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Deltas: Young, Fragile and Threatened Environments

Deltas are structures formed from sediments of mainly fluvial origin, built by a set of processes that combine the actions of rivers and the sea; they exhibit a set of fluvial and coastal forms and, in general, a morphology that protrudes from a coastline that may be more or less exposed.

Effectively, delta formations are constructed when sedimentary materials of continental origin hold more sway than the destructive action of the receiving aquatic environment; the latter being due, either independently or jointly, to longshore drift, swell, waves and tides.

Delta formations have developed over the last 6,000 years[1], approximately, in other words since the relative stabilization of the Earth's sea levels, at the mouth of watercourses entering an ocean or a sea.

Fluvial sediments are deposited when water flow coming from the continent, having lost its power when entering the marine environment, is forced to deposit its load. Deltas are developed fully when they extend large fluvial bodies that drain vast watersheds subject to high levels of erosion and that carry abundant sedimentary flows. Conversely, a river with little input of sediment ends with an estuary that is more or less filled in and subject to tidal effects.

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[1] In principle, they are younger in their distal sections (downstream), which go a long way to explain their fragility in the presence of oceanic currents.

1.1. Long-term construction of deltas: general mechanisms

1.1.1. *Processes and basic forms*

Delta formations generally fall into one of three types of basic formations and sedimentary facies. Regarding the sea level, deltas are organized from upstream to downstream in the following simplified way.

1.1.1.1. *Delta plains or subaerial deltas*

The upper delta plain (channels not affected by salt water) and the lower delta plain (subject to tidal effects) can be distinguished by the limit of influence of the tidal regime; this limit depends on the slope of the delta and the flow rate in the watercourse. The distribution channels* are produced by avulsion*, which creates a new channel when the main channel rises (or vertically aggrades) by sediment deposition, and a flood opens a breach in one of the levees bordering the channel. The levees, made up of sandy materials, are separated by shallow basins that form freshwater or briny wet zones which are rich in ecology. The general facies of the deposits features beds inclined at low angles at the surface; aggradation of the delta plain is slow because materials are transported at the surface towards the delta front.

1.1.1.2. *The delta front or proximal part*

The front combines a narrow subaqueous platform and the “front” itself, which progresses (or “progrades”) more or less rapidly depending on the intensity of fluvial input, generally sandy and/or silty. The front has a topographic slope of 10° to 25°, which conforms to the dip of deposits brought down to the mouth.

1.1.1.3. *The prodelta or distal part*

The prodelta is the subaqueous part of a delta that rests on the continental shelf*. The prodelta, created in a zone of deep water with an ocean floor of gentle slope, is made up of very fine deposits, silts and clays from suspended loads carried by plumes. The deposits are made up of laminated beds. This unit is itself fossilized by the progressing delta front.

1.1.2. *Dynamics of construction and redistribution in progress*

The plan form of a delta is conditioned by the interrelation of three competing forces specific to the receiving environment, one fluvial and the two others marine in nature; each of these forces can win over the others depending on the intensity level of its action. This set of influences is the basis for ternary classification of deltas, on a genetic basis, that remains the most widely used [BHA 06, GAL 75].

1.1.2.1. *River-dominated deltas*

River-dominated deltas are subject to the dominant combined action of the liquid and solid flow rates of the river (made up of the bed load* and the suspended material*). These deltas present characteristics of formations undergoing active construction, in contrast to the two following types. They have an elongated shape, whether it is simple or composite, constructed as an extended prolongation of the lower delta plain. The distribution channels or branches end in sandy mouth bars*. The branches separate bays that are progressively transformed into marshes. The Mississippi Delta is the archetype of a river-dominated delta, at least in its northern part, which is constructed along the main fluvial channel (Figure 1.1).

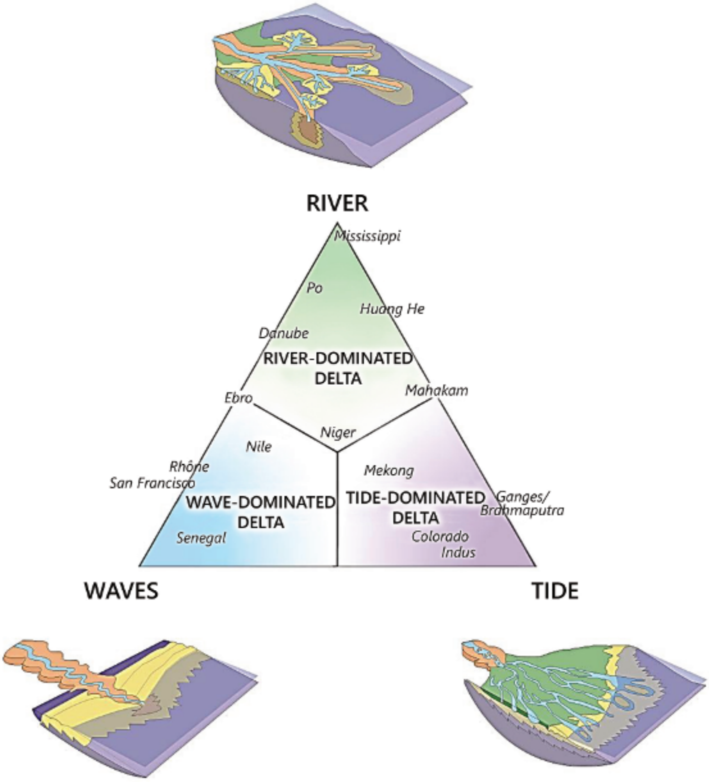

Figure 1.1. *Typology of deltas as a function of greater or lesser influence of the river, tides and waves. (Source: [FIS 69] and [GAL 75], redrawn by F. Salomon). For a color version of this figure, see www.iste.co.uk/bravard/sedimentary2.zip*

1.1.2.2. *Tide-dominated deltas*

These deltas are formed from the branches of distribution channels shaped in a lower delta plain by the action of tides; the branches are called “estuaries*”; the average tidal range is felt upstream and its influence is dominant in comparison with the influence of the river. Delta branches under tidal influence (flood* and ebb*) are the most stable. Delta construction extends slightly or not at all into the sea, apart from with subaqueous mouth bars lying in an extension of the distribution channels and shaped by tidal effects. Between the mouths, vast areas of mud can develop on the tidal flats*, often intersected by thin sandy bars called “cheniers*”, and colonized by mangroves which are forested formations adapted to salt water. This type of delta is well illustrated by the Amazon, Ganges and Brahmaputra Deltas, or even by the Yangtze Delta.

1.1.2.3. *Wave-dominated deltas*

The coarsest fraction of sediments carried down by the river (in general, sands that belong in part to the bed load and in part to the suspended load) is redistributed more or less actively by the waves (mainly as a function of their average height) and by long-shore drift*, in sandy bars parallel to the coastline of the delta; these bars or barrier beaches have seasonal openings and may isolate lagoons. Under the action of waves, the deltaic protuberance takes on a lobed form, often pointed in shape. When the deltaic lobe* loses input from fluvial materials, it erodes, regresses and melts into the coastal bars, shaping the shoreline between the active mouths. This type of delta is seen in the Senegal and Nile Deltas, as well as in the Tiber and the Rhône in the Mediterranean.

While this classification is convenient, in practice deltas often take on mixed and evolving forms, in particular by the association of forms reworked by waves and tides, whether the delta is progressing quickly or slowly under the influence of materials of continental origin. This is why certain specialists look at the balance between the suspended load of rivers at their mouth on the one hand, and the relative importance of the action of waves and tides by means of their ratio on the other; this is a means of providing a qualitative basis for grouping deltas together in large families [HOR 07a]. The deltas of the Orinoco, the Red River and the Mekong belong to a mixed type. The Mekong Delta has sandy coastal bars shaped by waves, as well as estuary-type branches in its northern part and mangroves to the south, where muds are deposited downstream of the direction of long-shore drift.

Furthermore, the proportion of sand and mud coming from the continent conditions the formation and future of deltas. Deltas with a high proportion of sand (more than 10% of the total load) have a greater area above sea level than mud deltas; however, the presence of mud is essential because it consolidates soils, makes them more resistant to fluvial and marine erosion and encourages good health in vegetation formations such as marshes and mangroves. The latter two increase the resilience of the delta to the forces applied to it by the ocean [GIO 14].

1.1.3. *Young and unstable areas*

1.1.3.1. *Natural sinking and delta equilibrium*

Natural or geological subsidence is a slow and regular movement that reduces the level of the ground surface. Several processes can exist, sometimes simultaneously:

– on the one hand, a deep process can sometimes be at play, generally related to the movement of the lithosphere, for example linked to downward movement due to fault tectonics or to large-amplitude warping that affects sub-delta sedimentary deposits;

– on the other hand, at a different timescale (of climate periods within the Quaternary epoch) and in the regions of the Earth that have undergone glaciation, these vertical movements can also be isostatic* in nature, and will become more obvious as they approach the poles. Under the weight of ice, portions of continent have sunk by several meters, causing an equilibrium process with uplift of their external marginal areas; this is called an “isostatic adjustment”. During melting of ice sheets, the process is inversed: deglaciated areas are uplifted and their marginal zones sink; this is called “isostatic rebound”;

– finally, subsidence can be due to compaction of sediments that have been deposited in delta formations. The recent age of deposits (see the later section) means that they have not yet developed cohesion; this develops over time and depends on the nature of the sediments deposited.

The scale of these types of geological sinking, generically described by the term “subsidence”, is modest, in the order of a few mm/year. It goes without saying that deltas have formed because the input of sedimentary materials from the continent has exceeded the loss of volume due to subsidence. While the speed of the processes acting in favor of subsidence is relatively slow and always active, and can be predicted and modeled, the (over)compensation imposed by continental materials (which leads to a net positive balance or construction of the delta structure) is faster, fluctuating in space and time. With today’s knowledge of the history of the Earth’s climates and erosion, we are able to understand the history of sedimentary budgets* in deltas and, to a certain extent, to model their future based on initial hypotheses that combine all the relevant factors in each case.

1.1.3.2. *Rise in sea levels (> 6,000 years BP), initial phase of delta construction on a global scale*

Fluvial valleys were deeply incised during the cold periods of the Quaternary in which “eustatic*” marine regression occurred; the last one had an amplitude[2] of 110–120 m. When the climate warmed, the sea level rose rapidly. Deep deposits were extracted from deposited materials by deep core drilling, which were then analyzed and dated [SMI 11].

A very clear change in the nature and rhythm of deposits took place around 8,500–9,500 cal BP* when the sea level rose abruptly; a very credible hypothesis is that part of this rise is believed, at least around 8,500 cal BP, to be due to the sudden unloading of North American lakes (Agassiz and Ojibway lakes) which had until then been blocked by the Laurentides ice sheet; the enormous volumes stored (163,000 km^3*) led to a presumed effect of several decimeters on global ocean levels over the course of a year [TEL 02]. Deposits associated with the rise in sea levels were estuarian in nature and strongly influenced by the tide, with marine waters penetrating the lower valleys that had been temporarily transformed into rias*.

The Earth’s deltas were created when the rise in the levels of oceans and seas that communicated with oceans slowed down; the balance of forces between fluvial material input and the rise in sea levels then reached an equilibrium before tending more towards construction behavior due to input of materials of fluvial origin [STA 94]. The “jump” in sea levels associated with unloading of continental waters, which is itself followed by a phase of stabilization, may even be at the origins of delta formation [HOR 07b]. Stabilization of the sea level, progressively achieved between 8,500 and 6,000 years BP*, is thought to have then allowed deltas to be constructed by uplift and by progradation or extension into the sea. A delta in its first stage of formation at the back of a bay is initially influenced by the tide; once formed, it extends into the ocean and becomes more sensitive to wave action, which is exhibited by the construction of coastal bars. The Po and Rhône deltas have not been subject to tidal influence, but only to the influence of waves and long-shore drift.

If the delta receives a good supply of materials from the continent, the delta plain uplifts and the delta front progrades. Deltas with high levels of fluvial activity (floods, deposition in the channel), such as the Mississippi, exhibit processes of

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[2] Eustatic glacial variation is in this case the reduction of sea levels related to the retention of water on continents in the form of ice.

channel migration by avulsion as well as deltaic lobes. In contrast, tide-dominated deltas with deep and stable channels undergo avulsion processes to a lesser extent, even though they can possess channels formed during the periods of high activity which were subsequently abandoned.

The deficit of a fluvial sedimentary budget – which has its origins in disruptions at the scale of a catchment* – is likely to modify the deltaic sedimentary budget. The deficit of input materials at the river exit disturbs, in particular, the accumulation on both the delta plain and the delta front. This accelerates the subsidence of the plain, even though the sea level rises under the effect of climate change that is affecting the Earth as a whole.

In addition, progression of the delta front can be slowed down or sometimes cease, and the front may regress. However, the observer is faced with a question of scale because the evolution of a sector should not be confused with the evolution of the sedimentary budget. Sectors of the coast can regress in a delta that is advancing, simply because the sediment cells* have a net negative balance under the action of long-shore drift; other cells benefit from material input from nearby mouths, where this fresh material is carried by long-shore drift. The balance at the scale of the delta cumulates the values obtained in the individual cells, which can thus be positive or negative overall.

1.1.3.3. *Dynamics of behavior of deltas in the Holocene period*

The behavior of deltas over the last 6,000 years differs from one to another depending on whether tectonics is causing a positive or negative movement of the continent at the regional scale, and whether the delta sediment itself is more or less compacted after deposition. While the sea level is rising, the delta regresses under the influence of the tide, and the action of the latter causes the funnel and estuary-type branches to migrate towards the interior of the delta.

The behavior of deltas is also different for different regions of the world as a function of the history of the rivers that have created them. Certain rivers have had small variations in their liquid flow rate and load over the course of the last few millennia; others have had strong reactions to land clearance associated with pastoral and agricultural activities, in which case the Anthropocene* epoch pairs up the mutation of rivers and that of their subaerial deltas. There was a much faster rate of progradation* of the Huang-He and the Yangtze after 2,000 years BP, due to the increase in sediment production* in their basin and perhaps to a reduction in deposition along the Yangtze.

1.2. Some of the Earth's last great natural deltas: two deltas in the Arctic

We will take two examples of Arctic deltas, the Lena in Russia and the Mackenzie in Canada. These deltas have remained very natural, with very little development of their fluvial basin and very low levels of human occupation, apart from a little navigation activity on the main Lena estuary. Very specific processes are at work under the effects of cold temperatures, but we have selected them because their characters have remained very natural.

1.2.1. *The Lena Delta*

The Lena River, 4,400 km long, drains a basin covering an area of 2,490,000 km^2, and has a flow rate of 16,300 m^3/s at its mouth. Its hydrological regime is characterized by a maximum in spring (60,000 m^3/s) and a low water period in January (3,000 m^3/s).

The delta, constructed in the Laptev Sea, has an area of 29,600 km^2 and is the largest in the Arctic regions. The permafrost extends below an active layer, 30–50 m thick, which alternates between freezing and melting each year. To the west of the delta, several pre-Holocene thermokarst* terraces have been lifted up by tectonics and slowly eroded by thermoabrasion* and thermoablation* (with the oldest terrace being at an altitude of +20 m) (Figure 1.2).

The active deltaic landscape in the Holocene is formed from several very distinct lobes. Recent work has shown that in contrast to publications about the Earth's deltas, Holocene deposits of the Lena Delta have been laid down in the last 8,000 years, especially under the influence of the sea, and more precisely during phases of marine transgression* (thick organic levels); fluvial deposits, forming thin layers of silts and sand, appear less here.

Organic deposits, quite different from peat, were laid down during summer in pools of standing water blocked during the phases of rising sea levels. Organic deposits are composed of mosses and sedges from the sweeping action of the repeated passing of marine waters across the coastal tundra.

The process of blocking estuarian waters by rising sea levels has occurred in several multisecular periods of time, for example around 2,500–1,500 years BP and 400–200 years BP; during the periods of marine regression, the deposits were partially eroded and the material was carried into estuaries that became active again [BOL 15].

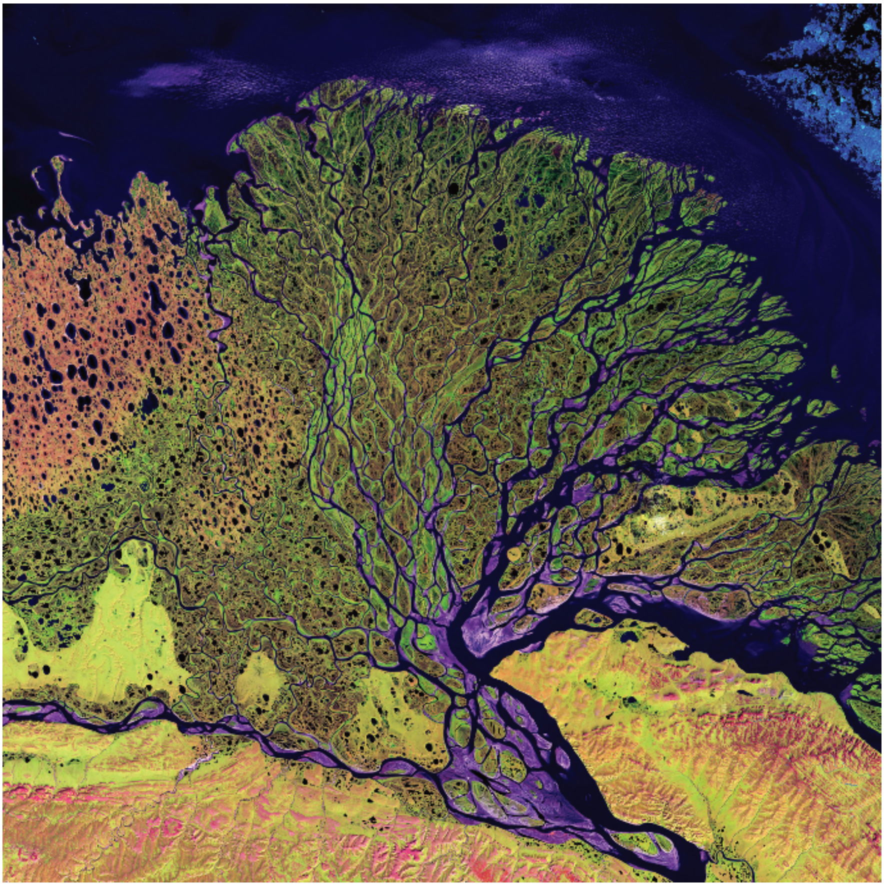

Figure 1.2. *The Lena Delta (Siberia). Infrared channel image taken on 27 July 2000, during unfreezing, by the satellite Landsat 7. We can distinguish the active channels that feed the eastern part of the delta (purple), the recently abandoned channels in the center (light green), the deltaic plain (dark green) and the Holocene levels raised to the west with lakes nestling in the thermokarst depressions and oriented in the direction of the prevailing wind. (Source: NASA Observatory and USGS ROS Data Center). For a color version of this figure, see www.iste.co.uk/bravard/sedimentary2.zip*

1.2.2. *The Mackenzie Delta*

The Mackenzie (1,738 km long) drains a watershed of an area of 1,810,000 km^2, and has a magnitude of 9,700 m^3/s. For this river in the Northwest Territories of Canada, high water occurs in June when the snow melts (21,500 m^3/s on average), and a low-water season lasts through the winter from December to April (3,400 m^3/s on average). The delta covers an area of 13,500 km^2 and has sediments that are 70–80 m thick; they rest on the substratum formed from Precambrian and Devonian rocks overlaid by Cretaceous layers with high potential for oil and gas exploitation. Below the surface of the delta, except for lakes and channels, the permafrost* holds its place. Global warming at the end of the 8th millennium BP allowed for the formation of aquatic plants and peat bogs, before a period of cooling that favored the development of permafrost, and later slowed down the formation of peat [VAR 97].

Today, the water surfaces are frozen for 8 months of the year and covered in snow. Despite the harsh climate, but thanks to the proximity of the northern edge to the boreal forest and the presence of water, biological diversity is high, which is the subject of a conservation policy. The geography of 25,000 lakes, covering half the surface of the delta, constantly changes as the active channels are eroded, fluvial sediments are brought in, the permafrost melts or fluvial branches are abandoned; it also depends on the hydrological balance between inputs and outputs (Figure 1.3).

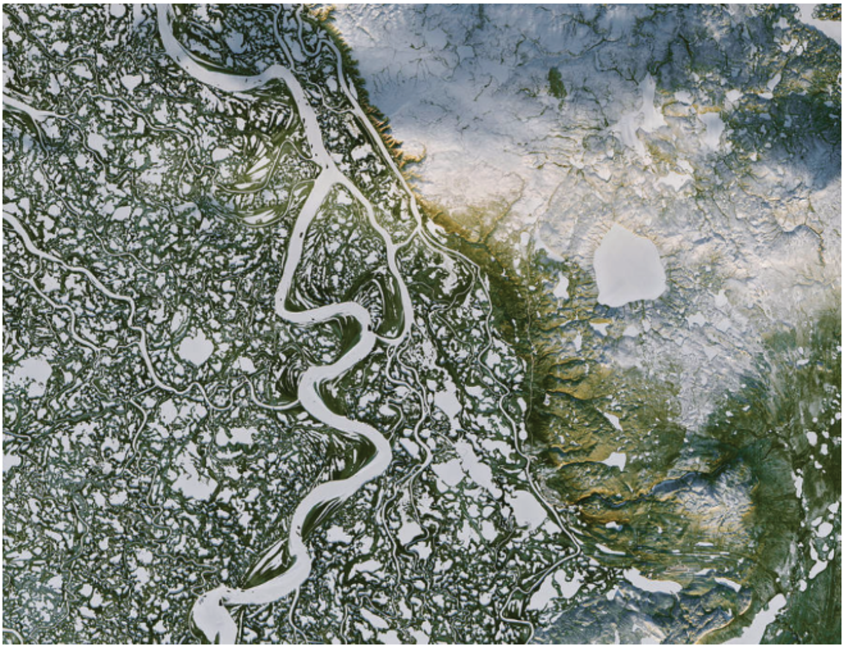

Figure 1.3. *Details of the Mackenzie Delta (Northwest Territories, Canada). This view, dated 16 November 2016, shows the eastern branch (East Channel) and the thermokarst lakes overtaken by ice. In the warm season, the river overflows but deposits few sediments. (Source: © NASA Earth Observatory, image by Joshua Stevens, using Landsat data from the US Geological Survey, available at the link: http://earthexplorer.usgs.gov/). For a color version of this figure, see www.iste.co.uk/bravard/sedimentary2.zip*

Lakes are defining features that characterize Arctic deltas, but their low levels of organic production do not cause them to be filled in. The majority of exchanges between the channels and the lakes (lake flooding) occur during the period of high waters in the month of May, whereas the lake levels are lower in summer because evaporation exceeds the input from rainfall. The frequency, intensity and duration of exchanges depend on the relative altitude of each of the lakes, an altitude that itself results from multiple influences (fluvial flow rates, logjams and debacles, variation of sea levels). Hydrologists believe that the alteration of fluvial flows by the construction of dam reservoirs would affect the levels, lake flooding and the high productivity level of the zone [MAR 88, MAR 89].

1.3. The Earth's deltas: what is their current situation in the face of terrestrial and marine constraints?

The rise in sea levels is a reality that combines several factors; it is modified in each of the Earth's deltas and even within each delta. Based on the results obtained for 40 deltas around the world, in terms of the predominant factor, the main causes are:

– the reduction of input materials of fluvial origin, in itself due to sedimentary retention and the consumption of water on the continent: < 70%;

– the extraction of resources, a factor that accelerates subsidence: 20%;

– the rise in sea levels: > 10%.

At the current rate of sea level rise, from now until 2050, specialists believe that 8.7 million inhabitants will be affected by flooding across about 5% of the total deltaic area studied [ERI 06].

1.3.1. *The rise in sea levels*

The rise in sea and ocean levels, estimated for a long time using tidal marker posts, was found to be 1.2–1.9 mm/year during 1900–1990. A precise estimate has been made possible at all spatial scales since the use of high resolution imagery with good stability, from the TOPEX-Poseidon satellite (1992), and subsequently from the Jason satellites, with a temporal resolution of 10 days. The average rise during 1992–2015 increased to 3.3 mm/year on average (incorporating variations over a short time step) [FAS 16].

The “rapid” rise in sea levels has become a social issue of primary importance since the release of the 4th Intergovernmental Panel for Climate Change (IPCC) report in 2007, and the certainty that the rate, which was 1.8 mm/year in the second half of the 20th Century, has now reached 3.1 mm/year or more [SOL 07]. The rise is considered to be rapid when it exceeds a rate of 3 mm/year; the reasons for this are the warming of the oceans (+0.64 $W.m^{-2}$ between 1993 and 2008), the volumes of which increase due to dilation, and the quantity of water input, due to the reduction of continental ice mass by melting and sliding into the ocean (more than 500 Gt/year*) [CHU 11, HAN 10].

In general, the global rise in sea levels is taken into account, but here we will examine the regional conditions, insofar as the very rapid melting of continental ice causes differential readjustments of the Earth’s surface. These include “glacio-isostatic adjustments*” (at the scale of millennia) and “elastic deformations” of the Earth’s crust that is lifted rapidly and immediately when it is freed from ice sheets, such as in Greenland and in the Antarctic (the rise in sea levels being reduced by a corresponding amount, but reversibly so); the rise due to elastic deformation can be in the order of 1 mm/year. The regional differences or anomalies also include the differences in water temperature (the western Pacific has warmer waters than the north-west Atlantic, for example) as well as the circulation of masses of oceanic water of greater or lesser degrees of salinity (spatial variation of –4 to +4 mm/year). Warming of the oceans at depths between –50 and –300 m also plays a role in the melting of glacial fronts in contact with waters, which is still not fully understood. All things considered, the rise is more rapid in the oceans of the Southern Hemisphere than in the high latitudes of the Northern Hemisphere (Arctic coasts and Alaska where the continent is being lifted). A summary of recent publications leads to an estimate of a rise of at least 10 mm/year in the decades to come [CRO 12].

However, storage of water in artificial reservoirs at the surface of continents (10,800 km^3 in total) is believed to have reduced the rise in sea levels by 0.55 mm/year over the last 50 years (therefore a total of about 30 mm), or 2.46 mm/year over the last 80 years [CHA 08]. However, this is without counting the effect of exhaustion of underground reservoirs to the benefit of surface flows and the atmospheric balance of the water; the negative balance of the use of underground water caused sea levels to rise by +0.57 mm/year around the year 2000, and this could exceed +0.80 mm/year around 2050. The net balance of the effect of reservoir storage and the effect of released water extracted from underground reservoirs was therefore –0.15 mm between 1970–1990 (a period of increased reservoir construction). It was positive at +0.25 mm/year between 1990–2010 due to the reduced rate of dam construction and to the accelerated rate of extraction; the rate could rise to +0.84 mm/year by around 2050 [WAD 12].

The rise in sea levels can be accompanied by risky situations. The coastal communities of the United States (East Coast and Gulf Coast) could justifiably live in fear of worsening storms and flooding related to exceptional tides:

> "Around the year 2045, so the time it takes for the mortgage on a house to be paid back, more than half of the 52 communities analyzed could see the risk of flooding by the tide increase 10-fold or more, and a third of these communities could be subject to more than 180 flood events of this type each year" [SPA 14].

Due to being lifted by 30 cm over a period of 30 years, communication channels outages are a current feature of life on many American coasts.

1.3.2. *Sedimentary exhaustion of continents*

The global sedimentary budget has been updated on the basis of numerous international publications (Volume 1, Chapter 4) (Table 1.1).

Sediment balances at river outlets	Billions of tons per year
Reconstituted geological or prehuman flow	15.1
Part of the flow stored by reservoirs	3.4–5
Reconstituted current flow, excluding the impact of reservoirs	16.2–17.8
Current flow	12.8

Table 1.1. *Sediment fluxes on the Earth's surface*

These figures show the scale of the reduction of fluvial input to the oceans in the last few decades. This evolution weakens the deltas in the face of the effects of dynamic processes at play, by creating an imbalance of their sedimentary budget at the scale of the deltaic plain and front. An evaluation on a global scale reveals a total trapped volume of 73 km^3, a volume that will not reach the oceans [SYV 11]; by supposing a deltaic progression wedge of an average thickness of 10 m, this corresponds to an area lost due to the effect of trapped material in artificial reservoirs of 7,300 km^2 for deltas around the world.

Asia provides a very large contribution to this reduction because its nations have chosen to follow an accelerated path to development. They have chosen to convert part of their carbonated energy production by focusing on green energy to design their new energy mix, while not giving environmental concerns the place they deserve.

A large summary [GUP 12] was carried out on the impacts of mega-dams* in East and South Asia (Table 1.2).

Watercourse	**Pre-dam flows (Gt or billions of tons)**	**Current flows modified by dams (Gt)**
Ganges–Brahmaputra	1.67	0.850
Indus	0.110	0.037
China *Huang-He*	1.8 *1.2*	0.415 *0.15*
Indian peninsula		0.083
Southeast Asia	0.572	0.81
Total		2.15

Table 1.2. *Reduction in sedimentary flux rates in East and South Asia by mega-dams [GUP 12]. The flow rate previously estimated was 4.74 ± 0.7 Gt [SYV 05]*

The sedimentary budgets can be specified at the scale of basins, as done in South Asia (Table 1.3). It is estimated that in this region, around the year 2050, nearly 9 million people and 20,000 km^2 belonging to 33 different deltas will suffer from flooding and coastal erosion aggravated as a result of input materials of continental origin which are incapable of compensating for subsidence and the rise in ocean levels.

Delta	**Percentage of reduction of the fluvial load**
Indus	94
Ganges–Brahmaputra	30
Krishna	94
Narmada	95
Cauvery	80
Sabarmati	96
Mahanadi	74
Godavari	74
Brahmani	50

Table 1.3. *Percentage of reduction of the load carried by the rivers of South Asia to their deltas over the course of a century [DAN 14a]*

1.3.3. *Extraction of resources and accelerated subsidence of deltas*

Globally, 300–500 million inhabitants live in deltas threatened by the effects of subsidence or simply susceptible to be affected by them at some point. And 20% of the Earth's deltas have accelerated subsidence, which is a primary cause of the relative rise in sea levels; accelerated subsidence must be understood as an aggravation of the process of natural subsidence by human activities. In the event of flooding, the very low altitude of the ground, at times negative, necessitates temporary displacement of the population, such as in Jakarta (200,000 people in 2007), with epidemics associated with mixing of contaminated waters with underground waters or flood waters. Pumping facilitates intrusion of salt water into underground waters, and the underground networks that transport pollutants can rupture [SCH 15].

Earlier, we saw that geological subsidence is a slow and regular lowering of the ground surface, observed in the regions of the Earth where relatively recent sediments undergo compaction processes; they can also be carried into a depression in the lithosphere that they cover. This natural movement is minor when compared to certain dynamic processes in progress. Under what mechanisms are they operating? Deltas can be areas of the Earth that contain natural riches, such as freshwater and hydrocarbons, trapped in layers deep underground. Exploitation of liquids results in a worsening of natural subsidence, but this time at rates that have no comparison to natural rates, in particular in Southeast Asia, nor with that of the rise in sea levels.

This is due to the following reason: pumping activities extract water from the pores present between the unconsolidated particles, and thus the pressure decreases, which induces compression and subsidence of the surface. An estimate made for the Bangkok plain produces a loss of volume at the surface of 0.05–0.1 m^3 for each cubic meter pumped at depth; in other words, daily pumping of 2 hm^3* should be compensated for by daily backfilling of at least 100,000 m^3 of earth; without this, the negative effects of subsidence are accentuated [PHI 06]. Subsidence would not be too serious if the pores between the grains could go back to their original volume when the water returns, in which case the ground would rise; the water table itself may rise if extraction of water or other fluids are abandoned, but its return to equilibrium would place it above the level of the soil because the latter does not rise.

1.4. Subsiding deltas in Southeast Asia

1.4.1. *An example of a young, mainly rural delta, the Huang-He*

One of the world records for accelerated subsidence, if not the record itself, has been found in the Huang-He Delta, where, in order to provide water for a young aquaculture establishment, pumping has caused local lowering of the ground surface by 25 cm/year [HIG 13]. The values reached fall into those monitored in some delta cities, therefore with an extreme range for urban areas. This delta is itself very young, since it has been in formation in the Bohai Sea since 1855 on the most recent mouth of the Huang-He, which we know to have been subject to avulsions over the course of its history. It has a surface area of 5,500 km^2 and a thickness of 15–20 m if just the contemporary sediments are taken into account. Chapter 4 of the first volume showed that the construction of dams caused the flow of water reaching the single lobe of the Huang-He to decrease from 43 to 4.9 km^3/year [HIG 13] and the sedimentary flux from over 1 Gt to 0.15 Gt/year.

Pumping of briny water to reduce salt levels in the water of shrimp farm containers, installed between 1970 and 2000, has reached the level of 1 km^3/year; at the same time, deep oil exploitation has developed, although its effects have not been clearly demonstrated up to the present day. The impact of these practices is considerable, as radar images have shown. Despite the construction of sea walls, the north coast has receded by 7 km, including the delta mouth area, even more quickly since the erosion is attacking a lower coastline. The shrimp hatchery area, affected by the peak in subsidence, has a diameter of more than 2 km. In 4 years of measurements, subsidence exceeded 5 cm/year in an area of 70 km^2. The high levels of subsidence are explained by the very high porosity of the clay and the uncompacted silt (40–55% voids).

1.4.2. *Urbanized deltas in Southeast Asia*

We will observe that the most serious situations are found today in deltas that have undergone significant urban development, since some of the world's megalopolises are located there. These are known as *sinking cities*. The distinction between how much is due to the rise in sea levels and how much is attributed to the acceleration in sinking due to the extraction of resources and the weight of the built environment is not clear; more precisely, converging effects are generally combined within the same dynamic. It goes without saying that New York, on the Hudson estuary, is the epitome of a sinking city in the eyes of Americans, but here the rise in sea levels takes precedence over subsidence[3]. We have chosen large cities in Southeast Asia.

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[3] "If there's any place in America that we're probably going to try and defend (from the sea), it's Manhattan and New York" [JOH 13].

1.4.2.1. *Kanto, Japan*

The Kanto region, home to the capital of Japan, Tokyo, has been particularly affected by water pumping [FUR 15]. The groundwater resource is found in quaternary sediments over a thickness of 2,500–3,000 m in the coastal basin. In addition to this extraction near the surface, natural gas is also extracted from the deep, fossilized marine beds. Subsidence began in the 1900s below Tokyo and spread around Tokyo Bay in the Koto area; it had already reached a cumulative level of 1 m in the 1930s but ceased when activities stopped during the war; it took off again sharply in the years 1950–1955 when industrial demand was 1.25 hm^3/day for the 40,000 factories in the region (industry uses 80% of extractions). Peak subsidence was even 24 cm/year at Edogawa-ku at the end of the 1960s due to the growing depth of wells bored in the plain (200 m in the Edogawa and Koto districts). The affected area was 290 km^2, and the cumulative sinking reached 4.5 m in industrial districts. Recent subsidence tends to migrate towards the north of Kanto since the extraction peaks have also moved.

Awareness of the issue came to the forefront at the beginning of the 1960s, with the risk of marine submersion by typhoons becoming an even more worrying reality since the rupture of dykes is likely to be accompanied by the submersion of areas that are now below the average sea level. The policy of extraction control only came into effect from the 1970s. It has been effective, sometimes to the point where the rise in water levels has locally affected cellars that were built during the phase of maximum reduction (sometimes + 30–40 m of rise for a maximum reduction of the water table of 60 m). It should be noted that demand is considerable for the 40 million inhabitants now living in this region, for its industrial waterfront and for agriculture, but it is acknowledged that human needs are now considered to be a priority; these are potable water and supply to air conditioning devices. Industry has had to resort to rivers and treatment of used water. The pumping of potable water for the population of Tokyo has been reduced to 0.5 hm^3/day, with very careful monitoring of water quality, which has in fact decreased. Underground reservoirs are also resupplied with surface rainwater flows. A clear result; in all places, the current rate of subsidence has returned to values below 2 cm/year [SAT 06].

1.4.2.2. *Bangkok, Thailand*

The capital of Thailand has 12 million inhabitants; located near the mouth of the Chao Phraya (a river with an average annual flow rate of 880 m^3/s), it covers more than 550 km^2 of a basin that has an area of 160,000 km^2, and that itself covers nearly one third of the country. Under the basin, the layers of the Tertiary and the Quaternary are 500 m thick, while some are aquifers that are separated by layers of clay. A major concern is how to distribute the water resources in a basin that suffers from a shortage during the dry season. With a low population in the middle of the 19th Century, the delta became a rice-growing area after installation of the capital city at Bangkok in 1767 and, above all, from the 1860s onwards. Competition for water is intense between agriculture in the Chao Phraya basin and exploding levels of urban demand. Thailand has taken advantage of the monsoon to store water in very large reservoirs in foothills, namely Bhumibol (1964; 13.5 km^3) and Sirikit (1974; 9.5 km^3), and by using it for rice irrigation. Based on this geographical distribution, it is logical that Bangkok has turned to underground water, abundant and of better quality than overused surface waters (the pumping rate being 36 m^3/s in 2006). However, in the context of local tensions, it is essential for the fluvial estuary to be crossed by a high flow rate of freshwater to limit salinization of the water by the upstream movement of the salt wedge, even though shrimp cultivation in the lower delta is not at all compatible with the high levels of pesticides used in rice cultivation [MOL 06].

Subsidence of the Bangkok plain came to light at the end of the 1960s. It has two major causes. The first is an excess of water extraction: pumping, mainly private initiatives for industry, occurring at a rate of 1.2 hm^3/day at the beginning of the 1980s and 2.8 hm^3 in 1998, before reducing to 2 hm^3/day. The second cause of overloading is the compacting of a thick layer of soft clay present on the surface by buildings and road infrastructure. Bangkok has, for example, 700 buildings with more than 20 floors and 4,000 buildings with 8–20 floors. Since the level of the overexploited water table has decreased by 70 m, subsidence is active. It began in the 1970s and reached a peak at the beginning of the 1980s, with a rate, fortunately brief, that exceeded 100 mm/year. However, its cumulative value has remained below that of some deltas, with a maximum of 2 m. General movement has clearly diminished since then thanks to measures to restrict consumption, but the surface of the affected zone is spreading. It affects, for example, the area around the Bangkok airport, with a cumulative value of 70–75 cm [BHA 13]. It goes without saying that sinking of the soil surface is a great inconvenience, because it causes damage to buildings and streets and because it is a great handicap for the management of fluvial floods. The layer of clay, which gets thicker in the deltaic part of the plain, effectively retains floodwaters in the basin depressed by subsidence.

The original site of Bangkok, created in 1782, is located on a levee of the Chao Phraya; since then, the city has extended down into the swamps, where the river flows next to a distributary* (the Tha Chin), a tributary (the Pa Sak) and many drainage channels. However, the fluvial network is not suitable for large floods, even though flooding is limited, in principle, by storage in the upper basin. The hydrographic network has almost no slope, and the rise in sea levels presents a problem for the evacuation of terrestrial waters. The roads, raised little by little as the marshes sink, railways on embankments, and the small dykes in the fields divide up the plain and constitute obstacles to flows when the basin is exposed to flooding, and the waters take weeks to dry off. Central districts are protected by high dykes, such as the Royal Dyke (constructed after the 1983 floods), drainage tunnels and locks that open out into the Gulf of Siam; some districts have even been polderized since water pumping has been permanently there.

The serious 2011 floods took place during a long rainy period, which lasted from May to October and produced cumulative precipitation of 1,700 mm over the capital city. Overflows began upstream from the plain of the Chao Phraya in July, and the floods reached the northern suburb of Bangkok in October, after the rupture of dykes in several places. Resistance of the town authorities to the principle of allowing water to pass – the town is a narrowing in the evacuation of the river towards the ocean – has created quite violent conflicts with the flooded suburbs. The town authorities, whose dykes of nearly 80 km in length were a dam for the flows coming from the basin upstream, were ordered by the government to allow the waters to pass through to the sea, even though this meant inundating the city. The rise in phreatic waters and the cumulation of rainwaters contributed to inundation of areas that were in principle protected. The 17 km^3 of floodwaters that were not retained by reservoirs did not totally recede until February 2012, with sea locks and pumps only able to evacuate 1 hm^3/day.

How could the sedimentary input coming from the basin balance out subsidence? A series of close-up satellite images taken in 2011 and 2012 show the path of floodwaters, as well as the relative water heights; they give information about their turbidity and show that sediments reach the plain through breaches created in the levees. They tend to be deposited close to former channels, but the network of artificial obstacles makes it impossible to spread them across the plain [LIE 16]. The load of the Chao Phraya strongly correlates with the flow rate, as shown by the values measured during the 1995 and 2011 floods, which are higher than values before the construction of reservoirs. The effects of clearance work that has been converting the natural vegetation into agricultural lands since 1960, and that has increased surface flows, have doubtlessly more than compensated for the impact of the reservoirs. The load transported during the 2011 flood was 28 Mt* (compared to an annual average of less than 6 Mt/year over a period of 60 years), but the technical measures put in place after the 1995 flood (dykes, upstream storage basins) must have reduced its transport towards Bangkok. In the end, the amount of solid material carried into the delta has reduced and cannot compensate at all for sinking of the plain [BID 17].

One of the major effects of the reduction of sedimentary input is seen on the coast. The delta of the Chao Phraya has advanced by an average of 1.5 km^2/year for the last two millennia, but coastal erosion has carried it away for around 40 years, with the regression reaching more than 1 km in 2005. The primary responsibility for regression is attributed to subsidence (1 m in 50 years) due to the reduction of sediment input of continental origin; the latter is also due to extractions of sand in the river estuary (but measurements do not exist). Recession of the coast has exhibited itself with a severe loss of mangrove areas (down from 140 to 20 km^2), since this loss is caused by the development of shrimp and clam farming pools. Deepening of the coast in the intertidal zone* following subsidence increases the energy of waves hitting the coast, and it has been possible to confirm that subsidence of coastal depths by 10 cm is sufficient for muddy coasts to be eroded [SAI 07].

The 2011 high water levels and flooding were disastrous for the population and the economy of the Bangkok metropolis, which were not so much due to the speed of the flooded waters but to their height, and above all, due to the time period during which they stagnated, which is exceptional on Earth. The 2011 flood caused more than 800 deaths around the country, created tens of thousands of displaced persons and significantly affected the economy of the country, with official estimates stating a cost of more than 100 billion euros. The flooding destroyed or damaged millions of dwellings, blocked traffic circulation (bridges became refuge car parks) and required airports to close (including the Don Mueang airport and the Suvarnabhumi International airport); it also paralyzed the production of industrial zones for several months, such as that of Navanakorn. Affected economic sectors were textiles; spare parts destined for the automobile industry of Japanese companies in Malaysia, the United States and Canada; and even the electronic chips used in industry in several countries. Industrial production chains were broken, and the authorities were worried about the confidence of investors in the future of the Bangkok economy.

Construction of a sea dyke is planned for a cost of 15 billion dollars, but certain particularly alarmist experts believe that the city of Bangkok may disappear by 2030 if new reservoirs and a more effective pumping system are not constructed [KOM 12].

1.4.2.3. *Jakarta, Indonesia: the Great Garuda project, the epitome of large hydraulic infrastructure*

The city of Jakarta, Indonesia's capital, with a population of 1 million inhabitants in 1930, today has nearly 10 million concentrated in an area of 660 km^2, to which 18 million inhabitants living in the wider agglomeration must be added. This small port of a Hindu kingdom became a Portuguese trading post in 1522, which was then under the control of the Netherlands under the name Batavia (1596). This port on the island of Java, which was established in 1619, has become the second largest megalopolis in the world after Tokyo. The city presents a striking contrast between the affluent suburbs, constructed in an amphitheater of hills, and the lower city; an area of slums, or at the very least precarious housing. The city authorities have recently razed the Sunda Kelapa district, which was the former Dutch port, after brutally expelling the inhabitants who were pushed back into a far-off suburb; this is just one example among many others of the policy of "urban cleaning" that was previously implemented by the governor Basuki “Ahok” Purnama (now deposed), a policy that can also be seen in the district of Bukit Dori, crossed by the Ci Liwung River channeled between concrete walls. The idea is to support, by means of real estate operations, grandiose projects of *reklamasi* (an Indonesian word derived from the English word *reclamation*) that are in progress in the bay [PHI 17].

As with many cities in Southeast Asia, Jakarta is sinking. Subsidence in Jakarta is the fastest of all large cities constructed on a delta. It causes damage to houses and disruption to the flow of fluvial waters (even causing a change in the direction of the flow) and of used waters (pipe ruptures); it is also responsible for the intrusion of salt water and coastal flooding. Subsidence results from three main causes: the pumping of potable water, the weight of the city and natural compaction of fine sediments carried down by small coastal rivers [ABI 15]. The ground surface has been sinking by 1–4 cm/year on average between 1974–1991; this rate increased from 3 to 10 cm/year in the period 1991–2010, varying as a function of the location and the years, and locally it is 20 cm/year. It is much higher than the rise in sea levels, which is on average 0.32 cm/year (3.2 mm). These two figures are added together. Jakarta holds the world record. The main cause is pumping of underground freshwater at a rate of 180–250 hm^3/day, an enormous quantity that is explained by the needs of large apartment blocks; the latter also have water of excellent quality and escape the cost of polluted surface waters treatment, and the fact that these waters, even treated, are mediocre. Another result of deep overpumping is that poor districts and certain districts inhabited by the middle classes have water that has been degraded by the addition of salt water from the sea, and that they are obliged to draw up from shallow depths, because they do not have access to the highly fragmented network of pipes supplied by private companies; this water is contaminated by floods and used water [FUR 17].

The average cost of flooding in Jakarta has been estimated at 270 million euros/year in an environment where increasing population density increases vulnerability, the exposure to risk (via localization of the stakes) is high and the physical factors evolve unfavorably [BUD 15]. The risk cumulates the effects of flash floods of coastal rivers and the threat posed by the sea. The input of 13 coastal rivers (the largest being the Ci Liwung) that flow into the Bay of Jakarta and the Sea of Java cannot compensate at all for subsidence in a highly urbanized environment that has no capacity to retain waters nor sedimentary deposition processes. The input into the ocean is made of black and foul-smelling clay, and the fluxes of carbon and nitrogen are very high, as are the fluxes of heavy metal. This is because 20% of urban effluents of all kinds exit into the hydrographic network. The erosion of slopes, the impermeability of soils and infilling of marshy depressions have increased the fluxes of water and waste towards the watercourse in such a way that the frequency of flooding has increased. After the tragedy of 1997, the 2002 floods caused 60 deaths and forcibly displaced 360,000 people (450,000 people in 2007 with half the city flooded); in 2013, the dyke constructed by the Netherlands along a flood evacuation channel broke and the waters inundated districts of the city center. If dredging, non-existent between 1970 and 2010, had not been carried out since 2012, the network would have been clogged up. At that time, the World Bank financed the extraction of 4,000,000 m^3 of mud and thus reduced the risk of flooding, but its directors emphasized that the city must introduce what is known as maintenance mentality, which includes stopping rubbish and cumbersome objects from being dumped into the network [COC 15].

The deltaic plain of Jakarta will continue to sink in the years to come, because the water extracted by pumping is considered to be necessary for economic and urban development, even though substitution resources are not available. Only knowledge of the process has made considerable progress. According to specialists, Jakarta, which has already sunk by 5–6 m, could sink by as much again from now to the end of the 21st Century. The rise in sea levels is added to this sinking; in the Bay of Jakarta, it has been 3–4 mm/year on average since the beginning of the 1990s. The threat of worsening intensity of rainfall and extreme flows influenced by the effects of climate change is added to this evolution. An enormous sea dyke is recommended to protect the population that lives below sea level, which today amounts to 4 million people.

Across an area of 2,700 ha, 17 industrial and residential port, polders including parks and water features, have been built or are planned in front of the concave coastline* that opens out into the bay and is protected by a dyke. Based on the power of Dutch hydraulic expertise, they each have an external dyke, a drainage device and pumps to control the level of the water table; pumps have a total capacity of 90 m^3/s to evacuate rains from events with a return period of 25 years and infiltrated waters; they also include partial infilling of polders with sand. This is the case of the Pluit polder, created for residential purposes with its three compartments that cover 220 ha, its body of water intended for water storage and leisure activities. However, both the rise in sea levels and subsidence weigh heavily on this type of construction, considered perhaps a little too quickly to be sustainable. At the scale of the agglomeration, difficulties are presented by the constantly increasing surface flow, the lack of financial means and the lack of coordination between public services for a Drainage Master Plan that has remained incoherent, and has even been considered to have “disintegrated”; at the scale of polders, floods are caused by pumps breaking down, such as in January 2013 [GUN 11]. The recommendations concern delocalization of companies with high levels of consumption to areas outside critical zones of the subsiding plain, as well as infill of topographical depressions when they are not covered by informal housing. The situation becomes very serious. In addition, a new protected city is rising out of the current city in the shape of the Great Garuda[4] project (Chapter 5), but, in the meantime, at the current rate of sinking, the coastal wall will be surpassed by sea levels before 2030 and perhaps before this; in which case, the city center will be flooded more than 6 km from the coast [KIM 17]. This constraint, among others, obliged the company KuiperCompagnons to adapt their project, which won the call for tenders.

1.4.2.4. *Shanghai in the Yangtze Delta, China*

The Yangtze Delta covers an area of 210,000 km^2 and houses a population of 156 million inhabitants; Shanghai accounts for 23 million alone (its population being 1 million inhabitants around 1900). Subsidence began in the 1910s and developed rapidly at the end of the 1970s and at the start of the 1980s, due to an excess of water extraction, then due to an intense pace of construction, which took place here as well as in many other regions of the world. Cumulated subsidence, including natural subsidence, has been recorded since the beginning of the 20th Century in the Shanghai region. It is already 3 m (a little less than the 3.30 m recorded in the region of Tianjin, to the east of Beijing); the area affected by subsidence of 20 cm covers 10,000 km^2 [DAI 16]. Pumping greatly reduced after the peak in the 1950s (did politics play a role?), but control began in earnest in the 2000s. Subsidence then reduced to an average value of 1.3 cm/year and subsequently reduced further, with areas where subsidence is just 1 cm/year today covering no more than 195 km^2. The volume extracted since the 1996 peak has rapidly decreased in comparison with resupply, the volume of which remains more or less constant. The Chinese authorities believe that subsidence in the Shanghai region caused direct and indirect economic losses of 1.7 billion euros between 2001 and 2010, and 38 billion euros since 1921.

Subsidence of the delta is accompanied by significant incision of the southern branches of the Yangtze, with muddy beds and very little cohesion, in the subaqueous part of the delta; the incision has reached the underlying Pleistocene sands. This evolution is due to the significant reduction in sediment input. The load of the Yangtze at its mouth was 240 Mt before 2,000 years BP (considered “prehuman”); today, it is only 130 Mt at the mouth of the delta, having reached higher values in relation to the agricultural enhancement of the basin. The solid flow rate at its point of entry into the China Sea, taking into account the sedimentation in the least active estuarian branches and the marshes, is less than 100 Mt. The reduction was softened by filling the Danjiangkou Reservoir and other reservoirs, by the protection of lands in the upper basin and finally by the Three Gorges Reservoir. The rise in sea levels (3 mm/year) and the erosive action of long-shore drift, which

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[4] This project was financed by the government of the Netherlands and associated with the Deltares network.

is twice the continental input, also explain a coastal recession of 6 m/year in the unprotected zones [LUO 17].

1.4.2.5. *Hanoi, Vietnam: the Red River*

Hanoi, the capital of Vietnam, has been constructed in the Song Hong Delta (also known as the Red River Delta), that pours into the Gulf of Bac Bo, an appendix to the China Sea. The city's population exceeded 3 million inhabitants and that of the agglomeration is 7 million. Hanoi has problems similar to those of the large Asian cities constructed on a delta.

The Song Hong has its source in Yunnan and drains a basin of 155,000 km^2. The delta is influenced by the waves and the tide, to which the parallel dune bars and the very blunt form of the headland bear witness to this, but the capital has developed upstream from the fluvial part in the western plain. Holocene deltaic deposits have filled in the basin with thick Neogene and Quaternary sediment over a depth of more than 3,000 m. The surface of the delta plain is intersected by sinuous channels, powerful levees formed around 6,000 cal BP and colonized for 2,500 years, and marshes. Reduction of the level of the sea and the river around 4,000 years BP caused a reduction in sedimentation in the deltaic plain, which has allowed the mouth to grow rapidly [FUN 12]. The Red River has a liquid flow rate of 23,000 m^3/s during high waters and 700 m^3/s at low water levels at the end of winter. The solid flow rate of the river, 100–130 Mt/year, circulates during the summer monsoon; it travels between the levees and the dykes without being able to supply the alluvial plain.

Water has been pumped from underground reservoirs since 1909, with a very high demand for it. Since the end of the 1970s, pumping is responsible for lowering of the top of the water table under the city, and for significant subsidence, occurring at the rate of 2–3.5 cm/year; since the beginning of the 1990s, subsidence has caused disorder to communication routes, factories and habitats. During periods of rain, drainage has been made difficult, affecting the streets [NGU 95]. Recent measurements made from satellite data show that the districts on the south bank of the river are lowering at an extreme rate of 6.8 cm/year. The city's surface area is increasing, the construction of large apartment blocks weighs on the alluvial deposits, and it has been shown that subsidence is spreading along with the growth of the city. Moreover, impermeability of the soils reduces recharging of underground reservoirs by infiltration [DAN 14b].

The risk of flooding is partly, but not only, due to the problem of subsidence. High water events and flooding are managed by actors who still lack coordination, despite the approval of a Water Law (1999), whether for management of the river, dykes (monitoring and maintenance), irrigation authorities or major transport routes. The deltaic zone is a juxtaposition of rice paddies, originally linked to the river by gravity (when the river is at a low water level) or pumps (when it is in flood). Today, the paddies have been converted for the benefit of other economic uses and have been partially filled in, which reduces the storage capacity of those that are flooded. The 1945 and 1971 floods have a return period of 100 years and 125 years, respectively, but flood defenses have not been tested at this hazard level since 1971. However, the risk posed to the paddies has been reduced by the increased height of the dykes, to the point of protecting them against a hazard with a return period of 250 years. However, the risk of rupture is very much present, whereas vulnerability is much greater than in the era of rice growing. Selection of paddies to be flooded by spillways, the purpose of which is to relieve the agglomeration, is impeded by the reticence of local authorities to act in the absence of decisions that must be made at the highest level [GIL 06].

1.5. Conclusion

The Earth's deltas are extremely varied and cannot be compared to one to another, due as much to their morphology as to their occupancy levels by humans. The oceanic environment is a feature that unites them, at least by the base level that it sets, if not by the intensity of factors acting to rework alluvial materials through waves and swell. Each one is under the control of a complex, changing, continental influence, with time steps and an intensity that are particular to each of them. However, the common characteristic of the Earth's deltas is their youth, testifying to extreme fragility.

At the two extremes of the scale, we have chosen to present two deltas that are almost intact, since they are located at the mouths of watersheds that are affected little by human actions, namely the Mackenzie and the Lena. We have then understood the contrast with the deltas of Southeast Asia that have undergone intense urban development in recent decades, accompanied by the characteristic impacts of this type of growth (extractions, water pumping, etc.). Thanks to these case studies, we have been able to summarize the effects suffered by the deltas. The fact that they are recent does not allow us to jump to conclusions about their intensity and their significant role in the degradation of deltaic environments; they allow us to understand the evolution of large deltas around the world.

Chapter 2 will present deltas that were enhanced by ancient societies and that simultaneously experienced an environmental history that reveals continental hydrosedimentary fluctuations.