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SEA-LEVEL RISE: IMPLICATIONS FOR WATER RESOURCES MANAGEMENT

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Abstract. Globally, sea level has been rising for more than the last one hundred years, and is expected to do so into the foreseeable future, and at an accelerating rate. The direct influences of sea-level rise on water resources come principally from the following: new or accelerated coastal erosion; more extensive coastal inundation and higher levels of sea flooding; increases in the landward reach of sea waves and storm surges; seawater intrusion into surface waters and coastal aquifers; and further encroachment of tidal waters into estuaries and coastal river systems. The impacts of sea-level rise are likely to be felt disproportionately in certain areas, reflecting both natural and socio-economic factors that enhance the levels of risks. The opportunity to learn about the likely nature of, and most appropriate adaptation to, the anticipated impacts of sea-level rise on water resources is arguably best developed in rapidly subsiding coastal areas, and especially in low-lying deltas where subsidence rates are typically much larger than the historic rise in global mean sea level. Significantly, such areas are often major centres of population and of economic activity, thereby highlighting the human dimensions of sea-level rise. Sound management of the risks to water resources associated with sea-level rise requires enhancing adaptive capacity, mainstreaming adaptation, harmonizing responses to extreme events, variability and long-term change and strengthening regional and international cooperation and coordination. In this regard, the policies and initiatives of international organisations are not always entirely consistent with the needs of developing countries.

Keywords: sea-level rise, impacts, water resources management, adaptation, adaptive capacity

1. Introduction

This paper, prepared in support of the Dialogue on Water and Climate (Kabat and van Schaik, 2002), is intended to assist water resources managers to strengthen their ability to address the impacts of increasing variability and significant trends in the world's climate, and specifically sea-level rise, as a consequence of global warming. It is based on an extensive review of the English language literature, both formal and informal, and of other languages to the extent possible. The paper summarises and captures the key elements of the current state of knowledge and experience, covering both changes in mean conditions and variability, including extreme events. The main focus is on developing countries, with the importance of international and regional cooperation and collaboration also being highlighted.

2. Sea-level Rise: What is Our Current State of Knowledge and Understanding?

Globally, over the last one hundred years sea level has *risen*, by 10–20 cm (IPCC, 2001a). It is expected to continue rising into the foreseeable future, and at an accelerating rate. But regional and local sea levels have *changed* – in some places rising, in others staying the same and in others falling, relative to a fixed point on the land. Thus accompanying the global rise in sea level are additional changes that contribute to regional and local variations in relative sea-level trends. These may exacerbate or reduce the global effect. Regional and local factors include uplift or sinking of the land as a result of crustal movements, and loading or unloading of the Earth's surface due to changes in the overlying mass of water or ice. Other variations are associated with local climatic and meteorological conditions (e.g. variations in air pressure, wind strength and direction), hydrological regimes (e.g. river discharge of freshwater) and with oceanographic conditions (e.g. strength and direction of ocean currents, water temperature, sea waves and swell). Such changes may be permanent or short term, the latter resulting in variations in sea level rather than persistent changes. Thus the level of the sea in relation to the land at a particular place results from a combination of global, regional and local factors, with the significance of the latter two varying considerably in time and space.

Atmosphere-Ocean General Circulation Models (AOGCM) parameterize the important processes contributing to changes in sea level, including thermal expansion of sea water as a result of an increase in its temperature, the melting of mountain glaciers and small ice caps, changes in the mass balance of the Antarctic and Greenland icesheets and changes in terrestrial water storage. Results from a suite of such models show that during the 20th century anthropogenic climate change made a steadily increasing contribution to sea-level rise (IPCC, 2001a).

Over the next millennium sea level will continue to respond to climatic change, even if greenhouse gas concentrations were to stabilize early in the 22nd century. This is due to lags in ocean warming and expansion, and in the response of land ice. The central value of projections of global sea-level rise from 1990 to 2100 is 0.48 m (IPCC, 2001a). This is between twice and four times the rate of rise over the 20th century. However, except for locations experiencing local subsidence (e.g. the Ganges-Brahmaputra-Meghna Delta, Bangladesh) or uplift (e.g. Rabaul, Papua New Guinea), changes in sea level will continue to be dominated by inter-annual variability, and by extreme events such as storm surges. The El Niño-Southern Oscillation and other inter-decadal oscillations are likely to remain key drivers of sea-level variability globally, even with climate change. Despite large uncertainties in all the foregoing projections, the ability to model the relevant processes means that "surprises" are unlikely. Importantly, but on time scales well in excess of 100 years, changes in ice sheet dynamics could result in significant loss of grounded ice. The present Greenland and Antarctic ice sheets contain sufficient water to raise sea level by almost 70 m.

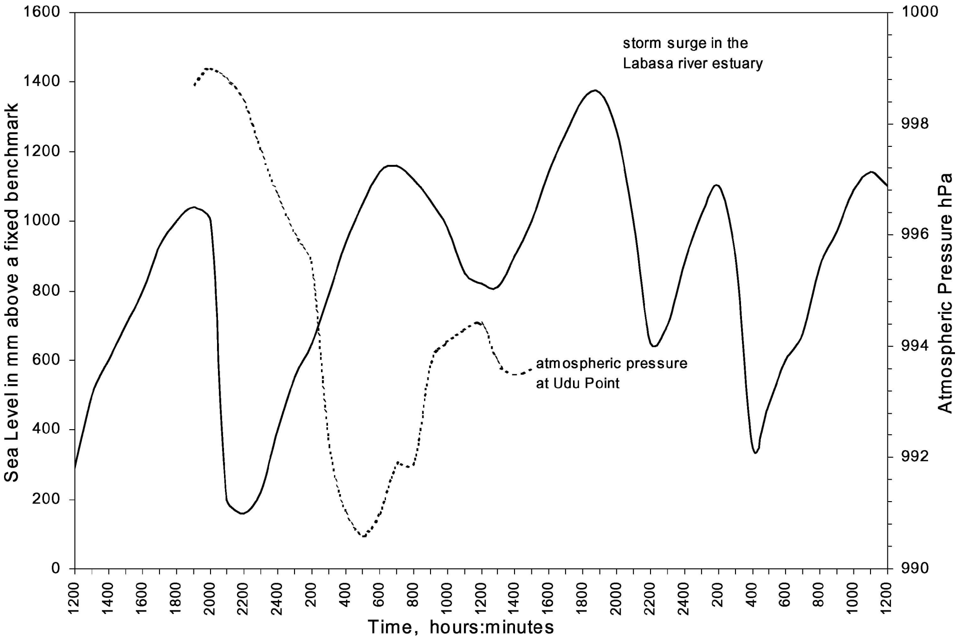

Figure 1. Water level in the estuary of the Labasa River, Fiji, and the barometric pressure at a site 75 km distant, as recorded during the passage of a tropical cyclone (from Terry and Raj, 1999).

Shorter-term changes in surface wind stress can also generate variations in sea level lasting a few hours to days, and may have far-reaching consequences when the effects are combined with those of low air pressure and high tides. Most noteworthy in this regard are storm surges (Figure 1). But all that is necessary for a change in the frequency of extreme sea levels at a specific location is a change in the mean sea level. Given the projected increase in global average sea level as a result of climate change, it is very likely that such frequency changes will be experienced in the 21st century, and beyond.

3. Water Resources Management: Why Does Sea-level Rise Matter?

Figure 2 highlights the wide diversity of direct impacts of sea-level rise on the water resources sector. These are also associated with a plethora of other impacts which encompass not only the water resources sector, but most if not all other sectors, including health, transport and agriculture. Since water resources are managed for the benefit of the populations served, the many, complex consequences of sea-level rise pose a particular challenge to those managing these assets (Bergkamp et al., 2003).

The direct influence of sea-level rise on water resources comes principally from the following: new or accelerated erosion of coastal wetlands; more extensive

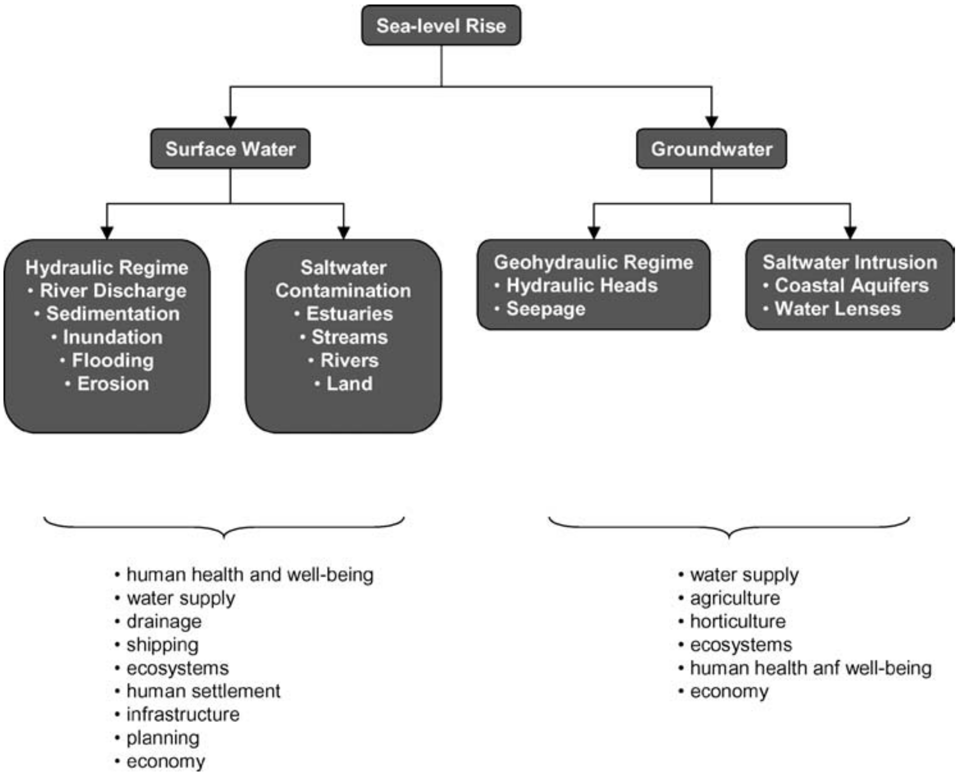

Figure 2. Effects of sea-level rise on water resources management (after Oude Essink et al., 1993).

coastal inundation and higher levels of sea flooding; increases in the landward reach of sea waves and storm-surges; seawater intrusion into surface waters and coastal aquifers (i.e. contamination); and further encroachment of tidal waters into estuaries and coastal river systems.

Sea-level rise, on its own, will not result in seawater contaminating a fresh groundwater lens. It merely raises the interface between the saline and fresh water. But frequently, when one or more of the other direct impacts occurs, seawater will penetrate further into coastal aquifers. For this reason, seawater intrusion into coastal aquifers is considered here to be a "direct" consequence of sea-level rise.

3.1. Increased Flooding and Inundation

Changes in the highest sea level at a given locality result primarily from a combination of a change in mean sea level at that location, and a change in storm surge height. The vulnerability of many coastal features, such as low beaches, lagoons, bays, estuaries, atolls, low-lying islands and deltaic plains, increases markedly with sea-level rise, as a result of their relatively low gradient. Initially coastal areas may

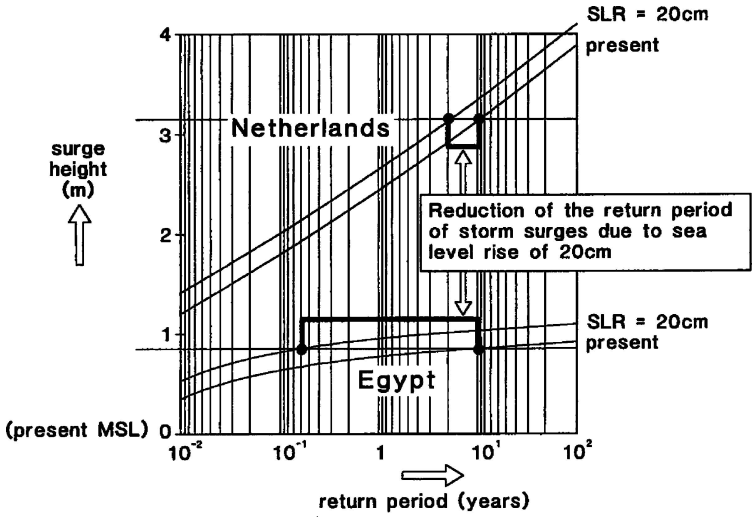

Figure 3. Impact of sea-level rise on storm surge return periods (from Hoozemans et al., 1992).

suffer episodic inundation (i.e. flooding), largely associated with storm surges. With continuing increases in mean sea level this may become permanent.

Figure 3 demonstrates the influence of sea-level rise on storm surge return periods. In countries with low decimating heights, such as Egypt, the frequency of extreme storm surge events will increase dramatically. Thus the increased risk of flooding as a result of sea-level rise is greater for small islands, the southern Mediterranean coast, the African Atlantic coast and the Indian coast (Hoozemans et al., 1992).

A rise in sea level may also lead to the silting of coastal channels as the nearshore sand prism moves landward, in response to the changing hydrodynamic conditions. This may result in the increased intensity of floods in coastal areas, as well as lower river reaches (Alam, 1996; Mimura and Kawaguchi, 1996).

Higher sea levels may, in some cases, result in a local rise in the water table. The distance inland that a water table will be affected by sea-level rise depends on a range of factors, including elevation and subsurface permeability. In some locations, particularly deltas as in Bangladesh, rising water tables can occur as far as several tens of kilometres inland. Thus, even for depressions that are some distance from the coast, sea-level rise may lead to an expansion of the standing body of fresh and brackish water. Drainage of these and other low-lying areas will often be impeded. The need to consider the consequences of rising water tables depends not only on the potential for saltwater intrusion into groundwater, but also the potential to reduce the supporting capacity of the ground and increased liquefaction as well as impacts on foundations, drainage systems and underground services.

In addition to the possibility of accelerated erosion (see Section 3.2), and even in the absence of the projected changes in storm intensity, sea-level rise may result in

TABLE I

Area and population of the Asia-Pacific Area potentially affected by inundation and flooding (from Mimura, 2000a)

	Present day		2100, with 1 m sea-level rise	
	High water	High water and storm surge	High water	High water and storm surge
Inundated and flooded areas (10^3 km^2)	311	611	618	858
Affected population (10^6)	47	203	200	450

increased storm damage. Wave runup and overtopping can be destructive to water management infrastructure and other assets for a considerable distance inland, as can salt spray that may be carried inland over long distances.

Mimura (2000a) has estimated the possible maximum land area and population of the Asia-Pacific region that are subject to inundation and flooding under four conditions – high tide level as at present; high tide and storm surge as at present; high tide with a 1 m sea-level rise and population projected for 2100; and high tide, storm surge, 1 m sea-level rise and population projected for 2100. The results (Table I) reveal the potential for an additional 240 000 km^2 of land to be flooded, and some 250 million people to be affected directly.

3.2. Accelerated erosion of coastal wetlands

Coastal erosion represents the physical removal of sediment by wave and current action. With rising sea level, sediment from the upper part of the tidal range is eroded and deposited subtidally. However, many wetlands are building up their surfaces at a similar rate to historic sea-level rise, through sediment trapping and soil formation. Thus, while the rate of wetland submergence is currently low in most coastal areas, this is unlikely to continue given that the rate of sea-level rise is projected to increase above historic values. Also, human activities such as the damming of rivers to create storage lakes and reservoirs mean that current rates of sediment supply may not be maintained into the future.

Based on regional and global studies of the impacts of sea-level rise on coastal wetlands, it is estimated that, by the 2080s, a 40-cm rise in global-mean sea level could cause the loss of up to 22% of the world's coastal wetlands (Nicholls, 2002). Direct and indirect destruction by humans could cause greater losses. Thus sea-level rise reinforces other adverse trends of wetland loss. The largest losses due to sea-level rise will be where the tidal range is lowest, such as around the Mediterranean and Baltic, the Atlantic coast of Central and North America and most small islands, including the Caribbean.

Wetland systems on low islands are more susceptible to disruption by rising sea level because the only sediment available is produced by the system itself, giving relatively low rates of sediment accumulation. For high islands and the coastal margins of continental areas there is more sediment coming off the land into intertidal areas. Ellison (1992) found that in the low islands of the Pacific, mangroves could keep up with a sea-level rise of 8 cm/100 years, but would be affected detrimentally if rates exceeded 12 cm/100 years. Mangroves on high islands could keep up with rates of 20 cm/100 years provided sediment supply was not restricted by human activities. In both cases these rates are at or above the projected minimum rate of global sea-level rise for the present century (see Section 2). Miyagi et al. (1999) suggest the threshold is 50 cm/100 years for mangrove survival and species changes.

Another vulnerable coastal feature is the sandy beach. This will be eroded at an accelerated rate as a result of sea-level rise. Mimura and Kawaguchi (1996) have evaluated the consequences for Japan and concluded that 56.6, 81.7 and 90.3% of the area of existing Japanese sandy beaches would be eroded due to sea-level rises of 30, 65 and 100 cm, respectively. As beach erosion is severe even today, due to a lack of sediment supply and discontinuation of alongshore sediment transport, this additional erosion will exacerbate coastal erosion problems.

3.3. Increased Saltwater Intrusion

Current and emerging problems resulting from saltwater intrusion will may also be exacerbated by sea-level rise, and new areas may be affected. The combined effect of impeded flow in rivers (often compounded by human activities upstream) and rising sea level could result in greater intrusion of saline waters into estuaries and streams. Tidal waters will penetrate further inland and will be able to contaminate larger areas. Similarly, contamination of coastal aquifers can occur, with the amount of intrusion being a function of local groundwater gradients. Seepage of salt into soil via groundwater is already a problem in many low-lying areas. All the preceding problems, including salinization of farmlands and the lower quality of water used for drinking and industrial purposes, are more significant during the dry season, when both river flows and infiltration are low and evaporation is high. Saline intrusion along estuaries, associated with higher sea levels and perhaps exacerbated by lower river flows, could also threaten low-lying freshwater intakes (IPCC, 2001b). As a result of rising sea levels the freshwater lens that typically underlies a small island is also vulnerable to saltwater intrusion, a situation that is aggravated by excessive groundwater extraction.

4. Where are Water Resources Most Vulnerable to Sea-level Rise?

The foregoing findings lead to the identification of areas where the localised vulnerability of water resources to sea-level rise is high, with serious implications for human health and well-being – so called “hotspots”. Generically, these include coastal areas where subsidence is occurring, due to natural and/or human factors; the land is low lying and low gradient, and subject to storm surges; extraction of groundwater is excessive; and engineering works exacerbate flooding, erosion and/or saltwater intrusion. Seldom do such contributing factors act in isolation. Rather, they often operate in concert, thereby compounding the adverse effects of sea-level rise on water resources and dependent systems such as human society, as well as requiring integrated approaches to managing the adverse impacts.

Moreover, social and economic factors often enhance the vulnerability of water resources to sea-level rise. Arguably, this is no better demonstrated than by the subsiding megacities in Asia, particularly those on deltas (Nicholls and Mimura, 1998). Some coastal areas (e.g. Jakarta, Calcutta, Bangkok) experience natural subsidence rates in excess of several centimetres per year, and hence more than ten times the present-day rise of global sea level (Emery and Aubrey, 1991). These subsidence rates reflect regional and local tectonic effects, as well as consolidation of the sedimentary strata underlying the delta. While such processes may be offset by the deposition of river-borne sediment, particularly during flooding, they can also be augmented through the extraction of groundwater (and, in some instances, petroleum), enhancing the rate of sediment compaction. For example, excessive withdrawal of groundwater to serve Bangkok's rapidly growing population in the 1960s to 1980s resulted in accelerated subsidence that locally exceeded 10 cm/year (Nutalaya et al., 1996). Subsequently extraction rates were regulated, slowing the rate of subsidence.

As Nicholls (2002) notes, the impacts of sea-level rise are likely to be felt disproportionately in certain areas, reflecting both natural and socio-economic factors that lead to higher vulnerability. He suggests that, in absolute terms, the most vulnerable locations are found around Africa and, most particularly, South and South-East Asia, with lesser impacts in East Asia. The vulnerability of Africa reflects rapid population growth, combined with a limited capacity to undertake responses, due to economic constraints. The vulnerability in Asia reflects significant population growth within the numerous large deltas, where flood management is much more expensive than in most other coastal settings. The vulnerability of small islands, particularly low-lying coral atolls, is also widely acknowledged. Studies suggest that the islands of the Caribbean, the Indian Ocean and the Pacific Ocean may experience the largest relative increase in risk to water resources as a result of sea-level rise. This vulnerability reflects the concentration of population around the coast, even on 'high' islands. Adaptation options in many small islands are more limited than other coastal regions.

Nicholls (2002) also draws attention to national studies that have identified hotspots of vulnerability. For example, Guyana and Suriname have a high impact potential and have similar problems to many of the Asian deltas. This contrasts with a lower vulnerability in most of South America. He emphasises the need for a systematic identification of hotspots at a detailed level around the world, in order to focus intensive effort on identifying and implementing adaptation activities.

5. Coping with Sea-level Rise

Natural coastal systems have a capacity to respond autonomously to external pressures such as climate change; that is, up to a certain threshold they can cope with the rise by "growing with the sea" (UNEP, 1998). For example, a healthy wetland could respond by enhancing sediment deposition rates. In many places, however, human activities have reduced the resilience of the natural coastal system to sea-level rise, to the extent that the potential for autonomous adaptation has decreased markedly. Such detrimental activities include infrastructure development and pollution. It is clearly beneficial to reduce such pressures, since the actions will bring benefits that extend well beyond reducing the adverse impacts of sea-level rise. Planned adaptation to sea-level rise (see Section 7) should therefore include consideration of options that address impediments to autonomous adaptation.

Socio-economic systems in coastal zones also have a capacity to respond autonomously to external pressures, including sea-level rise. People, and their support and lifestyle systems, are in a constant process of coping with environmental variability and change as well as with a range of economic, social and political factors. These coping processes are reflected in systems of resource use, including agriculture, water consumption, housing styles, settlement locations and the like. It is important to recognise that the coping process is dynamic, since the influences people and communities respond to, and their personal needs and wants, are constantly changing. Autonomous adaptation is likely to become more important as sea level rises, though its effectiveness is likely to decrease with the increase in rate of rise above historic values. Planned adaptation activities should always be undertaken in ways that reinforce coping processes.

6. What Lessons Have We Learned; What can We Do Better?

It is prudent to manage water resources in ways that prevent the adverse effects of climate variability and change. If adaptation is forced, as opposed to planned, the range of response options is likely to be fewer; delayed adaptation may also prove more expensive, socially disruptive and environmentally unsustainable. Recent and current experience can teach us much about the likely nature of, and most appropriate responses to, the anticipated impacts of sea-level rise on water resources. This opportunity to learn has perhaps been greatest in rapidly subsiding coastal areas, and especially in low-lying deltas where subsidence rates are typically much larger than the historic rise in global mean sea level. Significantly, such areas are often major centres of population and of economic activity, thereby highlighting the human dimensions of sea-level rise. The following discussion focuses on some of the major lessons learned when considering how the water resources sector can best adapt to sea-level rise.

6.1. Mainstream Responses to High Sea Levels (Including Disasters)

Since non-climate stresses often exacerbate the adverse consequences of sea-level rise for the water resources sector, responses to sea-level rise should be harmonized with policies in other areas, using such tools as disaster management plans, land-use plans, integrated watershed management plans and national- and community-level sustainable development plans. All should respond to the fact that, amongst other things, extreme, variable and systematically rising sea levels are significant impediments to successful economic development, i.e. they represent risks to the regional, national and local economies. Many countries are already experiencing the manifestations of these risks, in the form of disasters, but also via variations in sea level, especially where land subsidence is occurring. Such risks should be managed in a holistic manner as an integral part of national development planning, with a move away from disaster response to a focus on hazard assessment and risk management. Most countries already have policies and plans to manage financial risks, human health risks, biosecurity risks, agricultural risks, risks in the transport sector and energy supply risks. Risks related to sea level should be included and addressed in the same portfolio of national risks.

Many of the actions required to reduce or avoid the adverse consequences of extreme, variable and rising sea levels are the same as those which contribute in a positive manner to sustainable development, sound environmental management, and wise resource use (Mimura, 2000b). Risk reduction should involve, preferentially, the use of "no regrets" policies and measures. These are appropriate responses to current variations (including extremes) in sea level and to other present-day and emerging stresses on social, cultural, economic and environmental systems. Thus, "no regrets" strategies, plans and actions are beneficial even in the absence of climate change.

Examples of adaptation strategies involving mainstreaming of activities that address the adverse consequences of sea-level rise for the water resources sector include:

- use of a participatory approach to identify, research and communicate the actions that enhance policy and decision making in ways that ensure optimal, multi-sectoral and multi-stakeholder participation and uptake, and timely responses to sea-level rise and related pressures;
- identify, and support at appropriate times in the national development planning cycle, the key change agents who can, by implementing the above actions, facilitate the mainstreaming of adaptation to sea-level rise, including disaster risk management; and
- document and share relevant information, including success stories, lessons learned and good practice guidelines arising from the above activities.

An important countermeasure to extreme events is a combination of warning and evacuation systems, and soft and hard risk reduction measures. The former include early warning systems, education about disaster evacuation and damage relief assistance after disasters. For example, in Bangladesh casualties from tropical cyclones decreased dramatically between the 1970s and late 1990s. This is attributed to deployment of a cyclone detection radar system, supported by early warning using radios and evacuation shelters in villages. Examples of soft measures are the planting of mangroves along vulnerable coasts, beach nourishment and coral transplanting, while hard measures include seawalls and coastal dykes, such as in Japan. Since it is not possible to prevent very high sea levels, such as are caused by extreme storm surges and tsunamis, role differentiation amongst these measures is important.

6.2. Implementing Adaptation Strategies under Uncertainty

The intrinsic unpredictability of complex systems, such as those in the coastal zone, means there are significant uncertainties in estimating their responses to external pressures such as sea-level rise. Other sources of uncertainty include the downscaling of global, regional and national estimates of relevant variables to island and site scales, extrapolation and adjustment of point and areal data (including cost estimates derived from studies made outside the region). The Precautionary Principle (*where there are threats of serious irreversible damage, lack of full scientific certainty should not be used as a reason for postponing precautionary measures to anticipate, prevent or minimize the causes of climate change and limit its adverse effects*) has often been invoked to justify why action should be taken to address climate change issues, including sea-level rise. In the past, and to a large extent even today, uncertainties in risk estimates, and even more so in the likely success of adaptive responses, have been simply too large to convince most policy makers to divert scarce resources from one part of the national, enterprise or community budget in order to support activities related to addressing the anticipated or emerging adverse consequences of sea-level rise.

The high level of uncertainty which faces those responsible for incorporating sea-level rise in water resources management highlights the need for an adaptive management approach. Adaptive management treats management policies and actions as experiments, allowing continual improvement in the outcomes of management decisions are a result of learning from the success, or otherwise, of past management decisions. Adaptive management addresses uncertainties by linking credible science with the values and the experiences of stakeholders and managers in ways that improve the outcomes of management decision making. Because of large uncertainties surrounding the nature of local changes in sea level, and in the consequences for the water resources sector, perhaps extending to surprises, there is a need for flexible management approaches in the water resources sector, including open institutions that allow for learning and for the building of adaptive capacity. There is also a need for adaptive management processes and flexible, multi-level governance that can learn, generate knowledge and cope with change. Such systems generate a diversity of management options that heighten the ability to respond appropriately in the face of uncertainty and surprise (Folke et al., 2002b).

Beach nourishment, which can be implemented as relative sea level rises, as opposed to the use of less flexible responses such as the use of a dyke or seawall, is an example of an adaptation strategy that acknowledges the high level of uncertainty in characterizing the pressures and adverse consequences of sea-level rise for the water resources sector. Others are rolling easements, as opposed to setbacks, and damage insurance at rates that vary over time, in response to changing risks as sea level rises and storm surge frequency and intensity change. Where saline water intrusion threatens groundwater supplies, longer-term adaptation strategies include demand reduction initiatives such as improved maintenance of water reticulation systems to prevent and remedy leaks and conservation education and plumbing (Sphocleous, 2004).

6.3. Prevention and Anticipation are Better than Cure

Lessons learned from coping with extreme, variable and rising sea levels and related environmental pressures suggests that it is important to avoid short-term, "quick fix" adaptation strategies. For example, it is an almost automatic response to protect coastal land from flooding and inundation by building embankments and similar barriers. However, given the adverse consequences that frequently occur, including build up of sediment in the drainage channels and loss of fertility and accelerated subsidence and hence water logging of the protected area, in some instances it may be more appropriate to allow "natural" processes to take their course through a policy of managed retreat. This is especially so if population densities and infrastructure investments are low and if high and accelerating rates of sea-level rise are likely to prevail into the future, meaning that the costs of protective engineering works will escalate while the likelihood of successful protection will reduce rapidly.

Preventing the accelerated erosion of coastal wetlands as a result of rising sea level provides another example. Rather than taking direct action to protect the wetland ecosystems themselves, a more effective, longer-term solution may be to ensure the adequate supply and retention of sediment, while also reducing other pressures on the wetland ecosystem.

In Bangladesh, construction of embankments to protect coastal land from both river flooding and high sea levels has had many detrimental consequences (Moshin-Uddin and Islam, 1982). Responses with the potential to provide successful outcomes in the longer term include a proposal to build a series of dams in Nepal in order to store the monsoonal runoff and thereby reduce the downstream flooding in Bangladesh. The augmented river flows in the dry season would have the added benefit of reducing the intrusion of saltwater into the lower reaches of the major rivers and increasing hydroelectric power generation. Attention would have to be given to the potential of the dams to prevent sufficient sediment moving into the deltaic lowlands. An alternative approach that also reduces monsoonal river flows and enhances flows in the dry season is to construct a large number of deep artesian wells in the headwaters of the major river catchments (Alam, 1996). The wells would operate only in the dry season, in order to both augment river flows and lower the water-table, thereby creating the capacity to store water during the monsoon season. Both of these proposals would require resolution of complex riparian issues between Nepal, India and Bangladesh, including security of flow in the lower reaches of the rivers, improved catchment management practices to slow erosion rates and prevent rapid sediment accumulation upstream of the dams and international agreement to appropriately manage and operate the dams or wells (Alam, 1996).

Where a legislative response to extreme, variable and rising sea levels has been considered necessary, the tendency has been to take an expedient approach and introduce a specific regulation or law. This results in separate legislative responses for individual sectors, locations or resource users, with the risk of inconsistencies and loopholes. More effective results will likely arise if one piece of legislation is developed and passed. Addressing the problems in a more integrated manner will help ensure the controls and incentives are compatible, comprehensive and mutually reinforcing.

6.4. Implement integrated approaches that result in "win win" outcomes

Integrated approaches to problem prevention or solution are preferable since problems typically have multiple causes and consequences. Holistic perspectives avoid a single solution approach that may well simply transfer the problem to another locality or sector. An example is construction of embankments and polders in flood prone coastal areas that are also experiencing high rates of sediment accumulation and salinization of low-lying areas. Response strategies should also endeavour to maximize synergies with other strategies and plans, through identification and implementation of "win-win" responses. For instance, when the security of existing water supplies is improved by protecting the groundwater from contamination through the use of non-polluting sanitation systems such as composting toilets, multiple benefits result. These include production of a useful agricultural fertilizer (Ho, 2002).

Where excessive runoff and sediment removal in catchments would exacerbate flooding due to high sea levels, improved watershed management practices such as revegetation and soil conservation are appropriate. If higher sea levels are likely to accelerate erosion of wetland habitat, protection of critical ecosystems will be a priority. This might involve use of such measures as public awareness campaigns, "evacuation corridors" for ecosystem retreat, pollution prevention and controls, enforced penalties for reef and mangrove destruction, prohibition of sand mining and removal of coral, and promotion of sources of construction material other than from reef and other coastal systems.

6.5. Acknowledging the importance of monitoring and research

Successful choice and implementation of adaptation initiatives requires a solid knowledge base, in which the relevant conditions and processes are well characterised (Kobayashi, 2004). Incomplete information and understanding often result in well-intentioned preventative and remedial actions actually aggravating the situation. For example, in Bangladesh empoldering resulted in containment of silt deposition within the drainage channels, and many silted up, resulting in sluice gates becoming inoperative, causing serious drainage problems in the flood protection areas. Dykes designed to protect areas from floods have aggravated silting and flooding conditions on the delta (Moshin-Uddin and Islam, 1982).

Because of the high interannual variability that is evident in most coastal environments, one off, short term investigations may not be able to capture the relevant characteristics of the systems being studied. Long term monitoring is frequently a prerequisite to having sufficient knowledge of a dynamic environmental system.

Analogues and historic data (especially time series) of environmental, economic and social conditions, including projections into the future, are critical to developing an understanding of possible response options and identifying those that are most appropriate. As noted above, coastal areas experiencing rapid subsidence are an excellent analogue for future sea level as a result of global warming.

6.6. Improving Decision Making – Quantifying the Economic Costs and Benefits of Adaptation Options

All countries, communities and individuals face a dilemma – to focus on the uncertainties, and hope that further sea-level rise does not happen; to accept the worst case scenarios and embark upon major adaptation programmes involving a combination of accommodation, protection and retreat; or to take an intermediate approach between these extremes by defining an acceptable level of risk and implementing adaptation measures that mitigate those risks deemed to be unacceptable.

Governments of developing countries may well need to realign public expenditure and also work with donors and other key players to reallocate or attract the new development aid required to support rapid implementation of appropriate responses to sea level. To do this, it is necessary to have in place credible estimates of the economic costs of sea-level rise for the water resources sector, and of the costs and benefits of potential adaptation strategies. For example, economic analyses of flood protection in coastal China have shown large financial benefits relative to costs (Table II).

Until recently, uncertainties in characterising the local consequences of global sea-level rise, and even more so in the likely success of adaptive responses, were simply too large for adaptation to be incorporated in a meaningful way into national development planning and government-, private sector- and community-based activities. Studies, such as that featured in Table III, have clarified our understanding by highlighting the significant costs of extreme, variable and rising sea levels, by revealing how these costs are increasing with time, a trend that is highly likely to continue into the future. While the range given for anticipated costs is typically still large, the implications are clear – even in the near future extreme, variable and

TABLE II

Costs and benefits[a] of adaptation to sea-level rise, Pearl Delta Region, China (based on 1990) (values are in billion Yuan) (from Research Team of China Climate Change Country Study, 1999)

	Sea-level rise								
	30 cm			65 cm			100 cm		
Tidal level	Loss	Cost	Benefit	Loss	Cost	Benefit	Loss	Cost	Benefit
Highest recorded	13.6	1.76	11.8	41.6	2.91	38.7	60.6	4.75	55.8
100 year high water	19.0	2.08	16.9	38.9	3.37	35.5	67.1	5.11	52.0

[a] Loss – the adverse economic consequences of the event, without adaptation; Cost – the cost of adaptation measures; Benefits – the economic benefits arising from the adaptation measures.

TABLE III

Estimates of economic losses due to sea-level rise in the Pearl Delta Region, China (from Research Team of China Climate Change Country Study, 1999)

Coastal protection	Economic loss	Sea-level rise (30 cm) 1990	2000	2030	Sea-level rise (65 cm) 1990	2000	2030	Sea-level rise (100 cm) 1990	2000	2030
Nil	Billion Yuan	53.5	92.1	231.7	57.1	98.2	246.9	61.0	105.0	264.0
	Percent GDP[a]	84.4	145.2	365.4	90.0	154.9	389.4	96.2	165.6	416.3
Existing tide defences	Billion Yuan	13.6	22.6	56.0	41.6	71.9	180.8	60.6	104.4	262.5
	Percent GDP[a]	21.4	35.6	88.3	65.6	113.4	285.1	95.6	164.1	414.0

[a] On the basis of gross domestic product (GDP) of 63.41 billion Yuan in 1990.

rising sea levels are likely to impose major incremental social, environmental and economic costs. Importantly, such costs are distributed inequitably, preferentially affecting the poor and other vulnerable groups and countries.

Improved decision making will be facilitated by quantifying the likely economic costs of doing nothing, by highlighting the exorbitant costs of protecting land, ecosystems, people and infrastructure under worst case scenarios, and by identifying the co-benefits and cost effectiveness of a proactive, "no regrets" approach to adaptation that favours only those measures for which benefits exceed costs, even in the absence of climate change. Access to such information will assist in mainstreaming sea-level rise into the management of water resources and related assets.

Examples of adaptation-related activities that support identification and implementation of cost effective strategies that address the adverse consequences of sea-level rise for the water resources sector include use of such decision-support tools as economic cost-benefit analysis, environmental impact assessment, implementation of environmental accounting or similar systems that lead to increased internalization of environmental and other externalities and requiring that all major infrastructure projects undergo adaptation screening as part of an extended environmental impact assessment, thereby helping to proof such developments against sea-level rise.

6.7. Acknowledging the Importance of Local Factors

Local factors also determine the nature and extent of the impacts, and the economic viability, social acceptability and environmental consequences of given adaptation options. Thus response strategies that have proven successful in one location should not be applied at another, without consideration being given to making necessary modifications.

For example, the present population in the Asia and Pacific region is 3.8 billion. This number is expected to double within this century. Most of the population increase will occur in developing countries, where people tend to live in the coastal zones. In the Pearl (Zhujiang) River Delta, southern China, the coastline is moving 1 km seaward every 10 years, a consequence of tidal flats appearing above the water in the river mouth. Local governments plan to use the land, initially for farmland, as the pressure to find a new land is very high. In Bangladesh, occupation of emerging coastal land by poor landless people is also common, despite the high risk of inundation. In these two countries it is not acceptable to adopt the widely promoted option to retreat from the coastal areas at risk. Rather, people want to protect the land they have, for it is so precious. The situation is somewhat similar for small island countries, such as those in the South Pacific. In some instances protection is economically beneficial, as in the case of the Pearl River Delta (Table II).

Thus, adaptation options depend on the natural and social situation. Retreat may be suitable for countries with lower population densities while, as is the case for many parts of Asia, policy making and planning should consider the appropriateness of protection for the areas where many people already live, or are expected to live. For such areas, engineering works are required to ensure the safety of people and at the same time reduce the impacts on the natural environment.

The locale specific nature of the risks and responses also suggests that adapting freshwater systems to sea-level rise might best be implemented at the level where understanding and assessment of the anticipated or observed effects, and of the perceived options and benefits for response, are best developed. In many situations this may involve individuals, or members of groups such as households, extended families, community-based organisations, local councils or businesses. But under some circumstances local adaptation may not be satisfactory or successful, for reasons such as incomplete or erroneous understanding, lack of financial and other resources and the low cost effectiveness of many independent, small-scale initiatives.

6.8. Acknowledge the Importance of Traditional Knowledge and Practices

Over time communities have developed ways to cope with extremes, variability and change in sea level. This experience now provides a foundation of traditional knowledge and practices that can help form the basis of appropriate responses to sea-level rise and its consequential impacts. For example, in many low-lying coastal areas dwellings have traditionally been built on mounds, while cultivation practices have taken advantage of the advance and retreat of flood waters. Coastal aforestation has helped reduce the erosion of wetlands, as has deliberate trapping of sediment. The flooding of saline soils with fresh water has also been practiced.

There is an urgent need to document traditional knowledge and practices and to include this information in awareness raising and education programmes. This would allow past experience to be harmonized with modern approaches, thereby helping to ensure that the latter are locally relevant and culturally acceptable.

6.9. Using technologies to enhancing resilience to sea-level rise

Technologies, both hard (e.g. equipment and infrastructure) and soft (e.g. policies and guidelines) have important roles to play in improving the capacity of water resources managers to cope with the impacts of rising sea levels. Most adaptation options designed to avoid or mitigate the adverse impacts of sea-level rise on water resources involve technology, either directly or indirectly. Examples of specific technology-based adaptation measures include direct rainwater harvesting where groundwater supplies are degraded by saltwater intrusion, the design and construction of water supply infrastructure in ways that avoid and limit flood damage and avoid problems of excessive sediment accumulation, and management practices that protect coastal wetlands from excessive wave action and optimize freshwater and sediment flows.

7. Adaptive Capacity: How can We Ensure Successful Adaptation?

Adaptive capacity is the ability of a social-ecological system to cope with novel situations without pre-empting options for the future (Folke et al., 2002a). In social systems the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power amongst stakeholders, play an important role in ensuring adaptive capacity. Systems with high adaptive capacity are able to re-configure themselves without significant declines in crucial functions. A low adaptive capacity implies loss of opportunity, constrained options during periods of reorganisation and renewal, and an inability of a system to innovate.

A complex and dynamic mix of social, economic, technological, biophysical and political conditions determines the capacity of a system to adapt (IPCC, 2001b). These factors vary over time, location and sector. The main features of communities, countries and regions that determine their adaptive capacity include economic wealth, technology, information and skills, infrastructure, institutions and equity.

Both the impacts of sea-level rise and any adaptive responses place a large financial burden on a country. Only those with robust economies can absorb these costs. For example, the Research Team of China Climate Change Country Study (1999) has calculated the socioeconomic impacts of sea-level rise for the Pearl River Delta in conjunction with the highest tide on record (Table III). Table II presents a cost benefit analysis for these adaptation options. It is apparent that substantial benefits can be accrued even for minor rises in sea level. For a 1 m rise in sea level the benefits are similar to the GDP (1990) for the region. But in order to secure these benefits there has to be a substantial up front economic investment. This example illustrates how the adaptive capacity of a country, region or community can be enhanced, in part, by ensuring there are adequate economic resources to address sea-level rise issues.

The current level of technology, and the ability to develop or adopt technology, also has the potential to seriously impede the ability of the water resources sector to adapt to sea-level rise since most responses are technology based. Hence adaptive capacity is often influenced by the availability of, and access to, technology at the relevant level (e.g. community, national). For example, for many small island countries food security is threatened by sea-level rise. The resulting salinization of the groundwater and higher water tables threaten many root crops, due to their low salt tolerance. Small island countries in particular need to have improved access to technologies which prevent the salinization of groundwater, allow traditional crops to be grown well above the water table, and which facilitate the breeding of salt tolerant varieties of preferred crops.

Most water resources infrastructure will have a lifetime that extends far enough into the future that sea-level rise will become a significant factor in ensuring its security and maintaining its functionality. For this and other reasons, water resources infrastructure projects should undergo adaptation screening as part of environmental impact assessment. The screening process should include both an assessment of the likely impact of climate change on the project as well as the project's potential to increase the vulnerability of the area to environmental and related changes.

Adaptive capacity is also influenced by the "entitlement" of nations or communities to resources, and by the ability of management processes and systems of governance to ensure that the allocation of power within a community, a nation, or globally is such that access to the resources is distributed equitably, especially with respect to decision makers, managers and those who are most at risk (IPCC, 2001b). For example, there may be greater opportunity to ensure that centralised water resources infrastructure remains secure and functional despite a rise in sea level. But there may be little or no opportunity to modify the multitude of individually owned water supply systems in rural areas, to increase their resilience to sea-level rise. Owners may not even be aware of the need to adapt, until they find their system is not functioning, by which time the options for adapting may be few and costly.

The adaptive capacity of countries and communities, and implementation of specific adaptation activities, can be fostered through regional and international cooperation and coordination. Considerable progress has already been made under the United Nations Framework Convention on Climate Change, including the Kyoto Protocol. At another level, international cooperation and coordination can assist with documenting and disseminating success stories, lessons learned and good practice guidelines, based on preparatory and actual adaptation activities already being undertaken by water resource managers.

Whiled there are sound reasons for undertaking "no regrets" adaptation responses, as an immediate and urgent priority, structural and similar adaptive responses are often favoured due to the current preference and practice of donors and other funding bodies to meet only the incremental costs of adaptation. While predominantly a reflection of international policy, as well of the policies of some developed countries, the practice also distorts national adaptation and sustainable development policies in developing countries. A major shift in thinking and policy regarding which categories adaptation projects are eligible for funding is required, while also ensuring that appropriate levels of assistance are available to projects that are consistent with a "no regrets" approach to climate change, and to sea-level rise in particular.

If the risks to the water resources sector that are associated with sea-level rise and related conditions are to be managed successfully a partnership approach is required. While the onus for risk reduction through adaptation will often fall on central government, the locality specific nature of both the sea-level rise impacts and the required responses, mean that local communities, government and businesses will often be involved in highlighting the need for action and in undertaking the particular adaptation activities. This calls for open and participatory processes, with each party contributing in an equitable manner.

8. Conclusions

It is not possible to predict, with certainty, the nature and consequences of sea-level rise, especially at regional and local scales. Consequently, water resource managers and users must learn to address risks and uncertainties in more effective and efficient ways. Actions that are planned, meet the "no regrets" criteria and are cost effective are the responses of choice.

People will, as a result of their own resourcefulness or out of necessity, adapt to sea-level rise, based on their understanding and assessment of the anticipated or observed effects, and on the perceived options and benefits for response; in some cases such adaptations will be adequate, effective and satisfactory. But for many circumstances such adaptation, which is largely autonomous, may not be satisfactory or successful.

Planned adaptation should include initiatives that remove barriers to autonomous adaptation and reinforce the ongoing coping processes. Planned adaptation acknowledges that development initiatives typically have a life expectancy that requires future sea levels, and related changes, to be given due consideration.

People in coastal areas usually have a heavy dependence on local ecosystems that are sensitive and hence vulnerable to sea-level variability and change. While it still takes considerable time, it is far easier to enhance the ability of such ecosystems to cope with sea-level variability and change if they are healthy and not already stressed and degraded. Adaptation also requires enhancement of institutional capacity, developing expertise and building knowledge – these too take time.

While many risks related to sea-level rise are manifest locally, measures to alleviate them have important national and international dimensions. An external entity, such as central or local government, may be needed to facilitate the adaptation process to ensure that obstacles, barriers and inefficiencies are addressed in an appropriate manner.

References

Alam, M.: 1996, ‘Subsidence of the Ganges–Brahmaputra Delta of Bangladesh and associated drainage, sedimentation and salinity problems’, in J.D. Milliman and B.U. Haq (eds.), *Sea-level Rise and Coastal Subsidence: Causes, Consequences and Strategies,* Kluwer, Dordrecht, pp.169–192.

Bergkamp, G., Orlando, B. and Burton, I.: 2003, *Change: Adaptation of Water Resources Management to Climate Change*. The World Conservation Union, Cambridge, p. 53

Ellison, J.C.: 1992, ‘Impacts of sea level rise on Pacific Island mangrove swamps’, in J. O’Callahan, (ed.), Proceedings of the IPCC Workshop Held at Margarita Island, Venezuela, March 1992. Silver Spring, MD (USA): National Oceanic and Atmospheric Administration, pp. 641–657.

Emery, K.O. and Aubrey, D.G.: 1991, *Sea Levels, Land Levels and Tide Gauges*. Springer-Verlag, New York, p. 237.

Folke, C., Colding, J. and Berkes, F.: 2002a, ‘Building resilience for adaptive capacity in social-ecological systems’, in F. Berkes, J. Colding and C. Folke (eds.), *Navigating Social-Eclogical Systems: Building Resilience for Complexity and Change,* Cambridge University Press, Cambridge.

Folke, C. and 24 co-authors, 2002b: *Resilience and Sustainable Development: Building Adaptive Capacity in a World of Transformations,* Scientific Background Paper on Resilience for the Process of the World Summit on Sustainable Development, on Behalf of the Environmental Advisory Council to the Swedish Government, April 2002, p. 33.

Ho, G. (ed.): 2002 , *International Source Book on Environmentally Sound Technologies for Wastewater and Stormwater Management,* Technical Publication 15, International Environmental Technology Centre, United Nations Environment Programme, Osaka, Japan.

Hoozemans, F.M.J., Marchand, M., Pennekamp, H., Stive, M., Misdorp, R. and Bijlsma, L.: 1992, ‘The impacts of sea level rise on coastal areas: Some global results’, in O’Callahan, Joan (ed.), Global Environmental Change and the Rising Challenge of the Sea, *Proceedings of the IPCC workshop held at Margarita Island*, Venezuela, March 1992, Silver Spring, MD (USA), National Oceanic and Atmospheric Administration, pp. 607–622.

IPCC: 2001a, *Climate Change 2001: The Scientific Basis,* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK. p. 881.

IPCC: 2001b, *Climate Change 2001: Impacts, Adaptation and Vulnerability,* Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK, p. 1032.

Kabat, P. and van Schaik, H.: 2002, *Climate Changes the Water Rules*, Dialogue on Water and Climate, Delft, The Netherlands, p. 106.

Kobayashi, H.: 2004, Impact evaluation of sea level rise on Indonesian coastal cities – Micro approach through field survey and macro approach through satellite image analysis. *Journal of Global Environment Engineering* **10**, 77–91.

Mimura, N., 2000a: 'Distribution of vulnerability and adaptation in the Asia and Pacific Region', in N. Mimura and H. Yokoki (eds.), *Global Change and Asia Pacific Coasts*, Proceedings of APN/SURVAS/LOICZ Joint Conference on Coastal Impacts of Climate Change and Adaptation in the Asia-Pacific Region, Kobe, Japan, November 2000, Asia Pacific Network for Global Change Research and Center for Water Environment Studies, Ibaraki University, Japan, pp. 21–25.

Mimura, N.: 2000b (ed.), 'Climate Change Impacts and Responses', Proceedings of the Conference on National Assessment Results of Climate Change, San Jose, Costa Rica, March, 1998. Japan Environment Agency and Overseas Environmental Cooperation Center, Tokyo, Japan, p. 751.

Mimura, N. and Kawaguci. E.: 1996, 'Responses of coastal topography to sea-level rise', *Coastal Engineering* **2**, 1349–1360.

Miyagi, T., Charlchai, T., Pramojanee, P., Fujimoto, K. and Mochida, Y.: 1999, *Mangrove Habitat Dynamics and Sea-level Change – A Scenario and GIS Mapping of the Changing Process of the Delta and Estuary Type Mangrove Habitat in Southwestern Thailand,* TROPICS 8–3, pp. 179–196.

Moshin-Uddin, Md. and S. Islam: 1982, 'Polder development in Bangladesh Paper I: Past and present development', in *Polders of the World*, International Institute for Land Reclamation, The Netherlands, pp. 288–295.

Nicholls, R.J.: 2002, *Climate Change and Coastal Zones,* Oral Evidence to International Development Committee: Climate Change and Sustainable Development, 29th January 2002, p. 5.

Nicholls, R.J. and Mimura, N.: 1998, 'Regional issues raised by sea-level rise and their policy implications', *Climate Research* **11**, 5–18.

Nutalaya, P., Yong, R.N., Thongchai Chumnankit and Somkid Buapeng: 1996, 'Land Subsidence in Bangkok during 1978–1988' in O'Callahan, Joan (ed.), *Global Environmental Change and the Rising Challenge of the Sea*. Proceedings of the IPCC workshop held at Margarita Island, Venezuela, March 1992. Silver Spring, MD (USA): National Oceanic and Atmospheric Administration, pp. 105–130.

Research Team of China Climate Change Country Study: 1999, *China Climate Change Country Study*, Tsinghua University Press, Beijing, China, p. 328.

Sphocleous, M.: 2004: Climate change: Why should water professionals care? *Ground Water* **42**, p. 637.

UNEP: 1998, in J.F. Feenstra, I. Burton, J.B. Smith and R.S.J. Tol (eds.), *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies,* United Nations Environment Programme, Institute for Environmental Studies, Amsterdam, The Netherlands, p. 359.