Journal of Coastal Research	24	2	299–305	West Palm Beach, Florida	March 2008

Potential Implications of Sea-Level Rise for Croatia

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ABSTRACT

BARIC, A.; GRBEC, B., and BOGNER, D., 2008. Potential implications of sea-level rise for Croatia. *Journal of Coastal Research,* 24(2), 299–305. West Palm Beach (Florida), ISSN 0749-0208.

The Croatian coastline is long compared with the total national surface area. The coastal zone is mainly karstic and steep, with only one large alluvial plain, and contains approximately one-quarter of the total Croatian population. It is an important area for the national economy, particularly tourism and Mediterranean-type agriculture. Sea-level measurements at four points on the east Adriatic coast over the last 40 years indicate differential sea-level trends: from a rise between +0.53 and +0.96 mm/y to a decrease between −0.50 and −0.82 mm/y, a range mainly due to local tectonic activity.

In this paper, the effects of assumed 20- and 86-cm sea-level rises on the coastal area are assessed by expert judgement. Coastal areas appear to have, in general, a low vulnerability to changes in sea level. However, some important sites, such as historical town centres, the alluvial plain of the Neretva River, and Vrana Lake on the island of Cres would be seriously endangered. Because of its great length, the entire Croatian coastline cannot be fully protected. Therefore, long-term national adaptation strategies to sea-level rise and plans of actions should be prepared and adopted, and monitoring of the consequences of sea-level rise and further research should be implemented.

ADDITIONAL INDEX WORDS: *Adriatic Sea, vulnerability assessment, inundation, saltwater intrusion.*

THE NATIONAL COASTAL ZONE AND ITS IMPORTANCE TO THE ECONOMY

The Croatian coast is predominantly rocky with numerous small pocket gravel and sand beaches and few alluvial zones in river estuaries. The total length of the coastline is 5835 km, and it is highly indented, with an indentedness coefficient (the ratio between the total length of mainland coastline and the shortest distance between the two most distant points of the coastline) for the mainland of 3.4 (see Figure 1). Numerous islands are located in two or three groups lying parallel to the mainland (length 4058 km). Only 67 out of 1185 Croatian islands are inhabited.

Generally, the coastal strip is very narrow (1–5 km) and is separated from the hinterland by chains of mountains, the slopes of which often form the shoreline. Only two large coastal plains, the western part of the Istrian coast and the northern Dalmatia coast, lie between the towns of Zadar and Sibenik.

The Croatian coastal zone occupies 12,450 km^2 out of the total national area of 56,610 km^2. It has 1,224,771 inhabitants (1991 census), or 25.6% of the total Croatian population (ANONYMOUS, 1997). Hence, the population density in the coastal zone is higher than in the hinterland, where the densities are 98.4 and 80.6 inhabitants/km^2, respectively. In many places along the coast, historical towns, residential houses, tourist complexes, roads, and other infrastructure are constructed very close to the coastline.

DOI: 10.2112/07A-0004.1 received and accepted in revision 19 April 2007.

The main economic activities in the coastal area are related to the exploitation of coastal resources, such as tourism, fisheries and aquaculture, maritime transport, and shipbuilding. Coastal tourism represents 95% of a total tourist population of about 26.5 million overnight stays (ANONYMOUS, 2000). The total capacity of the 45 marinas is 11,860 berths. Fishing in the Adriatic Sea has expanded drastically (1027 fishing vessels on the Croatian side), resulting in the overexploitation of fish populations (VRGOC, 2000). However, aquaculture activities are expanding rapidly in terms of increasing production and extension to new locations. At present, 36 aquaculture sites have a total annual capacity of 2700 tonnes of finfish. Mediterranean-style agriculture is important for the local population, particularly on the islands and on the alluvial plain of the Neretva River estuary. The total national olive (35,000 t) and grape (178,320 t) production of 1999 (45% of the total country production) was produced in the coastal area (ANONYMOUS, 2000).

According to HERAK (1986), the eastern coast of the Adriatic comprises the geo-tectonic zones of Adriaticum, Epiadriaticum, and Dinaricum. Thick layers of predominately shallow-water limestone strata were deposited during the Mesozoic era from the upper Triassic up to the end of the Cretaceous and, on the Adriatic platform, during the Palaeocene. The Palaeocene deposits are composed of limestones and flysh layers. The limestone strata are water permeable, resulting in a scarcity of surface waters, despite the relatively high precipitation on the mainland (annual average range for the period 1981–1995 is between 714 and 1519 mm, depending on local orography) (HODŽIĆ and ŠORE, 2000).

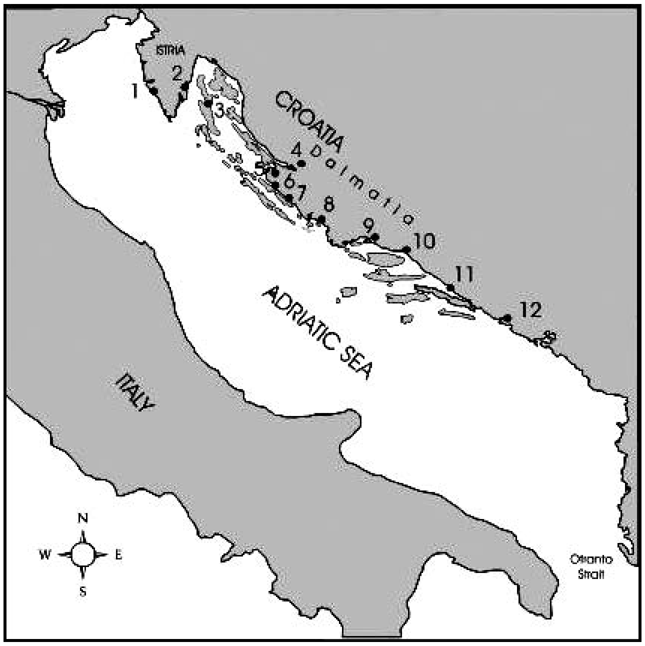

Figure 1. Croatian coastal zone and endangered areas. The numbers indicate 1, west Istrian Coast; 2, Rasa River; 3, Vrana Lake on the Cres Island; 4, Zrmanja River; 5, Nin; 6, Zadar; 7, Vrana Lake near Biograd; 8, Krapanj; 9, Split; 10, Cetina River; 11, Neretva River; 12, Dubrovnik.

The current morphology of the eastern Adriatic coast is the result of its geological basement and climatic changes that began in the upper Pleistocene. Approximately 18,000 years ago, during the last Glaciation (Würm), sea level was at a minimum, 116–126 m lower than present (FAIRBANKS, 1989). During glacial times (Upper Pleistocene–Würm 3, 40,000–17,000 BP), small rivers, such as the Rasa, Zrmanja, Krka, and Cetina, excavated their deep canyons (JURACIC, 1987, 1992). Thereafter, sea level rapidly increased (Flandrian transgression), but between 8000 and 6500 years ago, the rate of sea-level rise was drastically reduced (STANLEY, 1995). As the result of sea-level rise, numerous ancient springs were inundated and are currently active as underwater springs.

Ten relatively small rivers of karstic type are located along the coast. The largest one is the Neretva River (mean annual water flow 296 m^3/s), which is characterised by a delta-type estuary with a relatively large reclaimed alluvial plain. However, the majority of the other rivers have a canyon-type estuary. Rivers or their springs are used as the main freshwater sources for the entire coastal region. Only two lakes are located in the coastal zone, both are called Vrana Lake: one is situated on the island of Cres (surface area 5.8 km^2) and the other near the town of Biograd (surface area 30.7 km^2). The lake on Cres is used as the main freshwater source for the island (ANONYMOUS, 2000), and the other is connected to the sea by an artificial channel, where its water quality is affected by saline water intrusion through the artificial channel and groundwater flow. Consequently, this lake serves as

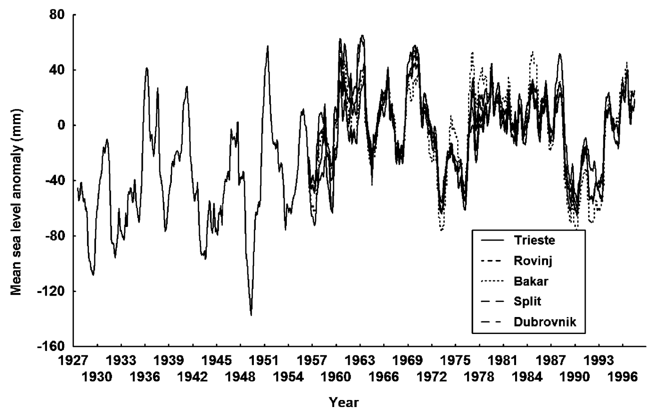

Figure 2. Long-term mean sea-level anomaly (from normal 1961–1990 period) in the northern Adriatic compared with the NAOI. Data for the NAOI were found at http://www.cru.uea.ac.uk/data/nao.htm.

a nature reserve and its water is used in relatively small amounts for irrigation.

CLIMATIC VARIABILITY AND SEA-LEVEL RISE

Although the extent and magnitude of climatic fluctuations remains uncertain, the oceanographic characteristics of the Adriatic Sea, and consequently mean sea level (MSL), are influenced by fluctuations occurring over areas larger than the Adriatic itself.

Over the Northern Hemisphere, the North Atlantic Oscillation Index (NAOI) measures the pressure difference between the Azores and Iceland normalized to the 1961–1990 period; it is positive when pressure is above normal in Iceland. The NAO is considered a primary climatic factor governing the hemisphere-scale climatic fluctuations centred over the Atlantic (MARSHALL *et al.,* 1997). Because the ocean is the world's heat reservoir, the primary factors in modulating the North Atlantic Oscillation (NAO) lie in its interactions with the underlying ocean. Significant correlations were found between the NAO and sea-level variability (Figure 2), leading to the conclusion that this variability is partly related to the NAO. The relationships between climate fluctuation over Europe and over the Adriatic were analysed in detail via simple correlation coefficients between the NAOI and air temperature. A significant correlation was found for the winter months (Figure 3), whereas the correlation is nonsignificant during the rest of the year, excluding September. An almost equal seasonal cycle was found for the correlation coefficient between MSL variation along the Adriatic eastern coast and the NAOI. It can be concluded that seasonal MSL variation can to a certain extent be explained by NAO variations.

On a multidecadal timescale, the analysis of the tide gauge stations at four points (Rovinj, the west coast of the Istra peninsula; Bakar, the Rijeka Bay, Split; central Adriatic; and Dubrovnik, south Adriatic) (Figure 4) for the period 1956–1991, indicates different trends: at Rovinj, sea level is falling with respect to the land at a rate of -0.50 mm/y; at Bakar,

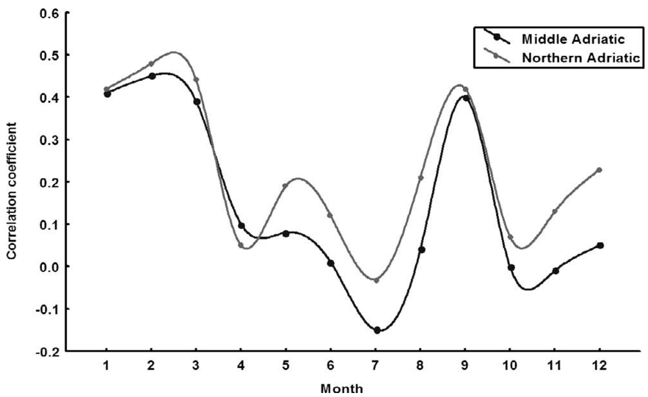

Figure 3. Correlation coefficients between the NAOI and air temperature anomaly (from normal 1961–1990 period) for the northern and middle Adriatic. Air temperature data are obtained from the Meteorological and Hydrological Service of Croatia.

a relative rise is occurring (+0.53 mm/y); at Split, relative sea level is dropping at −0.82 mm/y; and in the Dubrovnik area, relative sea level is rising by about +0.96 mm/y. Although this is below the 50-year time length recommended for mean sea-level analysis, these differences are probably the result of differential local uplift and subsidence of the coast, in that the east Adriatic coast is a tectonically active region. Year-to-year sea-level fluctuations can be related to climate variability over Europe, whereas longer term changes can be related to differential local tectonic movement. These changes are happening at different timescales—*e.g.,* Trieste (Italy) is clearly showing a long-term rising trend for relative sea level.

Spatial differences in MSL are not present at seasonal and interannual scales throughout the Mediterranean basin (MAZZARELLA and PALUMBO, 1989). This is clearly demonstrated by the spatial homogeneity of the existing mean sea-level time series (Figure 5). A similar result was used in studying atmospheric pressure patterns over the Adriatic and Mediterranean Seas (LASCARATOS and GACIC, 1990).

VULNERABILITY TO SEA-LEVEL RISE

So far, assessment of vulnerability of the Croatian coast to projected sea-level rise has been limited to two case studies undertaken within the Mediterranean Action Plan of the United Nations Environmental Programme (UNEP-MAP; BARIC *et al.,* 1996; RANDIC *et al.,* 1996). These two case studies focused on the islands of Cres and Lošinj and Kaštela Bay, an area near the town of Split. With the use of the University of East Anglia's Climate Research Group scenarios of expected temperature and precipitation changes for these areas over three time horizons (2030, 2050, and 2100; PALUTIKOF *et al.,* 1992) and corresponding rates of sea-level rise (+18 ± 12 cm, +38 ± 14 cm, and +65 ± 35 cm), the main aims of these studies were (i) to identify and assess the possible implications of expected climatic changes on the terrestrial, aquatic, and marine ecosystems, population, land use, sea use practices, and other human activities; (ii) to determine areas or systems that appeared to be most vulnerable to the expected climatic changes; and (iii) to give recommendations for planning and management of coastal areas and resources and planning and design of major infrastructure and other systems.

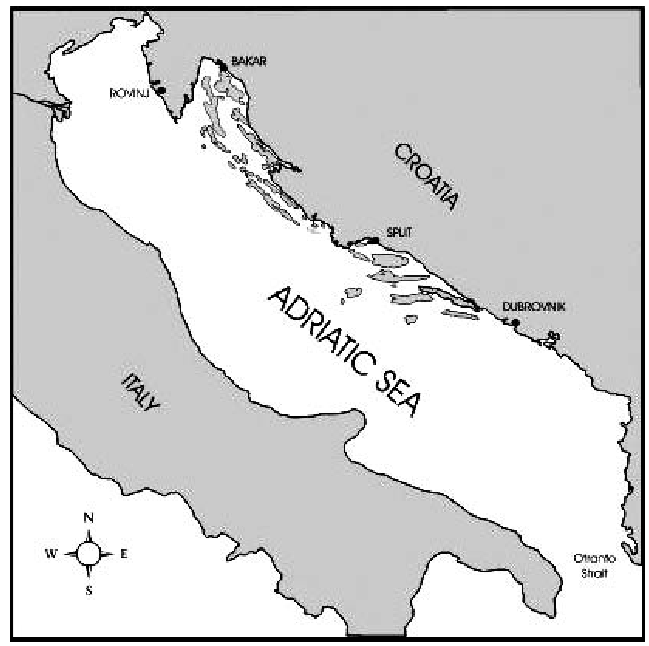

Figure 4. Locations of tide gauge stations.

Currently, UNDP/GEF project UNOPS CRO/98/G31 is being carried out, which aims to prepare the first national report on expected climatic changes and the identification of national capacities to cope with its potential effects. As part of this project, coastal areas on the mainland and islands that were thought to be vulnerable to sea-level rise were quali-

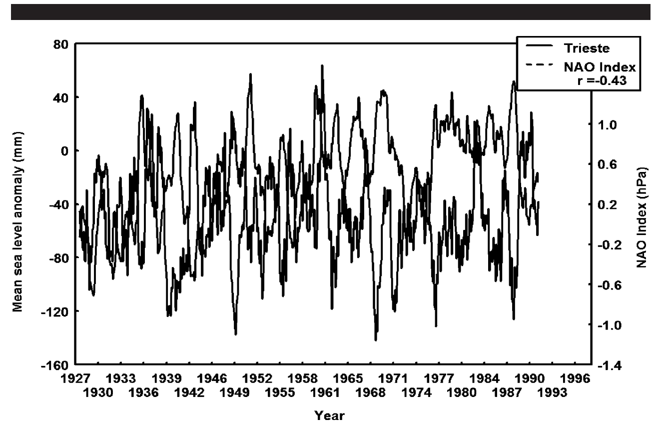

Figure 5. Time series of mean monthly sea-level anomaly (from normal 1961–1990 period) along the eastern Adriatic coast. Data for Croatian tide gauge stations were obtained from the Hydrographic Institute of the Republic of Croatia, and for Trieste station from Istituto Talassografico Trieste.

tatively assessed assuming sea-level rises of 20 and 86 cm. These analyses were based on expert judgement with the use of detailed geographic maps and town plans to project the landward shift of the land–sea interface as a consequence of estimated sea-level rise. Ideally, saltwater intrusion and increased flood risk associated with storm surges and extreme precipitation and runoff events, as well as a rise in coastal groundwater tables, would be taken into consideration (Klein and Nicholls, 1998), but the effects of sea-level rise on groundwater flow, water table levels, and saltwater intrusion in Croatia cannot be assessed at present because of the lack of data on the groundwater table and local soil permeability.

EFFECTS AND VULNERABILITY

The potential effects of sea-level rise include inundation, flooding, saltwater intrusion, and coastal erosion. For Croatia, a sea-level rise of 20 cm would not have significant consequences on the coastal zone in terms of inundation and surge flooding. However, individual areas, such as the towns of Rovinj, Pula, and Split, currently suffer from surge flooding and would therefore continue to be at risk. A 20-cm sea-level rise might have slight effects on the two freshwater lakes located in the coastal zone, as well as on the alluvial plains at the estuaries of rivers Rasa, Neretva, and Cetina. Additionally, some small effects would affect salt pans in Pag, Nin, and Ston, as well as numerous outlets of urban wastewater. The effects on coastal erosion and existing pocket beaches is expected to be negligible because the majority of the pocket beaches are relatively steep sand and gravel deposits and are therefore, along with most of coastline, resistant to erosion. At present, only two sites on the Croatian coast have noticeable coastal erosion problems: the island of Susak and an area of Nin town. The projected sea-level increase of 20 cm would probably exacerbate this problem.

A sea-level rise of 86 cm would have a much more pronounced effect on the areas mentioned above, primarily because of the increasing risk of inundation and surge flooding. In addition, inhabited low-lying areas, particularly the entire Istrian West Coast and areas of the towns of Zadar, Omis, and Dubrovnik, would experience moderate effects in terms of inundation and surge flooding. For example, the detailed study for the islands of Cres/Losinj showed that a sea-level rise of one meter would inundate or endanger approximately 13% of the current island population of 11,796 (Randic *et al.,* 1996).

An 86-cm sea-level rise scenario would also have serious effects on marinas, shelters for small boats, harbours, beaches, and infrastructure in low-lying area. The small-inhabited island of Krapanj would be almost totally inundated because its altitude is approximately 1 m above sea level. Historical town centres, such as Split, Pula, Rovinj, and Trogir, would also be at risk from inundation and surge floods. It is very difficult to assess the possibility of saline water intrusion into the Vrana Lake on Cres. However, this would probably occur near the town of Biograd because of its proximity to the seashore and the high porosity of the karstic coastal strip separating the lake from the sea.

Socio-economic Effects

A sea-level rise of 20 cm and associated biogeophysical effects would have, in general, negligible socio-economic consequences on the entire coastal area. However, an increase of 86 cm and associated biogeophysical effects would have moderate to high consequences. In particular, maritime transport and tourism would be affected because berths and piers would be inundated or frequently flooded. To cope with these effects a costly investment in coastal protection would be necessary. The majority of the small pocket beaches, if backed by a hard coastal defence, would be squeezed between the rising sea and hard defences and would require beach nourishment. The greatest potential effect would be on sewerage systems of coastal settlements located in low-lying areas. Sea-level rise would severely affect their functioning, and in many places, new sewage systems would be required. In addition, agricultural activities could be threatened, notably in the estuary of the Neretva River, where a large part of the alluvial plain has been reclaimed via the construction of dikes, channels, and pumping stations. Increased sea level might endanger this infrastructure, resulting in frequent surge flooding and intrusion of saline water.

Possible intrusion of saline water into the Vrana Lake on Cres would seriously affect the local population because the lake is used as the main freshwater source. The effect of possible intrusion of saline water into the Vrana Lake near the town of Biograd would also affect agricultural activities around the lake, since salty water can not be used for irrigation.

Vulnerability Analysis

Coastal areas where erosion is currently taking place would, very probably, be at greater risk because of projected sea-level rise, but because it is limited, it is primarily a local problem.

Existing pocket sand and gravel beaches would be inundated, but a significant number of them would be re-established further landward under wave activity and erosion where slopes permitted. In addition, artificial beaches could be constructed within tourist complexes. Therefore, in the long term, beach inundation would probably only have minor effects on tourism. Historical city centres located in low-lying areas that are of national interest would also be endangered by projected sea-level rise and increased inundation risk. Threats to infrastructure would vary from localised effects on the road system, which might be solved by the landward realignment, to effects on existing harbours, marinas, and piers, which would be a national problem. Existing structures along the coastline are adapted to a low tidal range (0.3 m in the south and 1 m in the north) and will require upgrade even given small increases in mean levels. The protection of all the low-lying areas in Croatia from inundation is not feasible. However, programmes should be initiated to protect sites of great natural, socio-economic, and cultural importance.

Groundwater is not used as the main freshwater source for either water supply or agriculture. However, at some locations, projected sea-level rise might affect the groundwater supply used locally for irrigation. In addition, the water supply function of the freshwater lake on Cres could be endangered by sea-level rise, which would drastically affect the population of two islands. Furthermore, the large reclaimed alluvial plain of the Neretva River would be threatened because of increasing risks of inundation and surge flooding. Increased protection would be necessary here.

POTENTIAL FOR ADAPTATION TO SEA-LEVEL RISE

In terms of population, Croatia is a small country with an economy in transition, suffering from the recent war and an inefficient transition from a socialist into a free trade economy. However, in terms of the length of its coastline (including islands), Croatia belongs to a small number of countries having a very long coastline. Such disparity between population, economic potential, and coastal length creates difficulties in strategic coastal defence planning. Therefore, national priorities should be established and areas to be protected identified according to their importance for social, economic, cultural, or historic reasons. In the absence of any national strategy or plan of activities to cope with sea-level rise, it is impossible to assess the national potential for adaptation to sea-level rise regarding technical and institutional aspects. However, it is likely that for the protection of some historical monuments, particularly those included in the UNESCO World Heritage list, international assistance would be required. This would include Diocletian's Palace in Split and the historic core of the town of Trogir. Unfortunately, proactive measures for sea-level rise are not being implemented so far.

FUTURE NEEDS TO MANAGE THE ISSUES RAISED BY SEA-LEVEL RISE

Climatic change, and in particular sea-level rise in coastal areas, is mainly a gradual phenomenon. When coupled with the inertia inherent to human nature, the usual response to this phenomenon is not characterised by immediate and urgent actions. This is particularly valid in the case of Croatia, where dangers of sea-level rise are not imminent and eventual negative effects are not visible in the short term. Such attitudes have to change because changes associated with sea-level rise will certainly occur, and an adaptation strategy, as a long-term planning activity, is highly desirable. The actual consequences of climate change will depend on both the magnitude of climate change and human adaptive capacity. Many of the effects of sea-level rise could be avoided or managed effectively given proactive measures today. This suggests the need to increase the national capacity to manage the coastal zones in the short, medium, and long terms.

It is widely known that some natural systems could exercise autonomous or "unplanned," adaptations to sea-level rise–induced changes (Klein and Nicholls, 1998). Although these responses are not to be discounted or ignored, it must be noted that the actual benefits of these responses are limited, mostly because of human interruption and interference in natural trends toward a dynamic equilibrium. Therefore, they should not be considered a substitute to planned and long-term adaptation strategies. Given the potential negative socio-economic effects of sea-level rise, comprehensive activities aimed at the mitigation of and adaptation to the adverse effects of these changes is necessary.

The establishment of a national strategy for climate change is in an early stage. The first step, which is under way, should identify coastal areas on the mainland and islands that might be affected by projected sea-level rise. In addition, biogeophysical and socio-economic effects should be identified. As the second step, the detailed analyses of identified vulnerable locations and evaluation of possible consequences should be undertaken. On the basis of these findings, a national strategy and plan of activities for the prevention, reduction, and mitigation of negative biogeophysical and socio-economic effects should be prepared and adopted by national authorities. The strategy and plan of activities should cover two main fields of concern: protection of national resources and existing and future infrastructure and buildings in the coastal zone, which should be sustainable and flexible enough to adapt to sea-level rise.

A national monitoring scheme of the consequences of sea-level rise on coastal erosion and on ground and surface waters at specific locations along the Croatian coast also needs to be established. Such a system will provide reliable data to help the decision-making process. The most appropriate locations would be in the vicinity of the towns of Nin and in the Neretva Delta (delta in estuary) for the monitoring of erosion and in Lake Vransko for the monitoring of saline water intrusion. Monitoring should be a permanent activity, and its results should be made widely available to raise the awareness on sea-level rise issues—not only at the level of decision makers and key stakeholders, but also among the general public because their participation is crucial for the success of any implemented strategy.

Research on the effects of global climate change on sea-level rise should be directed at understanding and projecting changes in sea level, extreme events, precipitation, and other consequences of global change on coastal areas. These projections could serve as the bases for global/regional models and scenarios that will help identify potential dangers long before they occur. Initial assessments should prepare detailed studies of identified vulnerable locations, whereby potential effects should be evaluated.

Any adaptation measures identified in the previous process must be consistent with, and be integrated into, existing coastal area management plans and programmes. It is widely agreed that there are three generic response strategies to sea-level rise: retreat, accommodation, and protection (Klein and Nicholls, 1998). Because of the diverse characteristics of the Croatian coast, it would be necessary to implement all types of response strategies, depending on the site characteristics and its importance from various perspectives. The retreat response strategy involves no effort to protect the land from the sea which, because of its characteristics, seems to be the most appropriate strategy for the major part of the Croatian coast. Accommodation and protection strategies would be best implemented in selected locations. The first one implies implementation of partial measures to mitigate negative sea-level rise effects (*e.g.,* erecting emergency flood shelters, elevating buildings, modifying drainage systems, *etc.*). This should be implemented for the protection of endangered settlements and economic activities (particularly tourism, transport, and agriculture), as well as some ecosystems (estuaries and wetlands of the rivers Neretva, Krka, and Cetina). The protection strategy is an "aggressive" form of adaptation that includes building sea walls and dykes, as well as other physical structures, with the objective of maintaining existing land uses and assets and allowing no loss of land or assets. This strategy is appropriate in coastal areas with no alternative land for resettlement, or with assets of high value. In Croatia, there are only a few locations for which this strategy would be necessary—notably, the historical town centres of Pula, Trogir, and Split; the island of Krapanj; and the estuary of the Neretva River.

However, every strategy implies significant trade-offs among all the stakeholders in the coastal zone (WCC '93, 1994). Also, each response strategy could result in a variety of environmental, economic, social, cultural, legal, and institutional implications. It is, therefore, of particular importance that adequate instruments be used in assessing these implications for any strategy that is to be adopted. Evaluation of alternative strategies should be undertaken before the decision-making stage on the basis of the use of a number of more or less sophisticated techniques, such as Benefit/Cost Analysis, Environmental Impact Assessment, Strategic Environmental Assessment, Multi-Criteria decision methods. The results of the application of these techniques could provide decision makers with valuable help in their endeavours.

CONCLUSION

The Croatian coast is mainly rocky and steep, with one large reclaimed alluvial plain (Neretva River). As such, coastal vulnerability to sea-level rise is assessed, in general, as low. However, some important sites, such as historical town centres, the alluvial plain of the Neretva River, and Vrana Lake on the island of Cres could be seriously endangered by the potential consequences of climate change and sea-level rise.

Assessment was done by expert judgement because of a lack of reliable quantitative data. The uncertainty of this assessment might be high, but the assumption was that it is better to have a first qualitative assessment than to wait until relevant quantitative data are generated. In addition, for countries like Croatia, where the dangers of sea-level rise are not imminent and the eventual negative effects are not significant in the short term, it is important to initiate this type of assessment to begin to sensitise and raise awareness on sea-level rise issues.

Because of Croatia's long coastline, it is obvious that protection of the entire coast is not feasible. Therefore, long-term national adaptation strategies and plans of actions should be prepared that identify areas and places of importance and include relevant adaptation/mitigation activities for each site. These should be adopted at all decision-making levels. In addition, monitoring of the effect of sea-level rise and research on the possible consequences of climate change on the coastal zone should be implemented.

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□ SAZETAK □

Hrvatska je obala veoma dugacka u usporedbi s ukupnom povrsinom zemlje. Obalno je podrucje uglavnom krsevito sa strmom obalom. Obalno podrucje, koje nastanjuje 23% ukupnog broja stanovnistva, je znacajno za nacionalno gospodarstvo, osobito za turizam i Mediteranski tip poljoprivrede. Mjerenja razine mora na cetiri lokacija na istocnoj Jadranskoj obali u posljednjih 40 godina pokazuju, kao rezultat lokalnih dizanja odnosno spustanje obale uslijed tektonskih poremecaja, porast razine izmedju 0.53 i 0.96 mm/godina, odnosno pad razine izmedju 0.50 i 0.82 mm/godina. Procjena utjecaja pretpostavljenog porasta razine mora od 20 i 86 cm na obalno podrucje nacinjena je metodom ekspertske procjene zbog nedostatka odgovarajucih kvantitativnih podataka. Procjenjeno je da u najvecem dijelu obala nije osjetljiva na pretpostavljene promjene. Medjutim, neka znacajna mjesta, kao sto su povijesna sredista nekih gradova, dolina rijeke Neretve i Vransko jezero na otoku Cresu, mogu biti ozbiljno ugrozena. Zbog velike duzine obalne linije sasvim je razumljivo, da se cjelokupna cjelupna linija ne moze u potpunosti zastititi. Stoga je nuzno pripremiti i prihvatiti nacionalnu strategiju za obranu od ocekivanog porasta razine mora te plan i program potrebnih aktivnosti koji treba ukljucivati pracenja utjecaja i istrazivanje na odabranim lokacijama.