pollution, overpopulation, desertification, water scarcity or water stress, overfishing, wetland loss, drought, land mismanagement, and flood risk, which create critical situations and enhance Mediterranean vulnerability. In particular, Mediterranean coastal systems such as deltas, islands, wetlands, beaches, low-lying coastal plains, and coastal cities, seem to be particularly vulnerable to climate change [El-Raey *et al*. 1995; Capobianco 1996; Sanchez-Arcilla and Jimenez 1997; Jimenez and Sanchez-Arcilla 1997; Timmmerman and White 1997]. Besides causing inundation[1] of low-lying areas which are at present emergent, it is very likely that climate change and sea level rise will not produce new impacts on Mediterranean coastal systems, but will rather intensify or expand existing critical problems (saltwater intrusion, water shortage, flood risk, coastal erosion, desertification, fire frequency).

Notwithstanding their elevated vulnerability to climate change, in the short and medium term (the next few decades) Mediterranean coasts will probably be more affected by impacts produced by other factors such as population growth, intensification of tourism, poor land and water management and rapid coastal development [Georgiades 1998; Georgas 1999; Chiamenti and Ramieri 1999]. However, the medium and long term perspective as well as a proactive approach in coastal planning and management in the Mediterranean basin must take in consideration climate change and its impacts in advance, in order to identify the appropriate measures and policies capable of eliminating or mitigating the induced negative effects. The most effective responses to climate change and sea level rise need to be combined with other planning instruments through an integrated coastal zone management approach [Klein and Nicholls 1998].

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[1] Inundation refers to the permanent submersion of the affected area.

## 2.	Climate change and sea level rise impacts in the Northern Adriatic

The Italian Ministry of the Environment has identified the potential impacts of climate change for the Italian territory [Ministero dell'Ambiente 1998]. Although the work of the Ministry represents a qualitative description of these impacts, it highlights the fragility and vulnerability of some specific areas. The areas which are considered to be particularly vulnerable to sea level rise impacts (such as increase in flood risk, increase in erosion and permanent submersion of low-lying areas) include the zones of the Northern Italian plain characterised by a low elevation (including the Po delta and the Venice lagoon), the coasts of Tuscany, the Tevere mouth, the southern part of Lazio and the Volturno plain in Campania. It is also likely that these areas will be affected by an intensification of saltwater intrusion in freshwater systems, particularly in groundwater.

In this context the Northern Adriatic basin is a particularly vulnerable zone. As far as the Italian shoreline is concerned, this area is characterised by the presence of dynamic coastal systems which are subjected to slow but continuous morphological modifications. These systems include beaches, dune barriers, lagoons (such as those of Venice, Caorle and Grado-Marano and the Valli di Comacchio), the complex Po delta system, reclaimed areas, coastal brackish and freshwater marshes. The elevation of this coastline rarely exceeds two meters and, due to the effects of natural and human induced subsidence as well as eustacy, various zones presently lie below the sea level. Natural subsidence is mainly caused by the natural compaction of sediments and partly by local tectonic adjustment. The anthropic subsidence has been principally induced by the overexploitation of groundwater reservoirs for industrial (such as in the case of Porto Marghera, in the Venice lagoon, and Ravenna), agricultural (such as in the case of Po delta) and tourism purposes (such as in the case of Romagna coastline) as well as overexploitation of the gas reservoirs of the Northern Adriatic sea.

In the inner part of the Po delta total subsidence locally reached the exceptional value of 30 cm/y and led to a lowering of the land by almost 3.5 m between 1958 and 1967 [Caputo *et al*. 1970; Sestini 1992]. Lower values were measured along the margins of the delta (70-85 cm). Total subsidence of 1.2 m affected a large area (700 km^2) close to Ravenna between 1949 and 1977 [Carbognin *et al*. 1984]. The reduction of excessive water pumping and the closure of some gas wells led to a marked decrease in the subsidence values during the following years. Recent data show a stabilisation of subsidence in the Po delta at values lower than 2-3 mm/y

[Ministero dell'Ambiente 1998, pp. 208-209]. Although accelerated artificial subsidence does not represent a problem anymore in most areas of the Northern Adriatic basin, it has led to an irreversible loss of elevation and other consequent problems which have been enhanced by the negative deficit in the sediment balance of most of the rivers. Like in other Mediterranean areas (such as for example the Nile delta [Stanley 1990; Stanley and Warne 1993] and the Ebro delta [Sanchez-Arcilla *et al.* 1996; Sanchez-Arcilla *et al.* 1998]) building of banks, sand mining, excavation of artificial canals and diverting of rivers have caused the reduction of river water flow and sediment supply in the Po delta. Together with the action of the sea due to waves and storm surges, these factors are the main cause of the retreat and erosion of the Po delta shoreline which started at the beginning of 1970. Furthermore, the construction of defensive infrastructure (such as jetties, piers, breakwaters, seawalls, groins), which has been necessary to limit erosion and flood risk, has modified the balance of sediments along the coast and has induced local negative effects, e.g. intensification of erosion and sediment starvation.

Occasional floods, which in the case of the Venice lagoon are known as high water events,[2] temporarily affect the coasts of the Northern Adriatic sea. These floods can be particularly critical such as in the case of the events which affected the Po plain in 1951 and 1966 or the high water of 1966 in Venice which reached the level of 194 cm. The high flood vulnerability of the Northern Adriatic basin is determined by its limited depth (north of the locality of Cattolica the average depth is only 35 m and the maximum depth is about 65 m) and its elongated shape. These two factors facilitate the temporary rise of the sea level caused by exceptional high tide events and particular meteo-marine conditions.

In a study conducted by UNEP [Sestini 1992, Jeftic *et al.* 1996b] the following major impacts of climate change and sea level rise on the Po delta system have been identified:

- Increased flooding
- Increased coastal erosion
- Retreat of dunes
- Damage to coastal infrastructure
- Salinisation of soils

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[2] High water is normally defined as a high tide event exceeding 80 cm respect to the average sea level measured at Punta della Salute in Venice in 1897 (l.m.m. 1897). 80 cm represents the level above which the lowest area of Venice, Piazza San Marco, is temporary submerged by water. An event of exceptional high water is a high tide exceeding 110 cm above the l.m.m. 1897.

- Alteration of seasonal water discharge regimes

- Reduced near-shore water mixing and primary production

- Increase in the frequency of anoxia events

The Department of Mathematical Methods and Models for Applied Sciences of Padua University has assessed the vulnerability of the Northern Adriatic in relation to the impacts produced by a possible increase in the sea level caused by climate variations and by future natural and human induced subsidence [CENAS 1997].

The macro-scale analysis, which considers the area between the localities of Monfalcone and Cattolica, has attempted to quantify the coastline retreat and the consequent inundation of zones which are presently emergent as a consequence of potential sea level rise and future natural and anthropic subsidence.

	Optimistic subsidence scenario		Pessimistic subsidence scenario	
Year	2050	2100	2050	2100
Surface area (km^2)	65	690	600	910

Table 1. Surface area of the zones permanently submerged as a consequence of sea level rise caused by global warming and two subsidence scenarios (optimistic and pessimistic) by the year 2050 and 2100 [*source*: Gonella *et al.* 1997b].

The subsidence scenarios have been elaborated by the same CENAS project [Gambolati and Teatini 1997; Gonella *et al.* 1997a; Teatini *et al.* 1997], while sea level rise projections (20 cm by 2050 and 50 cm by 2100) are those elaborated by IPCC in 1995 [IPCC 1996a]. The results of the analyses conducted for four different scenarios are summarised in table 1.

Figure 1 represents the potential regression of the coastline by the year 2100 as a consequence of sea level rise induced by climate change and the pessimistic subsidence scenario. According to the figure the most vulnerable area appears to be that between Ravenna and the Po delta.

The CENAS project has also quantified the surface area of the zones potentially affected by episodic floods in the years 1995, 2050 and 2100 as a consequence of an increase in sea level, future subsidence scenarios and particular sea storm events characterised by different return periods (1, 10 and 100 years) (see figure 2 and table 2). These latter events can cause a temporary sea level rise through the action of wind and low pressure conditions (storm surge) and through the effects of waves in proximity to the coastline (wave set-up) [Decouttere *et al.*

1997; Yu *et al.* 1997]. The frequency and magnitude of storm surges and wave set-up can be influenced by climate change, although their prediction is generally difficult.
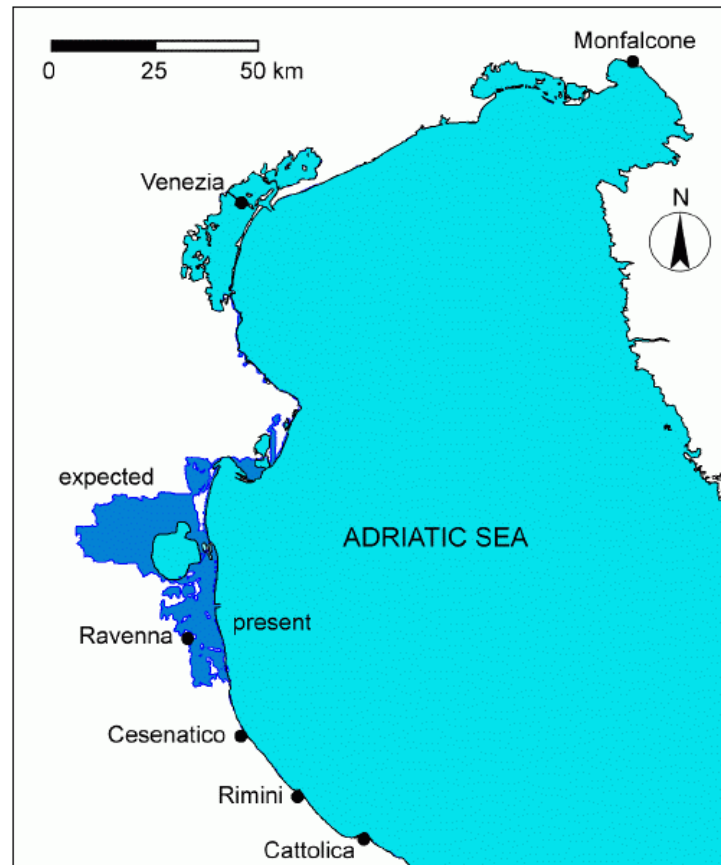

Figure 1. Potential regression of the Northern Adriatic coastline by 2100 as a consequence of sea level rise induced by climate change and the pessimistic subsidence scenario [*source*: Gonella *et al.* 1997b].

Figures 2a and 2b show that the surface area of the zones potentially affected in 2100 (the figures assume a pessimistic subsidence scenario) by occasional floods induced by sea storms with two different return periods (1 and 100 years) are quite similar and, in both cases, large. The optimistic subsidence scenario produces very similar results.

The CENAS project has also calculated a flood risk factor associated to each studied areas. The calculation of this factor has taken in consideration the probability of the flooding event (dependent on its return period), and the economic value of the flooded area and its vulnerability (defined as the potential damage to the area's economic value) [Gonella *et al.* 1997b].

Table 2 reports the result of this analysis for fifteen different scenarios. Considering the same subsidence scenario (optimistic or pessimistic) and the same time horizon, the highest risk factor is associated to flooding events with a 10 year return period. Events with a greater return period (100 years) will potentially affect a larger area, but their risk factor is smaller because of their smaller probability.
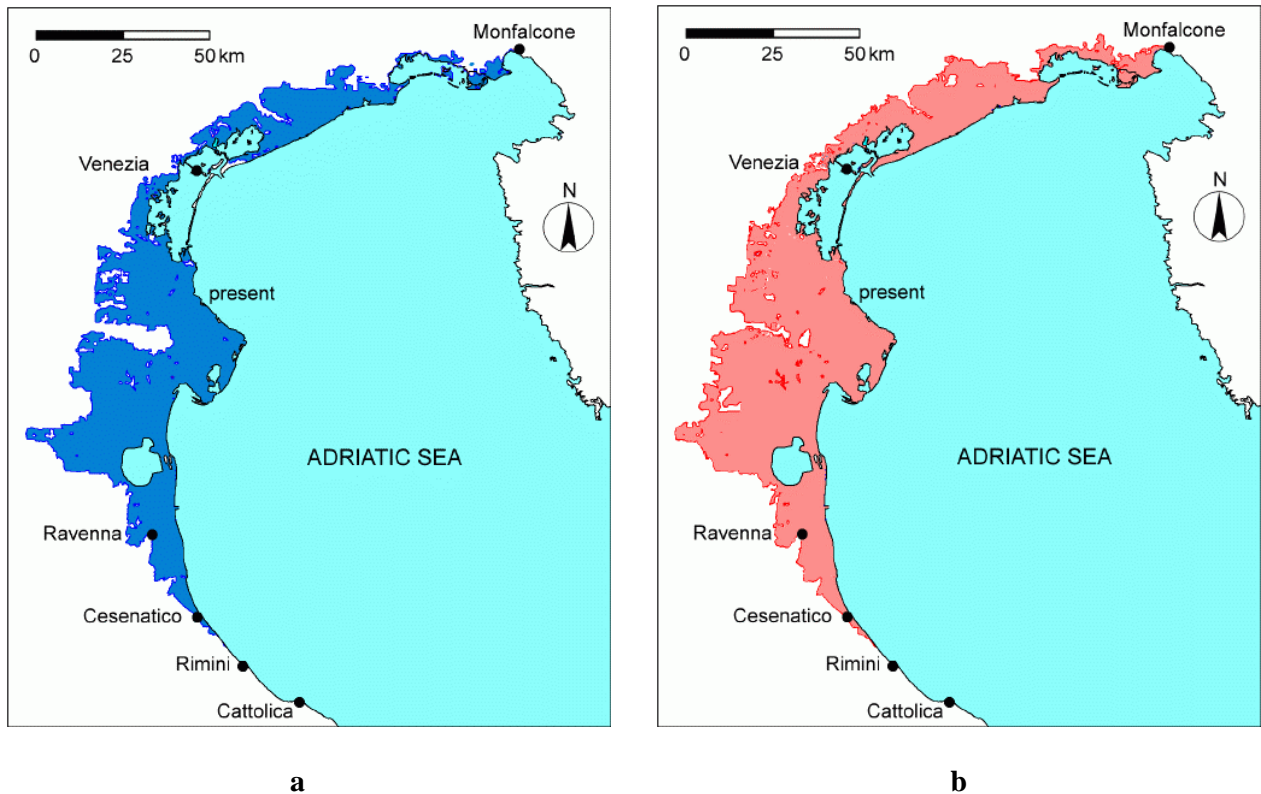

a   **b**

Figure 2. Surface area potentially affected in 2100 by episodic flooding events as a consequence of sea level rise induced by climate change, a pessimistic subsidence scenario and sea storm events with two different return periods (1 year - fig. 2a - and 100 years - fig. 2b) [*source*: Gonella *et al.* 1997b].

It is important to stress that the described impacts must be considered as potential. The resolution of the macro-scale study has not permitted an efficient modelling of existing defensive structures and dune systems which can obstruct and limit the intrusion of seawater and the consequent flooding.

However, the micro-scale analysis - which focused on the specific zones of Rimini, Ravenna and Cesenatico - considered the existence and the distribution of these natural and artificial obstacles and also provided an analysis of the evolution of the coastal morphology and of the balance of sediments. The main conclusions of the micro-scale study show that the areas characterised by

higher flood risk are those of Cesenatico and Ravenna, while in the case of Rimini the risk is elevated only for a limited portion of the beach [Gonella *et al.* 1997b].

Return period		1995	2050 opt.	2050 pes.	2100 opt.	2100 pes.
1 year	R	9.0	11.7	12.8	14.2	15.3
1 year	A	1714	1958	2020	2059	2108
10 years	R	11.1	14.1	15.2	16.2	17.5
10 years	A	1907	2072	2125	2219	2252
100 years	R	8.9	10.4	11.2	11.8	12.6
100 years	A	2082	2338	2370	2481	2502

Table 2. Mean normalised flood risk factor (varying between 0 and 100) for the studied region and surface area (in km^2) of the zones characterised by a value of the factor greater than zero. The flood risk factor has been calculated for fifteen scenarios, which have been elaborated by considering the same sea level rise value, as projected by IPCC (20 cm by 2050 and 50 cm by 2100), two subsidence scenarios (optimistic and pessimistic), three return periods of the sea storm events (1, 10 and 100 years) and three temporal horizons (1995, 2050, 2100) [*source*: Gonella *et al.* 1997b].

3.   Climate change and sea level rise impacts in Venice

The Venice lagoon is the largest wetland of the Mediterranean. It can be considered an ecosystem of transition between land and sea, which continuously exchanges matter and energy with the drainage basin (1,900 km^2) and the Adriatic Sea (figure 3). The connection with the latter is ensured by three inlets placed between the littorals of Cavallino, Lido, Pellestrina and Chioggia. The total surface area of the lagoon is about 550 km^2, 420 km^2 of which are open to the free expansion of tide. Further 90 km^2 are occupied by fish farming valleys, while the rest consists of islands (including the 117 islands which form the city of Venice) and banks. The Venice lagoon is characterised by different subsystems which determine its elevated complexity and diversity. These environmental typologies include coastal environments (e.g. dunes and retrodunal environments), salt marshes (*barene*), shoals (*velme*), marshes (*paludi*), shallow waters (*bassifondi*), seagrass meadows, open lagoon, islands, reclaimed areas, fish farming valleys and freshwater and brackish swamps [Torricelli *et al.* 1997]. Furthermore, the historical centre of Venice and other minor urban agglomerates, such as Chioggia, Murano, Burano and Torcello, are located within the lagoon.

3.1. Biogeophysical effects of climate change and sea level rise on the Venice lagoon

It is generally believed that climate change and sea level rise will cause a decrease in the surface area of the wetlands which will not be able to adapt to the new conditions.
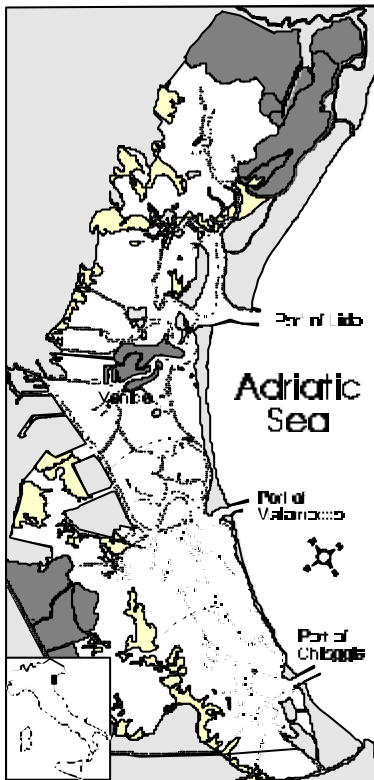

Figure 3. The Venice lagoon.

Permanent submersion of low-lying areas and increased erosion are considered the most likely impacts on these systems. In the case of climate change and sea level rise it is very likely that the Venice lagoon will experience similar problems. Some specific subsystems, such as salt marshes and shoals, are particularly vulnerable [Cecconi 1996]. Salt marshes, in particular those located in the central and southern portion of the lagoon, have been affected by intense erosion and during the last century their surface area has significantly decreased. The surface area of salt marshes covered about 17% (90 km^2) of the lagoon basin at the beginning of the 20th century and rapidly decreased to 13% in 1930 and to the present value of 8.8%.

The erosive process does not only affect salt marshes, but is causing damage to other typical morphological typologies - such as shoals and *ghebi* (small natural channels which flow through salt marshes) - the deepening of shallow waters, the filling up of shipping channels and the flattening of the lagoon basin. This process was triggered in the past centuries (mainly between 1500 and 1860) by the diversion of rivers flowing into the lagoon (Brenta, Piave, Sile and Bacchiglione) and of the final part of the river Po[3] which led to a marked decrease in solid discharge, and has been strongly intensified and accelerated by the construction of breakwaters at the three lagoon inlets (Malamocco 1840-1865; Lido 1872-1891; Chioggia 1912-1932) and the excavation of important shipping channels (Vittorio Emanuele channel 1925; *Canale dei*

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[3] These diversions had been necessary to avoid the filling in of the Venice lagoon.

Petroli-the Oil-Tanker Channel 1968) [Torricelli *et al.* 1997; Musu *et al.* 1998, pp. 129-137]. The 23 cm increase in relative sea level (see figure 4) due to subsidence and eustacy which occurred in the 20th century has enhanced the vulnerability of morphological structures which were previously emergent and has increased the wave action generated by winds, which is mainly responsible for sediment resuspension from the lagoon floor and for erosion of and damage to salt marshes. Furthermore, intense engine powered transportation and the use of high impact fishing systems are other locally important factors in the erosive process.

It has been calculated that the Venice lagoon loses about 700,000 m^3/y of sediment to the sea every year, while the sediment flow coming from the drainage basin is much lower, varying between 15,000 and 30,000 m^3/y [CVN 1997, pp.56-57]. A possible sea level rise and the consequent increased erosion and submersion of a great part of the salt marshes could cause their complete disappearance within a period of 30-50 years, particularly if the present anthropic and natural factors which are responsible for the erosive process continue. The loss of these important habitats will have negative consequences on the populations of migrating and nesting birds. Salt marshes characterised by a greater resilience, such as those located in the proximity of river mouths, might be able to counteract the effects of climate change and sea level rise.

The Consorzio Venezia Nuova (CVN) has qualitatively identified the most likely sea level rise impacts on the lagoon ecosystem [CVN 1997]:

- Increase in the volume of water contained in the lagoon and a less consistent increase in the water exchange with the sea, which could lead to a reduction of the mean daily water recycling rate;
- Increase in mean wave height produced by the wind, as a consequence of greater water depth. This would strongly increase the erosion of the typical lagoon morphologies;
- Reduced oxygenation of the water near the lagoon floor as a result of the increase in the water level. This latter factor could, however, partly contribute to causing a greater dilution of the pollutants generated by the drainage basin and a greater vivification of the lagoon;
- Increase in the mean salinity and modification of the mean temperature of the lagoon as a consequence of greater exchange with the sea;
- Submersion of low-lying areas of the lagoon and of the drainage basin and consequent loss of important natural habitats and land employed for human activities;
- Increase in coastal erosion.

From the above list it emerges that sea level rise and consequent impacts - such as submersion of low-lying morphologies, deepening of the lagoon, increased erosion, increased salinity, and intensification of water exchange with the sea - would cause the gradual transformation of the lagoon into a marine bay. This process has already partially occurred in the central basin of the lagoon ecosystem as a consequence of the greater water exchange with the sea and the deepening of the basin, both induced by the excavation of shipping canals, the construction of breakwaters at the lagoon inlets, and the loss of elevation caused by eustacy and subsidence.

The possible transformation of the lagoon into a marine bay will influence the composition and distribution of the lagoon's animal and vegetation communities. It is, for example, likely that the abundance of marine species will increase, while that of lagoon species will decrease, with consequent effects on other animal populations (waterfowl). Impacts on plant and animal communities can be exerted by other factors. For example, an excessive and prolonged flooding induced by sea level rise could create waterlogging problems in coastal soils with consequent lower plant productivity and vegetation mortality.

Although specific studies concerning the lagoon are not available at the present, according to Eduards [1995] seagrass meadows could generally suffer from an increase in sea-surface temperature. It is also likely that sea level rise will affect these biocenosis through the intensification of the erosive process and the consequent increased turbidity as well as through a decrease in light infiltration. However, major threats to these ecosystems will probably arise from other human induced disturbances, such as the use of highly impacting fishing techniques, sediment dredging, water pollution, and excessive marine traffic. Seagrass meadows are important systems because of their capacity to function as natural coastal protection agents which are able to limit wave action as well as to trap and stabilise unconsolidated sediments. Moreover, they are economically important because they provide nurseries, protective and feeding habitats for many fish species. The disappearance of these habitats might have negative implications for the fishing activity. It is not generally clear to what extent climate change would produce negative effects on fishing, although it is believed that in the Mediterranean this activity would be only marginally affected [Jeftic *et al*. 1996b]. It is possible that the productivity of the fish population in shallow coastal lagoons, deltas and estuaries will decrease as a consequence of the increase in temperature and salinity which can be very harmful to sensitive juvenile forms [Alm *et al*. 1993]. At the moment it is still very uncertain how climate change will influence some factors - frequency and intensity of macroalgal blooms, availability of nutrients for fish

populations, diffusion and distribution of allochthonous species - which can be very important in regard to fishing.

It is also likely that sea level rise will cause an intensification of saltwater penetration into rivers and freshwater canals, which could be further increased in summer by reduced river flows [Sestini 1992]. The larger extension of the salt wedge would prevent the use of freshwater for agricultural purposes and could lead to salt accumulation in soil. Furthermore, saltwater penetration would influence the distribution and consistence of the typical estuarine communities.

3.2.   Natural adaptability and resilience of the Venice lagoon

As a dynamic system, the Venice lagoon has the potential to respond to external and internal forcing factors and to cope with some of the impacts that could be induced by variation in climatic conditions and sea level rise. Vertical accretion can counteract the effects produced by sea level rise only if sedimentation and salt marshes' 'auto-accretion' are able to keep pace with the increase in erosion and the disappearance of low-lying morphological typologies due to permanent submersion. The present poor sediment supply from the rivers flowing into the Venice lagoon limits the ability of salt marshes and shoals to re-establish their mass in response to sea level rise and increased erosion in many areas. In this context the role of salt marsh vegetation in trapping sediments and in counteracting erosion becomes very relevant. Salt marshes' 'auto-accretion' also depends on soil production through biological processes.

Wetland inland migration represents another possible autonomous adaptation which depends very much on the rate of climate change induced modifications and on the degree to which the ecosystem has been modified by human interventions. Climate change, sea level rise and their consequent impacts must occur at a rate which allows the system to adapt to the new conditions. This is particularly important in relation to the response of animal and vegetation communities. The natural resilience and adaptability of the Venice lagoon has been gradually reduced by human interventions on the ecosystem - such as land reclamation, excavation of channels, construction of breakwaters at the natural inlets, and the physical delimitation of lagoon boundaries - which have profoundly modified the hydrology and morphology of the lagoon and contributed to its degradation. It has been estimated that since the middle of the nineteenth century until the present time, the lagoon's surface area has been reduced by about 15,000

hectares due to land reclamation for agriculture (4,000 ha), industry (2,200 ha) and infrastructure (7-800 ha) - i.e. roads and services - as well as the closure of fish farming valleys (8,500 ha) [Torricelli *et al*. 1997]. Lagoon migration in response to sea level rise is therefore hindered by these significant modifications of the inner lagoon margins, which have been intensively urbanised and dyked. Typical transition systems between land and the lagoon (freshwater and brackish swamps), which are extremely important in making the migration of this ecosystem possible, have practically disappeared due to land reclamation and the closure of fish farming valleys.

Similar consideration can be extended to the barrier islands of Lido and Pellestrina and the beaches of Cavallino and Chioggia. Their capacity to naturally adapt to new conditions and to respond to impacts, such as increased erosion, has been deeply decreased by urbanisation, tourism development, construction of defensive infrastructure and destruction of coastal environments, such as dunes or retrodunal woodlands.

3.3.   The vulnerability of the city of Venice to sea level rise

The city of Venice is considered to be one of the most vulnerable urban agglomerates of the Mediterranean because of its unique characteristics and its cultural and artistic value. It is well known how the city is already affected by occasional floods (high water - *acque alte*) which are caused by temporary rise in the sea level.

This rise is caused by the occurrence of high tides, particular meteo-marine conditions (low pressure and prolonged wind blowing from the south-east such as the Scirocco and, to some extent, exceptionally intense precipitation on the river basins) and periodical oscillations (21.7 hours) of the sea surface in the basin (seiches) which can persist for some days. Autumn and winter are the critical period during which the described factors often act in synergy to determine an increase in flood occurrence.

The frequency of high water events has significantly increased during the 20th century due to the 23 cm rise of the relative mean sea level, as shown in figure 4 [Carbognin *et al*. 1981; CVN 1988; Carbognin and Taroni 1996]. The same figure shows that the mean annual sea level rise in Trieste has been lower (1.13 mm/y). The city of Trieste can be considered stable in regard to subsidence and the measured sea level rise, which is due to eustacy, is similar to that observed in other Mediterranean stations (see table 3, which also reports estimates of sea level rise at a global

or a macro-regional scale). It is important to highlight that sea level has remained constant since the beginning of the seventies in both localities [Rusconi *et al*. 1993]. Table 4 reports the mean annual variation in the relative sea level observed in Venice and Trieste in three different periods.
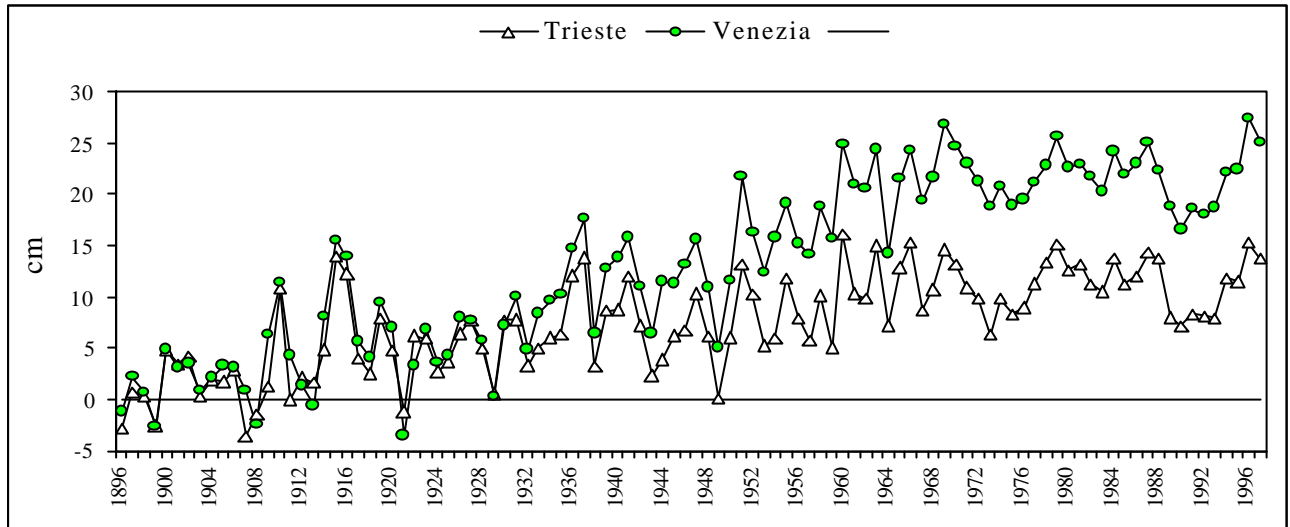

Figure 4. Sea level trend at Venice and Trieste in the period 1896-1996. Sea levels reported in the graph refer to the average sea level measured at Punta della Salute in Venice in 1897 (l.m.m. 1897) [*source*: Carbognin, L., CNR, Italian National Research Centre, Venice].

In the case of Venice, eustacy and subsidence are the causes which have determined the described sea level rise. During the 20th century eustacy has contributed 11 cm [Carbognin and Taroni 1996]. The latter factor has contributed more significantly. 4 cm can be ascribed to natural subsidence induced by the progressive compaction of fine sediment and partly by deep tectonic movements. Anthropic subsidence contribution has added to the natural component, principally induced by overexploitation of underground aquifers for industrial purposes in the period 1930-1970. The average loss of elevation in this century caused by human induced subsidence has been of 8-10 cm in the zone of Venice and of 12 cm in the area of Marghera on the mainland [Carbognin *et al*. 1981]. The highest values were recorded between 1968 and 1969: 17 mm/y at Marghera and 14 mm/y at Venice [Gatto and Carbognin 1981]. After 1970 a serious scientific campaign and the pressure of public opinion led to the regulation of groundwater exploitation and the use of alternative water resources, and consequently to the closure of the industrial wells and to a drastic decrease in the general consumption of groundwater. The result of this was the slowing down and successive termination of the human-induced subsidence, as

well as a partial recovery of 2 cm of land elevation. The comparison between the ground elevation in 1973 and 1993 has shown that the recent evolution of subsidence presents two different patterns [Co.Ri.La. 1999].

Source	Region	Sea level rise (mm/y)
Gornitz and Lebedeff [1987]	Global	1.2 ± 0.3
Trupin and Waht [1990]	Global	1.7 ± 0.1
Douglas [1991]	Global	1.8 ± 0.1
Peltier and Tushingham [1991]	Global	2.4 ± 0.9
Douglas [1997]	Global	1.8 ± 0.1
Shennan and Woodworth [1992]	North-western Europe	1.0 ± 0.15
Gornitz [1995]	Eastern United States	1.5
Milliman [1992]	Mediterranean basin	1-2
Piervitali et al. [1997]	Central and western Mediterranean	1.5
Nicholls and Hoozemans [1996]	Genoa (1930-1992)	1.2
Zerbini et al. [1996]	Genoa (1884-1988)	1.3
Nicholls and Hoozemans [1996]	Marseilles (1885-1992)	1.2
Zerbini et al. [1996]	Marseilles (1885-1989)	1.1

Table 3. Estimates of global and macro-regional sea level rise for the 20th century reported by different authors and values of sea level rise measured in some Mediterranean stations (Marseilles and Genoa). Besides the values reported by Milliman and Piervitali, all the other global or macro-regional estimates are based on the analysis of the tide gauge data set of the Permanent Service for Mean Sea Level. On the basis of these and other estimates, the IPCC [1996a, pp.363-364] maintains that globally sea level has risen by 10-25 cm in the last hundred years.

Locality	1896-1930	1931-1970	1971-1993	1896-1993 (whole period)
Venice	1.5 mm/y	3.8 mm/y	-0.08 mm/y	2.52 mm/y
Trieste	1.7 mm/y	1.5 mm/y	-0.03 mm/y	1.13 mm/y

Table 4. Mean annual variation in the relative sea level observed in Venice and Trieste in three different periods [*source*: Co.Ri.La. 1999].

The city of Venice and the mainland are characterised by very low values of subsidence (varying between 0 and 0.5 mm/y). The greatest values measured in these areas are typical of the natural component observed during the 20th century. In particular the ground elevation of the historical centre of Venice has, on average, remained stable during the period 1973-1993 [Carbognin *et al.* 1996]. Also in Venice, positive variations (0.3 cm) have been observed locally, while negative

values (subsidence) have been measured only in marginal areas of recent urbanisation. In contrast, some northern and southern zones neighbouring the Venice lagoon and some areas of the littoral islands are characterised by higher values (1-2 mm/y) due to greater sediment compaction and local groundwater exploitation [Carbognin *et al*. 1994].

As a consequence of the described rise in the sea level, the frequency of high water events in the last century has increased, too. The level of 110 cm, which defines a high tide as an exceptional high water event, is presently exceeded 30-35 times per decade, while at the beginning of the 20th century the frequency of the same events was 4-5 times per decade (figure 5). A similar increasing trend characterises the annual distribution of the tidal events exceeding the level of 80 cm, i.e. high water able to partially flood San Marco square. The mean frequency of these events during the first decades of the 20th century was 7-8 times per year, while the current frequency is much higher; 40 times per year [Camuffo 1993]. Even if exceptional high water has a greater impact on Venice, the damage produced by high tides exceeding 80 cm can not be underestimated due to the high frequency of these events.
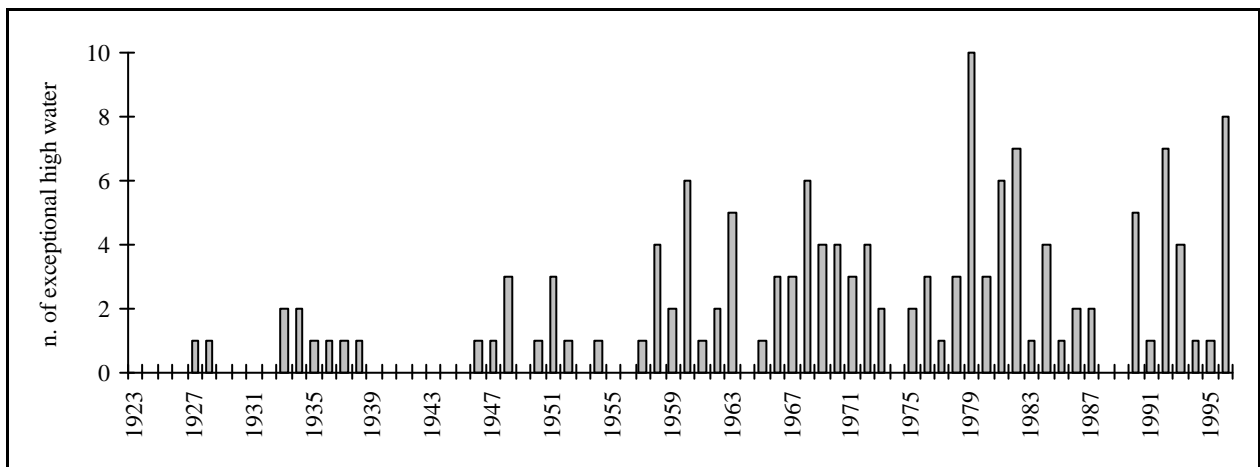

Figure 5. Annual distribution of exceptional high water events in the period 1923 - 1996 [*source*: Centre for tidal forecasting of the Venice Municipality].

A further sea level rise, such as that which global warming could produce, would cause an intensification of the problems caused by flooding in Venice. A 30 cm sea level rise would determine an increase in the frequency of inundation of Piazza S. Marco to 360 times per year [Francia and Juhasz 1993; Bandarin 1994].

On the basis of previous studies carried out by the Consorzio Venezia Nuova [CVN 1997], the Co.Ri.La. [1999] has elaborated two scenarios of sea level rise for the period 1990-2100 for the Venice lagoon.

The first scenario (A1) foresees a sea level rise of 16.4 cm as a consequence of eustacy (1.13 mm/y) and natural subsidence (0.4 mm/y) rates similar to those measured during the 20th century. This scenario makes the strong assumption that the effect of possible climate changes will not be able, before 2100, to exert a great influence on the relative sea level. A more precautionary version (A2) of the same scenario takes in consideration the greatest eustacy rate measured in the 20th century (1.5 mm/y in Venice and 1.7 mm/y in Trieste). This rate and the contribution of natural subsidence generates a scenario of a 21-23 cm rise in sea level.

According to scenario B, sea level will rise by 31.4 cm by 2100 as a consequence of the effect of global warming and natural subsidence. The contribution of subsidence is the same as foreseen in the other scenario, while that induced by change in climatic conditions (27 cm) is that projected by the IPCC [1996a, pp. 385-388] considering the IS92a emission scenario and 'advanced models'.[4] [5]

The sea level rise rates foreseen by the described scenarios would cause an increase in the annual frequency of tidal events exceeding the level of 100 cm from the present value of 7 to 37 in case of scenario A1, 58 in case of A2 and 128 in case of B [Co.Ri.La. 1999, pp. 26-27]. The annual frequency of these events, which can temporarily submerge about 12% of the city of Venice, has already increased from 1 to 7 during the 20th century.

The effects that the occurrence of a 10, 20 and 30 cm sea level rise would have on the frequency of high water events, as quantified by CVN [1997], is reported in table 5.

It is important to note that the evaluation of the variation in the frequency and distribution of high water events should also theoretically take in consideration the future changes of those parameters which influence the high water phenomenon (such as the levels and distribution

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[4] These models incorporate various advancements in modelling in respect to the other models used by IPCC in 1995. The considered climate sensitivity is 2.2 °C, while for glaciers and ice caps a range of values of sensitivity was used. The 27 cm projection assumes changes in aerosol concentration beyond 1990.

[5] In a previous CVN's study [1997] two other scenarios were elaborated:

The 'optimistic scenario' is based on the trend observed in the last twenty years and foresees an increase in the relative sea level rise by about 4.4 cm between 1990 and 2100 as a consequence only of the natural component of subsidence (0.4 mm/y).

The 'pessimistic scenario' foresees a sea level rise of 53.4 cm due to natural subsidence (0.4 mm/y) and the effect of global warming (49 cm), as projected by IPCC [1996a, pp. 359-405] considering the IS92a emission scenario, a climate sensitivity of 2.5 °C, mid-value ice melt parameters and changes in aerosol concentration beyond 1990.

along the Adriatic basin of the barometric pressure, the direction and intensity of relevant winds, the intensity of precipitation on the drainage basin, the marine circulation).

The case of high water clearly shows the complexity of climate change impacts on coastal zones, which are strictly linked to variations in sea level but also depend on other variables. Unfortunately reliable projections of these parameters which include the effect of global warming on them, are not available at the moment, in particular at the regional and sub-regional scale. With the current knowledge, it is therefore very difficult to analyse the future influence of changes in these key variables on the high water frequency and distribution.

Tidal peaks (cm)	Mean annual frequency for current m.s.l	Mean annual frequency for m.s.l. +10 cm	Mean annual frequency for m.s.l. +20 cm	Mean annual frequency for m.s.l. +30 cm
+80	39	94	204	356
+100	7	16	39	94
+120	1	3	7	16
+140	1/6 y	½ y	1	3

Table 5. Annual frequency of specific peak tidal levels according to four different sea level rise scenarios (0 cm; +10 cm; +20 cm; +30 cm). Peak tidal levels are measured with reference to l.m.m. 1897 [*source*: CVN 1997, pp. 80].

However past trend analysis and elaboration of arbitrary scenarios can be very useful in providing information on possible consequences produced by these factors. According to Cecconi *et al*. [1998], no significant trend in storm activity and storm severity (and consequently in storm surges) has been observed in the Northern Adriatic during the 20th century. The storm events have been, however, characterised by a large annual and interdecadal variability.

The increase in the frequency of high water events due to sea level rise would intensify their impacts on the urban and lagoon systems. These negative effects include damage to physical structures (drainage system, canal banks, buildings, foundations, forms of historical and artistic heritage, and lagoon embankments), temporary interruption of economic activities, damage to goods stored in shops and warehouses and interruption of mobility [Cecconi 1997; CVN 1997; Bourdeau *et al*. 1998]. Damage to physical structures would be mainly due to salt aggression and wave action which can both be enhanced by sea level rise.

4.   Conclusions

The Venice lagoon can be considered a system highly vulnerable to climate change and sea level rise. The most likely impacts are: increased erosion of the lagoon morphologies (in particular salt marshes and shoals); permanent submersion of low-lying lagoon and coastal areas; change in ecological parameters (e.g. salinity, temperature, tidal range and nutrient availability); and the gradual transformation of the lagoon into a marine bay and the consequent effects on vegetation and animal communities. A future increase in the relative sea level will be particularly harmful for the historical centre of Venice, which is already affected by occasional floods (high water events) and whose physical structures are damaged by the effects of salt aggression and wave action.

Notwithstanding this elevated fragility, a detailed assessment of the Venice lagoon's vulnerability to climate change and sea level rise has not yet been performed. Attempts to quantify the impacts of climate change and sea level rise on this lagoon have been made only in relation to the frequency of high water events, while other effects have not been studied by the local scientific community. The quantification of these effects is a difficult task which requires the modelling of the interrelations between changes in climatic conditions and in sea level and potential effects on natural and human sub-systems.

A very delicate step is the elaboration of future local plausible scenarios which describe how critical parameters will change in future. Not only climate change and sea level rise scenarios are required. According to Klein and Nicholls [1998; 1999], since vulnerability is a multi-dimensional concept which embraces biogeophysical, economic, institutional, and socio-cultural factors, it is important to generate various scenarios which can be grouped in four classes: scenarios of climate-induced change in environmental variables (e.g. sea level, rain and temperature pattern), scenarios of non climate-induced change in environmental variables (e.g. vertical land movement), scenarios of climate-induced change in socio-economic variables (e.g. autonomous and planned adaptation), scenarios of non climate-induced change in socio-economic variables (e.g. population, land use). It also important to consider a wide spectrum of scenarios which are able to include in their evaluation process the uncertainty of the future.

International literature provides various examples of methodologies and conceptual frameworks to assess the vulnerability of coastal systems to climate change and sea level rise, such as the Common Methodology developed in 1992 by the former Coastal Zone Management Subgroup of

the IPCC [IPCC CZMS 1992] or the Technical Guidelines for Assessing Climate Change Impacts and Adaptations published by the IPCC [Carter *et al*. 1994]. It is also worth mentioning the UNEP's Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies [Feenstra *et al*. 1998] which contains a specific section presenting a conceptual framework for the vulnerability assessment of coastal zones to sea level rise [Klein and Nicholls 1998; 1999; Sterr and Klein 1999]. A first step in the assessment of Venice's vulnerability requires that these general methodologies are targeted and tested on the specific considered area. The lack of accurate and suitable data sets is a problem commonly encountered in vulnerability assessment. It is therefore necessary that the study is preceded by the construction of a specific database. In order to pursue this objective co-operation between different research institutions becomes fundamental. In the case of Venice, the Istituto Veneto di Scienze, Lettere e Arti (IVSLA) and the Consorzio Venezia Nuova (CVN) are putting a lot of effort to creating a database on the lagoon ecosystem.

A gradual evolution of the vulnerability study which, as suggested by Klein and Nicholls [1998], is firstly performed through a screening assessment, secondly through a vulnerability assessment and finally through a planning assessment should also be considered for the Venice case.

Vulnerability assessment to climate change and sea level rise should be included in the broader issue of Integrated Coastal Zone Management (ICZM) which can deal with the various competing pressures and stresses affecting the lagoon ecosystem [EC 1999]. In this perspective, climate change induced effects would represent only one of the important elements of ICZM.

As a last consideration, the integrated management of coastal zones should also address the issue of 'maladaptation', which has been defined by Burton [1996] as the human interventions that reduce natural coastal system's adaptability and resilience. The Venice lagoon can not be considered exclusively as a natural ecosystem but must be seen as a system whose existence and characteristics have been defined by human and natural factors, and by the interaction between these. In this view the Venice lagoon as been often defined as an 'artificially conserved natural system'. However, this does not imply that human interventions, in particular some of the most recent ones, have not generated negative and significant impacts on this system. Some human induced modifications have actually decreased the lagoon's capacity to respond autonomously to climate change impacts, such as through vertical accretion and inland migration, and have posed limitations to planned adaptation.

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