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## Shrinking Megadeltas in Asia: Sea-level Rise and Sediment Reduction Impacts from Case Study of the Chao Phraya Delta

Yoshiki Saito [1], Niran Chaimanee [2], Thanawat Jarupongsakul [3], James P.M. Syvitski [4]

[1] Geological Survey of Japan, AIST. Central 7, Higashi 1-1-1, Tsukuba 305-8567, Japan. E-mail: yoshiki.saito@aist.go.jp

[2] CCOP Technical Secretariat. E-mail: niranch@ccop.or.th

[3] Department of Geology, Chulalongkorn University. E-mail: thanawatjrp@yahoo.com

[4] INSTAAR, University of Colorado. E-mail: james.syvitski@colorado.edu

Continental large rivers in Southeast and East Asia, which together supplied ~2.5 x $10^9$ t $yr^{-1}$ (Gigatonnes per year) of suspended sediment in the past, are delivering less than 1 x $10^9$ t $yr^{-1}$ currently because of human activities. In the past, more than 40 $km^2$ of new land was formed annually by these rivers as delta plains; at present new land formation has come to a standstill, and some deltas are even shrinking. The megadeltas of Asia are thus at risk of destruction because of the reduction of sediment supply and relative sea-level rise caused by human activities.

### 1. Introduction

Coastal erosion is a crucial ongoing problem along most Asian coasts. Human activities in drainage basins and on coastal plains have led to a decrease of sediment supply to the coasts, caused mainly by dam construction, sand mining, and irrigation, and to a relative sea-level rise (i.e., land subsidence), caused by excess groundwater extraction. These activities, together with the destruction of coastal ecosystems, such as mangrove deforestation (e.g., Syvitski and Saito, 2007) have resulted in the present severe coastal erosion of the megadeltas of Asia.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) identified Asian megadeltas as one of the environments most vulnerable to future global changes. However, megadeltas are already experiencing acute environmental problems as a result of human activities. To address these issues an international workshop on „Coastal Erosion and Geological Assessment for Deltas in Southeast and East Asia," was held in Bangkok, Thailand, on 24–25 May 2007. Here, we review some of the workshop findings, on the coastal erosion problem.

### 2. Reduction of Sediment Discharge

There are many large, well-known rivers in the Southeast and East Asia region, including the Huanghe (Yellow River), the Changjiang (Yangtze River), the Zhujiang (Pearl River), the Song Hong (Red River), the Mekong River, the Chao Phraya, and the Ayeyarwady (Irrawaddy) River (Figure 1).

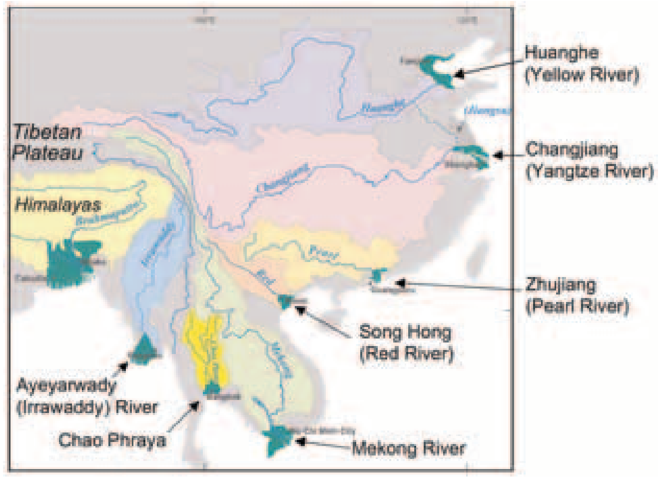


***Figure 1:*** *Megadeltas in Southeast and East Asia. Modified after Woodroffe et al. (2006)*

In the past, these rivers together (Ganges System not included) supplied ~2.5 x $10^9$ tonnes (Gigatonnes, Gt) of suspended sediment annually, accounting for significantly more than 10% of global sediment discharge (Milliman and Syvitski, 1992). However, the annual sediment discharge has decreased to less than 1 Gt recently as a result of human activities. During the last 2000 years, these rivers together deposited more than 40 $km^2$ of new land annually as delta plains along the Southeast and East Asian coasts. At present new land formation has reached a standstill; some deltas are even shrinking.

The Huanghe provides a good example of the reduction in sediment load caused by human activities. The river delivered to the sea more than 1 Gt of sediment annually for the past 1000-2000 years, up until the 1960s. However, since then, the amount of sediment delivered has decreased stepwise with the successive completion of reservoirs and the use of water for irrigation: Sanmenxia Reservoir (in 1960), Liujiaxia Reservoir (1968), and Longyangxia Reservoir (1985), and finally down to only about 150 million tonnes (Mt = $10^6$ t) per year after the completion of the Xiaolangdi Reservoir in 1999 (Wang et al., 2007). Soil conservation practices, afforestation, and a decrease in precipitation have also tended to reduce the amount of sediment delivered by the Huanghe to the sea.

The amount of sediment supplied to the East China Sea by the Changjiang, ~0.5 Gt of sediment annually for the last 2000 years (Saito et al., 2001), has been decreasing since the middle 1980s, mainly because of the construction of numerous dams and reservoirs in the drainage basin. Since water began to be stored in the Three Gorges Reservoir in 2003, the river delivers only 150-200

Mt of sediments annually (Yang Z et al., 2006; Yang et al., 2007). The Zhujiang shows a similar reduction of sediment delivery. The annual sediment discharge from the Zhujiang has declined from 80 Mt to 54 Mt on average since 1995. As a result of the steady decline since the early 1990s, in 2004 the annual sediment discharge was about one-third the mean pre-1990s discharge (Zhang et al., 2007).

The Song Hong and Mekong rivers show similar patterns of reduced sediment discharge. After the construction of the Hoa Binh Dam on the upper reaches of the Song Hong in 1989, sediment delivery decreased by more than 30%, from an average of 114 Mt annually during 1959–1985 to an annual average of 79 Mt during 1986–1997 (Thanh et al., 2004). Moreover, it decreased to 51 Mt annually during 1992–2001, on average. Sediment supply to the river mouth of the main distributary (Ba Lat) of the Song Hong decreased from about 26 Mt $yr^{-1}$ in 1949 to 11 Mt $yr^{-1}$ in 2000 (van Maren, 2004).

The Mekong River has also been affected by dams, particularly dams constructed in China. After the completion of the Manwan Dam on the upper reaches of the Mekong River in China in 1993, the annual sediment load was reduced from 71 Mt to 31 Mt at Chiang Saen in northern Laos and from 133 Mt to 106 Mt at Pakse in southern Laos (Kummu and Varis, 2007). A slight reduction of sediment load has also been recorded in the lower reaches of the Mekong in Vietnam (Lu and Siew, 2006).

Sediment discharge of the Chao Phraya, in Thailand, has also been affected by dam construction. For example, the sediment load at Nakhon Sawan, about 300 km upstream from the mouth, decreased markedly after the completion of the Bhumipol Dam in 1965 and the Sirikit Dam in 1972. The sediment load at Nakhon Sawan, more than 30 Mt annually before 1965, had fallen to less than 5 Mt $yr^{-1}$ by the 1990s (Winterwerp et al., 2005). Moreover, construction sand exploitation from the Chao Phraya at Nakhon Sri Ayuthaya, about 120 km upstream from Bangkok, during the last 30 years has cause further reduction of the sediment load .

### 3. Coastal Erosion of Megadeltas

Reduction of river sediment load impacts sediment deposition in coastal zones and causes shoreline changes. Some Asian megadeltas are clearly shrinking and shorelines are retreating as a result of coastal erosion and other phenomena, such as land subsidence.

The Huanghe delta, which historically received more than 1 Gt of sediment annually, prograded into the Bohai Sea for the past 1000-2000 years, for a land growth rate of 20–25 $km^2$ $yr^{-1}$, (Saito et al., 2001). This progradation built a cuspate delta on the western shore of the Yellow Sea, formed during 1128–1855, and a huge lobate or bird's foot delta on the western shore of the Bohai Sea, formed after 1855. In 1976, the river again shifted its course, abandoning its mouth on the north side of the present lobate delta to debouch on the east side, and since then, the area of the former river mouth on the northern side of the delta has been obviously eroding.

The shoreline there retreated more than 7 km during 1976–2000, for a mean net erosion rate of 0.29 km $yr^{-1}$; conversely, at the new river mouth, the delta has prograded more than 20 km, for a mean net accretion rate of 0.83 km $yr^{-1}$ (Chu et al., 2006; Yang and Wang, 2007; Syvitski and Saito, 2007). Nevertheless, the reduction of the sediment load of the Huanghe has affected delta formation at the new river mouth. Although the total delta area increased until 1995 owing to rapid progradation at the new river mouth, it has been decreasing since 1996 (Chu et al., 2006). Moreover, since the Xiaolangdi Reservoir began to fill in 1999, the shoreline has been generally retreating even in the area of the new river mouth (Wang et al., 2005). Thus, the Huanghe delta, which in the past was the largest delta in the world with a delta plain formation rate of 20–25 $km^2$ $yr^{-1}$, is now shrinking.

The Changjiang delta prograded more than 200 km into the East China Sea during the last 6000 years (Saito et al., 2001), and the Shanghai megacity has grown up on the southern part of the delta plain. Sediment load reduction of the Changjiang since middle 1980s has also affected coastal sedimentation. Though shoals have been transformed into tidal flats by delta progradation, the rate of progradation of intertidal wetland has been decreasing for the last 40 years (Yang SL et al., 2006), and the sediment accumulation rate on the delta front slope has also clearly decreased for the last 20 years (Wei et al., 2007). After the start of water storage of the Three Gorges Dam since 2003, sediment discharge of the Changjiang has been decreasing significantly from originally 480 Mt $yr^{-1}$ down to 150–200 Mt $yr^{-1}$ (e.g., Yang Z et al., 2006; Yang SL et al., 2007), it could be impacting sediment deposition along the deltaic coast.

The Song Hong delta has prograded approximately 100 km over the last 6000 years. In particular, sediment discharge increased during the last 2000 years because of deforestation in the drainage basin (Li et al., 2006), with the result that the river formed a huge delta plain of 2500 $km^2$ during that time (Tanabe et al., 2006). The delta plain accretion rate increased to 3.6 $km^2$ during 1958–1995 along the whole deltaic coast. However, the sediment discharge of the main distributary of the Song Hong has recently decreased from 20–25 Mt $yr^{-1}$ to ~10 Mt $yr^{-1}$, and the delta has been seriously affected as a result.

Along a 30 km-long stretch of the Vanly coast southwest of the present river mouth, the mean rate of coastal erosion increased from 8.6 m/y during 1965–1990 to 14.5 m $yr^{-1}$ during 1991–2000, following the completion of the Hoa Binh Dam in the Song Hong catchment at the end of 1989 (Thanh et al., 2004, 2005).

The Mekong River delta has formed a new delta plain of 18,000 $km^2$ during the last 3000 years (Ta et al., 2005). The average accretion rate is 6 km2 $yr^{-1}$. Coastal progradation occurs mainly around the mouths of the Mekong River distributaries and on the western side of the Camau Peninsula. This peninsula expanded westward at a rate of 1.2 $km^2$ $yr^{-1}$ between 1885 and 1985, but the 60-km-long shoreline on the eastern side of the peninsula is mainly eroding. The rate of shoreline retreat is 30-50 m $yr^{-1}$ on average, and a land area of 1.1 $km^2$ $yr^{-1}$ was lost during 1885-1992 (Nguyen et al., 1999).

#### 4. Coastal Erosion of the Chao Phraya Delta, Thailand

Along with a reduction of sediment supply, a relative sea-level rise resulting from human activities can also be an important cause of coastal erosion. The Chao Phraya delta prograded into the Gulf of Thailand with an average accretion rate of ~1.5 $km^2$ $yr^{-1}$ during the past 2000 years (Tanabe et al., 2003), but has experienced serious coastal erosion over the last 40 years (Figure 2) (Vongvisessomjai, 1992; Vongvisessomjai et al., 1996; Rokugawa et al., 2006).

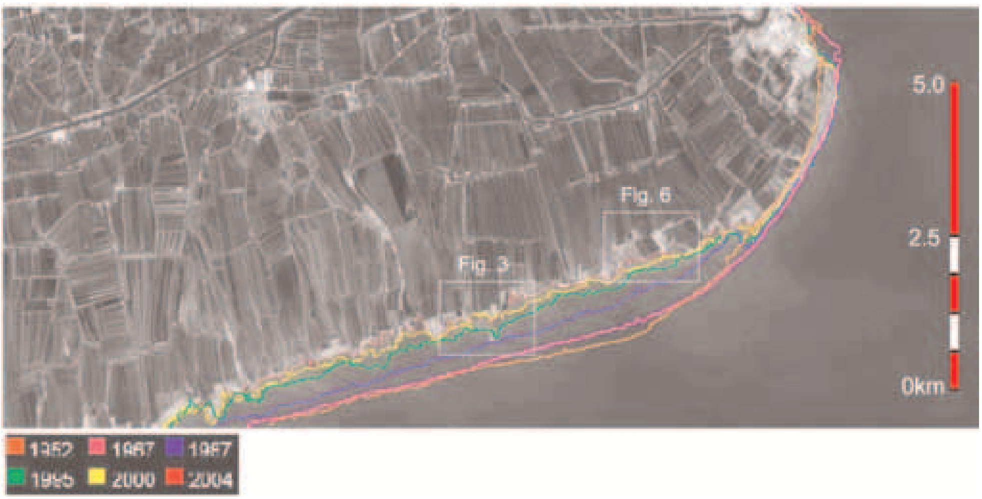


***Figure 2:*** *Shoreline changes of the Chao Phraya delta west of the river mouth in 1952, 1967, 1987, 1995, 2000, and 2004 (modified after Rokugawa et al., 2006). The shoreline retreated overall more than 1 km.*

Since the 1960s, the coast around the river mouth and the neighboring coastal zones has been eroding, mainly because of land subsidence due to excess groundwater extraction and changes in land use. The shoreline had retreated 700 m by the early 1990s, and a maximum of more than 1 km by 2005 (Jarupongsakul and Suphawajruksakul, 2005; Rokugawa et al., 2006). In the upper Gulf of Thailand, where the Chao Phraya debouches, the area of accretion was 8.9 $km^2$ and that of erosion was 4.5 $km^2$ during 1969–1976, for a net accretion rate of 0.62 $km^2$ $yr^{-1}$; during 1976–1987, they were 4.9 $km^2$ and 10.3 $km^2$, respectively, for a net accretion rate of –0.49 $km^2$ $yr^{-1}$, and during 1987–1997, they were 7.4 $km^2$ and 4.5 $km^2$, respectively, for a net accretion rate of 0.25 $km^2$ $yr^{-1}$ (Jarupongsakul and Suphawajruksakul, 2005). A total of only 1.5 $km^2$ of new land formed during the entire 28 years from 1969 to 1997; that is an amount equal to the area of land that previously formed annually under natural conditions.

Though several causes of coastal erosion have been identified (e.g., subsidence, decrease in sediment supply, deforestation for shrimp farms), the main cause on this coast is coastal subsidence. Around 1980, subsidence was rapid, at about 5 cm $yr^{-1}$, reaching a total of 20 cm within 3–4 years (Haq, 1994; Nutalaya et al., 1996), and this subsidence was accompanied by significant coastal erosion, accounting for the net erosion in the upper Gulf of Thailand during 1976–1987. Sediment reduction, on the other hand, has occurred gradually, particularly in the 1960s and early 1970s, as a result of dam construction (Winterwerp et al., 2005); thus, a close relationship cannot be identified between sediment reduction and coastal erosion around 1980.

The area of mangrove forest has decreased drastically in the lower Chao Phraya delta. During the last 40 years, more than 140 $km^2$ of mangrove forest has decreased to less than 20 $km^2$. However, more than 90% of the decrease in the 1980s occurred at Samut Sakhon, in the western part of the delta, where no serious erosion has occurred. The area of mangrove forest in the river mouth area and neighboring coastal zones (Bangkok, Samut Prakarn) did not significantly decrease during that period, because already, by the early 1960s, the area was very small there as a result of the construction of salt farms and fish ponds, charcoal production, agricultural development, port expansion, and urbanization (Szuster, 2003). Therefore, only rapid subsidence can explain the severe coastal erosion that occurred around 1980.

An approximately 60 cm relative sea-level rise occurred during the 1960s to 1980s as a result of land subsidence in the river mouth area and neighboring coastal zones

(Emery and Aubrey, 1991; Haq, 1994). Though groundwater extraction in Bangkok is regulated, subsidence is still continuing, particularly in the areas surrounding the city. During 1992–2000, there was subsidence of more than 20 cm along the coast, with a maximum subsidence of more than 30 cm, which is equivalent to a relative sea-level rise of 2–4 cm $yr^{-1}$ (Winterwerp et al., 2005). During the last 10 years, ongoing subsidence and coastal erosion have been severe. Total subsidence during the last 50 years has been more than 1 m at the river mouth, where the shoreline has retreated more than 1 km.

The main mechanisms of the erosion and shoreline retreat that result from subsidence are submergence and an increase of wave energy in the subsidence-deepened intertidal to nearshore zones, particularly the latter. The slope of the nearshore zone of the Chao Phraya delta is very gentle, with a gradient of 1 m/km. Therefore, subsidence of 10 to 20 cm causes an increase in water depth of 10% to 20% at a point 1 km offshore, and of 5% to 10% 2 km offshore. The mean tidal range here is about 1.2 m, and the maximum tidal range is about 2.5 m. One meter of subsidence means roughly that the previous mean sea-level position becomes the level of the lowest tide, and the level of the highest tide becomes the new mean sea level, assuming that sediment accumulation is negligible.

As most of the mangrove ecosystem develops in the upper part of the intertidal zone, between mean sea level and the level of the highest tide, 1 m of subsidence should cause the mangrove zone to shift landward. However, such a shift has not been observed, though some landward expansion of mangrove vegetation has occurred because of saltwater intrusion. Erosion and a 1 km retreat of the mangrove zone represent a serious problem, but only 1 km of the 20 km-wide mangrove zone was submerged, abandoned, and finally eroded. This is far smaller than the retreat distance estimated from the topography to result from simple inundation associated with a 1-m sea-level rise.

Subsidence has also led to rapid sediment accumulation in the intertidal zone of the Chao Phraya delta , particularly in the upper part of the gulf. The temple Wat Khun Samutchin used to be located on the shore. However, it is now on an artificially protected headland (Figures 2 & 3).

The temple is partially inundated, and the floor of the temple building has been elevated by about 1 m (Figure 4).

An approximately 40 to 50cm-thick layer of sediment has been deposited on the temple grounds, burying three steps leading into the building (Figure 5).

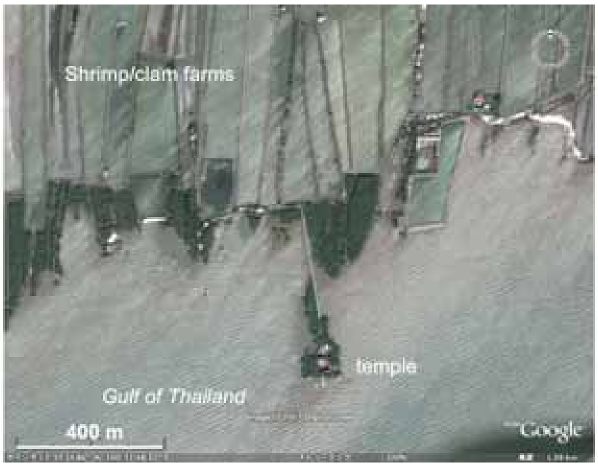


***Figure 3:*** *with kind support of Google Earth™ mapping service Satellite image of coastal erosion of the Chao Phraya delta near the Wat Khun Samutchin (after Google Earth). Approximate location is shown in Figure 2.*

***Figure 4:*** *Wat Khun Samutchin. Photograph taken by Ms. Vareerat Unwerawattana on 24 May 2007. Location is shown in Figure 2.*

***Figure 5:*** *Wat Khun Samutchin. Three steps are buried below the present ground level. Photograph taken by Ms Vareerat Unwerawattana on 24 May 2007. Location is shown in Figure 2.*

Thus, rapid sediment accumulation has also occurred in the intertidal zone in response to the rapid relative sea-level rise. In addition to this natural response of sediment accumulation in an intertidal zone, banking of roads and ridges in aquaculture ponds has also raised the ground level. These mechanisms, along with the physical protection of the mangrove forest, are protecting the shoreline against retreat.

The currently observed 1 km retreat caused by the 1 m of subsidence means that a 1-km-wide strip of the intertidal zone has changed into an offshore slope environment (delta front slope), because the subsidence/shoreline retreat ratio is the same as the offshore gradient of 1 m $km^{-1}$. If enough sediment is supplied to fill the accommodation space in the intertidal zone, the amount of shoreline retreat will be controlled by a new equilibrium profile offshore (delta front slope) and by the related landward migration of the offshore break.

Aquaculture ponds for clam and shrimp have also accelerated coastal erosion. Once the frontal mangroves are destroyed, the ocean encroaches into the shrimp ponds, exposing the next mangroves to face the sea (Figure 6).


***Figure 6:*** *with kind support of Google Earth™ mapping service*
*Satellite image of coastal erosion of the Chao Phraya delta near the river mouth. Mangrove collapse at the ocean front has led to a landward shoreline shift to beyond the aquaculture ponds. Approximate location is shown in Figure 2 (after Google Earth).*

The reduction of sediment discharge and the decrease of water discharge caused by dam construction have also led to coastal erosion. If the submergence of coastal zones is to be prevented, sediment must accumulate in the intertidal zone to maintain the ground level. However, the sediment supply from rivers has already been reduced during the last 40 years.

This reduction of sediment supply to the coastal zones is also recorded by the measured annual siltation volume in the 18-km-long Bangkok Navigation Channel between the Port of Bangkok and the Chao Phraya river mouth. The siltation volume decreased from 4.4 million m3 $yr^{-1}$ during 1981–1985 to 3.1 million $m^3$ $yr^{-1}$ in 1993 (Vongvisessomjai, 2007). Dredging and sand mining in the rivers also cause a reduction of sediment supply to the coast. We need more precise data on these sediment removals.

One of the lessons from the Chao Phraya delta is that a relative sea-level rise of only 10 cm can induce coastal erosion along muddy coasts. During the initial phase of subsidence from 1969 to 1973, the total area of coast lost to erosion was 1.8 $km^2$ (Vongvisessomjai, 1992). The future sea-level rise predicted by the IPCC will surely cause inundation and erosion of some vulnerable muddy coasts. Subsidence resulting from human activities, as in Thailand, has more serious impacts than natural sea-level rise because the rate of relative sea-level rise due to subsidence is usually large. The knowledge gained by studying the Chao Phraya example suggests that mangrove forests will be important mechanisms of physical protection and also sediment trapping for the preservation or restoration of shorelines when relative sea level rises.

### 5. Conclusion

Megadeltas are characteristic coastal features in Asia. The huge delta plains of Asian megadeltas are important areas in which people live, carry on economic activities, and grow or collect food. The formation of these delta plains took several thousands of years, during which they expanded by more than 40 $km^2$ annually because of the huge sediment supply from the rivers of Southeast and East Asia. However, most of these megadeltas are currently at risk of destruction and collapse because of human activities in the river drainage basins and on the delta plains.

There is sufficient evidence that human induced relative sea level rise due to intensive land use change is overarching climate related pressures. Natural system response reflects in resilience mechanisms such as mangrove system development/changes but holistic knowledge of their interplay with increasing pressures is still lacking.

Therefore we need more integrated data and knowledge about the drainage basins and coastal zones taking an ecosystem-based perspective so that we can maintain and manage these megadeltas.

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### Figure Captions

Fig. 1. Megadeltas in Southeast and East Asia. Modified after Woodroffe et al. (2006)

Fig. 2. Shoreline changes of the Chao Phraya delta west of the river mouth in 1952, 1967, 1987, 1995, 2000, and 2004 (modified after Rokugawa et al., 2006). The shoreline retreated overall more than 1 km.

Fig. 3. Satellite image of coastal erosion of the Chao Phraya delta near the Wat Khun Samutchin (after Google Earth). Approximate location is shown in Fig. 2.

Fig. 4. Wat Khun Samutchin. Photograph taken by Ms. Vareerat Unwerawattana on 24 May 2007. Location is shown in Figure 2.

Fig. 5. Wat Khun Samutchin. Three steps are buried below the present ground level. Photograph taken by Ms Vareerat Unwerawattana on 24 May 2007. Location is shown in Figure 2.

Fig. 6. Satellite image of coastal erosion of the Chao Phraya delta near the river mouth. Mangrove collapse at the ocean front has led to a landward shoreline shift to beyond the aquaculture ponds. Approximate location is shown in Fig. 2 (after Google Earth).

## CABRI-Volga and the Volga Delta: Recommendations for an Integrated River Basin Management

Elena Nikitina [1] and Frank Wefering [2]

[1] Dr. Elena Nikitina is the Director of EcoPolicy Research and Consulting in Moscow and Scientific Coordinator of CABRI-Volga.

[2] Frank Wefering is a Senior Consultant at Rupprecht Consult Forschung & Beratung GmbH in Cologne and Project Manager of CABRI-Volga.

[3] Partners from the EU: Rupprecht Consult Forschung und Beratung GmbH, Germany (project coordinator); Institute for Water Resources Management of the University of Karlsruhe, Germany; United Nations University-Institute for Environment and Human Security, Germany; Aristotle University of Thessaloniki, Greece; Centro di Cultura Scientifica “Alessandro Volta”, Italy; International Ocean Institute, Malta; Compagnie Nationale du Rhône, France; The Regional Environmental Center for Central and Eastern Europe, Hungary; Wageningen University, The Netherlands.

Partners from Russia: Environmental Policy Research and Consulting, Moscow (scientific coordinator); Caspian Marine Scientific and Research Center, Astrakhan; Ecological Projects Consulting Institute, Moscow; Nizhny Novgorod State University of Architecture and Civil Engineering; Research Innovation Projects Institute “Cadaster”, Yaroslavl; Saratov State Socio-economic University; UNESCO Moscow Office; Ammophos, Cherepovets.

### About CABRI-Volga

CABRI-Volga (Cooperation Along a Big River) is a LOICZ-affiliated international coordination project to facilitate cooperation and to coordinate research in environmental risk management in large river basins in the EU, Russia and the New Independent States (NIS). It is based on a partnership of seventeen partner organisations from Russia and seven EU countries, including universities, private research institutes, industry, NGOs and international organizations dealing with a variety of aspects in environmental risk management [3]. The project focus is on the Volga Basin (Figure 1) which comprises 40 percent of the population of Russia, 45 percent of the country's industry and 50 percent of its agriculture.

The key objectives of the project are to:

- Mobilise people and institutions to cooperate internationally
- Enhance joint research on environmental risk management in large river basins
- Follow an integrative approach in environmental risk reduction and sustainable river basin development
- Exchange of scientific knowledge and good practices of various stakeholders in river basins in Europe;
- Strengthen links between scientific community, policy-makers, and society.