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Geological Considerations on the Effect of Sea-level Rise on Coastal Lowlands, in Particular in Developing Countries*

by

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KEYWORDS. — Holocene; Coastal Processes; Sea-level Reconstruction; Sediment Budget; Subsidence.

SUMMARY. — The coastal lowlands of developing countries in particular are among the most densely populated and economically productive. Therefore, it is essential to get a realistic appraisal of the likely response of these areas to the predicted sea-level rise due to global warming. A short review of the different factors causing sea-level rise is presented and shows that the conception of global sea level must be abandoned. The methodologies used to assess the impact of a sea-level rise are critically evaluated whereby it is noticed that the coastal processes and the controlling factors are not sufficiently considered. The geological history of the last 10,000 years of deltas and estuaries provides an analogue of the way coastal lowlands may respond to the predicted sea-level rise, and indicates that these areas will be able to keep pace with the predicted rate of sea-level rise providing that sufficient sediment is continuously available and dikes are absent. The high rate of human-induced subsidence in big cities is a far more devastating problem than the effects of sea-level rise.

TREFWOORDEN. — Holoceen; Kustprocessen; Zeespiegelreconstructie; Sediment budget; Subsidentie.

SAMENVATTING. — *Geologische bedenkingen betreffende de invloed van de zeespiegelstijging in lage kustgebieden, in het bijzonder in ontwikkelingslanden.* — De lage kustgebieden in de ontwikkelingslanden behoren tot de dichts bevolkte gebieden met grote economische productiviteit. Daarom is het essentieel om een realistisch beeld te hebben van de mogelijke reactie van deze gebieden op de voorspelde zeespiegelstijging ten gevolge de opwarming van de aarde. Een kort overzicht van de verschillende factoren die een zeespiegelstijging veroorzaken doet besluiten dat het begrip globale zeespiegel moet verlaten worden. De methoden die gebruikt worden om de invloed van een zeespiegelstijging in te schatten worden kritisch geëvalueerd waarbij tot uiting is gekomen dat er onvoldoende rekening gehouden wordt met kustprocessen en de factoren die kustveranderingen bepalen. De geologische geschiedenis van de laatste 10 000 jaar van de deltas en estuaria die kan gebruikt worden als analogie om te achterhalen hoe de lage kustgebieden kunnen

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veranderen ten gevolge de zeespiegelstijging, toont aan dat deze gebieden gelijke tred kunnen houden met de snelheid van de voorspelde zeespiegelstijging op voorwaarde dat voldoende sediment beschikbaar is en dat dijken geen obstructie vormen. De door de mens veroorzaakte sterke subsidentie in de grote steden vormt een veel groter probleem dan de invloed van een zeespiegelstijging.

MOTS-CLES. — Holocène; Processus côtiers; Reconstruction du niveau de la mer; Budget sédimentaire; Subsidence.

RESUME. — *Considérations géologiques sur les effets de l'élévation du niveau de la mer dans les plaines côtières, en particulier dans les pays en développement.* — Les plaines côtières, en particulier celles des pays en développement, sont parmi les plus densément peuplées et les plus productives économiquement. En conséquence, il est essentiel d'obtenir une évaluation réaliste des réactions éventuelles de ces zones soumises à l'élévation prévisible du niveau de la mer liée au réchauffement global. Une synthèse rapide des différents facteurs provoquant l'élévation du niveau de la mer est présentée et prouve que le concept de niveau marin global doit être abandonné. Les méthodologies employées pour mesurer l'impact d'une montée du niveau de la mer sont évaluées de manière critique suggérant que les processus côtiers et les facteurs de contrôle ne sont pas suffisamment pris en considération. L'histoire géologique des 10 000 dernières années des deltas et estuaires fournit une analogie de la manière dont les plaines côtières peuvent répondre à l'élévation prévue du niveau de la mer, et indique que ces zones pourront suivre le taux prévu d'élévation sur base d'un apport suffisant et continu de sédiments. Le taux élevé de subsidence induit par les activités humaines dans les mégalopoles démontre que son effet est bien plus dévastateur que ceux de l'élévation du niveau de la mer.

Introduction

Changes in sea level are widely considered one of the most certain consequences of climatic change (BINDOFF *et al.* 2007). Global warming is predicted to cause a sea-level rise ranging from 0.18 m to 0.59 m by the year 2100 AD (Intergovernmental Panel on Climate Change, IPCC 2007). The components considered to contribute to the sea-level rise are thermal expansion of ocean water, melting of mountain glaciers and small ice caps, probable changes in the mass balance of large polar ice sheets, and possible ice-flow instabilities. The general conception about the effects of the future sea-level rise is that it would permanently inundate coastal lowlands (LEATHERMAN & NICHOLLS 1995, NICHOLLS 2004, ROWLEY *et al.* 2007).

The potential impacts of sea-level rise are especially important to consider because coastal regions, particularly in developing countries, are among the most densely populated and economically productive. Since ancient times, coastal lowlands have belonged to the most preferred areas for human settlement. Soil fertility, availability of freshwater from the rivers, accessibility because of the flat relief, and the sea and waterways as first-rate trade routes, made coastal lowlands valuable agricultural and economic resources. The river's distributary channels protected sites for harbours and shipping, and provided navigable access to the hinterland. Many cities developed into enormous seaports and industrial centres and are nowadays megacities such as Calcutta, Bangkok and Dacca that lie from the coast on large river systems. However, all large urban centres with harbours in *e.g.* SE Asia are located in low-lying land and most of them are on deltas. Likewise, Bangladesh has one of the most populous delta regions in the world and has 46 % (62.5 million in 2000) of its population in the coastal lowland area (Mc Granahan *et al.* 2007). Also the slightly elevated flood plains of major rivers (*e.g.* Ganges-Brahmaputra, Mekong) are characterized by large population agglomerations.

Because of the population concentration and economic activities on and near the coast, decision-makers, political officials, policy makers, and not least, population must get correct information on the impact of a future sea-level rise on their lowland. The catastrophic scenarios as frequently presented should first be evaluated on a local scale before passing on false messages. Therefore, this paper will present some considerations on the impact of sea-level rise in a geological perspective. First, some remarks will be addressed concerning the conception of global sea-level rise. Then, the simple flooding and land loss of coastal lowlands as currently predicted will be considered to document a more realistic appraisal of the likely response to sea-level rise. Therefore, the geological history of the lowlands along deltas and estuaries with shallow continental shelves will be briefly reviewed to document how such areas have responded to changes in sea level since the last glacial period (last 10,000 years). The records from the past provide an analogue for the likely response of lowlands to future sea-level rise. This will be illustrated with data from literature.

The IPCC Sea-level Rise Predictions

According to the sea-level graph presented by IPCC (2007), it seems that sea level started to rise from about 1870 AD with a rate of 1.2 mm/a until 2000 AD. This coincides with the period in which instrumental records were used. The period of seventy years before is presented as estimates of the past where no sea-level changes are indicated. However, sea-level rise is not new (see below) and the term 'accelerated sea-level rise' would be more appropriate.

The sea-level rise predictions by IPCC are presented as global averages. It should be noticed that the predictions are solely ice- and thermal-expansion equivalent sea levels, *viz.* melting of land-based ice and by thermal expansion. Over the last 10,000 years (Holocene) there has not been a single global sea-level pattern. Instead, the interaction of changes in the volume and distribution of ice and seawater have led to regional- and local-scale isostatic adjustments, and sea-level histories have varied from place to place. The most marked adjustments have been glacial isostatic responses in the areas close to the melting ice sheets. As ice was accumulating, the earth crust was loaded and depressed. Due to this pressure the viscous mantle material of the earth crust flows to an area around the ice-sheet margins that is called the forebulge. When ice is accumulating the forebulge is uplifted. When it melted, the unloaded crust gradually rebounded and the forebulge collapsed and sunk. This phenomenon may affect a zone 50 to 300 km wide adjacent to the loaded and unloaded crust and is continuing to the present day (Woodroffe 1990, Einsele 1992, Gehrels & Long 2008, Kiden *et al.* 2008).

Tropical coasts, being in the far field of these polar regions, have not responded to ice melt directly, but have undergone subtle hydro-isostatic adjustment as a result of loading by water which moreover was not evenly distributed across the globe depending on where meltwater came from. Processes that influence the redistribution of water associated with loading and unloading by ice and water are ocean siphoning in which water flows from the equator towards the collapsing forebulge of the mid and high latitudes, and continental levering whereby water loading of the continental shelf causes rebound of the coast (Mitrovica *et al.* 2001, Mitrovica & Milne 2002, Gehrels & Long 2008).

Many other factors also cause differences in sea level from place to place. Relative sea level can change because of tectonic movements of the earth crust, changing the shape of ocean basins and raising, lowering or deforming the continents. These movements then change the shape and capacity of ocean basins. An increase in the capacity causes a lowering of sea level, and a reduction causes sea level to rise. Neotectonic movements, such as earthquakes, cause irregular displacement of the coastline by uplift, lowering or tilting either gradually or suddenly. Sea-level changes have also been influenced by shifts in ocean surface topography. Oceans have an undulating surface configuration, with bulges and troughs rising and falling up to 90 m measured relatively to the centre of the earth. This is known as the geoid related to gravitational and hydrological forces and the rotation of the earth. A change in the gravity pattern caused by a change in ice-sheet mass can deform the sea-surface topography on shorter timescales (Bird 2000, Gehrels & Long 2008). The volume of seawater also diminishes as salinity increases, and rises as it freshens. Ocean volumes vary with the density of seawater, salinity and atmospheric pressure. Although these latter factors cause seasonal effects, they may not be neglected. This is of importance when measurements from satellites are evaluated over a time frame not sufficiently long to eliminate the seasonal effects.

No region on the globe has been free from many of these effects that cannot be equated directly with a change in sea level. Therefore, the conception of global sea level must be abandoned. Volumes of water matter less than their distribution because sea levels are time- and space-specific.

Drawing Contour Lines versus Coastal Processes

A frequent method used to determine the areas that will be affected by the future sea-level rise (SLR) is checking for the elevation of the coastal area in relation to the predicted rise. The corresponding contour line is then drawn and the area below the concerning contour line is considered as being prone to flooding or indicated as land loss (Huq *et al.* 1995, Nicholls 2004, Rowley *et al.* 2007). Several websites (*e.g.* http://flood.firetree.net; http://maps.grida.no/region/geoseasia) present such simulations of land loss in relation to different scenarios of SLR in many parts of the world.

Many developing countries do not have contour maps that are sufficiently detailed, particularly in low-lying areas. Consequently, the contour lines are drawn with the big brush providing erroneous data. Remote-sensing data and GIS analysis tools, and recently radar and lidar elevation mapping, are more accurate elevation measurements. However, all digital elevation models also contain sources of error, which arise from the deterioration of data in the collection process, and inaccurate interpretations of the terrain surface due to the effects of trees and infrastructure (Fisher & Tate 2006). Moreover, this method requires thorough investigation and is time-consuming. Therefore, such elevation measurements are only available for few case studies that are not particularly located in developing countries.

Some investigations also determine the coastal vulnerability in relation to SLR on the basis of vulnerability index assessments. The index used consists mostly of variables that influence coastal evolution such as: geomorphology and elevation, historical shoreline change rate, regional coastal slope or bathymetry, relative sea-level change, mean significant wave height, and mean tidal range (Belperio *et al.* 2001, Pendelton *et al.* 2010, Kumar *et al.* 2010). It is said that this approach combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions. These approaches, however, omit sediment supply in relation to the rate of relative SLR as major controlling factor determining whether a shoreline will recede, prograde or remain stable, and whether a coastal lowland will emerge or submerge.

Factors Controlling Coastal Change Documented by the Geological Record

The present coastal lowlands have a geological history of about 10,000 years. They developed along rivers as a result of the drowning of river valleys due to the post-glacial or Holocene sea-level rise converting the Pleistocene fluvial landscape into a tidal environment or back-barrier basin. The river valleys filled with sediments of different near mean sea-level depositional environments each of them responding to the effect of major controlling factors. The depositional environments that might occur are (listed in landward direction): shoreface, coastal barrier, tidal deltas and channels, sub- and intertidal flat, mangrove, supratidal flat (salt marsh), coastal peat bog, and floodplain with channels. Each environment has its specific relation to sea level, and their position one to another shows a typical zonation pattern. Moreover, they form a dynamic system capable of shifting landward or seaward, and one over the other, in relation to the controlling factors.

Each coastal lowland has its own depositional history with punctuated coastal changes that occur locally. However, the general framework of infill is identical for all drowned river valleys and is governed by the following controlling factors: rate of relative sea-level (RSL) rise, sediment budget and accommodation space. During the infill the relative importance of the individual factors changed in the course of time (BAETEMAN 1998). Although sea-level history has varied from place to place depending on the interaction of changes in the volume and distribution of ice and seawater, the general pattern shows an early Holocene phase of rapid sea-level rise (*ca.* 8-10 mm/a) followed by a mid-Holocene phase of slow rise (*ca.* 4-2.5 mm/a) and eventually a relative stability (*ca.* 1 mm/a) (PIRAZZOLI 1991). However, around the Pacific and Indian Ocean sea level was 1-2 m above present sea level in the period between 6,000-3,000 years ago with a gradual fall to the present level, while along the other seas and oceans sea level continued to rise but at a decelerating rate up to the present time (CHAPPELL 1982, WOODROFFE 1990, FUNABIKI *et al.* 2007).

In the early Holocene the rapid RSL rise was the driving mechanism behind the infill. The sea invaded the deepest parts of river valleys that changed into embayments in which the different sedimentary environments developed. The rapid RSL rise caused a very rapid landward shift of the sedimentary environments across the continental shelf towards a position close to the boundary of the present-day lowland. This shift was associated with a significant vertical sediment accretion. The landward and upward migration of the shoreline in space and time resulted in a transgressive succession, *i.e.* replacement of sedimentary environments with progressively more seaward environments. This period was mainly governed by the direct impact of the RSL rise, and the effects of the other controlling factors were subordinate. Once the rate of the RSL rise slowed down, the rapid landward shift of the sedimentary environments stopped and the shoreline stabilized. Sediment supply outran the accommodation space created by the RSL rise so that sediments filled the tidal basins. Former sub- and intertidal areas were raised to an elevation appropriate for vegetation colonization. Periods of emergence lasted longer resulting in a widespread seaward extension of coastal marshes followed by freshwater marshes with peat accumulation.

Because of the strong deceleration of the rate of RSL rise from about 6,000-5,000 years ago, sediment supply exceeded the creation of accommodation space. Landward migration of the tidal system stopped completely, the stabilization of the shoreface shifted to shoreface accretion and the shoreline moved seaward. This seaward migration of all sedimentary environments due to sedimentation rates in excess of the rate of RSL is called progradation. Parallel beach accretion ridges behind the active shoreline with each ridge marking a former position of the shoreline usually characterize such prograding coastal areas. Eventually major parts of the former coastal plain were covered with alluvial sediments. It was the slow RSL rise together with the overwhelming supply of sediment that caused deltas to protrude into the marine environment on the continental shelves.

The primary factors controlling the direction of shoreline migration and the infill of coastal plains through time also include the rate of change of accommodation space. Delta and coastal plains are all subject to natural subsidence. Most of them are located in tectonically-subsiding basins. Substantial sediment load causes additional crustal subsidence. Most of the sediments in the subsoil of delta and coastal plains were deposited below or near sea level and consist of fine-grained sediments, such as silts and clays. They are characterized by high moisture content and are very compressible. Deposits with high organic and moisture content like peat from coastal swamps and mangrove can be subject to extensive consolidation. Not only will it compress beneath an applied load, but, under certain conditions, it will also compress under its own weight. The compaction of the deeper deposits due to progressive burial of sediments results in an additional subsidence, a process that continues for thousands of years, although at an exponentially decreasing rate. However, the overwhelming supply of sediment into the deltaic area in general compensates the increased accommodation space caused by the total subsidence.

The relative importance of individual controlling factors should be considered and identified in order to establish the link between RSL rise and coastal response that should no longer be attributed solely to changes in sea level. Therefore, the simple flooding and land loss as predicted have to be reconsidered and a more realistic appraisal of the likely response to RSL rise should be developed.

The Predicted Scenarios in a Dynamic Geological Context

It is obvious that the assessment of the response of lowlands to a future sea-level rise is not a simple exercise applying general rules. The geological context and the dynamic character of the coastal system must be investigated for every specific area taking into consideration its former depositional history. Different deltas and estuaries will respond differently to RSL rise. This is particularly true for the modern river deltas, because following the rapid sea-level rise in the early Holocene, most deltas began to form near their present location and prograded since then despite a rate of sea-level rise decelerating from 4 mm to 1 mm/a over about 7,000 years. From the records of the past it became clear that the total amount of sea-level rise matters less than the rate of sea-level rise which can or cannot be compensated by the sediment budget.

Studies on sediment budgets for the major eastern and southern Asian river systems (Huang Ho, Yangtze, Mekong, Ganges-Brahmaputra, Irrawaddy, Red River), for example, suggest that 30-50 % of their huge suspended sediment load (13×10^9 tons per year) are trapped in the river’s low reaches and contribute to extensive floodplain and delta plain development. About 20-30 % of the part that is not trapped inside the estuary or delta accumulates on the shelf adjacent to the river mouth and the remaining part is transported along the shore several hundreds of kilometres from the river mouth. The huge sediment load is delivered by the Himalaya and surrounding plateaus characterized by a high relief, steep gradients, frequent tectonic activity, highly erodable rocks, coupled with seasonal melting of its glaciers and abundant monsoon rainfall (Liu *et al.* 2009). This sediment load has, and still does, play a key role in the sustainable development of the coastal plains of these rivers despite a sea-level rise. There is no doubt that in the future the Himalaya will continue to provide huge masses of sediment and thus contribute to the development of the coastal and nearshore areas of these river mouths and their adjacent regions.

This is of great importance for *e.g.* the Ganges-Brahmaputra delta in Bangladesh which is often cited as a major loser to accelerated sea-level rise. It is said that a 1 m rise would be devastating. Seventeen million or 15 % of the total population would be affected and over 17.5 % of the country would be under water at high tide, and the mangrove swamp, one of the largest in the world, may be lost (Leatherman & Nicholls 1995). However, it has been demonstrated that the G-B delta was largely able to keep pace with rapid RSL rise (*ca.* 10 mm/a) in the early Holocene. After the initial delta aggradation in the period between 11,000-7,000 years ago the delta has prograded steadily with a seaward movement of the shoreline (Pate *et al.* 2009). It has been documented that for about 6,500 years the shoreline progradation and basin infilling has accounted for 30 % of the modern delta plain (Allison 1998). This exceptional situation is explained by the immense sediment flux to the Bengal Bay, where tides and coastal circulation sufficiently distribute sediments across a broad delta plain at rates sufficient to offset even rapid rates of RSL rise (Pate *et al.* 2009).

The statement that the large mangrove forest characterizing the lowlands of Bangladesh may be lost needs a more differentiated approach. Mangrove forests, composed of halophytic long-lived trees and shrubs that grow in the upper part of the intertidal zone, are very efficient at adjusting soil elevations in response to sea-level rise where there is sufficient sediment supply (McKee *et al.* 2007). Once the mangroves have colonized the mudflat and become established, they promote accelerated accretion of mud within the network of stems that diminishes the current flow and wave action whereby sediment is trapped and retained, and the surface gradually builds up (Bird 2000). Many Holocene sea-level studies have shown that there are indications that in some cases mangrove forests may be able to keep up with rates of RSL rise of the order of those predicted as a result of global warming. It has been documented that past rates of vertical accretion below mangrove forests kept up with RSL rise up to 8-10 mm/a, although with erosion at the seaward margin. A sea-level rise of rates up to 10-15 mm/a is unlikely to jeopardize the overall existence of mangrove forests providing that the area is characterized by sedimentation surplus (Woodroffe 1990).

Likewise mangrove forests, intertidal and supratidal flats can easily follow a rising sea level and build up thick sediment sequences if the sedimentation rate is high enough. If RSL rise is slow, intertidal and supratidal flats may prograde seaward and thus enlarge their areal extent. Slowly subsiding shallow platforms enhance to maintain a tidal flat environment over long time periods. Otherwise they build up too high and get colonized by vegetation (Einsele 1992). It is predicted that storm events would increase in frequency because of global warming. However, storms are not necessary devastating for such areas. On the contrary, storms are able to mobilize sufficient sediments in coastal areas to increase the sediment supply to the supratidal flats (Reed 1990). However, the cyclones that hit Bangladesh regularly are extreme events causing widespread damage. Likewise are the river floods associated with destruction of islands in the river due to the extremely high water discharge caused by snowmelt from the Himalaya mountains and during the abundant monsoon rainfall. These phenomena, however, may not be attributed to sea-level rise. Tree cutting in the hinterland and badly organized urbanization are among the major causes of flooding rather than global warming as is frequently claimed.

The simulations of changing shorelines characterized by coastal barriers covered by dunes must be reconsidered as well. Also here, the principle of simply drawing contour lines according to the predicted rise is frequently applied (Marbaix & Nicholls 2007). However, coastal barriers are also dynamic systems responding to changing sediment input and RSL changes. With RSL rise the barrier can migrate either landward or seaward (Roy *et al.* 1995). If sediment input from the hinterland or alongshore is high enough, the barrier will move seaward. Only when the rate of RSL rise is very high, the barriers are drowned on site. With a moderate rising sea level the barrier will migrate slowly landward. It will not simply disappear.

The Effect of Human Activities in Coastal Lowlands

Coastal and sea-level studies of the Holocene period have shown that the sedimentary environments building up the lowlands are dynamic. Regression and transgression, or simply the direction of lateral migration of the sedimentary environments through time is controlled by several factors. However, the lateral migration can only happen under natural circumstances, *i.e.* when the immediate hinterland is not obstructing the landward movement. Such a major obstruction in many cases are dikes that have been raised with the embankment of lowlands or seawalls for coastal defence. It may sound contradictory but in fact lowlands are better off without dikes. In this case the elevation of lowlands can keep pace with the rise in sea level. Where sediment supply is not sufficient, the RSL rise will result in a gradual landward displacement of the different sedimentary environments providing that a gentle slope is present which is the case in lowlands.

This landward displacement will be associated with erosion of the riverbanks, shoreface and coastal barrier. The eroded sediments, however, will be transported landward and will increase the rate of delta/estuarine plain sedimentation (Woodroffe 1990).

Embanked lowlands, however, are very vulnerable to RSL rise because they are situated below at least high water level. This is the result of compaction followed by land subsidence. Once a coastal plain was silted up until high water level and colonized by vegetation, it became out of reach of the daily tidal flooding. Hence large areas became suitable for human activities although inundations happened periodically. Mainly to prevent further inundations, dikes were raised to protect agricultural resources and eventually settlements. However, building a dike in coastal lowlands inevitably implies artificial drainage in order to evacuate runoff and precipitation. Since a high groundwater level and saturated sediments in the subsoil characterize these areas, water cannot penetrate into the soil. Due to the high compressibility of the deposits, digging ditches and canals drain the sediments resulting in compaction and subsidence of the land, which elevation becomes lower than the original high water level.

Also river management structures disrupt the natural sedimentation process that otherwise helps mitigate the adverse consequences of RSL rise. Seasonal river floodings deposit sediments onto the plains that contribute directly to elevation gain, and counterbalance the effects of natural subsidence and RSL rise. A major disturbance, however, are dams on the rivers. Dams not only trap large amounts of sediments in the reservoirs behind the dam, but also prevent seasonal flooding which distributes sediments on the plain (Rybczyk 2005). Reduced sediment discharge directly affects the progradation of the coastal area, leading to severe coastal erosion. For example, in the Nile River the sediment load has been reduced by 95 % since the building of the Aswan High Dam, and as a result, much of the delta coastline is eroding by up to 125-175 m/a (Chen 2005).

Sea-level rise is not the only threat to the vulnerability of coastal lowlands. Much more important is the human-induced land subsidence caused by compaction due to groundwater withdrawal. For example, subsidence around Manila Bay has been ten times faster than the RSL rise of 2 mm/a since 1980 when the population rose drastically and overpumpage of groundwater occurred (Pabuayon 2002). The majority of streets in Manila are below mean sea level; hence flooding of the Pasig River almost brings the city to a halt if it coincides with high tide in Manila Bay. In the period between 1993 and 2005, Central, North, East and South Jakarta sank by 240, 57, 11 and 28 cm respectively (Rukmana 2007). This is at a rate ten times faster than the rate of sea-level rise. Also Bangkok is affected by the problem of land subsidence. Subsidence reached its most critical state in the early 1980s when it occurred at a rate as high as 12 cm/a (Phien-wej *et al.* 2006). Due to a strict enforcement of groundwater laws resulting in a marked drop in groundwater use, the subsidence rate decreased to 1.5 to 2.2 cm/a in 2001 (according to the Department of Mineral Resources, Bangkok State of the

Environment). This is still a huge rate considering that the elevation of the city is hardly above mean sea level.

The problem of land subsidence is much more critical than the predicted accelerated sea-level rise. However, in the densely populated lowlands groundwater is practically the only water source for agriculture, industry and domestic purposes. Moreover, once it starts, land subsidence will continue for a long time owing to the time-dependent consolidation behaviour of the compressible deposits (Baeteman 1994, Phien-wej *et al.* 2006).

Conclusion

Coastal and sea-level studies of the Holocene period show insight into possible responses of shoreline migration and wetland evolution to RSL rise. Studies provide an analogue of the way coastal lowlands may respond to the predicted future accelerated RSL rise. Simple flooding and land loss as predicted in many scenarios must be reconsidered. A balance between sediment budget, rate of sea-level rise and accommodation space is clearly the key to coastal lowland survival. The effects of human actions may be far more devastating in the short term than the effects of RSL rise.

The ability of deltaic plains to keep pace with RSL rise will depend on the rate of sediment supply. The low-gradient coastal plains provide conditions for rapid sediment build-up. Shoreline progradation and deltaic plain vertical accretion will continue for those rivers that transport a large sediment volume into their deltas. These lowlands will be able to keep pace with the predicted rates of RSL rise. However, specific impacts need to be assessed for individual areas taking into account all the local conditions. RSL rise itself, at the rates now anticipated, is not likely to lead to catastrophic disruption or flooding of the large deltaic and estuarine systems, although some erosion of the seaward margin is always to be expected.

This ability, however, is only possible when dikes, coastal defence structures and river management structures are not obstructing natural processes. The megacities in developing countries, however, do need these structures because the highest concentration of population, which, moreover, are the poorest people, do live in the most vulnerable areas of the cities. It is clear that industry and commerce also need protective measures. In view of the natural processes, it is recommended to leave the natural landscapes to nature for the sustainability of coastal lowlands because defence structures are more damaging than beneficial. Fortunately, in the developing world, coastal defences are less or even not developed outside the cities.

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