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Coastal Geomorphic Response to Future Sea-level Rise and Its Implication for the Low-lying Areas of Bangkok Metropolis

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Abstract

Evidences on the relative sea-level rise in a tidal mangrove areas of this shoreline are useful to compile the measured and assumed rates of sea-level rise over the land for predicted conditions in the future and to compare the charts indicating the movements of the local sea-level change in the historical trend. In the low-lying areas of Bangkok Metropolis, an increase in sea-level of at least 1 m is accepted for the next 100 years due to the warming effect of present super-interglacial. The most serious current problem of Bangkok now is related to the excessive exploitation of groundwater which has resulted in wide-scale subsidence and groundwater contamination. In the Bangkok metropolis areas, a combination of subsidence and sea-level rise will seriously affect residential area, pollution of surface water and groundwater, flooding, wastewater drainage and treatment, agricultural land, and industrial and commercial activities in the foreseeable future.

Introduction

This paper aims to put coastal studies into the context of sea-level variations, especially where there is a direct bearing on shoreline changes. The position of the shoreline in coastal lowlands is dominated by the influx of sediments by rivers, tectonic movements and sea-level changes. During the Quaternary, the last-mentioned factor played an important role, i.e., eustatic sea-level changes of more than 100 m occurred as a result of the alternating glacial and interglacial periods. From 18,000 B.P. until about 6,000 B.P., the shift of the shoreline is dominated by the restoration of ocean level due to the melting down of land ice caps. During this period the shoreline of the coastal lowland moved landward. After 6,000 B.P. the position of shoreline was dominated by tectonics, geoid changes, and to a lesser degree, to glacial eustasy. This resulted in the alternate advance and retreat of the shoreline in the overall process of progradation of coastal areas.

In historical time, the position of shorelines has been influenced by human activities. Cutting down the forest in the catchment area of rivers results in a high amount of sediment influx into coastal areas. Examples are the prograding shoreline in Java, Indonesia, the arisen of the Po delta in Italy, and the Ebro delta in Spain [Jelgersma 1988b]. The construction of dams and reservoirs in rivers for power generation and irrigation greatly reduces the sediment supply to the shoreline, and this may result in a serious shoreline erosion. It may be concluded that most coastal

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lowlands of the world are experiencing damage from erosion, partly as a consequence of a small sea-level rise, but mostly due to human activities. There is now a clear evidence that human activities affect the shoreline change, not only at the regional level but also on a global scale. Tide gauges indicate that sea-level has risen between 10 and 15 cm during the last century [Barth and Titus 1984; Jelgersma 1988a; Carter 1988; Hendry 1988; Charney 1979]. This rise, greater than in the recent geological past, is thought to be caused by global warming due to the increase of carbon dioxide and certain trace gases in the atmosphere, the "greenhouse effect." It is estimated that the temperature will rise between 1.5 and 4°C in the coming 100 years due to this greenhouse effect [Charney 1979]. The associated rise of sea-level is estimated at between 0.50 and 1.50 meters. At the present time most coastal lowland is already in a critical balance with sea-level change. Accordingly, an accelerated rise of sea-level in the coming century will have a profound and widespread impact on the social and economic conditions of coastal lowland areas. The following discussion examines the geomorphic effects of the projected sea-level rise on the low-lying coastal landforms of the Chao Phraya delta.

Geology and Morphological Changes of the Chao Phraya Delta

The Chao Phraya basin in Southeast Asia, remarkable for its tropical delta, is also a storehouse of fascinating and complex paleotectonic, paleoenviromental and paleogeographical records of deposition over a long geological period [Emery and Niino 1963; Achalabhuti 1975; Bunopas 1981; Nutalaya and Rau 1983; Somboon 1988; 1990]. The Quaternary and Tertiary sediments represent a complex sequence more than 2,000 m thick, of which only the uppermost 200 m is well known. Sedimentation was controlled throughout most of Tertiary and Quaternary time by a combination of tectonic movements both within the plain and in the adjacent mountains. The plain is situated over a large structural depression that has been filled with an assortment of clastic sediments, chiefly of clay to medium grain size. The north-trending axis of the Chao Phraya depression is related to the north-south structural trend of the Paleozoic and Mesozoic fold belt of western Thailand. The sediments reach a thickness of at least 1,859 m at a site 15 km west of Bangkok, where a borehole reached upper Cretaceous granite. Thirteen other deep boreholes have been drilled in the lower central plain but few have penetrated bedrock. The data suggests that the Chao Phraya trough has been tectonically active during most of Tertiary and Quaternary times, receiving alluvial and deltaic sediments when the adjacent ranges were uplifted [Nutalaya and Rau 1983].

A Holocene sedimentological model for the Chao Phraya delta is summarized by Somboon [1990]. This model infers an initial northerly prograding tidal-estuarine delta that deposited the marine clay, overlain by coastal and deltaic plain. The delta results from progradation of a prism-like terrestrially derived sediment into the Holocene marine basin. In general, a tidal-estuarine delta system comprises a number of individual deltas from the

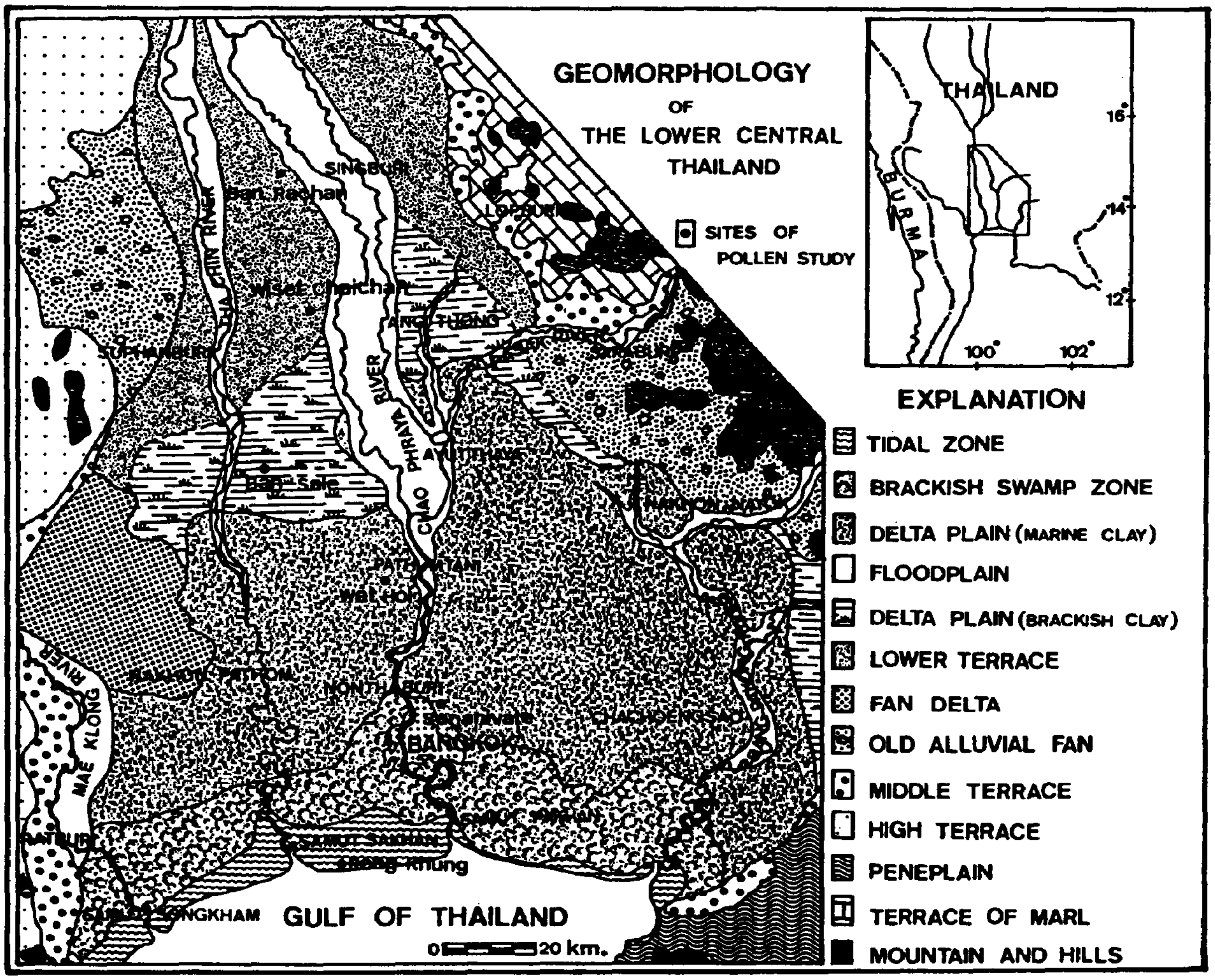

Fig. 1 Geomorphology of the Chao Phraya Delta, Thailand

rivers feeding the basin that have coalesced laterally and/or undergone progradation. This configuration of laterally interfingering alluvial systems results in a sedimentary body with a more regular rectangular distribution of facies than is seen in isolated deltas. The morphology of deltaic plain changes in response to the incidence of sediment-laden floodwaters which promote vertical accretion, particularly on channel margins; to the effects of the vegetation which colonizes the depositional terrain; and to the extent of continuing subsidence, due to compaction of underlying sediments or neotectonic movement. The present feature of the Chao Phraya delta is classified into 13 units of landform in Fig. 1.

The Present Super-interglacial Period

On the basis of definition, the present interglacial age (the Holocene Epoch) began about 10,000 years ago. An analysis of deep-sea cores shows that no Pleistocene interglacial has lasted more than about 12,000 years and that most have lifespans of about 10,000 years [Ericson *et al.* 1956; Ericson and Wollin 1968]. Climatic changes of the present interglacial in Fig. 2 show general trends

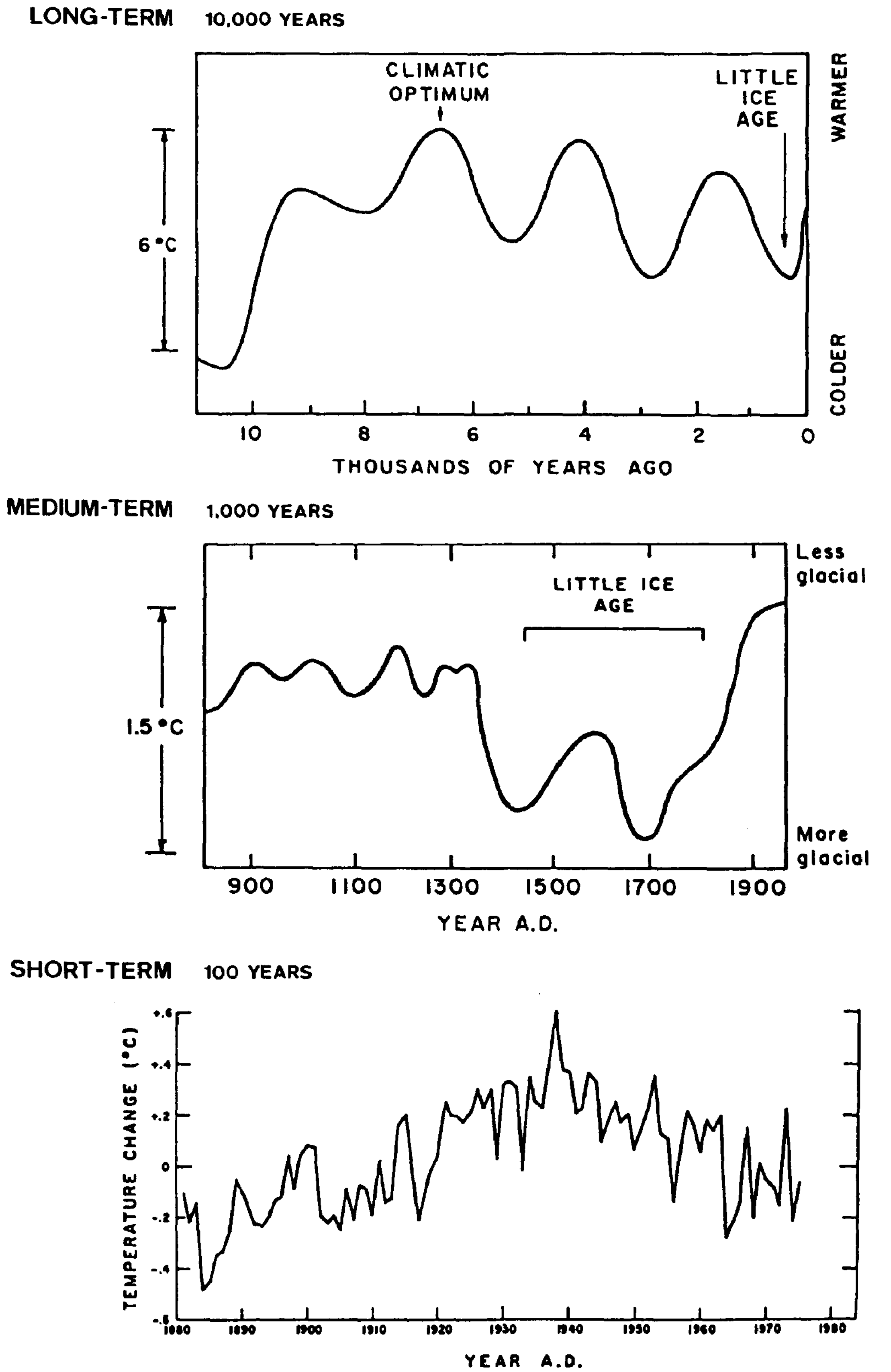

Fig. 2 Climatic Changes on Different Time Scale of the Present Interglacial Period (Adapted from Lamb [1969], Mitchell [1977a] and Imbrie, J. and Imbrie, K. P. [1986])

in global temperature, as estimated from geological records of mountain glaciers and fossil plants. One such trend is the long-term warming that began at 10,000 years ago and continued until at the postglacial climatic optimum of about 7,000 years ago, when temperatures were about 2°C warmer than today, and rainfall was also greater. Since then, the average temperature has been gradually declining (Long-term trend). As discussed further below, short episodes of warming and cooling known as the Little Ice Age cycle have been superimposed on this general cooling trend (Medium-term trend). The net result has been a 2°C lowering of the average global temperature. The clearest indication of this trend are changes in the geographic ranges of animals and plants. In the Short-term trend by averaging thermometer readings made at a worldwide network of weather stations, Mitchell [1977a] was able to show that global climate has been cooling since 1940. Since 1939, average temperatures of the northern hemisphere have declined about 0.6°C.

Statistically speaking, the present interglacial is already on its last legs, tottering along at the advanced age of 10,000, and can be expected to end within the next 2,000 years. Climatic forecast of the next 25,000 years is shown in Fig. 3. According to the astronomical theory of the ice ages, the natural course of future climate (shown by the dashed line) would be a cooling trend leading to full glacial conditions, 23,000 years from now [Croll 1867a; 1867b; Van den Heuvel 1966; Broecker *et al.* 1968; Mesolella *et al.* 1969; Vernekar 1972; Hays *et al.* 1976; Imbrie, J. and Imbrie, J. Z. 1980; Imbrie, J. and Imbrie, K. P. 1986]. Although many human activities influence climate (for example, agriculture, irrigation, forest cutting, urbanization, and accompanying discharges of heat and smoke), by far, the greatest impact

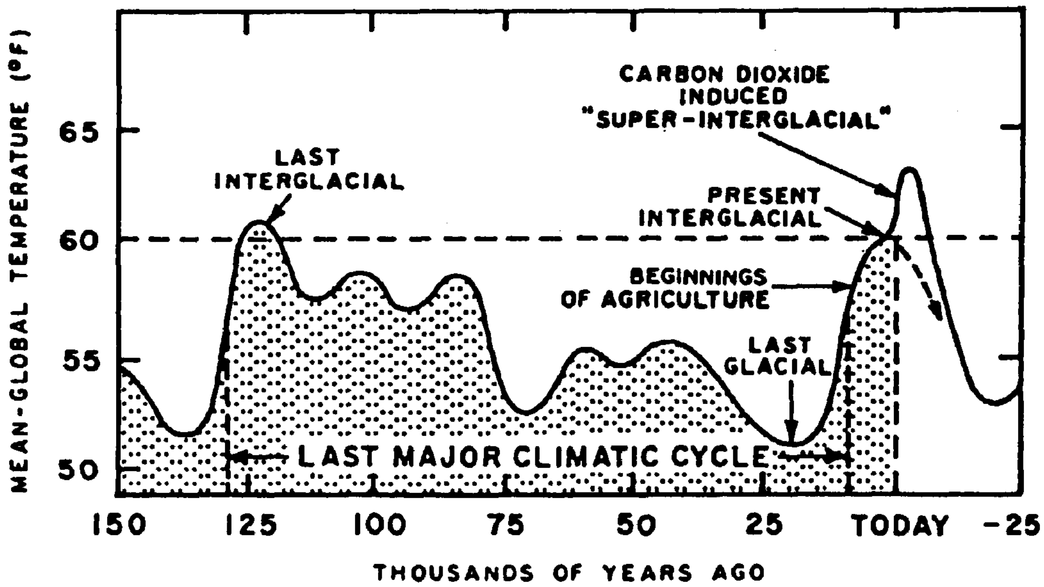

Fig. 3 Climatic Forecast of the Next 25,000 Years

The industrial man continues his ever-growing consumption of energy and in the process adds further pollution to the global atmosphere. It would plunge the planet into a "Super-interglacial age." (Modified from Broecker [1975] and Mitchell [1977b]) on climate comes from the burning of fossil fuels and the accompanying production of carbon dioxide gas. This pollutant is an inevitable product of combustion of all hydrocarbon fuels, including coal, oil, natural gas, and a variety of lesser fuels. Since atmospheric carbon dioxide acts as a thermal blanket, the warming effect of burning fossil fuels may well interpose a "super-interglacial," with global mean temperatures reaching levels several degrees higher than those experienced at any time in the last million years. In that case, onset of a cooling trend leading to the next ice age would be delayed until the warming had run its course, perhaps 2,000 years from now.

A Future Sea-level Rise

During the past half-decade, many conferences have been devoted to the amount and the impacts of a future sea-level rise. The first was an international conference on the assessment of the role of carbon dioxide and other greenhouse gasses in climate variation and their associated impacts, held at Villach, Austria, in October 1985 (By UNEP, ISCUS and WMO). The second was an international conference on the health and environmental effects of changes in stratospheric ozone and global climate, organized by the US. Environmental Protection Agency and UNEP in June 1986 at Crystal City, U.S.A.; which also included a workshop on sea-level rise. In August 1986, the Delft Hydraulics Laboratory organized an international workshop in the Netherlands on the impact of sea-level rise on the society. Recently, in September 1989, the International Geological Correlation Program (IGCP 274) organized an international symposium on coastal evolution, management and exploration in Southeast Asia held in Ipoh, Malaysia. Concerning the future sea-level rise, the more forward-looking assessments have been published by the US. Environmental Protection Agency [Hoffman *et al.* 1983; Hoffman 1984; Barth and Titus 1984]. The Agency has attempted a realistic summary of the cause of sea-level rise, and considered possible tactics to offset the consequences. Projected global warming could cause the global average sea-level to rise 10–20 cm by 2025 and 50–200 cm by 2100. Hoffman [1984] presented a range of sea-level rise estimates, termed scenarios, that were developed on the basis of knowledge collected from a variety of disciplines, including energy economics, geochemistry, biology, atmospheric physics, oceanography, and glaciology. The most restrictive assumptions from these disciplines were linked together to generate a "baseline" scenario, which projects a sea-level rise of 56.2 cm by 2100. The least restrictive assumptions were used to generate a "high" scenario, which projects a rise of 345 cm by 2100. Two mid-range scenarios were also developed: a low scenario which projects a rise of 144 cm and medium scenario which projects a rise of 216 cm. In order to use these projected rises in sea-level to predict the coastal geomorphic response in the areas of Chao Phraya delta, it is neccessary to derive the estimated rate of sea-level rise by the scenario of Hoffman [1984] which can be compared with the actual sedimentation rate of the present coastline. The estimated rate of sea-level rise (mm/year), in 1990–2100, based

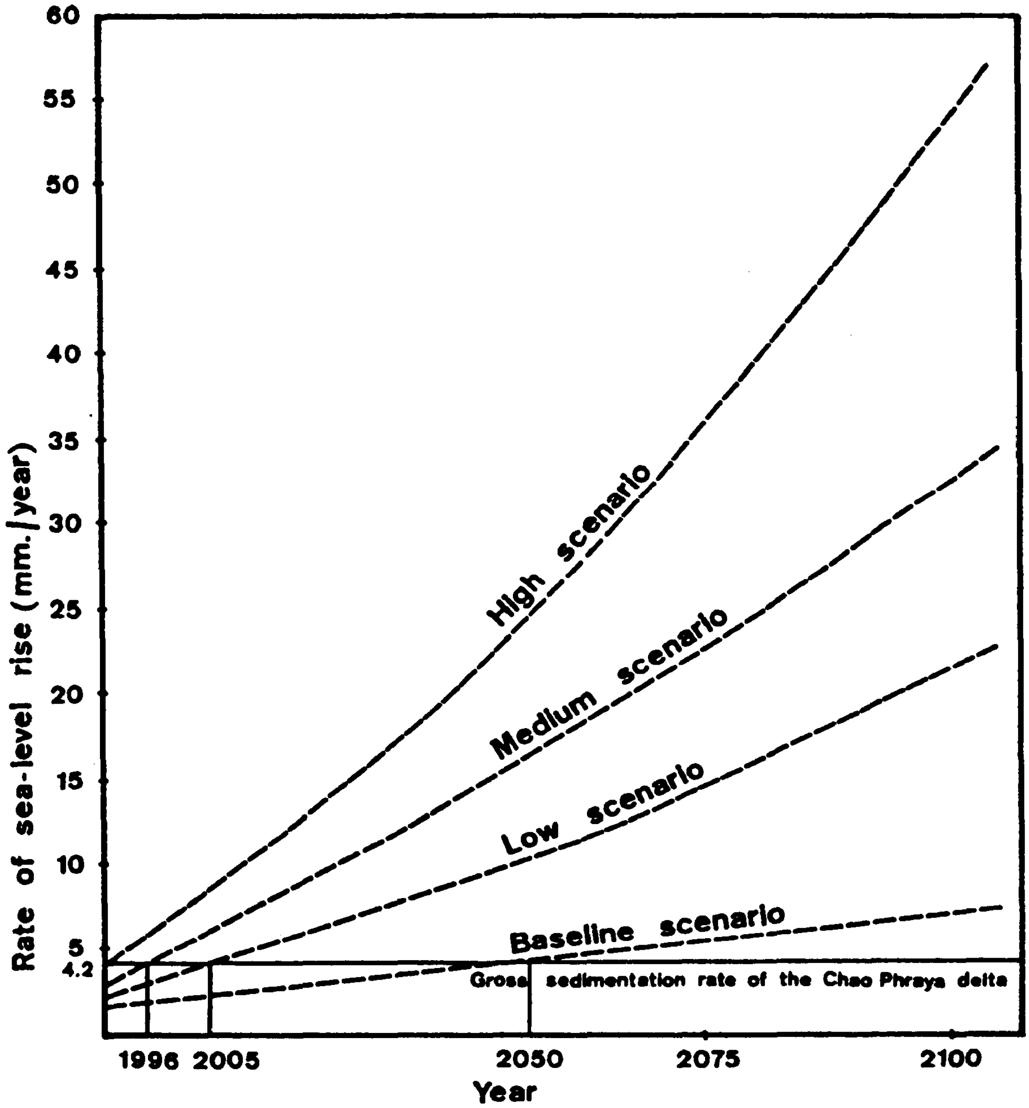

Fig. 4 Estimated Rate of Sea-level Rise, 1990–2100, by Scenario (mm/year), Together with the Gross Sedimentation Rate of the Chao Phraya Delta (mm/year)

on the scenario of Hoffman [1984], together with the gross sedimentation rate of the Chao Phraya delta (mm/year), is shown in Fig. 4.

Projected Sea-level Rise for the Chao Phraya Delta

This discussion describes the geomorphic effects of the projected sea-level rise on low-lying coastal landforms of the Chao Phraya delta. Two categories of physical response are addressed: shoreline changes representing landward displacement of the land/water interface, and groundwater changes resulting from saltwater intrusion into coastal aquifers. The position of the shoreline in coastal lowlands is dominated by the influx of sediments from upland sources (the sedimentation rate), tectonic movements, and the sea-level changes. Sedimentation rates and tectonic movement of the Chao Phraya delta have been of the same order of magnitude as during the Holocene. Changing sea-level is probably the

Table 1 Predicted Conditions of the Chao Phraya Delta by the Year 1990–2100 after Sea-level Rise

Year	Baseline Scenario	Low Scenario	Medium Scenario	High Scenario	Historical Extrapotation
1990	P	P	P	E	—
1996	P	P	E	3.2 (1.6)	1–2
2005	P	E	4.0 (2.0)	9.6 (4.8)	2–3
2050	E	10.8 (5.4)	46.7 (12.4)	97.8 (20.72)	1.8–3.2
2065	1.2 (0.6)	34.0 (8.8)	80.0 (16.0)	128.4 (27.2)	4.5–9.0
2075	3.4 (1.68)	57.0 (11.56)	113.3 (19.28)	177.3 (32.0)	9.5–15.5
2100	13.0 (3.28)	101.3 (17.28)	189.5 (27.92)	318.9 (48.92)	12–18

P = Progradation of the coastal plain
E = Equilibrium stage or erosion of the coastal plain
Note: Sea-level rise over the land is given in centimeters with the rate of sea-level rise over the land in parenthesis (mm/year).

major factor determining coastal evolution. The coastal geomorphic response to sea-level conditions can be recognized as: rising (transgression of the sea over the land or erosional shoreline); falling (regression of the sea or progradational shoreline); and stationary (equilibrium). The rising and falling stages are ones of massive sediment release and transport, while the stationary stage allows time for adjustment and reorganization towards equilibrium. Throughout the ensuing discussion, it must be borne in mind that sediment availability as well as sea-level fluctuation exercise a strong control over changes in coastal forms.

Studies of sea-level over the last two centuries show that the average sea-level has been rising at a rate of 1–1.2 mm/year [Bruun 1962; Fairbridge 1966]. It is postulated that a local stationary stage of sea-level would have occurred when the rate of sea-level rise equalled the gross sedimentation rate. Gross sedimentation rate of the present Chao Phraya delta is therefore given by: Gross sedimentation rate = Net sedimentation rate + present rate of sea-level rise + basin subsidence.

The net sedimentation rate can be calculated if the rate of delta advance and the delta slope are known. As the advance of the Chao Phraya deltaic plain is 4–5 meters/year and the deltaic slope is 0.05% [NEDECO 1965], the net sedimentation rate is calculated at 2–2.5 mm/year. Subsidence in contemporary sedimentation basins or geosynclines is fairly low, at 0.1 mm/year, whereas deltaic basins have larger subsidence rates due to higher sedimentation rates and the secondary consolidation of the more compressible sediments in the surface layers. The subsidence rate of the Chao Phraya delta is 0.5 mm/year as calculated from the basal peat of age around 6,000 year at 3 m depth below the present sea-level. It would appear that transgression of the sea over the present deltaic areas may occur when the future rate of sea-level rise equals or exceeds the gross sedimentation rate of 4.2 mm/year. In Fig. 4, it is useful to compare the measured and assumed rates of sea-level rise over the land for predicted conditions of the Chao Phraya delta areas after the sea-level rise. More specifically, Table 1 gives a long-term projections of the relative rise of the sea-level for the Chao Phraya delta by the year 2100.

A Preliminary Assessment for the Bangkok Metropolis

Experience in mangrove areas of the Chao Phraya delta points to the physical effects of a significant rise in sea-level on this shoreline. Mangrove development in the Chao Phraya delta generally have slowed down, and in places stopped due to the killing of the mangrove trees (Fig. 5), as the local sea-level rose to the equilibrium stage. In the author's opinion, the future sea-level rise for the Chao Phraya delta is most likely to fall in the medium scenario or at least in the low scenario (Table. 1). If the sea-level rises at the rate predicted by the medium scenario, the projected rise in sea-level will lead to coast erosion and redistribution of sediments, wetland submergence, floodplain water-logging and salt intrusion into coastal aquifers.

For the Bangkok metropolis, the most serious current problem is related to an excessive exploitation of groundwater, which has resulted in wide-scale subsidence and groundwater contamination. The high level of pumpage of groundwater from interconnected sands in eastern Bangkok has resulted in the lowering of ground surface and development of a major subsidence bowl (Fig. 6). This bowl is very shallow, with an average depth of less than 0.5 m, but it covers an extensive area of the eastern suburbs. The area encompassed by the 10 cm/year subsidence contour includes about 250 sq km of eastern

Fig. 5 Local Sea-level Rise to near the Equilibrium Stage from the Evidence of Slow Down or Stopping of Mangrove Development (At the shoreline of Wat Asokaram, Southwest of Samut Prakhan)

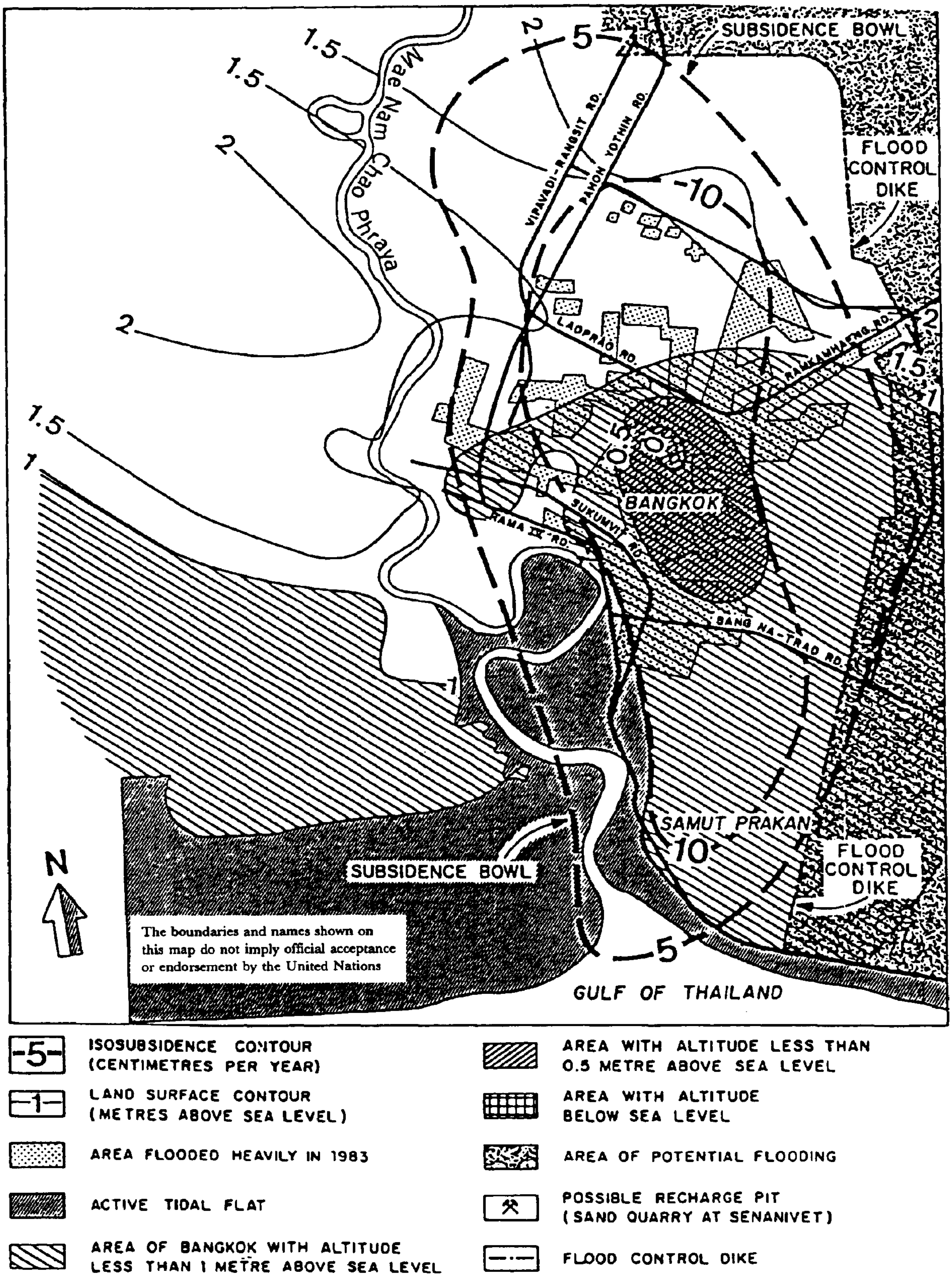

Fig. 6 Map of Subsidence Bowl Showing the Rate of Subsidence and Other Constraints [ESCAP 1988]

Bangkok. The area shown on Fig. 6 is also prone to more severe flooding as water drains more slowly through its natural drainage and man-made canal systems. All of these canals drain west to the river and must climb the western lip of this bowl before discharging into the Chao Phraya river. The major effect of the 1983 flood was felt precisely within the most rapidly subsiding area of the city, with the most serious flooding occurring in the lowest topography. Recent predictions indicate that parts of this area would be below sea-level by the year 2000 if present groundwater pumpage rates continue unabated. For the future of Bangkok metropolis, a combination of subsidence, due to over exploitation of groundwater, and a future sea-level rise will seriously affect residential, industrial, economic and commercial activities, and agricultural land.

Determination of Shoreline Change

Two different approaches can be used to model shoreline reconfiguration in response to sea-level rise. The Bruun rule describes the equilibrium profile achieved after material removed during shoreline retreat is transferred onto the adjacent shoreface/inner shelf [Bruun 1962; Weggel 1979; Schwartz and Fisher 1979]. The second approach is less sophisticated for modeling purposes but more realistic in a geomorphic sense; it involves the empirical determination of new shorelines using trend lines. In this case, shoreline response is correlated to the historical trend with respect to the local sea-level changes during that time period. This procedure accounts for the inherent variability in shoreline response based on differing coastal processes, sedimentary environments, and coastline exposures.

One of the sources of historic information is the charts of the Chao Phraya river and the shoreline, kept in the archives of several countries outside Thailand, Great Britain, France and the Netherlands, and dated back to the 17th Century. These were made after surveys carried out by missionaries, naval parties and merchants trading with Thailand (Siam) in those days [NEDECO 1965]. Reproductions of charts made of the shoreline area are shown in Fig. 7, the oldest one drawn around 1650. Some indications can be obtained from these charts regarding the topographic changes which took place in the respective years. The chart of 1856, for example, made from a survey carried out by one Capt. Richards of the Royal Navy, states that "the depths of sea bottom are given in meters below low water of April" [NEDECO 1965]. The datum of the chart is, therefore, not very closely defined, and the exact difference between low water in April 1856 and M.S.L. in 1960 is not known, but must be estimated in order to make a comparison of both charts possible.

The chart of 1797 shows the last few kilometers of the Chao Phraya delta and the river-mouth areas. Starting-point for a comparison with later situations is the bend in the river, drawn at the top of this chart, which appears to be the same as is now to be found just north of Paknam. The direction of the entrance of the Chao Phraya river in 1797 was south-south-west, the same as the present direction of the river just below Paknam. Comparison of the 1797 chart with the next one, made in 1856, seems to suggest that in the intervening period of nearly 60 years, the shoreline shifted about 4 km to the south, or at an average rate of about 70 m per year. Comparing the charts of 1856 and 1960, however, it appears that in the past hundred years or so, the eastern shoreline has practically kept its place, while the western shore adjacent to the river-mouth has grown in a southeastern direction over a distance of approximately half a kilometer, at an average rate of only about 5 m per year. This apparent considerable change in accretion rate is rather strange. A sudden change in the accretion rate as is suggested by the charts of 1797, 1856 and 1960 can be confirmed of the trend of sea-level rise dating back to the 18th century. It is true that in the course of centuries the growth of delta may gradually slow down as the local sea-level of this shore has been rising for the past few hundred years. In the final stages of delta formation, an equilibrium may even be attained in the near future.

The future positions of shoreline can be plotted by manual interpolation between the existing altitude (Fig. 8), recent man-made rate of land subsidence, and minimal projected rate of sea-level rise (at the low scenario for this area). The next step is to adjust and to correlate shoreline positions based on geomor-

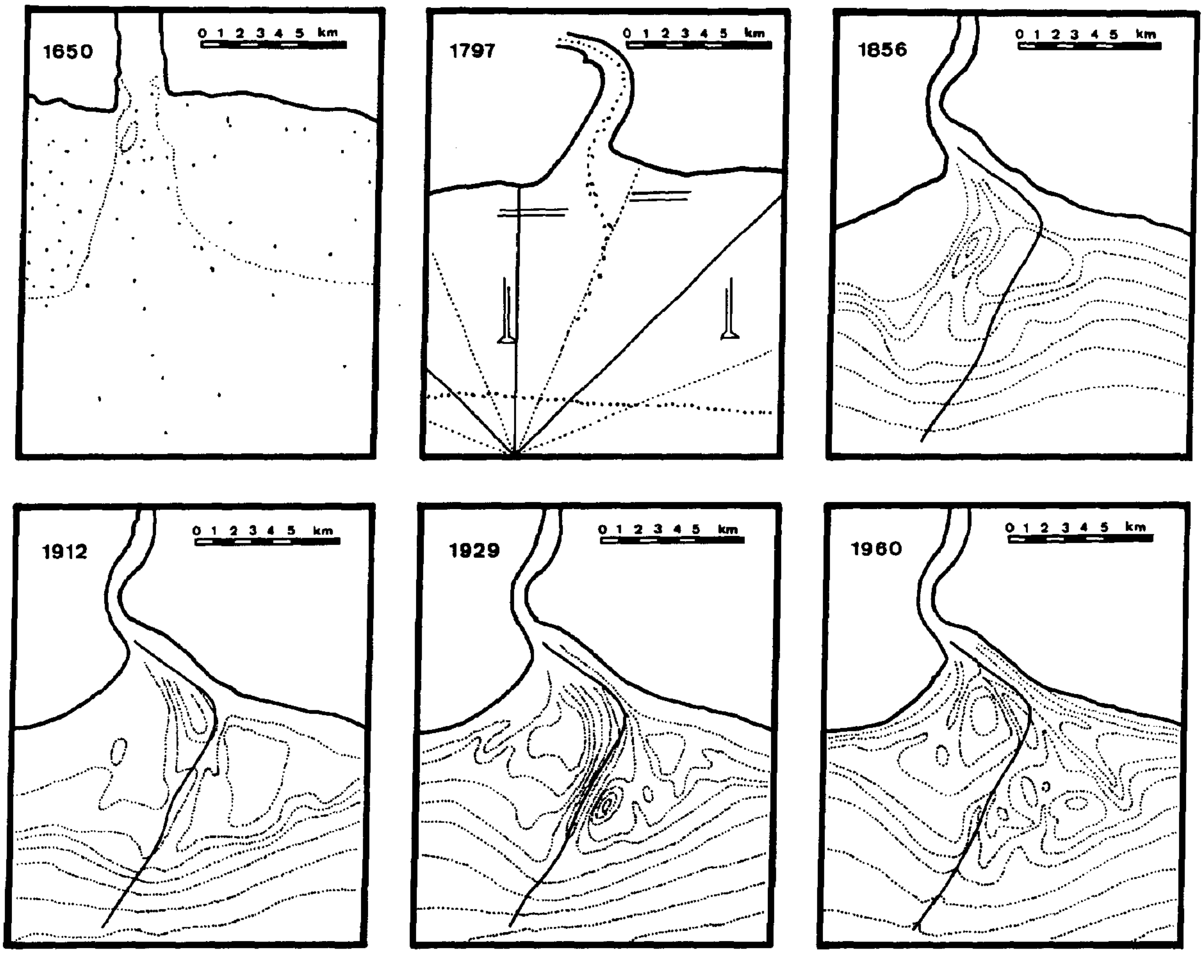

Fig. 7 Historical Shoreline Changes of the Chao Phraya River-mouth Areas, 1650–1960 (After NEDECO [1965])

phic approaches, such as historical trends of erosion and accretion, coastal processes, sedimentary environments, and coastline equilibrium exposures (by the Bruun rule). The Fig. 9 shows the area of the Bangkok metropolis which can be covered by sea-water

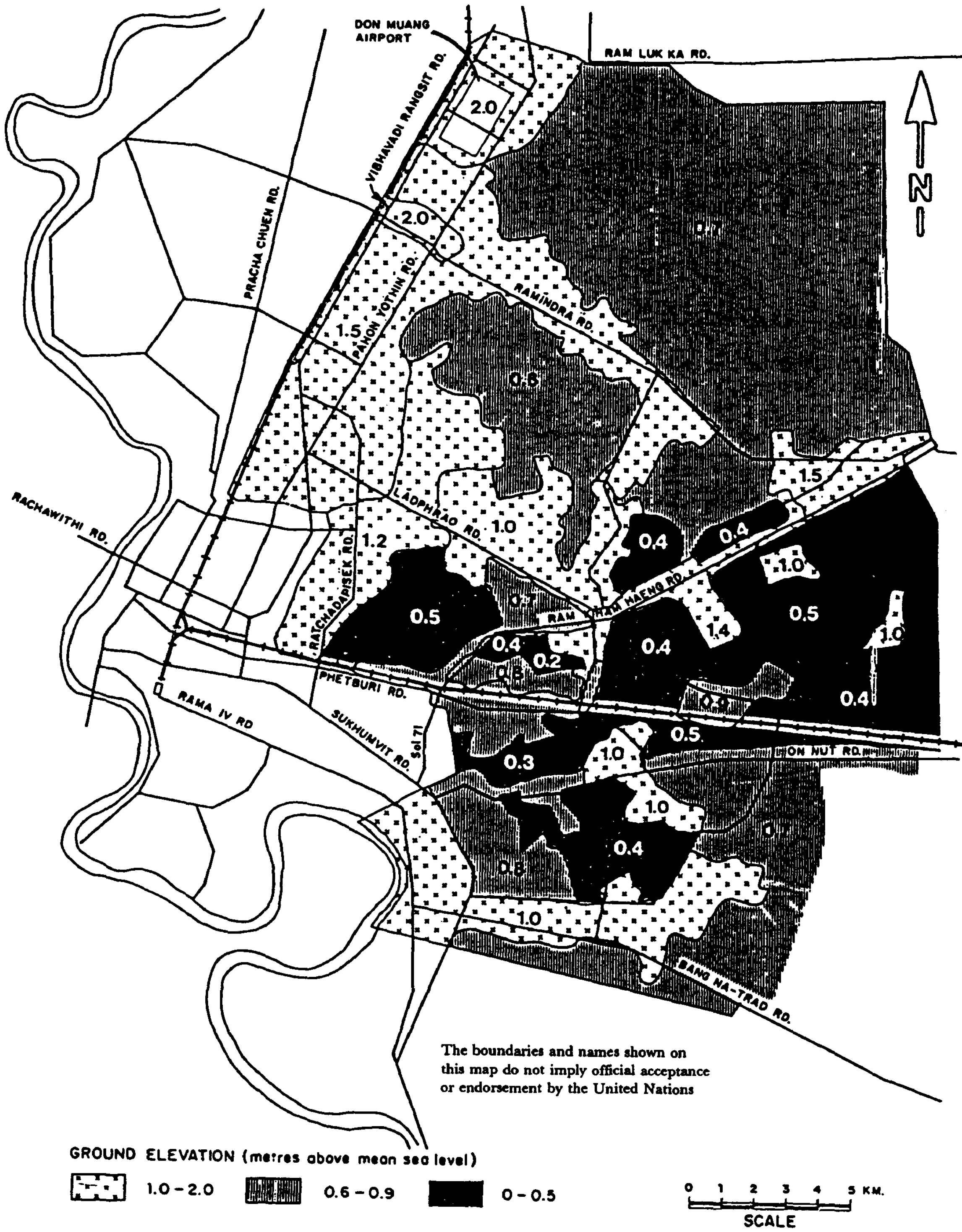

Fig. 8 Map Showing Recent Altitude in Meters above Mean Sea Level of Parts of Bangkok Metropolis (After JICA [1984])

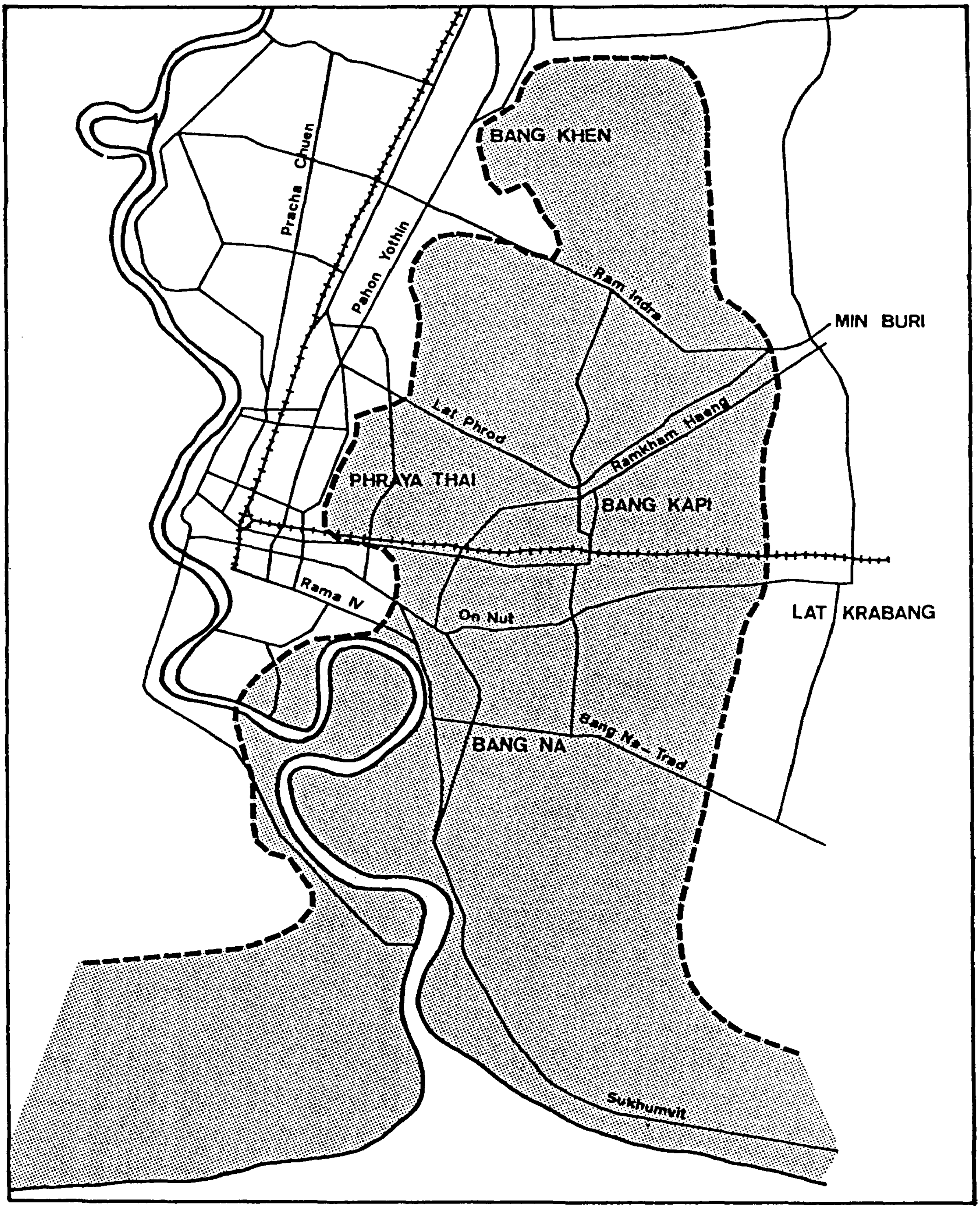

Fig. 9 A Minimal Projected Shoreline Changes of the Chao Phraya River-mouth Areas in the Year 2100, by the assumption: 1) Sea-level rise will fall at least in the low scenario; 2) Groundwater pumpage and subsidence rate will continue unabated; 3) No protection strategy will be constructed.

by the year 2100, if the rate of sea-level rise falls in the low scenario and groundwater pumpage rates continue unabated from their 1984 levels. In all foreseeable circumstances, sea level is likely to rise with the amounts considerably greater than the rise of this past century. In order to improve substantially the estimates of future sea-level rise in the areas of Bangkok metropolis, more time and more scientific research will be needed. Merely waiting for observations will be the slowest way to learn more about sea-level's future rise. To maximize the value of future observations, the theoretical base and models used to interpret the relevant data must be improved. Rapid progress can be made by accelerating the research aims at improving our basic understanding of the process.

Conclusions and Recommendations

The geomorphology of Bangkok metropolis has been largely ignored in the planning and development of the city. Decision-makers need to have some basis for establishing priorities when faced with the question of selecting suitable areas for development, especially if parts of the municipality are faced with either natural or man-induced hazards. Of the technical constraints to the urban development of Bangkok, the most serious current problems are related to the future sea-level rise and the excessive exploitation of groundwater which has resulted in wide-scale subsidence and groundwater contamination. An increase in sea-level rise of at least 1-1.5 m is accepted for the next 100 years, and an increase in flooding and storm, especially severe tropical storms can not be excluded as a result of the increase of world temperature and its effect on lowlands. Like the physical effects of sea-level rise, the environmental impacts will create a problem for the growth of the city as the pollution of surface water, wastewater drainage and treatment, water supply (good quality), etc. were generated by increased population, and the sea level became a serious problem. The following are conclusions and recommendations concerning all of the coastal lowland of the Bangkok metropolis:

1. Observe tide gauge measurements; if no tide gauges are available they should be constructed.
2. Make an infrastructure to control man-induced subsidence caused by groundwater and drainage. An important evaluation should take place before planning new urban coastal settlements.
3. Map and measure coastal erosion and aggradation.
4. Make "Coastal Hazard Maps" related to the increased rise of sea-level and changes in storminess. Indicate areas in extreme risk, high risk and moderate risk.
5. A database should be developed for the collation, storage and retrieval of relevant geologic, hydrologic, geohydrologic and engineering information.

How can the areas of Bangkok metropolis respond to the predicted rise in sea-level? They can either try to defend the Bangkok areas or to move present activities and development to suitable places. The protection can be done by dykes, sea walls, and other engineering solutions. It must be realised that economic and environmental impacts can make such a protection strategy unacceptable. Also, moving present activities will have a serious economic and social effect to the city. City planners will have to do more long-term studies to solve the foreseeable problems.

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References

Achalabhuti, C. 1975. Petroleum Geology of the Gulf of Thailand. *Economic Geology Bulletin* 7. Department of Mineral Resources, Bangkok.

Barth, M. C.; and Titus, J. G., eds. 1984. *Greenhouse Effect and Sea-level Rise*. New York: Van Nostrand Rheinhold.

Broecker, W. S.; Thurber, D. L.; Goddard, J.; Ku, T.; Matthews, R. K.; and Mesolella, K. J. 1968. Milankovitch Hypothesis Supported by Precise Dating of Coral Reefs and Deep-sea Sediments. *Science* 159: 1–4.

Broecker, W. S. 1975. Climatic Change: Are We on the Brink of a Pronounced Global Warming?. *Science* 189: 460–463.

Bruun, P. 1962. Sea-level Rise as a Cause of Shore Erosion. *Journal of Waterways and Harbours Division, ASCE* 88(ww1): 117.

Bunopas, S. 1981. *Paleogeographic History of Western Thailand and Adjacent Parts of Southeast Asia: A Plate Tectonics Interpretation*. (Geological Survey Paper No.5). Department of Mineral Resources, Bangkok.

Carter, R. W. G. 1988. *Coastal Environments: An Introduction to the Physical, Ecological and Cultural Systems of Coastlines*. Academic Press.

Charney, J. F. (chairman; Climatic Research Board). 1979. *Carbon Dioxide and Climate: A Scientific Assessment*. Washington D.C.: NAS Press.

Crawfurd, J. 1828. *Journal of an Embassy to the Courts of Siam and Coclin China*. Oxford University Press. (Reprint ed., Kuala Lumper, 1967.)

Croll, J. 1867a. On the Excentricity of the Earth's Orbit, and Its Physical Relations to the Glacial Epoch. *Philosophical Magazine* 33: 119–131.

_______. 1867b. On the Change in the Obliquity of the Eliptic, Its Influence on the Climate of the Polar Regions and on the Level of the Sea. *Philosophical Magazine* 33: 426–445.

Emery, K. O.; and Niino, H. 1963. Sediments of the Gulf of Thailand and Adjacent Continental Shelf. *Geol. Soc. American Bull* 74: 541–544.

Ericson, D. B.; Broecker, W. S.; Kulp, J. L.; and Wollin, G. 1956. Late-Pleistocene Climates and Deep-sea Sediments. *Science* 124: 385–389.

Ericson, D. B.; and Wollin, G. 1968. Pleistocene Climates and Chronology in Deep-sea Sediments. *Science* 162: 1227–1234.

ESCAP Secretariat. 1988. Geological Information for Planning in Bangkok, Thailand. In *Geology and Urban Development: Atlas of Urban Geology* Vol.I, pp. 24–60. ESCAP, United Nations.

Fairbridge, R. W. 1966. Mean Sea-level Changes, Longterm, Eustatic and Others. In *Encyclopedia of Oceanography*, edited by R. W. Fairbridge. Reihold Publishing Co.

Hays, J. D.; Imbrie, J.; and Shackleton, N. J. 1976. Variations in the Earth's Orbit: Pacemaker of the Ice Ages. *Science* 194: 1121–1132.

Hendry, M. 1988. Implications of Future Sea-level Rise for Caribbean Shorelines. In *Extended Abstracts of International Symposium on Theoretical and Applied Aspects of Coastal and Shelf Evolution, Past and Future, 19–24 September 1988, Amsterdam* (By Roy. Neth. Acad. Sci/IGCP), pp.37–39 (abstract).

Hoffman, J. S.; Keys, D.; and Titus, J. 1983. *Projecting Future Sea-level Rise: Methodology, Estimates to the Years 2100 and Research Needs*. 2nd. Rev. ed. U.S.GPO. No.055-000-00236-3. Washington D.C.: Government Printing Office.

Hoffman, J. S. 1984. Estimates of Future Sea-level Rise. In *Greenhouse Effect and Sea-level Rise*, edited by M. C. Barth; and J. G. Titus, pp.79–103. New York: Van Nostrand Reinhold.

Imbrie, J.; and Imbrie, J. Z. 1980. Modeling the Climatic Response to Orbital Variations. *Science* 207: 943–953.

Imbrie, J.; and Imbrie, K. P. 1986. *Ice Ages: Solving the Mystery*. England: Harvard University Press.

Jelgersma, S. 1988a. A Future Sea-level Rise: Its Impacts on Coastal Lowlands. In *Geology and Urban Development: Atlas of Urban Geology* Vol.I, pp.61–81. ESCAP, United Nations.

_______. 1988b. The Swinging Shoreline: Past, Present and Future. In *Extended Abstracts of International Symposium on Theoretical and Applied*

Aspects of Coastal and Shelf Evolution, Past and Future, 19–24 September 1988, Amsterdam (By Roy. Neth. Acad. Sci./IGCP), pp.49–50 (abstract).

JICA (Japan International Cooperation Agency). 1984. *Studies on Flood Protection/Drainage Project in Eastern Suburban-Bangkok*. Preliminary Study.

_______. 1985. *Studies on Flood Protection/Drainage Project in Eastern Suburban-Bangkok*. Masterplan Study.

Jermias Van Vliet. 1910. *Description of the Kingdom of Siam*. Translated by L. F. Van Ravenswaay. JSS7, pt.I.

Lamb, H. H. 1969. Climatic Fluctuations. In *World Survey of Climatology 2; General Climatology*, edited by H. Flohn, pp.173–249. New York: Elsevier.

Mesolella, K. J.; Matthews, R. K.; Broecker, W. S.; and Thurber, D.L. 1969. The Astronomical Theory of Climatic Change: Barbados Data. *Jour. Geol.* 77: 250–274.

Mitchell, J. M., Jr. 1977a. The Changing Climate. In *Energy and Climate, Studies in Geophysics*, pp. 51–58. Washington: National Academy of Sciences.

_______. 1977b. Carbon Dioxide and Future Climate. In *Environmental Data Service*, March, pp.3–9. US. Dept. Comm.

Moreland W. H., ed. 1934. *Peter Floris: His Voyage to the East Indies in the Globe, 1611–1651*. London.

Nicholas Gervaise. 1689. *The Natural and Political History of the Kingdom of Siam*. (Translated by H. S. O'Neill, 1928). Bangkok.

NEDECO (the Netherlands Engineering Consultants). 1965. *Siltation: Bangkok Port Channel*. Vol.2. Report to the Government of Thailand.

Nutalaya, P.; and Rau, J. L. 1983. Geomorphology and Land Subsidence in Bangkok, Thailand. In *Guidebook for Field Trip Itinerary in the Short Course on Applied Quaternary Geology*, edited by P. Nutalaya, pp. 181–202. Bangkok: AIT.

Pallegoix, J. B. 1854. *Description du Royaume Thai ou Siam*. Vol.I. Gregg International Publishers. (Reprint ed., Farnborough, England, 1969.)

Schwartz, M. L.; and Fisher J. J., eds. 1979. *Proceeding of the Per Bruun Symposium*. Newport, R. I.: IGU Commission on the Coastal Environment.

Smyth, H. W. 1898. *Five years in Siam from 1891 to 1896*. Vol.I. London: John Murray.

Somboon, J. R. P. 1988. Paleontological Study of the Recent Marine Sediments in the Lower Central Plain, Thailand. *Journal of Southeast Asian Earth Sciences* 2(3/4): 201–210.

_______. 1990. Geomorphology of the Chao Phraya Delta, Thailand. Ph. D. dissertation, Kyoto University, Japan.

Somi, E.; and Morner, N-A. 1988. Sea-level Changes and Coastal Erosion in Tanzania. In *Extended Abstracts of International Symposium on Theoretical and Applied Aspects of Coastal and Shelf Evolution, Past and Future, 19–24 September 1988, Amsterdam* (By Roy. Neth. Acad. Sci/IGCP), pp.120–123 (abstract).

Van den Heuvel, E. P. J. 1966. On the Precession as a Cause of Pleistocene Variations of the Atlantic Ocean Water Temperatures. *Geophys. J. R. Astr. Soc.* 11: 323–336.

Vernekar, A. D. 1972. *Long-period Global Variations of Incoming Solar Radiation.* Meteorological Monographs 12. Amer. Meteorol. Soc., Boston.

Weggel, R. 1979. *A Method for Estimation Long-Term Rise in Water Level.* CERC Technical Aid 79–2. Fort Belvoir, Va.: Coastal Engineering Research Center.

Zhao, X. 1988. A Brief Introduction on the Project "Preliminary Study on Sea-level Changes in China and Their Trends and Impacts." In *Extended Abstracts of International Symposium on Theoretical and Applied Aspects of Coastal and Shelf Evolution, Past and Future, 19–24 September 1988, Amsterdam* (By Roy. Neth. Acad. Sci./IGCP), pp.151–152 (abstract).