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Deltas on the move

Making deltas cope with the effects of climate change

Report nr. 001/2006

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Contents

Samenvatting

Delta's ontstaan waar rivieren uitmonden in een oceaan of zee en grote hoeveelheden sediment worden afgezet. Hier wordt laag na laag afgezet, waardoor een platform van sediment ontstaat dat langzaam tot boven zeeniveau uitgroeit. Aan de zeewaartse kant van de delta speelt erosie door stroming, getij en golven een rol. Echter zolang de netto toevoer van sediment overheerst, zal de delta zeewaarts blijven groeien.

De vruchtbare bodem, aanwezigheid van zoet water en transportroutes over rivier en zee, maken een delta aantrekkelijk om te wonen en voor economische activiteiten. Er zit echter ook een andere kant aan het verhaal: doordat delta's in de lage kustzone liggen, zijn ze kwetsbaar voor rampen als orkanen en tsunamis. In de toekomst neemt deze kwetsbaarheid verder toe vanwege zeespiegelstijging ten gevolge van klimaatsverandering. Gemiddeld over de hele aarde zal de temperatuur met enkele graden stijgen, waardoor het weer op veel plaatsen extremer zal worden, met meer stormen en grotere rivierafvoeren. Ook de zeespiegel zal sneller stijgen dan in voorgaande eeuwen. Deze veranderingen zullen een grote invloed hebben op de natuurlijke processen in delta's, en op het leven van de deltabewoners.

Een delta kan met een stijgende zeespiegel meegroeien zolang natuurlijke processen ongehinderd hun gang kunnen gaan en er voldoende sediment wordt aangevoerd. Bewoners van delta's hebben hun leefomgeving echter vaak al eeuwen lang aangepast, met een verminderde sedimentaanvoer tot gevolg. Erosie krijgt hierdoor de overhand en voor deltabewoners nemen de overstromingsrisico's toe. Tot op heden hebben we de zee en rivieren vooral bedwongen met behulp van technische maatregelen zoals dijken en dammen. Louter technische maatregelen blijken echter in toenemende mate ontoereikend en hebben vaak neveneffecten omdat ze de natuurlijke processen in een delta blokkeren. Een flexibele, integrale systeembenadering, waarbij juist gebruik wordt gemaakt van de natuurlijke, dynamische processen, lijkt geschikter om met klimaatsveranderingen om te gaan.

We hebben de mogelijkheden voor systeembenaderingen in delta's over de hele wereld bekeken en onderscheiden vier strategieën:
1. fysieke maatregelen gericht op sedimentbeheer;
2. fysieke maatregelen gericht op waterbeheer management;
3. adaptatie;
4. geen actie.

Strategie 1 en 2 bestaan uit fysieke maatregelen die de water- en/of sedimentdynamiek van de delta beïnvloeden. Deze maatregelen kunnen bestaan uit volledig of gedeeltelijk systeemherstel of het sturen van de natuurlijke processen in het deltasysteem. In strategie 3 worden geen maatregelen met betrekking tot de deltavormende processen uitgevoerd, maar het menselijk gebruik van de delta wordt aangepast. De spreiding van mensen en activiteiten in een delta kan worden gereguleerd m.b.v. ruimtelijke planning. Ook oplossingen die de schade beperken, compensatie door een noodfonds of verzekeringen en de tijdelijke evacuatie van bewoners tijdens overstromingen vallen onder deze strategie.

De DELTAS website geeft toegang tot de informatie die we hebben verzameld over delta's van over de hele wereld. In de studie hebben we gebruik gemaakt van de elektronisch beschikbare World Delta Database en DIVA-tool. Informatie uit deze databases is gebruikt om voorbereidende, kwantitatieve evaluaties te verrichten voor drie categorieën indicatoren, namelijk kwetsbaarheid, de hoeveelheid mensen die risico loopt en de potentie voor "zachte" op een systeembenadering gebaseerde maatregelen. De interactieve DELTAS tool maakt rangschikking van delta's voor allerlei indicatoren mogelijk, zodat het gebruikt kan worden voor innovatief deltamanagement, dat gestoeld is op een systeembenadering.

Drie simpele, algemene indicatoren die een eerste, kwantitatieve blik geven op kwetsbaarheid, de hoeveelheid mensen die risico loopt en het potentieel voor zachte maatregelen zijn: de 1 in 100 jaar stormvloedhoogte, mensen die mogelijk in een overstroming geraken (voor de situatie in 2000) en oppervlakte van de kustvlakte tussen 0 en 2 meter. Naast deze drie algemene indicatoren wordt een assortiment aan specifieke indicatoren ter beschikking gesteld. Zij geven gedetailleerde informatie over specifieke aspecten van kwetsbaarheid, de hoeveelheid mensen die risico lopen en het potentieel voor zachte maatregelen

Onze delta's zijn divers, en zo ook hun reactie op klimaatsverandering en de mogelijkheden voor zachte maatregelen om deze reactie te stimuleren dan wel teniet te doen. Verschillende delta's zijn geschikt voor verschillende varianten van de systeembenadering. Door naar een individuele indicator te kijken versimpelen we uiteraard de complexe realiteit. De werkelijke diversiteit kan gevisualiseerd en bestudeerd worden met het DELTAS systeem voor innovatief delta management. Uit rangordelijsten van alle indicatoren zijn de vier hoogst genoteerde delta's genomen en samengevoegd tot twintig delta's die interessant zijn voor de volgende fase van het onderzoek:

Chao Phraya	Godavari	Mekong	Parana
Danube	Krishna	Mississippi	Po
Fly	Lena	Niger	Shatt el Arab
Fraser	MacKenzie	Nile	Yangtze-Kiang
Ganges-Brahmaputra	Mahakam	Orinoco	Yukon

Een aantal delta's scoort hoog op meerdere indicatoren:
- Lena 4
- Ganges-Brahmaputra 3
- MacKenzie 3

Door verschillende criteria te hanteren kan uit deze lijst van 20 delta's een nadere selectie gemaakt worden. Dat is echter een meer locatiespecifieke (subjectieve) aanpak.

De Rijn-Maas-Schelde delta neemt een speciale plaats in. Hij komt niet voor in de gebruikte databases en valt niet onder de gehanteerde definitie van een delta. Echter deze delta is wel degelijk geschikt voor een systeembenadering, sterker nog: deze wordt al op meerdere plaatsen in de delta toegepast. Daarom wordt ook deze delta opgenomen in de lijst met delta's die interessant kunnen zijn voor de volgende fase van het onderzoek.

Summary

Where a river enters an ocean or sea, sediments transported by the river are deposited. As layer upon layer is deposited a platform of sediment, the delta, is built up and rises above sea level. At the seaside of the delta erosive forces like currents, tides and waves play a role. As long as the net rate of sediment supply exceeds the rate of removal a delta will build seawards.

Their fertile soil, presence of fresh water and the proximity of transport routes over river and sea make them an ideal place to live and for economic activities. However there is a downside: lying in the low coastal zone makes deltas vulnerable to all kinds of disasters like hurricanes and tsunamis. In the future this vulnerability will only further increase, because of sea level rise as a result of climate change. The global temperature is set to increase by a few degrees, resulting in the weather becoming much more extreme in many places, with more storms and changed river discharges. The sea level will also rise faster than in the preceding centuries. These changes will have a severe impact on the natural processes in deltas and in the lives of those living in these areas.

As long as the natural processes in a delta are allowed to run their course and sufficient sediment is transported, a delta can grow at the same rate as a rising sea level. But inhabitants of deltas have been adapting their environment for centuries to suit their own needs. The main effects of human interventions is a shortage of sediment and the disruption of the natural processes. Consequently, the relative influence of the sea increases, resulting in erosion at the delta front and subsidence of the delta. As a result affected deltas are no longer able to respond to modified circumstances such as climate change. For inhabitants of the delta area, this means an increased risk of flooding.

Until recently, society relied on technical engineering measures. A re-appraisal of natural, geomorphological processes, however, is currently gaining in importance. A fuller consideration of natural, dynamic forces in a delta, in an integrated, system-based approach seems to be a more flexible and promising way to cope with climate changes.

We explored the potential for soft system-based measures in deltas all over the world and distinguished four strategies:
1. physical measures aimed at the management of sediment;
2. physical measures aimed at the management of water;
3. adaptation;
4. no action.

Strategies 1 and 2 consist of permanent, physical measures that influence the water and/or sediment management of the delta. These measures can include full or partial system recovery or the steering of natural processes in the delta system. In strategy 3, no measures are carried out with regard to the actual delta processes but human use of the delta is modified. The distribution of people and activities in a delta can be regulated with spatial planning. In addition, solutions that limit the damage as much

as possible, compensation by means of an emergency fund or insurance and the temporary evacuation of residents during floods are part of this strategy.

The DELTA website gives an accessible overview of compiled information on deltas across the World. The study is limited to two data sources for which larger sets of data were available in freely accessible form: the World Delta Database and the DIVA-tool. Information retrieved from these databases has been used to carry out preliminary, but quantitative evaluations for three categories of indicators along the world's deltas: vulnerability, stocks at risk and the potential for system-based engineering solutions. The interactive DELTA tool makes it possible to rank deltas for all kinds of indicators so that it can be used for innovative system-based delta management.

From the available data three simple, generic indicators were extracted that provide a first, quantitative glance of vulnerability, stocks at risk and the potential for system-based measures. These are: 1/100 yr surge height, people potentially flooded in 2000 and area of the coastal plain between 0 and 2 m above mean sea level. In addition to these generic indicators, a range of specific indicators is provided that can offer detailed informed on specific aspects of vulnerability, risk and the potential of system-based measures.

The world's deltas are quite diverse, and so will be their responses to climate change and the potential for soft measures to accommodate or counteract this. Different deltas are suitable for different 'soft' system-based approaches. Looking at a single indicator simplifies the complex reality. The real diversity can be visualized and studied using the DELTAS system for innovative delta management. Taking the 4 highest-ranking deltas for all individual indicators mentioned in section 6.4 gives a list of the following list of 20 deltas that might be interesting for the next phase:

Chao Phraya	Godavari	Mekong	Parana
Danube	Krishna	Mississippi	Po
Fly	Lena	Niger	Shatt el Arab
Fraser	MacKenzie	Nile	Yangtze-Kiang
Ganges-Brahmaputra	Mahakam	Orinoco	Yukon

The deltas that score three or more times with the best 4 are:
- Lena 4
- Ganges-Brahmaputra 3
- MacKenzie 3

For further interpretation, a subset can be created from these 20 deltas by applying several criteria. That is, however, also a more context-dependent (subjective) approach.

The deltaic complex of Rhine, Meuse and Scheldt has a particular position. It was not included in the present study, since it did not feature in the data bases used. Since system-based measures are equally applicable on delta-similar coastlines, this complex of river mouths will be included in the subsequent phase of this project. Because system-based measures have been applied here, we presume that the area is potentially promising.

1. Introduction

The world's deltas will be affected by climate change, probably in the near future. Sea level rise, an increase in the frequency and power of storms and changes in the discharge of rivers will affect the dynamic balance between water and land in virtually every delta in the world. Thus the future of people and their economies is at stake as well.

Until recently, society relied mainly on technical engineering measures. At present, many dikes are higher and stronger than ever before. However, future climate change means that even more, expensive measures will be needed to reduce the risks of flooding. A re-appraisal of natural, geomorphological processes, however, is currently gaining in importance. A fuller consideration of their potential in an integrated system-based approach would seem worthwhile.

In a system-based approach, the natural and dynamic forces in a delta are not fought against but instead exploited. In this way, the natural resilience of water systems increases and the natural protection against flooding ultimately also increases. In addition, such interventions make a significant contribution to the quality of the natural environment and the landscape. System-based measures are not new, and such measures have been applied around the world for centuries. On the basis of all sorts of considerations (costs, shortage of space, socio-economic aspects), technical measures were often opted for rather than system-based measures. However, bearing in mind the predicted climate change and the accompanying consequences for deltas, it is time to take a serious look at the options presented by system-based measures.

The solution for most deltas probably lies somewhere in between, in a combination of technical measures and system-based measures. Considerable expertise has already been accumulated with regard to the potential of technical measures as a solution for flooding etc. This study therefore concentrates on the possibilities offers by system-based measures.

Objective and outputs
This scoping study is the first phase of a study aimed at:
- providing knowledge on the potential of a system-based approach to deal with the effects of climate change as an alternative for the more traditional technical measures such as dams, dikes and surge barriers. This should be shown for both rich and poor countries and should address hydrological, ecological as well as socio-economic aspects;
- identifying the potential to market these results worldwide.

To reach these objectives four research steps are defined:
1. to make an inventory of deltas: their vulnerability to the effects of climate change;
2. development of indicators for successful use of a system-based approach;
3. to provide an overview of the potential of soft measures for these deltas;
4. to select a number of deltas with potential for marketing system-based measures and the development of strategies to link economic and ecological objectives.

This scoping study addresses step 1 only. The results from step 1 will be used as a starting point for steps 2 and 3.

The outputs of this scoping study are threefold:
- a background report (this report);
- a flyer with a brief description of the findings;
- a website http://ivm10.ivm.vu.nl/deltas with information on delta's and how these may be affected by climate change.

This study should be of use to a wide array of professionals, institutions, policy makers and ngo's, who are concerned with the future of delta's. It is hoped however that already the results of phase 1 will provide first guidance in development of system-based measures for dredging companies, ngo's and (multi-lateral) funding institutions. The scoping study will roughly outline which deltas are still functioning in a more or less natural manner - or could be (re)developed in that direction - and thus would be good candidates for a system-based approach.

What is not covered by this scoping study?
It could well be true that in many deltas eventually a combination of technical and system-based measures is the best approach. In order to make an objective choice (or strike a balance) between a system-based approach and technical measures, a more complete picture of the advantages and disadvantages of both approaches will be necessary, including a cost-benefit analysis which covers both the social and economic effects. Such comparisons are beyond the scope of this definition study but could be part of research in the following phases (see paragraph on objectives and outputs below), possibly as part of the umbrella-project "Water-Kust" (Water-Coast) currently being set up by the Ministry of Transport, Public Works and Water Management.

In deltas which have been strongly developed in economic terms (harbors, oil refineries, cities, etc.) the possibility for a system-based approach may be different from deltas with only a few settlements. On the one hand larger sums of money for adaptive measures (either technical or system-based) will be available in highly developed deltas and on the other hand special conditions and the attitude of the people in the area may reduce the chances of success. The opposite is probably true in less-developed areas. The limited scope of this study did not allow for a quantitative approach of this issue – it is only briefly touched upon in a qualitative manner.

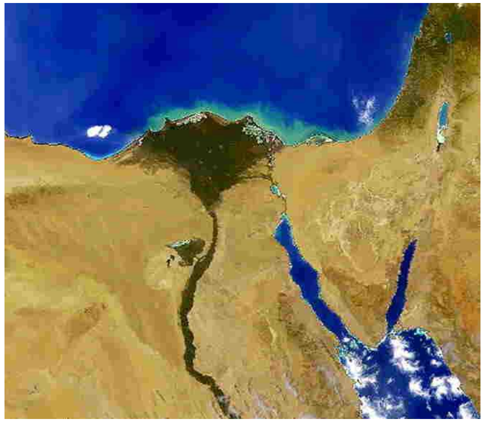
Structure of the report
Chapter 2 gives a description of the geomorphological and ecological processes in a delta. In addition, those aspects of climate change that can have an effect on deltas are described. The third chapter deals with human interventions in deltas and whether or not they fit within a system-based approach. In a system-based approach, as presented in Chapter 4, natural processes are given free reign where possible. Chapter 5 shows how available data on deltas could be used in such a system-based context. Subsequently, a system was built to facilitate the handling of quality controlled data and results. This system has a web interface. Chapter 6 provides technical details, explains the use of the website and displays rankings of deltas with the DELTAS tool. Four examples of system-based measures in deltas are presented in Chapter 7. Finally, the conclusions of the study and recommendations for the next phase are presented in Chapter 8.

2. Deltas

Deltas are found where rivers meet the sea. In this highly dynamic environment they are able to develop and sustain themselves. They owe their very existence to the forces of waves, tidal currents and river flows. This chapter describes the geomorphological and ecological processes in a delta. Understanding these processes is of key importance when trying to find ways to maintain, restore or even enhance a delta's capacity to cope with the effects of climate change.

2.1 Deltas of the world
Deltas are a worldwide phenomenon, they occur from the arctic region to the tropics. Some of the world's greatest rivers have built massive deltas at their mouths. The most famous is that of the Nile River. The term "delta" is derived from the mouth of the Nile as it has a characteristic triangular shape, like the Greek capital letter delta (Δ, see photo).

Most rivers flow into a sea or ocean, but there are also rivers that flow into lakes, such as the Jordan and the Okavango, or into a desert. Even though almost all rivers carry sediment, the conditions at the river mouth are not always favorable for the development of a delta. In particular, no delta can be formed if the sediment is carried away too quickly. In this study, we concentrate on river mouths that do have a delta. We limited our scope to the deltas represented in the databases World Deltas Database and DIVA (see Chapter 5). In all cases these represent deltas of rivers entering a sea or ocean.



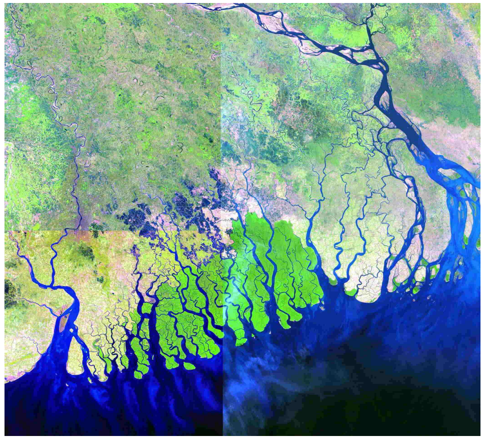
The Nile delta with a characteristic triangular shape (Hart & Coleman, 2004).

Delta, estuary, river mouth….

There are many definitions of “deltas”. A common definition of a delta (Wikipedia) is: “the mouth of a river where it flows into an ocean, sea, desert or lake, building outwards (as a deltaic deposit) from sediment carried by the river and deposited as the water current is dissipated”. This definition includes the processes (transportation of sediment and the movement of water). The Van Dale Dutch dictionary provides a less process-oriented description: a delta is “land enclosed by the arms into which a river divides itself at its mouth.” Geologists use a definition that is based primarily on the form: “a deposit of sediments made by a stream at the place of its entrance into an open body of water, resulting in progradation of the shoreline” (Visser WA, 1980). A common factor in all these definitions is that a delta consists of a plain/area of land where a river flows into a sea, ocean or lake.

Commonly a delta is seen as a different type of river mouth than an estuary. However, the underlying processes shaping deltas and estuaries are the same. The type of shape depends on which of the geomorphological and hydrodynamic processes dominate at a given place at a certain time. Also the scale at which a river mouth is studied plays a role. Typically a river mouth may divide itself in different channels before entering the sea. The mouth of these different channels often take the shape of an estuary, whereas the larger picture is that of a delta. This is true for e.g. the Ganges delta (see photo) but also for a country like the Netherlands. In summary: the difference between a delta and an estuary is not as clear at might appear initially.

However, it is of little consequence for the people living in the coastal area concerned whether their home is on a real delta or not. All these flat coastal areas will be heavily influenced by climate change. As this human aspect forms the focus of this study, the concept of deltas will be interpreted broadly in this report.

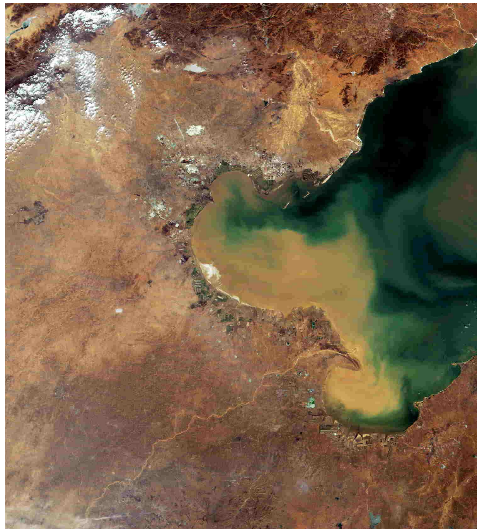


Ganges delta (Hart & Coleman, 2004).

2.2 A game of sand and water

The four most important natural factors that control the processes in a delta are: river processes, coastal processes, climate factors and tectonics.

Where a river enters an ocean or sea, sediments transported by the river are deposited. As the flowing river water bumps into the calmer waters of the ocean, it loses its velocity and transport capacity and the sediment load of the river is dropped. The amounts can be enormous; e.g. the Huang He (Yellow River, see photo) brings in over 1 billion ton of sediment a year in the Pacific Ocean (Hart & Coleman, 2004). As layer upon layer is deposited a platform of sediment, the delta, is built up and rises above sea level. At the seaside of the delta erosive forces like currents, tides and waves play a role. As long as the net rate of sediment supply exceeds the rate of removal a delta will build seawards.

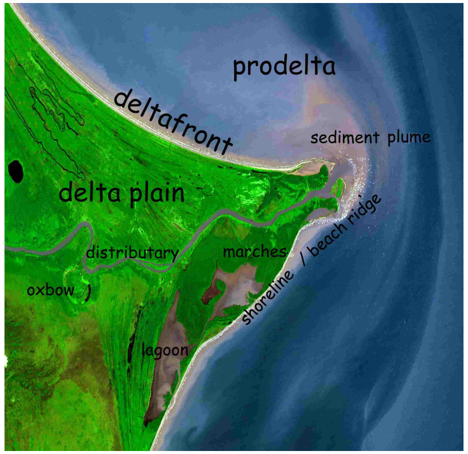


Sediment plume of the Huang He in the Bohai Gulf (Hart & Coleman, 2004).

A delta consists mainly of three sub environments (Figure 2.1): *the delta plain* (where river processes dominate), *the delta front* (where river and marine processes are both important) and *the prodelta* (where marine processes dominate).

The delta plain is the actual platform of sediment where the river processes dominate. It usually contains multiple river channels (distributaries) and a wide variety of non-marine to brackish environments like swamps, marshes, tidal flats and interdistributary bays. The delta front is the site where the most active deposition in a delta takes place, particularly at the mouths of the streams where the coarsest sediment is deposited. The prodelta is the marine area where the fine sediments settle out to form the gently sloping front of a delta.

Figure 2.1: Characteristics of a delta.



River processes

As soon as a river reaches the flat delta plain it changes: the channel broadens and divides into distributaries. During average discharges, these distributaries carry the water and sediment away to the sea. During periods of greater flux, however, they break their banks. Consequently, the sediment also reaches the delta plain. Fine suspended sediment like clay is transported into the lower parts of the floodplain. Sand and silt are deposited next to the channels on natural levees. The result is the development of a pattern of levees, floodplains and channels that is constantly changing its form and position due to the active character of the distributaries.

Coastal processes

The delta front is under influence of coastal processes. In areas with waves and coastal currents, the sand carried along by the river is picked up again and redeposited parallel to the coast in the form of barriers, spits, beaches and beach ridge complexes. The bodies of sand sometimes lie right alongside the coastline, for example in the form of a beach with sand dunes, but they can also lie some distance from the coastline as beach ridges, creating an enclosed bay with a lagoon or marsh in the center. In this situation the sand bar protects the lagoon from waves and currents and in some situations delta formation can start from here. For example both the Rhine and the Danube delta were formed in shallow seas behind strand bars.

The tides can also exert a strong influence on the development and form of a delta. Near the shore tidal currents can form deep tidal channels and sand ridges perpendicular to the coast. Vast tidal flats can develop within the delta plain itself, becoming salt marshes, mangroves or even evaporites (in dry climate zones) further inland. Tidal flats and marshes are often dissected by many meandering tidal channels situated in the less active parts of the delta plain.

Climate

The influence of the regional climate on the development of a delta is mainly indirect. The temperature and the amount of precipitation partially determine the river discharge, the development of vegetation and consequently also the amount of available sediment. On the delta plain, vegetation ensures that sediment is trapped, thus stabilizing the top of the delta and preventing it from eroding. In cold regions, such as the area of the McKenzie delta in Canada, permafrost and the freezing up of the sea also play a role.

Tectonics

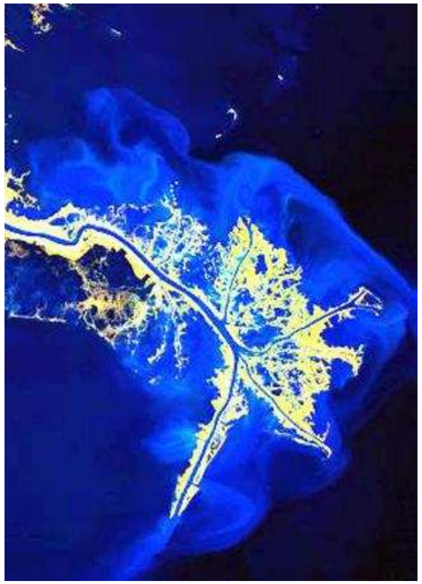
Also the rate of movement of the earth's crust influences the delta. When the rate of subsidence of the seafloor is higher than that of the deposition of sediment by the river, the delta will drown. This is the case in some of the old Mississippi lobes where the delta top disappeared under a shallow sea. The Ganges-Brahmaputra delta in Bangladesh has a large-scale autonomous soil subsidence as well.

2.3 Bird feet, lobes and other delta forms

The morphology of a delta is determined by the rate in which the above described processes take place. Mostly deltas are classified in three types: *river-dominated deltas*, *wave-dominated deltas* and *tide-dominated* deltas.

River-dominated deltas

In deltas like the Mississippi delta (see photo), fluviatile processes dominate over marine processes. In these deltas sedimentation has a stronger effect than the erosive processes of tide and waves. As a result, the delta grows seaward. Dependent on the water depth, a lobate delta (shallow water) or a more elongate delta (deep water) will form.



The Birdfoot delta of the Mississippi River is the youngest of the recent delta lobes (600 to 800 years). Its narrow, elongated form is due to a relatively high input of river sediment and its situation in a relatively deep sea with little wave action and a small tidal range. The main channel of the river is almost 2 km wide, 30 to 40 m deep, and contains well-developed natural levees. The "toes" of the bird foot developed due to bursting during floods. The Birdfoot delta is expanding (mainly towards the sea) at rates of 100 to 150 m per year due to the tall, broad levees. Situated between the channels are interdistributary bays which are usually shallow (generally less than a few meters). Sedimentation rates in the bays are relatively low because they only receive sediment during floods (Hart & Coleman, 2004).

Wave-dominated deltas

In other deltas, wave currents play an important role. These deltas consist primarily of broad, sandy lobes and have a smooth arched form (see photo). In wave-dominated deltas, the sediment supplied by the rivers is reworked by waves and currents and is then redeposited along the coast in the form of beach ridges, barriers and spits. Wave-dominated deltas therefore do not protrude far into the sea but have a wide, flat form.

The Sao Francisco River in Brazil rises in the coastal mountains of Brazil and flows into the Atlantic Ocean via one single distributary. Strong long shore currents carry the sediment along the coast. The high wave energy produces a relatively smooth delta shoreline with only a minor protrusion at the river mouth. The delta plain is composed almost entirely of closely spaced beach ridges with narrow swales and eolian dunes. The delta shoreline is composed of large, broad sandy beaches (Hart & Coleman, 2004).

Tide-dominated deltas

Tide-dominated deltas like the Mahakam (see photo) are characterized by river mouths that quickly expand and deepen in the direction of the sea. This is a consequence of the large quantity of water flowing from the sea into the river twice a day. A river mouth thus takes on the form of an estuary, with sand banks, mudflats and salt marshes along the banks. This is particularly the case if inland lakes and lagoons are connected with the river and also fill up with tidal water. During storm tides, the sea water can reach far into the delta via the wide river mouth, inundating large areas. In this way, sediment that had already been deposited in the sea can be redeposited by the sea on the delta plain.

The Mahakam river rises at the borders of Indonesia and Malaysia on the island of Kalimantan. The delta plain has a classic fan-shaped form with many distributaries. Numerous sinuous tidal channels scar the delta surface. Behind the delta front, tidal mudflats dominate. Most of the delta plain is actively accreting. Wave energy is extremely low and few beaches are present along the shoreline (Hart & Coleman, 2004).

2.4 Deltas and nature

The large variety of water types, substrate and dynamic processes make deltas rich in natural biotopes. With the water, the river brings large quantities of nutrients to the delta where these are transformed into food for many organisms. Sedimentation of organic material and the subsequent decomposition purifies the adjacent coastal waters from their organic load and is one major source for the high biological production. This is called the “biological pump”.

Biological productivity in coastal waters near deltas is among the highest reported anywhere in the sea (e.g. Kaiser et al., 2005). Deltas are therefore an important nursery for fish, and a stepping-stone for birds on migration that are dependent on the food they find in its lagoons, tidal flats and mangroves.

Most plants and animals in deltas are adapted to the extreme environmental conditions and often occur in high abundance. Many species in deltas are endemic. One strategy to inhabit such a permanently changing environment is a high reproduction capacity.

Many deltas are rich in riverine forests, tidal flats and mangroves. Birds often establish large breeding colonies in the trees, e.g. pelicans and herons. The nutrients from the river also 'feeds' the sea in front of the delta and the shallow waters of the delta front are amongst the richest marine ecosystems.

2.5 Deltas and climate change

Due to their position on the border between land and sea, deltas are very sensitive to climate changes. Climate research has demonstrated that the global temperature is set to increase by a few degrees, resulting in the weather becoming much more extreme in many places, with more storms and changed river discharges. Due to climate change extreme circumstances with floods, heat-waves, mudflows etc will increase with as a result losses of natural habitats like wetlands, damage to infrastructure and buildings especially near the coast and along rivers (IPCC, 2001b). The sea level will also rise faster than in the preceding centuries (IPCC, 2001a). These changes will have a severe impact on the natural processes in deltas and in the lives of those living in these areas. The economic losses can be enormous. For example one severe storm in December 1999 caused a loss of 6 billion Euro in Western Europe.

The following aspects of climate change could have an effect on the processes at work within a delta:

Temperature

The main effect of a higher temperature is the rising of the sea level, due to both the melting of ice and the expansion of the sea water as it warms. Coastal processes will then become stronger, resulting in more erosion. Relatively speaking, less sediment will be available for the build-up of the delta front, so the delta front will shift inland. With a rapidly rising sea level, the shortage of sediment could become so severe that the delta “drowns” and disappears under the water permanently.

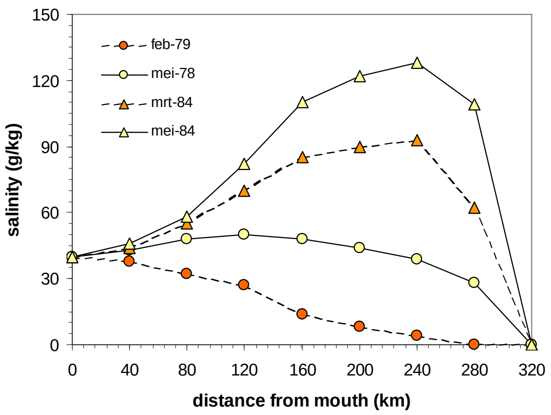
Precipitation

Changes in precipitation primarily influence river discharge. If extremely high water levels occur more often, erosive flooding will increase and more sediment will be transported by the river. In drier climate areas, extra precipitation may also result in the development of more overgrowth in the hinterland. This overgrowth "traps" precipitation, resulting in less extreme high water situations. The plants also protect the soil against erosion. In cooler climates, the formation of peat moors has the same delaying effect on the drainage of water. It is difficult to predict the exact influence of changes in the precipitation on deltas. During peak discharges fresh water plumes may extend over many km's in coastal waters. If the sea level rises, or the river discharge decreases, salt water can gradually displace freshwater, reaching far inland, as was the case in the Casamance estuary (Figure 2.2). Salt water can thus influence areas a long way inland.

Storm

When storms become more severe, the waves combined with currents will wash away more sand from the coast. This sand will end up on the foreshore and will later be partially deposited back on the coast. However, some of this sand can also end up deep in the sea or be transported elsewhere, making it unavailable for the delta.

Figure 2.2: Longitudinal salinity distribution in Casamance estuary. During the Sahelian drought of the early 1980s
the Casamance estuary turned hyper saline with dramatic ecological changes as a result (Savenije et al., 1992).



2.6 Summary

The four most important natural factors that control the processes in a delta are: river processes, coastal processes, climate factors and tectonics. Sediments that are principally transported by the rivers forms the most important "building blocks" for a delta. The water ensures that the sediment ends up in the right place in the delta. The influence of the river, tides, waves and currents varies from delta to delta. Some deltas are dominated by the river, whereas other deltas may be influenced more by waves or tidal currents.

As long as the natural processes in a delta are allowed to run their course and sufficient sediment is transported, a delta can grow at the same rate as a rising sea level. It is therefore essential for the continued existence of the delta that sufficient sediment is available and that the dynamic processes are not hindered. If the potential of system-based measures is to be mapped out, it is important to first gain a good overview of the dominant processes at work in a delta. Appropriate system-based measures can then be implemented on the basis of this.

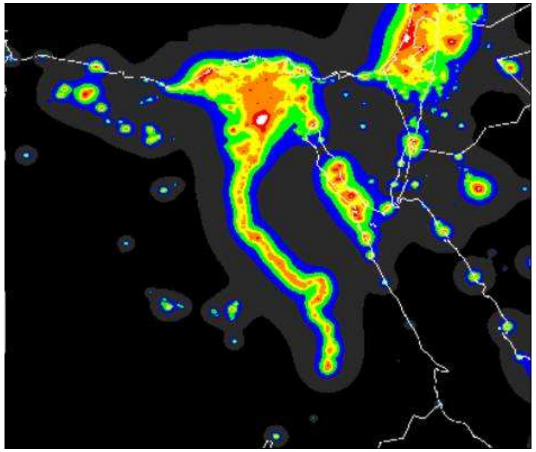
3. Deltas and men

Under natural circumstances deltas are well adapted to changes in sea levels, sediment loads, river discharges etc. Climate change in itself therefore is not a threat to deltas. However, over the past centuries human interventions have in many places paralyzed the system's inherent natural resilience to climate change. These may be interventions in the delta itself (e.g. dikes preventing the influx of sediments building up the area), but also interventions elsewhere in the watershed (e.g. afforestation decreasing sediment loads) or in the sea (e.g. off-shore harbor development affecting long-shore drifts). This chapter deals with human interventions in deltas and whether or not they fit within a system-based approach.

3.1 Why do people live in deltas?

Coastal zones and deltas have always been attractive settlement sites. In 2001 over half the world's population lived within 200 km of a coastline. Eight of the top ten largest cities in the world are located by the coast.

One of the main reasons why people settle in deltas is the availability of food. The soil is generally fertile and easy to cultivate. The freshwater of the river can be used for irrigation. In addition, there are often rich fishing grounds where the sea and river meet. This has set a precedence for populations to naturally migrate towards coastal areas.

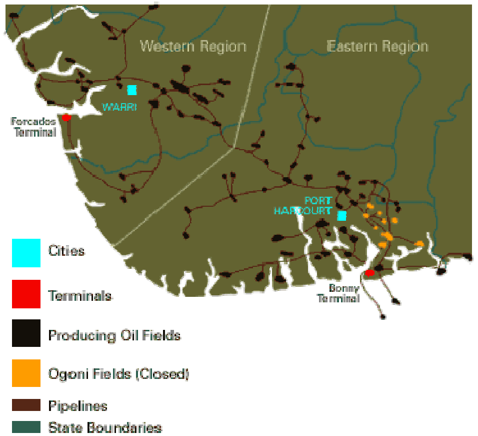


Satellite photograph of the Nile and its delta. The colors show the night sky brightness (Cinzano et al., 2002).

An example of a densely populated delta is the Ganges. Between 115 and 143 million people live here, despite from risks from floods caused by monsoons, heavy runoff from the melting snows of the Himalayas, and tropical cyclones. It is believed that upwards of 300 million people are supported by the Ganges Delta, and approximately 400 million people live in the Ganges River Basin, making it the most populous river basin in the world. Most of the Ganges Delta has a population density of more than 520 people per square mile, making it one of the most densely populated regions on earth (Wikipedia). Other examples of densely populated deltas are the Fraser delta in Canada (2647 people km^{-2}) and the Chao Praya in Thailand (1763 people km^{-2}).

Deltas are also important areas in economic terms. Many of the world's major ports are situated at the mouths of delta-forming rivers, including Rotterdam and Shanghai. The proximity of transport routes over the water, where the sea and the river are directly connected with each other, makes such a site ideal for trade and industry. Products, and therefore, money traditionally flows into countries through their ports. Rotterdam harbour in the Rhine delta for example contributes 7,5% to the BNP of the Netherlands (Kamer van Koophandel Rotterdam). In many cases deltas have the fastest economic growth (Figure 3.1).

Figure 3.1: Oil and gas reserves are often related to delta regions, for example in the Niger delta (Nigeria). Here, the delta sediment has been deposited on a much older oil-bearing sedimentary basin (Urhobo Historical Society, 1996-2006). The Mississippi and the Rhine also discharge into oil and gas-bearing deltas.



As human population increases in coastal areas, so does pressure on coastal and deltaic ecosystems through habitat conversion, increased pollution, and demand for coastal resources. The more people that crowd into coastal areas, the more pressure they impose both on land and sea. Natural landscapes and habitats are altered, overwhelmed and destroyed to accommodate them. Lagoons and coastal waters are 'reclaimed', wetlands are drained, the floodplains are built over and reduced, and mangroves and other forests are cut down (UN atlas of the oceans).

Alongside the many advantages, however, living and working in a delta region also has a major disadvantage. Since deltas are found in low-lying coastal areas, they are naturally vulnerable to all kinds of natural disasters such as flooding, storms and tsunamis. Hurricane Katrina (see photo), which raged over New Orleans last winter, demonstrated once again just how dangerous life in a delta can be (Hecht, 2006).

The levee break allowed water from Lake Pontchartrain to flood New Orleans (www.Katrinahelp.com).

3.2 How do societies influence a delta ?

In a natural delta, the supply of sediment from the land is in a dynamic equilibrium with the sea level and the erosive processes at work along the coast. If anything changes on either side, the delta will find a new equilibrium. Inhabitants of deltas have been adapting their environment for centuries to suit their own needs. Measures have been taken to prevent flooding (through the construction of dikes, dams and delta works), to make shipping possible (by canalizing and/or damming rivers and constructing harbors), to enable farming (by cutting down woods and leveling and draining the land), and to allow the extraction of natural recourses (sand, clay, peat).

Human intervention has generally led to the disruption or complete obstruction of the natural processes within a delta. Consequently, a delta can lose its natural flexibility and is no longer able to adapt to changing circumstances. For example, the removal of mangroves and the damming of major rivers for the benefit of shrimp farms has resulted in large-scale erosion of the coastline of Thailand (Thampanya et al., 2006).

The construction of dikes in the Dutch delta, in combination with drainage, has resulted in large areas no longer being flooded and no more sediment being deposited and subsidence. Consequently, large areas of the Netherlands now lie below sea level. Due to the construction of dams and reservoirs in the hinterland of deltas, the supply of sediment to the sea has in many cases been drastically reduced.

The Nile delta is currently undergoing an overall transgression as a result of decreasing water discharge and sedimentation rates caused by construction of the Aswan Dam upstream. The use of river water for irrigation can even result in the lower reaches of a river running completely dry, as in the case of the Colorado river in the USA. The water of various distributaries is sometimes also brought together in a single water course, for example where there is a port. In tidal-dominated deltas in particular, changes in the water management of the various distributaries of a delta results in salty seawater reaching further into those distributaries where the drainage of water has decreased.

A part of the Colorado river flows into the Salton Sea. The great demand of river water for irrigation and drinking water causes a large decrease of the river discharge, with siltation and algal bloom (green color) in the Salton Sea as a result. The need for fresh water from San Diego and Los Angeles is still growing. System-based measures are required!

Changes deeper underground such as the extraction of oil, gas or salt and the pumping up of water also have effects. They ensure that the ground subsides more quickly than in a natural situation.

In the Philippines large areas of mangroves are converted to fish ponds (Ron Janssen).

The main effect of the majority of human interventions is a shortage of sediment in the delta. Consequently, the relative influence of the sea increases, resulting in erosion at the delta front and subsidence of the delta. For inhabitants of the delta area, this means an increased risk of flooding. People often try to prevent this by constructing dikes, resulting in areas no longer profiting from the natural build-up due to the supply of sediment. The resulting situation is even further removed from a natural situation.

This pair of images shows the Three Gorges Dam in the Yangtze River in China, before and after closure. In the upper photo (July 2000) the dam is partially closed, but sediment-filled water still flowed freely along the river's south bank. By May 2006, the dam spanned the entire river, and a large reservoir had already filled, in which all the sediment is captured. Clear water shoots through gates in the center portion of the dam (www.esa.int).

However, there are also human interventions that cause deltas to grow. For example, cutting down woods upstream increases the supply of sediment in some deltas. In Spain the expansion of the Ebro delta has largely been caused by human efforts to maintain the course of the river (Hanson, 1990). This resulted in an increased sedimentation rate and therefore delta growth. In a number of cases, for example near the Seyhan delta in Turkey, deforestation in the hinterland has even led to the development of a completely new delta area.

Aswan High dam in Egypt (www.fotojinak.info).

3.3 Interventions

In order to come up with measures that do not impact upon the natural processes in a delta, it is necessary to first look at measures that do influence those natural processes. The amount of sediment available (the building material) and the amount of water flowing in and out (the transport system for the building material) are the most important ingredients of a delta. Human influence can be exerted on both and in three different sections of the delta system: on the seaward side of the delta, in the delta proper, and upstream in the watershed of the river.

Table 3.1 shows a number of measures that all have a negative impact on the development of a delta due to the fact that they fully or partially obstruct the natural processes. The table also indicates the part of the delta where these interventions take place and the aspect that is influenced: the water and/or the sediment. The opposite of these interventions offers starting points for the formulation of measures that have no negative impacts on the natural processes.

Table 3.1: Technical interventions with a negative influence on the sediment supply and distribution within a delta.

	Seaward side	**Delta proper**	**Riverbasin**
Water	defense of shores with hard structures	construction of dikes, preventing areas from flooding	Dikes on the shores
	wave breakers	relocation or damming of crevasses, as a result of which areas are no longer influenced by the river	Dams in the river
	dams	closure of river mouths	Changes in land-use
Sediment	sand extraction at the delta front	agricultural use: increased erosion and sediments no longer “caught” by the delta	Sand extraction
	construction of deep navigation channels or harbours	cutting of mangroves	Deepening of navigation channels for shipping
			Land use
			Fixation of shores and deep river beds with rocks/stones

3.4 Summary

Intentionally and unintentionally, people have a great impact on deltas when they change the natural processes within the delta in order to be able to live and work there. These human interventions are almost always of a technical nature and are chiefly directed at limiting or halting natural processes such as floods and sedimentation. However, fighting these processes also means a halt to the development of the delta. Human interventions in the hinterland can also have major consequences for the supply of sediment and water to the delta, as can interventions that are not directly related to the delta, such as oil extraction and the extraction of groundwater. Most human interventions disturb the equilibrium between the supply of sediment and erosion. As a result, affected deltas are no longer able to respond to modified circumstances such as climate change.

4. System-based approach

For centuries, inhabitants of deltas have been taking all kinds of measures –mainly technical – to tailor the area to suit their wishes. For example, they have built dikes to prevent flooding and they have deepened distributaries to make shipping possible. The other side of these technical measures is the fact that they obstruct the natural processes within a delta, removing its ability to adjust to changing circumstances. This chapter looks at system-based approaches that do not disrupt the system.

4.1 System-based approach

Protection against flooding, be it from the sea or from rivers, usually is obtained by building dikes, barriers and pumps. This battle against the floods is often talked about with admiration and certainly has created impressive technical structures around the globe. However, there is another side to the story. Whereas dams and barriers effectively prevent flooding, their side-effect is that they lock out the very forces, especially sedimentation, which under natural circumstances enable a delta to elevate itself above the water level.

A system-based approach aims to harness and use dynamic forces and creates a dynamic equilibrium between land and water (Figure 4.1). In this scoping study we define a system-based approach as “a set of interventions aimed at maintaining, restoring and harnessing the natural and geomorphological processes in a delta, a coastal segment or a river basin”.

The system-based approach has two advantages over most technical measures: it is often cheaper and it is more sustainable in the long run. A disadvantage is that societies which have grown accustomed to the fixed equilibrium existing in many deltas today, will need to adapt their way of life in such a way that they can cope with the dynamic equilibrium associated with a system-based approach. This will in many cases not be easy. However, there is a lot at stake and both costs and sustainability are crucial when dealing with the question how societies in deltas around the world – also in developing countries – can best cope with the effects of climate change.

Technical measures are often referred to as “hard solutions” and system-based measures as “soft solutions”. It should be borne in mind however, that a system-based approach can require “hard” interventions (e.g. constructing a dam to direct a sediment loaded longshore drift to the coast). Likewise, a “soft” intervention is not necessarily system-based. Ideally a system-based approach only requires a one-off intervention, after which natural processes take over as “custodians” of the area.

Figure 4.1: Schematic model of a delta with on the left side interventions that have a negative influence on the natural processes within a delta and on the right side system-based measures (drawing by Jeroen Helmer).

4.2 System-based strategies

The core of the system-based approach is the fact that natural processes are given as much free reign as possible within a delta area. Only then can a delta adjust to changing circumstances such as those brought about by climate change.

In principle, there are four possible strategies by which natural processes can be given the scope they need:

1. physical measures aimed at the management of sediment;
2. physical measures aimed at the management of water;
3. adaptation;
4. no action.

Strategies 1 and 2 consist of permanent, physical measures that influence the water and/or sediment management of the delta. These measures can include:

- full or partial system recovery: undoing human interventions, for example cutting dikes and breaking down dams etc;
- the steering of natural processes in the delta system, for example by creating flood areas and making use of sand suppletion along the coast.

In strategy 3, no measures are carried out with regard to the actual delta processes but the use of the delta by people is modified. Spatial planning is a formalized and systematic way to influence (regulate) the distribution of people and activities in a delta. The guiding principle in spatial plans and programs is a sustainable spatial utilization and development that balances the social and economic requests upon a region with its ecological functions (CPSL, 2005). Spatial planning can reduce the flooding risk in deltas. *Risk is the product of the probability of an event to occur and its consequences.* Thus, by managing the spatial distribution of people and human activities, the flooding risk may be reduced. Deltaic spatial planning can for example work in a way that special *buffer zones* and *flood hazard zones* are identified. In the buffer zones space can be reserved to future defense measures or retreat of the coast line. In the flood hazard zones restrictions or regulations for spatial utilization aim to reduce the damages of storm surges and floods. This can go as far as removing people and economic activities from (parts of) the delta, whether permanently, fully or partially, space is left or created for the natural processes within a delta. Solutions are also sought to limit the damage as much as possible, such as living on mounds and creating refuge mounds. The damage caused by the natural processes can be compensated by means of an emergency fund or by offering insurance. The temporary evacuation of residents during floods is also included in this strategy.

Strategy 4 consists of taking no action. This strategy is particularly cost-effective in sparsely populated areas where people can be evacuated quickly and the economic interests are small in scale. In these deltas, the damage carries less weight compared with the high costs involved in taking physical measures.

Not all system-based measures can be applied everywhere, and not all are successful. This is dependent on a large number of factors, such as the natural processes at work within a delta and the scale of the intervention, as well as all kinds of social aspects such as the space that is still available within a delta, the extent to which the natural processes have already been influenced, and the relevant period.

Scale

It is also important not to lose sight of the scale. In virtually untouched deltas, the starting point is still such that the problems of a rising sea level can be tackled over the entire delta using system-based measures. However, in deltas that have long been subject to the influence of man and that have therefore undergone major changes, system-based measures will probably not have sufficient effect to exclude the need for technical measures. However, on a smaller scale and locally, they will probably be adequately effective. For example, “depoldering” (returning reclaimed land to the sea) and the creation of controlled floodplains is an interesting prospect locally, but is of minor importance for the delta as a whole.

It will not be possible to save an entire delta with a single type of “soft” intervention because:

- many deltas are so large that measures taken in one location will no longer have an effect on another location;
- there are often multiple natural processes with an impact on a delta. For example, the influence of the sea will be the most important at the delta front, while the influence of the river is dominant on the delta plain. Sand suppletion along the coast may counteract erosion of the delta front but does not help prevent flooding on the delta plain;
- system-based measures will not be sufficiently effective to completely exclude the need for technical measures in deltas.

In most cases, it will therefore be necessary to implement a whole range of measures, technical and system-based, and to take action at various locations within the delta. Each delta will need to be looked at individually with regard to where the problems lie, the natural processes that play a role locally, and also which measures can be taken.

Other coasts

Although all coasts will be exposed to some consequence of climate change, this report focuses on deltas and their specific problems. Hence, cliff-erosion or other specific issues at other coastal types have not been touched upon in this report. However, the system-based approach and the focus on sediment budgets is by no means limited to deltaic coastal stretches and can therefore have value elsewhere, for example in estuaries and a long sand barriers. Rivers and the ocean meet at a delta, hence these land forms are part of both the coastal and the river plain. This underlines the necessity of an integrated approach.

Forgotten strategies

Although the term may not be very well known, system-based measures are not new and such measures have been applied in various places around the world for centuries. Perhaps one of the oldest and best-known examples of a system-based measure is living on artificially constructed hills (see photo). There are also refuge mounds, where people take refuge temporarily during periods of high water, taking their possessions with them.

This practice has been going on for thousands of years all over the world, and is still practiced in various countries today. The fact that people have not switched to other methods may be due to the lack of knowledge or funds to take expensive technical measures. However, the technique of mound construction is still used in developed countries, on a large scale in some cases. In many harbors, buildings such as oil refineries, terminals and chemical factories are built on artificial mounds that are high enough to remain dry during floods.


Left: Modern dwelling mound (terp) in the German Wadden region.
Right: Many industrial activities in Rotterdam harbour are situated on mounds.

4.3 Examples of system-based measures

Experience has been gained in recent decades with system-based measures in the Netherlands in particular, with its long tradition of protection measures against the forces of the sea and rivers. In this section, a number of examples drawn from the Rhine-Meuse-Scheldt delta will be briefly elaborated.

At the coast

Nourishment along the coast

The Dutch coast consists of a long sea wall alongside the beaches, interrupted by tidal inlets here and there, protecting the land from the sea. For numerous reasons, including the rising sea level, the natural supply of sand (approx. 2 to 3 million m^3 each year) has been coming under increasing pressure in recent times. In order to compensate for the shortages, an average of 12 million m^3 has been pumped to the Dutch coast from the deeper sections of the North Sea each year since 1990 in order to reinforce and preserve the coast from erosion (see photo). As a extra source of sand it also helps to stabilize the dunes.

Concerns exist with respect to interferences with nature that result from extraction and deposition of the sand. Hence the measure should be applied in a way that minimizes the effects on the environment. For example by deposing the sand in deep tidal inlets, from where it is carried further by sea currents.

Nourishment of the Dutch beaches. Nowadays, foreshore nourishment is common practice, whereupon currents transport the sand, reinforcing the coast elsewhere: a fine example of how use can be made of natural processes along the coast (Rijkswaterstaat).

Removing sea walls and coastal defense works

In places where the coastline used to be weak, or where there are enclosed sea inlets, the coast is heavily protected by rubble, sea walls or other coastal defense works. Strangely enough, breaking through these coastal defenses could actually offer a solution to the problem of the future rising of the sea level (Figure 4.2).

Figure 4.2: The Hondsbossche sea wall along the Dutch coast. By breaking through the sea wall, part of the land behind it will flood with the tides. The silt caught up in the vegetation ensures that the land gradually increases in height in line with or even above sea level (Drawing by Jeroen Helmer).

Dune management

Closed dune lines protect coastal lowlands against flooding from the seaward side. Dune management comprises of a number of measures (dune restoration, dune relocation, natural dune dynamics and over-wash) that ensure the functionality of dunes as flood defenses (CPSL, 2005). Allowing natural dynamics and over-wash have clear ecological benefits as they add to the naturalness of the environment. Natural dune dynamics encompass the wind driven transport of sand to the inner part of the coast line where accumulation causes a gradual shift and heightening. When allowing over-washes, water and sand is, during storm surges, transported through wash-over channels, where accumulation causes a gradual shift of the land with the rising sea level (CPSL I, 2001). Natural dune dynamics are only applicable when enough sand (from a natural origin or from sand nourishment) is available.

Dune restoration and relocation, e.g., by building sand fences or planting grasses, do interfere with nature. However, from an ecological point of view, these techniques are to be preferred above hard constructions like dikes or groynes that would otherwise become necessary. Especially with rising sea level, dune relocation in combination with sand nourishment might be a sustainable strategy to maintain defense standards.

Vegetation management

For coastal defense salt marshes, mangroves and other coastal vegetations are in the first place important because the energy-impact of storm waves is reduced. In front of dikes they also prevent damage at the outer dike foot. Furthermore, coastal vegetations create a low-energy environment where the sedimentation of suspended material is enhanced, and erosion of accumulated sediment is hindered (CPSL, 2005). Management of coastal vegetation comprises of techniques to enhance and maintain the vegetation.

In the Dutch Wadden sea most salt marshes developed in combination with the construction of groynes, which reduce wave energy and currents, and create an environment where sedimentation prevails and erosion is lessened. In groyne fields sedimentation rates up to 30 cm/yr occur in the first year after construction (Erchinger et al., 1996), creating an environment where vegetation can germinate. Construction of groynes interferes with natural dynamics and should only be induced in areas where the recovery of vegetation in a natural way is not possible. In combination with vegetation large beds of mussels, oysters or sea grass also aims at stimulating accumulation on, and stabilization of inter tidal flats.

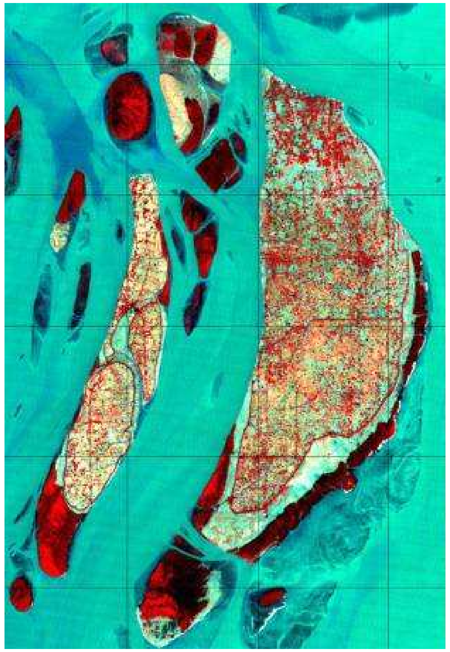
Separation of shipping routes and waterways to port towns

Traditionally, many ports in river mouths are situated in delta areas. Major modifications have often had to be made in ports in order to be able to accommodate increasingly large ships. For example, frequent large-scale dredging is needed in order to maintain the depth of the harbors, which act as settling basins for a lot of sediment. The natural flows of sediment and water in the delta are disrupted by this. The sediment no longer benefits the maintenance of the delta front, resulting in the erosion and receding of the delta. Research needs to be carried out into whether it is possible to separate the routes used by the deep ships from the waterways used by the water and the sediment.

On the delta plain

Development or planting of mangroves and lowland riparian forests

Vegetation and woodlands in delta areas play an important role, as they trap the sediment during flooding, thus allowing the land to rise (see photo). They also hinder the process of erosion and form a natural barrier for waves and floating ice that can pose a threat to dikes and residential areas in the delta area. Mangrove areas and lowland riparian forests can be combined well with storage areas. Due to the high production level, woods can also satisfy a portion of the energy needs of the inhabitants of a delta area.



Left: Landsat TM Image of the Bengal island of Hatia (Ganges-Brahmaputra delta). A dense zone of vegetation (red color) prevents the coast from eroding by wave currents (Boskalis).

Down: Mangrove forests trap sediment during flooding, thus allowing the land to rise (www.toddadams.net)

Managed retreat (ontpolderen)

In tide-dominated deltas, the dimensions of the distributaries through which the water flows in and out are determined by the size of the area behind them that is allowed to flood (the tide storage). If that flood area is reclaimed, the size of the tide storage declines and the natural response of the system is for the river mouth to silt up. Numerous towns and cities in the Rhine delta area have lost their open connection with the sea in this way in the past. The response of the inhabitants of those towns and cities is to try to maintain the depth of the river mouth by means of dredging. The decision was recently taken to “depolder” 600 hectares of diked-in land along the Western Scheldt at the same time as dredging work was being carried out in order to maintain the equilibrium in the river mouth (see photo). A further consequence of this is that sediment-rich water can reach these areas once again, allowing the land to rise in step with the sea level.

Saeftinghe. “Depoldered” areas where the tide is once again allowed to enter – sometimes after several centuries – have the potential to grow into unique wildlife areas (www.hetzeeuwselandschap.nl).

Wetlands as retention areas

Due to the reclamation of land (impoldering) and the construction of dikes, the flooding that is generally characteristic of delta plains is largely a thing of the past in the Dutch delta. By removing the dikes in sparsely populated regions and allowing controlled flooding in certain areas, sufficient storage space will once again be created, thus preventing the breaking of dikes in more densely populated locations in the event of extremely high water (Figure 4.3). By building controlled inundation areas along the river Scheldt the same degree of safety is achieved as in the Netherlands, where people have chosen to close most of the branches of the Rhine. But the Belgian solution proves to be more flexible than the Dutch approach. Instead of large scale erosion and loss of tidal flats, the morfodynamic forces in this branch of the delta are still intact allowing the land to rise with the sea level through sedimentation (Saeijs et al., 2004).

Figure 4.3: In the region around the Biesbosch, a former freshwater tidal marsh in the Netherlands, there is sufficient space to create such a storage area, thus enabling drainage peaks in the Rhine and the Meuse to be leveled off (Drawing by Jeroen Helmer).

At Kruibeke (Figure 4.4), to the south of Antwerp, along the Scheldt in Flanders (Belgium), a number of former agricultural polders are being turned into emergency overflow areas. In the event of a storm tide at sea, the water in the Scheldt flows over the lowered polder dikes (bottom figure), thus preventing flooding in the nearby city of Antwerp. In order to allow the adjacent area to act as a freshwater tidal marsh, water is also allowed in and out through a number of inlet works at average water levels (top figure).

Figure 4.4: Scheldt river in Flanders (Drawings by Jeroen Helmer).

Reopening of distributaries

Due to the closure of sea inlets, the delta's inland water and sediment management is thrown completely off balance. In the Dutch delta, the delta works led to the intended freshwater lakes changing into severely eutrophied bodies of water, suffering from algal blooms. A further consequence was that the river sediment did no longer reach the coast; instead, it settled in the former tidal inlets, where it remained due to the lack of tidal currents.

The natural system can only recover by reopening the distributaries on the seaward side and to use a storm surge barriers (see photo) instead of permanent dams. Since the closure of inlets had the important additional goal of making fresh water available for agriculture throughout the delta, an alternative solution for the transportation of fresh water to the west of the Netherlands will need to be found. This could be made possible by situating the entry points of fresh water further up the rivers.

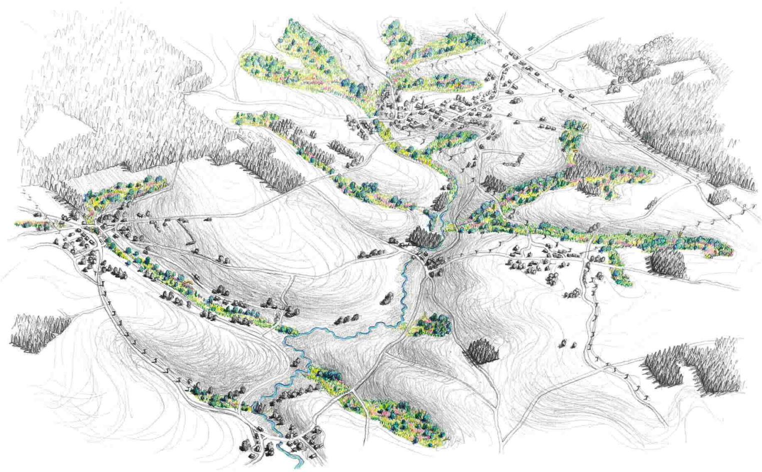
Storm surge barrier. With the aid of storm surge barriers, river mouths can be closed off in such a way that the natural processes remain active, while still protecting against the risk of flooding (Rijkswaterstaat).

Upriver from the delta

Storage at the source

One of the consequences of climate change is the increased risk of extreme precipitation and therefore also of higher river discharges. The consequences of this will be felt most keenly in low-lying areas, including the delta. Most of the peak discharges of the Rhine and the Meuse originate in the low mountain ranges. Since a relatively large amount of land is available there, compared to the densely populated delta, it is much cheaper to implement measures in the mountain ranges to retain water there instead of immediately sending all of it downstream. Such measures include the restoration of marshes in the uppermost sections of the stream valleys and the development of deciduous forests on the hillsides (Figure 4.5). As a result of these measures, the sponge effect of the drainage basin can be revitalized. Besides lower maximum discharges following extreme precipitation, this can also result in water being supplied over a longer length of time in dry periods.

Figure 4.5: In the lower mountain ranges, the restoration of marshes in the upper reaches of streams (10% of the surface area of the catchment) can increase the sponge effect of the drainage basin (Drawing by Jeroen Helmer).

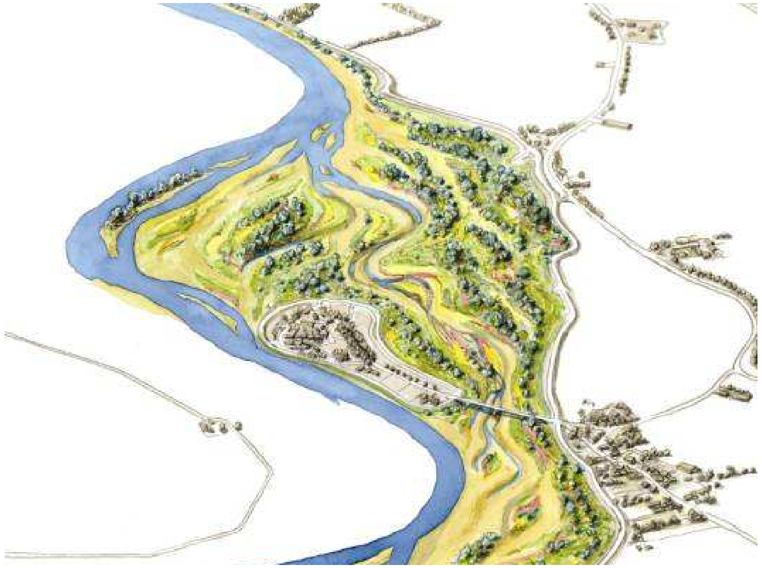


Restoration of sediment flow at dams
Reservoirs have been constructed upstream in many rivers, trapping all the sediment carried along by the river. Consequently, sediment is no longer transported to the delta. Well-known examples are the Nile and the Colorado. Due to the lack of sediment, these deltas are receding by tens of meters per year. In most cases, breaking down the dams is not an option. Methods or technologies could therefore be sought to let the sediment pass through while still keeping the dams in place.

Restoration of sediment balance of streams and rivers
The sediment balance has been disturbed in many drainage basins by fixing the location of streams and river beds. Erosion has thus been checked, but sedimentation continues at the same level. Consequently, many naturally eroding stream and river beds now have a sedimentation surplus. The result is that these river beds gradually silt up, leaving less room for the storage of high water. At the same time, less sediment reaches the delta, resulting in a shortage of sediment. Where possible, options must be sought in river and stream systems to restore the process of erosion.

By means of a careful, shallow method of gravel extraction, the Border Meuse is regaining a broad, natural floodplain along a 35 km stretch of the river on the border between the Netherlands and Belgium (Figure 4.6). As the river is no longer fixed in place, the river's eroding character is preserved and the created space will not be filled up again with sediment; instead, this sediment will be carried further downstream.

Figure 4.6: The Border Meuse (Drawing by Jeroen Helmer).



4.4 Summary
Four strategies of system-based measures can be distinguished: physical measures aimed at the management of sediment and water, adaptation and no action. The extent to which measures could contribute to the continued existence of deltas is partly dependent on the space and scope available within a given delta. Which measure can best be taken depends on local ecological, economic and social circumstances.

In densely populated deltas, it will be difficult to take system-based measures that require a lot of space. In the case of many deltas in poor countries, where the costs are much greater than the benefits, it may be an option not to take physical measures at all. Spatial planning is then a way of adaptation in which different zones in a delta are identified by which the spatial distribution of people and human activities is regulated. At last political measures (gradually removing the population from the delta) and/or economic measures (insurance, compensation for losses) can be applied. Even if deltas cannot be fully protected by system-based measures, this can still be a suitable localized solution.

5. Data on deltas

As outlined in our introduction, the objective of this study is to provide an accessible overview of compiled information on deltas across the world. We based our study on datasets that already provided a comprehensive set of parameters for a bunch of deltas. This approach allows providing a consistent overview of the incorporated deltas, but as a consequence, we also missed some deltas. This chapter shows how we checked and used the available data to link deltas with system-based approaches.

5.1 How to characterize deltas?

There is physical and socio-economic data available on deltas. The information is available in different formats, in quantitative and qualitative databases, in maps and images and as GIS-material. Together, all this information will be used to characterize deltas according to:

1. physical vulnerability (for example to erosion, e.g. due to sea-level rise);
2. societal stocks at risk, i.e. socio-economic indicators of the delta and its immediate hinterland;
3. the potential for ‘soft’ system-based approaches.

In this way, a wide audience of potential users may find the compilation useful.

The present chapter explains where this information was obtained and how it was processed. We identify two main data sources. These databases are described, and an overview is presented of potentially useful variables in each. The allocation of indicators to the above three categories is carried out in section 5.5. Subsequently, observed variation among deltas was used to select the indicators that are useful in the present context.

The steps taken in the selection process are given in detail in Annex 1, which includes an overview of the major patterns of variability in indicators that can be distinguished among deltas. The indicators selected are then included in the project website as explained in Chapter 6.

5.2 Sources of information

For the present pilot study, we have limited ourselves to data sources for which larger sets of data were available in freely accessible form. Furthermore, our interest was both in geomorphological features of a delta and its surrounding coast, as well as in socio-economic aspects of adjacent human society. In addition, it was thought preferable that remote sensing imagery would be available of selected deltas. This has put constraints on the sources of information available.

Most fortunately, we could depend on two major compilations of information, the World Delta Database (WDD, www.geol.lsu.edu/WDD/), and the DIVA-tool, recently finalized by the DINAS-COAST consortium (www.dinas-coast.net/). Together, these two sources contain a wealth of information that can be used to carry out preliminary, but quantitative evaluations of vulnerability, stocks at risk and the potential for new, soft engineering solutions along the world’s deltas.

We adopted a three-step approach in the selection of deltas. First, we selected those deltas from the WDD for which data availability was high and for which also satellite imagery of some form was available. This led to a list of 42 deltas (section 5.3). Then, we matched those to the data available in DIVA. The DIVA tool allows modeling of plausible future SRES scenarios (e.g. Lorenzoni et al., 2000) along the world's coast. Its structure and content will be briefly explained in section 5.4. Finally, possible indicators for the potential of applying system-oriented coastal engineering are introduced, and matched to the contents of these databases.

5.3 The World Delta Database

Studies by Hart & Coleman (2004) resulted in the open on-line World Deltas Database (http://www.geol.lsu.edu/WDD/). The purpose of the WDD is to facilitate the development and use of a public domain distributed knowledge base on modern global deltaic systems. The WDD contains two sub-databases that are particularly useful for the physical characterization of deltas in our project:

A. For 43 deltas, geomorphological, hydrological and oceanographical variables were summarized in an excel file (Coleman & Huh, 2004);
B. For 54 deltas, satellite pictures and a description of physical characteristics were given in a pdf file on the WDD site in "Appendix A: The Major River Deltas Of The World" (Huh et al., 2004).

For 42 Deltas both A and B were available. A list of physical characteristics results from close examination of the content of A and B (Table 5.1).

The information can easily be combined using location (coordinates), delta name (or an ID). Location (latitude and longitude) also allows the link with DIVA output. A selection of variables from the WDD may be suitable for assessment of coastal vulnerability (mainly physical vulnerability) and possibly soft engineering potential. This will be addressed in section 5.5.

Table 5.1: Variables for 42 deltas in the two subsets of the WDD.

Variables DB A		**Variables DB B**
Generic	DELTA (name)	Selected High Quality Images
	LATLONG	Classified Ex. of Delta Types
	Area X 103	Location
Drainage Basin	Stream Length	Landmass Drained
	Relief	Ocean Basin of Deposition
	Ave El (USGS)	Climate
	Max El	Air Temperature
	Min El	Tide
	Drainage Density	Discharge (water & sediment)
	# Days Freeze	ID
	Ave Rainfall	
	Max Rainfall	
	Min Rainfall	
	Ave Monthly Rainfall (MM)	
	Annual Ave Discharge	
	Max Discharge	
	Min. Discharge	
Delta	Delta Area	
	Subaerial/Subaqueous	
	Abandoned/Active	
	Shoreline	
	# River Mouths	
	Distributary Density	
Receiving basin	Offshore Slope	
	Spring Tide	
	Wave Power	
	Shoreline RMS	
	Wave Height	
Form-Process relationships	Drainage Basin Area x Delta Area	
	An. Ave Discharge x Delta Area	
	Offsh. Slope x Wave Power Shoreline	

Socio-economic emission scenarios of the Special Report on Emissions Scenarios (SRES), based on Lorenzoni et al. (2000).

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system.

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

5.4 The DIVA tool

Aim of this toolkit is to allow assessments of coastal vulnerability worldwide to sea level rise and global change at a considerable spatial resolution. It allows users to run pre-defined as well as tailor-made scenarios and investigate consequences for the world's coasts.

Database and model

The database is organized hierarchically using coastal segments of variable length as basic units. Each coastal segment is allocated to a country and an administrative unit of lower hierarchical level. For these latter higher-level spatial units the database contains economical and demographical statistics as well as a host of other statistics (e.g. GDP, the GINI index of income distribution, life expectancy, tourist arrivals and departures, population and economic growth rate). It is well explained in a documentation text (Vafeidis et al., 2005). DIVA has 12.148 coastal segments. For each coastal segment, the database again offers a range of quantitative or categorical variables, including indices for density of the coastal population, sediment supply, tidal range, presence of dikes, rates of uplift or subsidence, coastal morphological characterization, surge heights and a tidal classification. In addition, the DIVA tool has identified world heritage sites occurring on coastal segments based on UNESCO data.

The DIVA model combines the worldwide database with user-adjustable input scenarios to calculate coastal change over a time frame of 2000 – 2100. Built-in SRES scenarios for the world (see box above) have been implemented with a medium-resolution global circulation model CLIMBER, developed at the Potsdam Institute of Climate Research (e.g. Pethoukov et al., 2000). Mean change in relative sea level is estimated for each 0.5x0.5 degree CLIMBER grid cell and extrapolated to the coastal segments compared to the reference year (1995) weighted by segment length (admin level). It considers (1) human-induced climate change under the selected scenario, (2) uplift/subsidence due to glacial-isostatic adjustment and (3) natural subsidence of deltaic areas. Possible climate-induced changes in river discharge pattern have not been implemented in DIVA. The design and interplay of database and model is illustrated in Figure 5.1. DIVA results can be outputted in the form of graphics, tables or a map (Figure 5.2). The tool combines built-in fixed variables and scenario-related drivers with initialized model input variables and output variables as results. Several from all these categories can be extracted.

Figure 5.1: Structure and approach of the DIVA tool (from Hinkel & Klein, 2005).

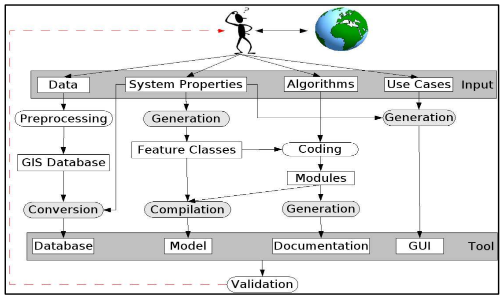


Figure 5.2: Sample output generated by DIVA and exported as bitmap.

Deltas in DIVA

DIVA contains a separate set of 115 major world rivers, it does not identify whether these rivers have a delta at their mouth. Each river is matched to a coastal segment. It contains mean depth, slope and discharge at the river mouth obtained from various sources. Since the river data are linked to coastal segments, it is possible to address queries on coastal vulnerability (comprising both the physical and socio-economic aspects) and soft engineering potential with a manual pre- and post-processing step.

The pre-processing is explained above. Post-processing in the present pilot study involved a screening of potentially useful output variables and the development and testing of a set of indicators. Indicator development is carried out below in section 5.5, whereas WDD and DIVA output screening, matching and preliminary indicator testing is done in section 5.6.

5.5 Developing three types of possible indicators

Having access to these rich data collections, the challenge is now to extract the variables from these databases that can be matched to the three major types of indicators covering different aspects of the coast at a cross section with a riverine delta. As previously announced in section 5.1., these are:

1. the physical vulnerability of the coast;
2. the stock at risk for the human society;
3. the potential of soft, ecosystem-oriented engineering solutions to allow adaptation or mitigation responses of coastal society with consideration of natural, ecosystem processes.

The DIVA tool does offer a range of indicators that can be extracted and reflect a substantial proportion of the information needed for a first assessment of deltaic vulnerability and potential for soft engineering measures. The WDD in turn, contains geomorphological indicators including a number that describe the catchment. Thus, these indicators could serve for physical vulnerability and physical potential for soft engineering.

Physical vulnerability

The first type of indicator, physical vulnerability, would include a risk assessment combining geophysical probability with effects on coastal ecosystems. Thus, physical vulnerability is interpreted here as vulnerability of coastal land and ecosystems to flooding by the sea and by rivers including effects of any associated sediment loads and deposition. Geophysical probability would include storm surges, net sea level rise, possibly tsunami's and their consequent flooding.

A range of processes is included in coastal engineering estimates of dike failure, often derived from incidence statistics to date and reported as a 1 in 10, 100 or 1000 year probability. The DIVA tool calculates a compound indicator of vulnerability for each coastal segment, labeled the Current Segment Vulnerability Score (CSVS). It reflects the combined forcing resulting from four environmental forcing factors: sediment supply, accommodation space, relative sea level rise and tidal range. This CSVS does not include the effects in society, it is only an indicator of the probability of coastal land loss. However, for the sake of transparency, the present study has opted to mainly focus on the simpler, constituent components of the CSVS. The WDD offers an estimate of delta area, a proportion of it that is subaqueous, the offshore slope, height of spring tide and wave power as interesting indicators.

Socio-economic risk

In the second type of indicator, the consequent risk of coastal human society would be covered. This would entail human lives and economic loss, but also human infrastructure as well as other valuable items, such as world heritage sites. For example, DIVA does also estimate the number of people at risk (PAR) of flooding as average number of people flooded per year by storm surge allowing for the effect of flood defense for each administrative unit and per time slice and scenario applied. A range of cost estimates are only estimated on a per-country-basis, these are aggregated up into a total cost of adaptation. Therefore these DIVA-indicators are less suitable in the present project.

Soft, ecosystem-based engineering

The potentials for soft, ecosystem-based engineering are the third type of indicator. These would depend on (a) overall gross sediment availability in a sediment budget (tons km^{-2} y^{-1}) including terrestrial and marine sources, (b) local coastal topography (sea bed and coastal plain), i.e. availability of space for a natural coastal development. Strength of the local hydrodynamics (currents, tide and wave climate) may well modulate sediment availability. As an example, DIVA estimates an indicator of sediment supply (SEDSUP) as input for each coastal segment. This compound indicator includes tectonics, river supply, adjacency of sea ice, local geomorphological setting, history of land use and present coastal management (presence of dikes). SEDSUP is reported in 5 categories, from high supply coupled to low vulnerability to low supply. The WDD offers data to estimate the potential space available and local hydrodynamics.

Traditional soft-engineering measures are beach nourishment, reservation of flood-containing plains, and managed, local retreat. Clearly, the potential success of these will depend on the above listed availability of sediment and accommodation space in the coastal zone. Local adaptation (e.g. refuge hills), or mitigation (financial compensation) measures would have different bases of success. Their potential maybe coupled partly to GDP and population density, but the causal links do not appear straightforward.

Available indicators in WDD

Going back to the ideas presented in the introductory chapters, many of the problems and measures facing deltas are related to water and sediment. A first inventory of WDD variables is presented in Table 5.2. Vuln/pot indicates that the variable could possibly be an indicator under either the vulnerability group, or the potential for soft measures group. WDD does not contain socio-economic data. Section 5.2 gives a description of Database A and B. Coleman et al. (2004) provide a more detailed description of the variables of Database A.

Table 5.2: Spreadsheet with potential WDD indicators. Given are the abbreviation of the indicator as used in the database, its potential as indicator for vulnerability or potential for soft measures, respectively, the source of the data (i.e. which database) and a brief description.

abbreviation	vuln/ pot*	db a/b**	description
Annual Ave discharge (m^3/s)	v	a	discharge of water, data for river discharge came from various sources notably Vorosmarty, Fekete and Tucker (1998)
Max Discharge	v	a	
Min Discharge	v	a	
Sed Discharge	v + p	b	
Delta Area	v + p	a	delta area in sq km, interpreted from maps and satellite images
Subaerial/Subaqueous	v + p	a	ratio of subaerial/subaqueous delta area, calculated from the area of the delta plain as measured on maps and images and data derived from bathymetric maps for the area of the subaqueous delta
Shoreline	v	a	ratio of actual shoreline length to the width of the delta plain, an indication of the smoothness of the delta shoreline. Those deltas with very large ratios are usually the deltas in which riverine processes are dominant, while those with very low ratios are deltas in which wave energy and currents smooth the delta shoreline
# River Mouths	v	a	number of active river mouths from examination of maps and satellite images
Offshore Slope	v + p	a	average offshore slope fronting the delta, derived by measuring offshore profiles at selected intervals along the delta front on hydrographic maps
Spring Tide	v	a	tidal range, from published articles
Wave Power Shoreline		a	wave power computed at the 10 meter contour in 107 ergs/sec/m coastline, from a computer program
RMS Wave Height	v	a	root mean square wave height derived from marine atlases. Input for significant wave height (Hs) and maximum wave height (Hmax)

* Potential as indicator for physical vulnerability (v), or potential for system-based approaches (p)
** Source: database a/b

Available indicators in DIVA

The DIVA tool reports some indicators on a per-segment basis, others per administrative unit and again others on a per-country basis. We list a number of DIVA-indicators tabulated according to spatial scale (segment, admin unit or country, Table 5.3) and ranked as either signifying ‘physical vulnerability’, ‘societal stock at risk’ or ‘potential for soft measures’. Clearly, the number of potentially relevant indicators is substantial. Socio-economic stocks at risk can be read from GDP per country or per administrative unit, people at risk, total land loss, the flooded zone, people in the hazard zone, or from a compound indicator combining these. Most of these are reported at the administrative unit (province) level. Geomorphological, physical vulnerability indicators are more often available at the coastline segment level.

DIVA output is aggregated to the administrative unit before it is made available at the users interface in DIVA. Still, a few output variables have been selected that are specific for rivers. DIVA calculates the distance upriver where the influence of the sea is still measurable (i.e. as tidal fluctuations), but also the distance of salt intrusion upriver.

Table 5.3: Spreadsheet with selected DIVA indicators. Given are a qualification of the spatial scale of the indicator applied by the DIVA tool, its abbreviation used in the database, its potential as indicator for physical vulnerability, stock at risk or potential for soft measures, respectively, the type of DIVA variable, and a brief description.

scale	abbreviation	v/s/p	PDIVOV	description
country	sdikecost	s + p	p	country-specific costs of rising a standard dike of 1 km length with 1 m in US$ of 1995
	gdpc	s	iv	per capita GDP in 1995 US$
	tourarr	s	iv	number of international tourist arrivals in a country in 1995
admin unit	gdpmulti	s	p	GDP per capita multiplier to adjust GDP for an admin unit from the average of a country
	Potlandloss erosion	v + s	ov	Potential land loss due to direct and indirect erosion, ignoring beach nourishment, km^2/y
	paf	s	ov	People at risk of flooding: average number of people flooded per year by storm surge allowing for the effect of flood defenses (administrative level). Aggregation rule, sum of coastline segments within administrative unit.
	potfloodplain	v + s	ov	Land area below the one in one thousand flood level, ignoring see dikes (km^2)
	people potentially flooded, ppf	s		People in flood hazard zone: people living below 1000 year surge (admin level). Aggregation rule, sum of coastline segments within administrative unit (1000s of people)
	rslr	v	ov	Mean change in relative sea level compared to the reference year (1995) weighted by segment length (admin level). It considers (1) human-induced clim. change under selected scenario, (2) uplift/subsidence due to glacial-isost. adjustment and (3) natural subsidence of deltaic areas (m)
	Sumn wetl	p	ov	sum of area of all coastal wetland types in admin unit (km^2)

scale	abbreviation	v/s/p	PDIVOV	description
coastline segment	areaunderx (x=1,2, .., 13_16)	v	p	area in the coastal zone with elevation below 1m above AMSL or in the elevation class 1-2 m, 2-3 m etc given, derived from GTOPO30 digital elevation dataset
	csvs	v	ov	coastal segment vulnerability score, a compound variable, use with caution
	latitude		p	latitude of midpoint of segment
	longitude		p	longitude of midpoint of segment
	surgeh1yr, 10, 100, 1000	v	p	1in 1 1in 10 etc surge height including high water level, above mean sea level, maxsurge = surgeh1000 + 3 (m)
	sedsup	v + p	p	compound variable, scaled to 5 cat: 1=low vulnerability so high sed availability, 5 = high vulnerability so low sediment supply; includes tectonics, river discharge and distance tot that river, sea ice and distance tot that ice, inlet or open coast, presence of dikes, history of exploitation of the coast; all weighed and then the total scaled between 1 and 5
	slope	p?	p	slope of land up to 3 m above max surge level.
	mediantide	v	p	tidal range, based on LOICZ classes: 1 no tide, 2 < 2 meter, 3: 2-4 m, 4: 5-8 m 5: >8m; here median values of each class are taken
	upsub	v	p	uplift/subsidence (mm/yr), uplift is positive.
	wavclim	v	p	wave climate based on LOICZ classes: 0 no waves permanant sea ice; 1 0-2.5 m, 2: 2.5-3.5 m, 3 3.5-5 m, 4 5-6.5 m, 5 > 6.5 m
	aspace	v + p	iv	accommodation space, potential for wetland migration into land, depending on landforms and presence of dikes, scaled between 1 and 5, with 5 = vulnerable, loss is probable so little room for accommodation
	copopd	s	iv	population density on the coast, that is in a zone of 2.5 km behind the coastal segment (N/km2)
	sdikehght	v	iv	sea dike height, calculated height of a dike on a segment
river segment	rivimpact	v	ov	distance to where the influence of the sea is still measurable (km)
	salintru	v	ov	distance of salt intrusion into the river (km)

notes:

scale — spatial scale of DIVA input/output

v/s/p — whether the indicator would feature for physical vulnerability (v), societal stocks at risk (s), or potential for soft measures (p)

PDIVOV — type of DIVA-defined variable: parameter (fixed), driver (fixed), initial or input variable output variable.

For the following output variables (ov) the values have been estimated with DIVA for A2 and B1 scenarios and the year 2100: potlandlosserosion, paf, potfloodplain, rslr, sumnaturalwetlands

5.6 Indicator testing and selection

Which potential indicators should now become the DELTAS indicators to be incorporated in the computer-based system? The potential indicators become DELTAS indicators once they have passed our tests. The testing comprised of: looking at the quality and validity of the data by plotting potential variables and examining their variability. Variability was assessed first in bivariate correlations, and second by an objective data reduction approach, here a simple Principal Component Analysis (PCA; Jongman et al., 1987). Note that the correlation results do not necessarily imply causal links: correlated phenomena can have a separate, common cause. The PCA was introduced because the values for the potential indicators should differentiate over deltas to enable ranking of these deltas, and because covariance among the many different potential indicators necessitated selection of a few major indicators that together would explain most of the total observed variation. After all, our aim is to show which deltas are most suitable for (certain groups of) system-based measures. These steps lead to an objective selection of a few major indicators, and are placed in a separate, well elaborated Annex 1.

In this Annex 1 we first show some of our best results of testing within the individual WDD and DIVA databases. We then merge the two data sets and come to a consolidated list of indicators, which is presented below. This list is subsequently entered as a spreadsheet table for querying through the website user interface (see Chapter 6).

Selected indicators

Based on an efficient representation of the total variability present in the database, and our detailed assessment of all potentially useful indicators in WDD and DIVA (Annex 1), we propose to select three priority indicators: surge height with a 1/100 y probability, ‘coastal lowland area available 0-2 m above mean sea level’ and ‘people potentially flooded in 2000’. The latter is the main indicator for stocks at risk, and the former two serve as indicators for vulnerability, which will be higher with higher surge heights and in smaller coastal plains. The potential for soft system-based measures would then be best judged from the area of coastal plain. We propose a range of specific indicators from our combined WDD and DIVA database and have arranged them in Table 5.4 below, where we also give a brief justification for each.

Table 5.4: Indicator variables grouped into three categories, and split into generic indicators and sets of specific ones. A justification for the latter is given as well. These specific indicators have been subdivided in the category potential for soft measures, to identify those that are most suitable for (a) restoring sediment dynamics, (b) water flow and storage solutions, (c) a combination of adaptation measures, or (d) no action.

Category	Generic indicator	Specific indicator	Justification
Physical vulnerability	Surgh100y, area 0-2m above MSL		
Stock at risk	Ppf2000	GDP, copopd	multipliers
Potential for 'soft measures'	Area 0-2m above MSL		
(a) restoring sediment dynamics (e.g. suppletion, removal of dams, sludge dumping at sea)		Upsub	Where positive uplift, nourishment ('suppletion') will be effective more easily
		Area 0-2m above MSL, delta area, accommodation space, dike height	Wider coastal plains offer more space for the removal of dams, areas with lower dikes will have these dikes removed more easily
		Offshore slope	Steep slopes will limit the efficiency of sludge dumping and beach nourishment
(b) water management and flood storage (e.g. floodplain clearing, side channels)		Delta area, sumnatural wetlands, river impact	All these indicate a wider floodplain or delta which will offer more possibilities for temporary flood storage
(c) adaptation sensu lato (e.g. relocation of population and industry, restricting or directing land use types in delta, flood refuge hills, early warning systems, financial insurance or compensation)		Slope(on land), area 0-2m above MSL, aspace, ppf2000; GDP, copop	Wider plains offer more options for relocation; GDP and coastal population will be used in a cost-benefit balance to assess the possibility for financial adaptation measures
(d) do nothing		Copopd	Where few people live, the coastal erosion and flooding is more easily feasible

6. The DELTAS website

A system was built to facilitate the handling of quality controlled data and results from WDD and DIVA on deltas and indicators. We opted for an application that will work both on the Internet and on a desktop from a cd-rom with a web browser (such as Internet Explorer or Mozilla) as a viewer tool. This Chapter provides technical details, explains the use of the website and displays rankings of deltas, as an illustration of some of the results it allows you to generate. The structure of the system, and the layout of the user interface are introduced in section 6.1. Subsequently, a step-by-step guide of how to retrieve information from the system is given in 6.1. Finally, a preview of some results, namely the ranking of deltas for the three generic indicators and several specific indicators is given in 6.3.

6.1 Structure and functionality

The system

Users communicate with the system through a web browser. This has the following three advantages:

1. a web browser is familiar to most people;
2. web-browsers exist for every computer platform (having different hardware and software);
3. costs and efforts for additional tool development are minimized.

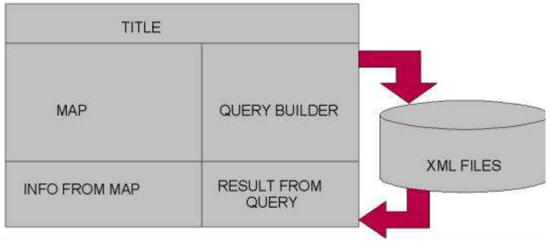
Although designed to run from a web server, all technologies used can run locally without need to install special software, allowing the DELTA tool to be put on a portable 'demo-CD'.

The system is structured as indicated in Figure 6.1. The interface in the rectangle at the left hand side and allows you (the user) to visualize and query (that is to request information) from an underlying database of XML files for all deltas. As user you will mostly be interacting with the interface so this will get ample attention in section 6.3, but in this section you'll first get more technical details about the system. Such interesting background information can also be useful if you'd like to add data or adapt the system.

The database contains information about each delta and every soft measure included in this study. This is stored on the computer as a collection of text files per delta structured in the eXtensible Markup Language convention. These plain-text data files allow parameter modifications to be made at the lowest level without having to understand programming. More extensive inspection, sorting and further analysis can be carried out with the underlying database, since it can be exported as an xls-spreadsheet.

To remain flexible, open and fully standardized formats are used: Scalable Vector Graphics are used for the interactive map, HyperText Markup Language together with Cascading Style Sheets for layout, the calculations are done in functions created with ECMA script, and the underlying data is stored in documents structured with eXtensible Markup Language tags. Each of these is an approved W3C standard (http://www.w3.org/).

Figure 6.1: Architecture.



What does the innovative DELTAS system look like?
The user interface looks as follows (Figure 6.2). It comprises a map and areas with text that can contain either the tabs and buttons the you use to query, or results from a query or mouse over. This is further explained in section 6.3. What's good to notice now is: what you see in the map is related to what you will see in the text files.

Figure 6.2: Visualization: A preview of the start-up screen.

6.2 Retrieving information from the website

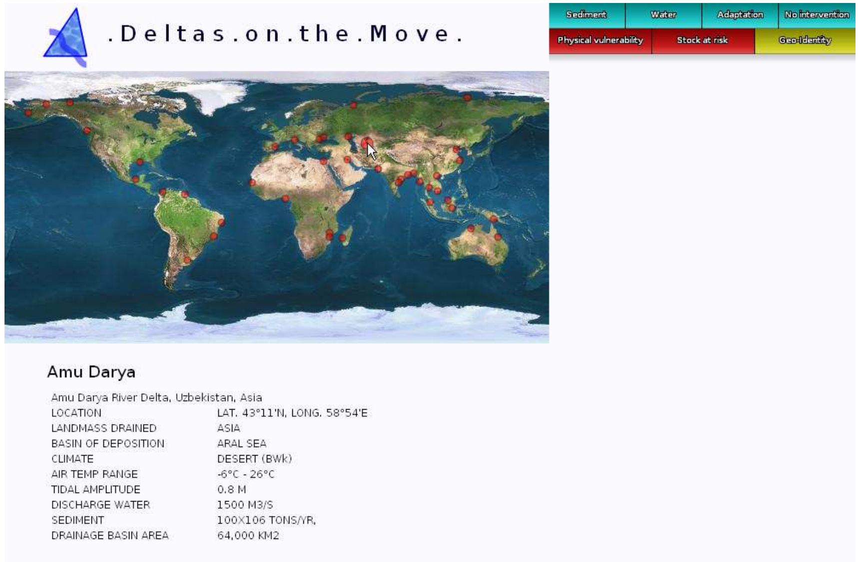
In short
There are two approaches towards selecting and retrieving data from the database:
1. graphical: through selection on the interactive map (point-and-click), or
2. thematic: by querying all of the data at once through form fields.

Both approaches can be taken consecutively. Viewing basic information (Figure 6.3) and accessing the database (Figure 6.4) through the map is suitable for users who want to browse through the available data, or who know in advance in which delta(s) they are interested. Querying through a form field (Figure 6.5) is suitable for users who wish to discover which deltas match their criteria and retrieve detailed

information about these (Figure 6.6). For those wishing to perform further statistical analysis after exploration through the system, finally the underlying data can be downloaded (in Excel format). This is elaborated below in a step-by-step journey through the functionality of the system.

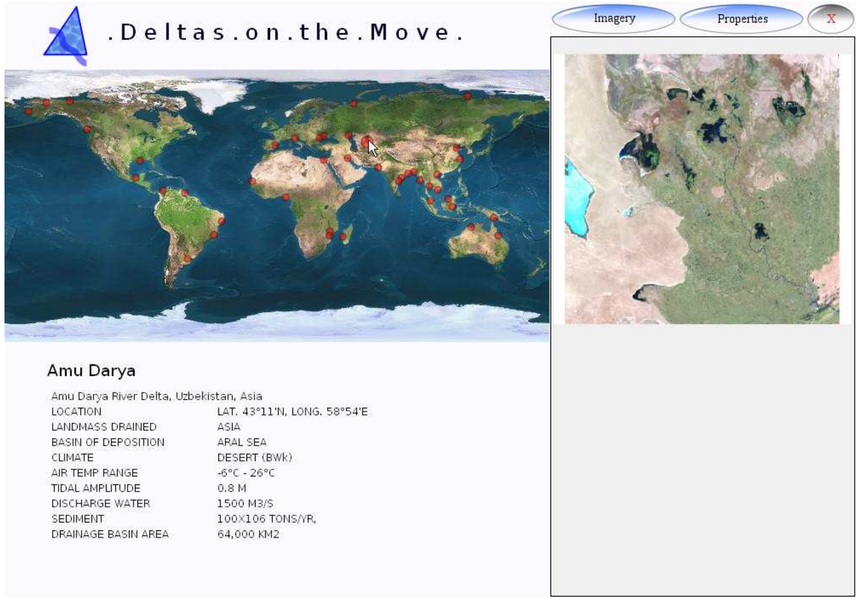
Step-by-step guide
Step 1) Right from the start-up some information about the deltas appears if you move your mouse over the (red) dots indicating the deltas that are in the system. The information is presented just below the map.

Figure 6.3: Delta information (on Amu Darya in this case) appears upon Mouse over.



Step 2) You can click on one of the red dots if you want more information on a particular delta. After clicking a satellite image of that particular delta appears under the tab image at the right hand side of the screen. If you subsequently click on the neighboring tab Properties you will see all information from WDD and DIVA that we selected and validated for this delta (information about the latter procedures is given in Chapter 5). Finally, you can close both tab windows by clicking on the 'closing' cross at the upper right hand side.

Figure 6.4: More information (in this case a satellite picture) of a particular delta pops up when clicking on the red dot indicating this delta.



Step 3) Now that you have a feel for the tab structure, and the underlying thematic information for one delta, you might wish to query the database thematically. Again on the right hand side of the screen you'll find eight colored tabs. These will give you the possibilities to query on:

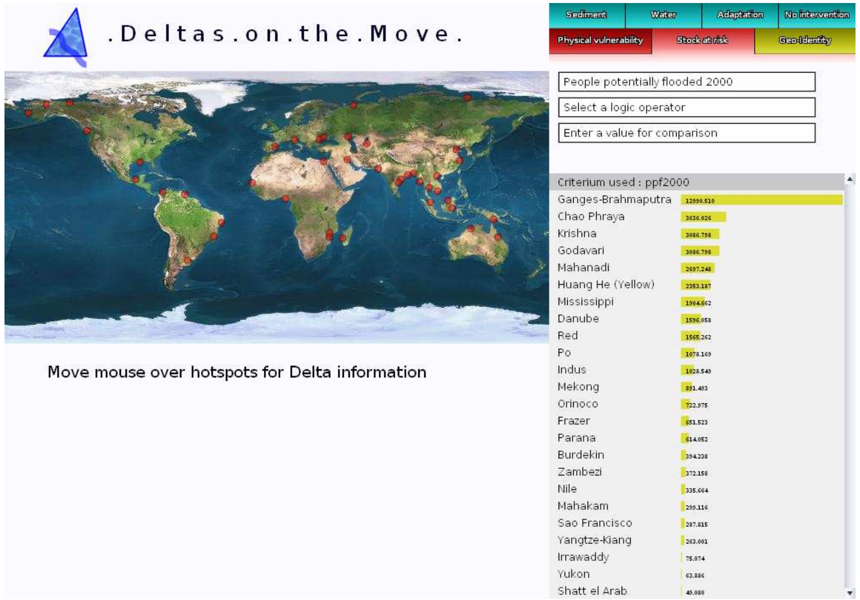
1. physical vulnerability (PV)
2. stock at risk (SAR)
3. four system-based approaches
4. and a geographical ID (This will allow querying on, e.g., latitude or continent)

Figure 6.5 shows how you can query all deltas on an indicator for stock at risk. Click the red stock at risk tab and select for example the indicator people potentially flooded in 2000 (ppf2000). Subsequently, you can select whether you would like to see all deltas, the 10% of delta populations that are in greatest danger, or the deltas above a certain threshold (e.g. over 2000 persons potentially flooded). Click Select.

Figure 6.5: A selection of deltas using the drop-down menus.

Step 4) Figure 6.6 shows the result for such a query. Note that the results are also visualized on the map. You can click on a particular delta in the map to get an overview of all information for this delta (back to Step 3) or perform another query (back to Step 4).

Figure 6.6: The query result: a list of deltas that fulfill the criteria.



Optional: Should you wish to make more analysis in Excel, you can also click the download button. This will allow you to download the full excel database on your PC.

Step 5) You can close the application by closing the DELTAS browser window.

Check it out at http://ivm10.ivm.vu.nl/deltas,
the interactive on-line system for innovative delta management!

6.3 Ranking of deltas, an illustration

The DELTAS system produces a ranking of deltas for indicators according to physical vulnerability, for stock at risk, and potential for soft measures (Table 5.4). Specific indicators depict the different categories of system-based soft approaches. The next sections aim to show how these rankings should be interpreted, and how they can be used for innovative system-based delta management.

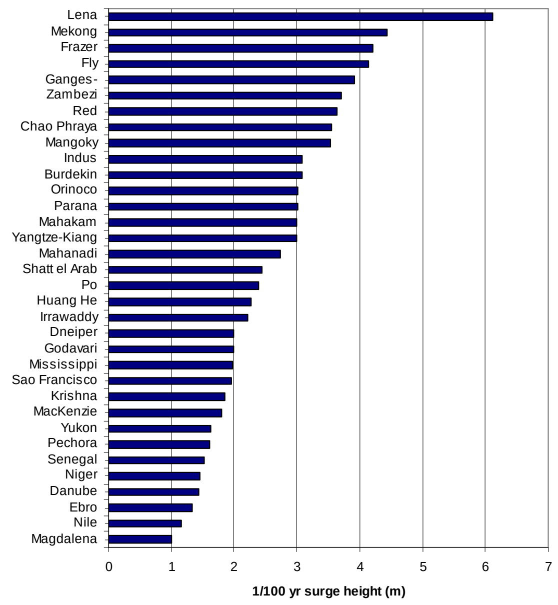
Physical vulnerability

Both the one in a hundred year surge height and the area between 0 and 2 m above mean sea level were identified as prime indicators for physical vulnerability in Chapter 5. The latter is also considered useful to indicate the overall potential for soft system-based approaches. Some deltas are located in areas of high surge (listing below and Figure 6.7), whereas others discharge in quieter seas.

The following deltas are found in high surge regions:
1. Lena;
2. Mekong;
3. Fraser;
4. Fly;
5. Ganges-Brahmaputra.

The other indicator, area between 0 and 2 m, is important because larger coastal plains with low storm surges, such as Yukon, Mackenzie and Mississippi are probably less vulnerable. These examples show that, depending on the context, more than one indicator should be considered. The DELTAS system offers this possibility. When in doubt, we suggest that here you adhere the precautionary principle and consider high-ranking deltas for both indicators to be very vulnerable.

Figure 6.7: Ranking of deltas for physical vulnerability based on 1/100 yr surge height.

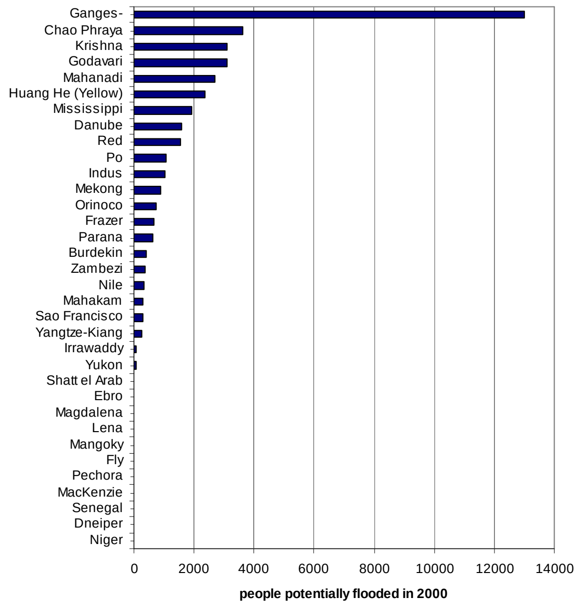


Stock at risk

The next five deltas have a particularly high stock at risk (when using people potentially flooded in 2000 as an indicator for stock at risk):
1. Ganges-Brahmaputra;
2. Chao Phraya;
3. Godavari;
4. Krishna;
5. Mahanadi.

The first thing to notice is that these five deltas are all Asian. If we, subsequently, compare this ranking to the one for physical vulnerability, we are fortunate that only the Ganges-Brahmaputra ranks high in both lists, and is therefore both physically vulnerable and has a high stock at risk. This delta, which is one of the largest in the world, covers some 105.640 km^2 and has one of the highest population densities of all deltas, and consequently DIVA gives a relatively high number of peoples potentially flooded (Figure 6.8). The major river floods occur during the months from June through September (Coleman & Huh, 2004). The inland part of the tidal plain has been reclaimed, and the former saline lands have been converted to various agricultural and marine farming practices (see also Section 7.3.)

Figure 6.8: Ranking of deltas for stock at risk: people potentially flooded in 2000.



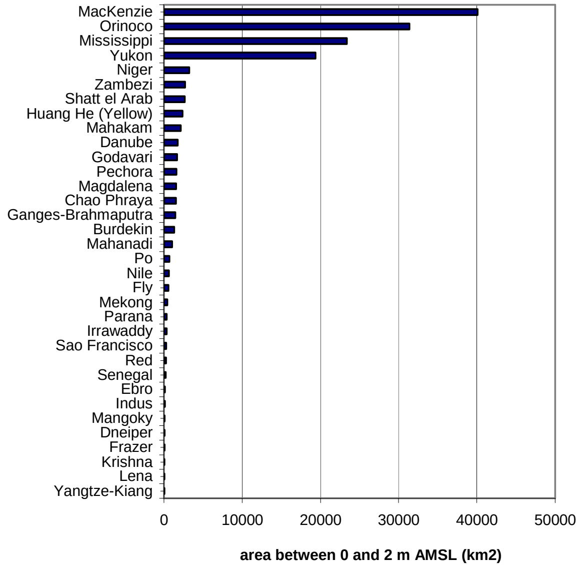
Potential for system-based soft measures

The area of the coastal plain between 0 and 2 m above mean sea level has been suggested as a generic indicator that can give information whether deltas are suited for 'soft' system-based approaches. The straightforward argument is that large areas of low-lying coastal land offer the availability space and sediment for several system-based measures. The indicator area of the coastal plain between 0 and 2 m above mean sea level is also somehow positively correlated to the GDP per capita (Annex 1), which could be important for various other adaptation measures.

The following deltas rank high for this indicator:

1. Mackenzie (see photo);
2. Orinoco;
3. Mississippi;
4. Yukon;
5. Niger.

Figure 6.9: Ranking of deltas for the potential for soft measures: area of the coastal plain between 0 and 2 m above mean sea level.



The system ranks the MacKenzie delta (Hart & Coleman, 2004) as highly suitable for a system-based approach, because of its large coastal plain. There are several reasons why the coastal plain is so large for the MacKenzie delta. The MacKenzie River is the longest river in Canada, covering a distance of 1.470 km. The delta has been formed in a sheltered embayment. Tides are low in the Arctic Ocean and spring tides are less than 0,3 m. Amongst others due to prolonged periods of ice cover, wave action is also relatively low, with the root mean square wave height being only 0,15 m. Finally, the delta has been forming for quite some time: drill holes reveal that there is about 70 to 80 m of deltaic sediment overlying bedrock (Coleman & Huh, 2004).

The ranking of deltas for our selection of specific indicators for ‘soft’ system-based approaches (Table 5.4) is discussed in the next sections.

Best deltas for restoring sediment dynamics

Three indicators for the potential of restoring sediment dynamics are shown in Figure 6.10. These are delta area, uplift or subsidence, and offshore slope. Other specific indicators mentioned in Table 5.4 are area coastal plain, accommodation space and dike height. Their relative importance is related to the exact measure (e.g. nourishment, removal of dams) considered. Delta area and lowland coastal plain (area 0-2 m above mean sea level) are not correlated (Annex 1, Section 3), probably because an active delta does not need to be formed in the vicinity of existing coastal lowlands (compare 6.9 and 6.10). Still, a large area of the delta proper should store vast quantities of sediment that could be released in a controlled fashion.

Table 6.1: Delta rankings for the potential of restoring sediment dynamics using various indicators.

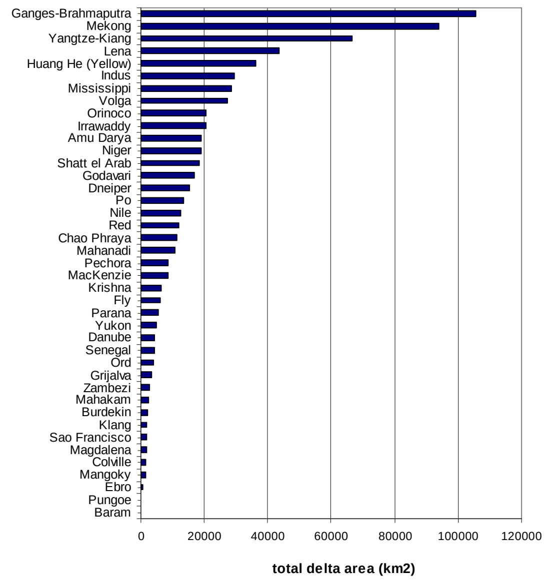
Delta area	Uplift	Offshore slope
1. Ganges-Brahmaputra	1. Mississippi *	1. Parana
2. Mekong	2. Mackenzie	2. Chao Praya
3. Yangtze-Kiang	3. Nile	3. Yangtze-Kiang
4. Lena	4. Danube	4. Ganges-Brahmaputra
5. Huang He (Yellow)	5. Po	5. Lena

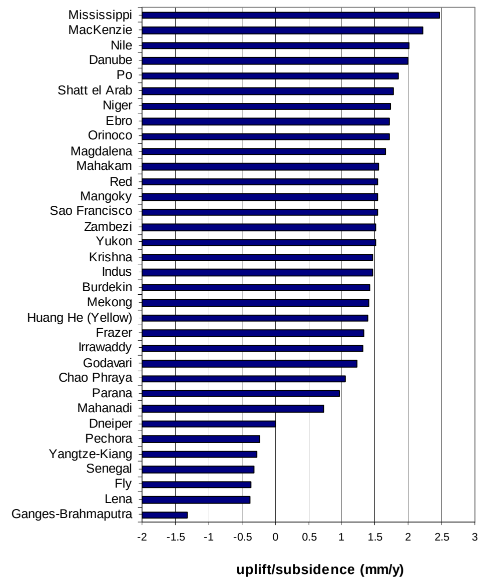
* In contrast to what you would expect from this ranking, the Mississippi delta is prone to unrelenting subsidence, which occurs even beyond the limits of the deltaic plain (Dokka, 2005). In the DIVA database uplift or subsidence ($mm.yr^{-1}$) was calculated from estimates of glacio-isostatic adjustment (inverse distance weighting interpolation of a point dataset of Peltier, 2000) minus an assumed 2 $mm.yr^{-1}$ for deltaic areas. The erroneous value for the Mississippi could simply be de to an interpolation error.

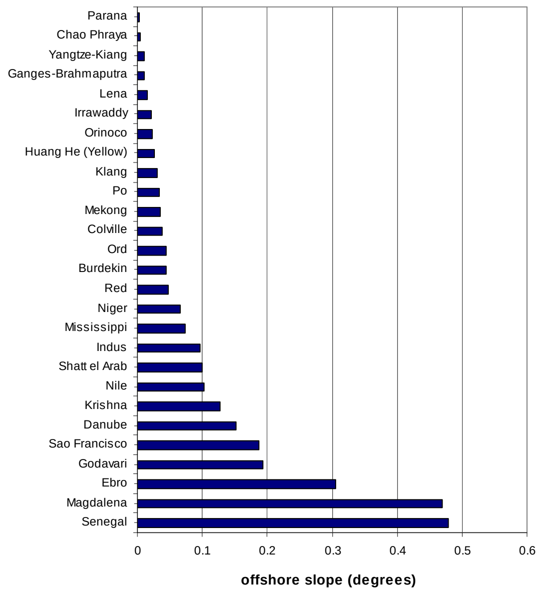
The Ganges-Brahmaputra, Yangtze-Kiang, and Lena rank high for delta area and have low offshore slopes (Table 6.1). These indicators are negatively correlated (see Annex 1). Total delta area varies greatly, but at least half of the deltas studied have and area of over 10.000 km^2 in size. Here it should be feasible to find opportunities for restoring the sediment dynamics, but equally so, to find space for water retention and controlled flooding measures (Table 6.1). Most deltas have a rather gradual offshore slope, but some have a steeper slope. From Niger (0,075%) to Senegal River (0,48%), offshore slopes may be too steep to allow much scope for substantial sediment entrainment along the coast. Conversely, deltas with shallow slopes and extensive submerged deltas should offer opportunities for nourishment.

Uplift could be an interesting indicator because particular measures such as beach nourishment might be more effective when it is placed in an uplifting area. Uplift is a DIVA indicator that results from an interpolated point data set of estimates of glacio-isostatic adjustment plus an assumed inherent subsidence of deltaic areas at a rate of 2 mm/yr (Vafeidis et al., 2005).

Figure 6.10: Ranking of deltas according to several indicators for restoring sediment dynamics (which is one category of soft system-based measures): delta area, rate of uplift or subsidence, and offshore slope. Delta area and offshore slope originate from WDD, uplift/subsidence is from DIVA.







Best deltas for water management and flood storage measures

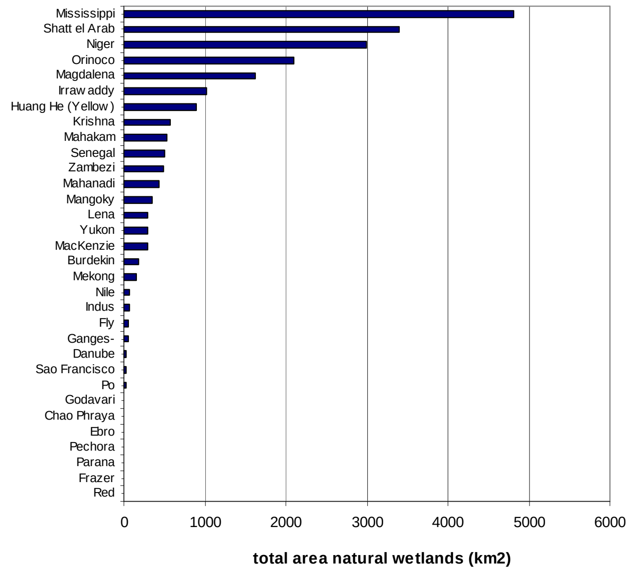
Several indicators can be related to various water management and flood storage measures (Table 6.1). Here we look at one of the more generic ones, the total area of natural wetlands in the vicinity of a delta. The argument is that natural wetlands can accommodate floodwater with little harm to society.

Vast expanses of natural wetlands are present near the mouths of the following deltas (Figure 6.11):

1. Mississippi;
2. Shatt el Arab;
3. Niger;
4. Orinoco;
5. Magdalena.

The high ranking of Mississippi illustrates again that, in the real world, it is often not sufficient to examine only one indicator. High population pressure would require carefully designed and managed flood storage measures. This could follow from including the indicators stock at risk and (sea) dike height.

Figure. 6.11: Deltas ranked for water management and flood storage measures based on total area of natural wetlands.



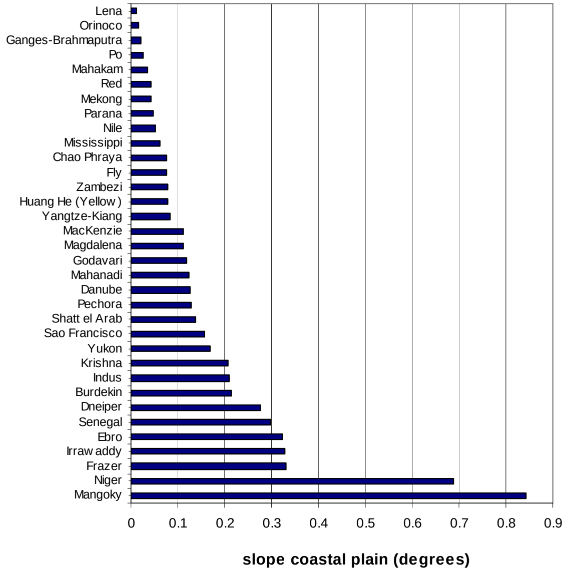
Most suitable for adaptation: slope of coastal plain

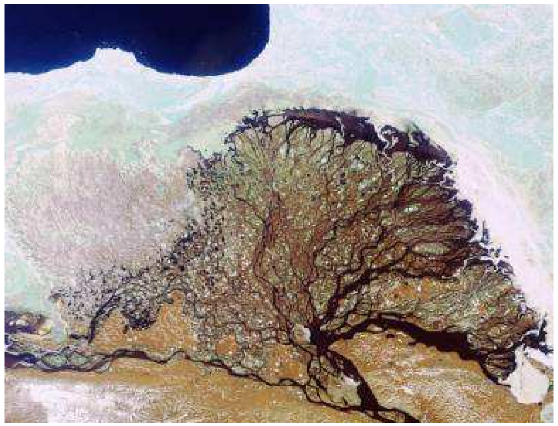
Adaptation is a broad category comprising measures such as relocation of population and industry, restricting or directing land use types in delta, flood refuge hills, early warning systems, financial insurance or compensation. Subsequently, there are also many indicators associated with adaptation: slope (on land), area coastal plain 0-2 m above mean sea level, accommodation space, people potentially flooded in 2000, GDP, and coastal population (Table 6.1). Here we elaborate slope on land as an example, but the best combination of indicators is probably context specific.

The gentlest slopes of the coastal plain were found for:

1. Lena (see photo);
2. Orinoco;
3. Po;
4. Mahakam;
5. Red.

Figure 6.12: Deltas ranked for adaptation, based on the slope of subaerial coastal plain (slope on land).





The Lena delta (Hart & Coleman, 2004) ranks as highly suitable for adaptation because of its low sloping (1,1 %) coastal plain. The low slope is caused by various physical factors. Discharge of the Lena River is extremely high. It abruptly increases from 5.578 m^3/s in May to a maximum of 73.997 m^3/s in June, when spring melt begins. Nearly every year in the late spring, ice blocks the flow of water at the mouth of the Lena River in north eastern Russia and gives rise to floods across the Siberian plains, because water upstream thaws earlier than water at the mouth of the river. Close to the apex of the delta, the Lena River cuts through broad coastal Pleistocene terraces. As a result the fan-shaped delta covers some 43.563 km^2 and is a maze of small distributaries. The delta located in sparsely populated North Eastern Siberia (see also Figure 6.13).

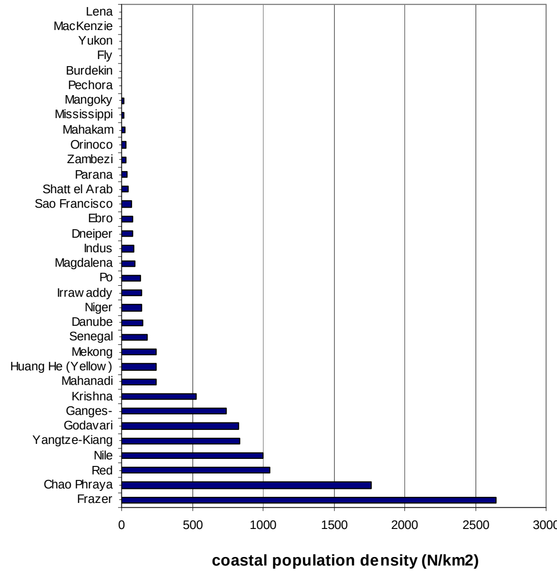
No intervention as a sustainable approach

Surprisingly many deltas have a comparatively low population density: here the last option of a system-based approach, i.e. taking no measures, would be quite feasible. Most suitable for doing nothing, based on coastal population density, are the following deltas (Figure 6.13):

1. Lena;
2. MacKenzie;
3. Yukon;
4. Fly;
5. Burdekin.

The first the deltas are located at high latitudes, the Fly and Burdekin are relatively small deltas (see Figure 6.10, delta area).

Figure 6.13: Deltas that are particularly suitable for doing nothing based on coastal population density.



6.4 Deltas in the next phase

One of the objectives of phase 1 was to come up with a list of deltas that might be interesting for the next phase. Carefully examining the correlations between variables describing the deltas (in the Annex), defining indicators for physical vulnerability, stock at risk, and potential for system-based approaches (in Table 5.4), and subsequently ranking the deltas (section 6.4) provides the firm grip and thorough understanding need for such a selection. Nonetheless, we would like to stress that whether a delta is interesting or not for phase 2 is context and scale dependent.

Taking the 4 highest-ranking deltas for all individual indicators mentioned 6.4 gives a list of the following list of 20 deltas:

Chao Phraya	Godavari	Mekong	Parana
Danube	Krishna	Mississippi	Po
Fly	Lena	Niger	Shatt el Arab
Fraser	MacKenzie	Nile	Yangtze-Kiang
Ganges-Brahmaputra	Mahakam	Orinoco	Yukon

The deltas that score three or more times with the best 4 are Lena (4), Ganges-Brahmaputra (3) and MacKenzie (3).

For further interpretation, a subset can be created from these 20 deltas by applying several criteria. That is, however, also a more context-dependent (subjective) approach. Here we provide two examples of the results:

1. For a focus on *deltas where many live* (ppf2000 top 10), *which are physically vulnerable* (surgeh100y top 20), and that *have potential for soft measures* (area02 bottom 20), the following listing pops up:
   1. Red Asia
   2. Po Europe
   3. Ganges-Brahmaputra Asia
   4. Mahanadi Asia

   Note that ppf2000 and surgeh100y are correlated (Annex), and that the number of deltas selected 10 or 20 was determined by taking the curve of the bar charts (rankings, figures in section 6.4) into account.
2. If a selection is made on *stock at risk* (Top 10) and *delta area* (Top 10):
   1. Ganges-Brahmaputra Asia
   2. Huang He (Yellow) Asia
   3. Mississippi North America

   Note that ppf2000 and delta area are correlated.

The Rhine-Meuse-Scheldt delta
The complex delta of Rhine, Meuse and Scheldt that forms the low plains of The Netherlands and a part of Belgium is not included in previous chapters, since it is absent from the data bases used. This is probably due to the fact that it does not comply with the definition of a delta applied in these data bases. It is our experience that system-based measures are applied along its coasts, as exemplified in chapter 4. Parts of this complex delta thus must be suitable for this type of measures.

6.5 Summary

From the pervious sections can be seen that the world's deltas are diverse, and that different deltas are suitable for different 'soft' system-based approaches. It is graphically apparent from the rankings that there is a difference in position of deltas depending on indicator, and a difference in pattern: some bar charts show a monotonous increase, whereas others are distinctly exponential, or even curved in a complicated fashion. This highlights the need of a comprehensive and context-specific consideration of different indicators! This is facilitated by the DELTAS system because it gives easy access and to all rankings and background data stimulates comparison through its navigational options.

7. Examples of system-based measures in four deltas

This chapter examines the results of the previous chapters with regard to four deltas. This is done using the four system-based strategies mentioned in Chapter 4: physical measures aimed at the management of sediment (7.1), physical measures aimed at the management of water (7.2), adaptation (7.3) and no action (7.4).

7.1 Restoring sediment dynamics

Intervening in the sediment management of a delta can be an effective manner of combating coastal erosion and flooding resulting from climate change. Previous analyses (see Chapter 6) show that deltas that fulfill one or more of the criteria presented below are potentially particularly suitable for this type of system-based measure:

- Deltas with uplift: in such deltas, relatively little sediment is required to bring the delta into balance with the rising sea level. Measures that restore the sediment balance are much more effective here than in deltas confronted with subsidence;
- Deltas with a large coastal plain and a lot of space: a lot of physical space is generally necessary to take measures to restore the sediment dynamics, such as 'depoldering' and the restoration of mangroves;
- Deltas with a low offshore slope: steep slopes will limit the efficiency of sludge dumping and beach nourishment as a large proportion of the sediment disappears down the steep slope into the sea.

The Danube delta is an example of a delta that seems to be suitable for restoring sediment dynamics. It will be affected greatly by the rising sea level in view of the large number of people potentially flooded in 2000 and has a high rate of uplift.

The Danube delta
The Danube is the second largest river in Europe. The 2.860 km long river has a total catchment area of 817.000 km^2 and runs through twelve countries. Near the delta, the river divides into several branches towards the Black Sea through a vast delta with a surface area of 564.000 hectares. 80% of the delta lies in Romania, the rest in Ukraine. The delta hosts a variety of natural habitats; the most celebrated of these are the largest reed beds in Europe, covering over 50% of the delta.

The Danube delta is the result of interaction between dynamic processes in the transition zone between the river and the sea over the last 7.500 years. On the seaward side, the north-south current of the Black Sea once created a long, narrow sandbar, forming a lagoon. The Danube filled this large lagoon to the west of the sandbar until 1770. The outer delta, to the east of the sandbar, was formed from about 1770 onwards. Of the three main branches of the Danube, the youngest and most northern one, the Kiliya branch, is currently the most active branch, transporting more than 60% of the water and the sediment.

The floodplain
Over the course of thousands of years, the lagoon to the west of the sandbar gradually filled up with sediment from the river in a complex history of rising and falling sea levels. Today, the area still is extremely flat. The western part lies only 2 meters higher than the eastern part 150 km away. In the past, the delta would be

almost completely flooded during flood seasons, and some nutrients and silt reached the flood plain. This regular flooding had a major impact in the following ways:
- making the flood plain soil naturally fertile;
- desalinization of the flood plain;
- refreshing the water in the lakes;
- creation of natural biotopes for plants and animals.

However, the capacity of the deep main river channel was so large that most of the water, along with most of the silt and nutrients and all of the sand, was transported directly to the sea. The Romanian part of the delta is still regularly flooded during spring floods, but the Ukrainian, northern part of the delta receives almost no water, sediments or nutrients since the construction of embankments over the last 40 years (Figure 7.1, WWF, 2002). This has significant consequences for several key processes in the delta as a whole since 75% of the water flows through the northern part of the delta:
- Slow growth of the inner parts of the delta. As much of the sediment passed through the delta to the sea, there was not much available for building up the height of the delta. These circumstances account for the existence of the very extensive plains with reed beds and lakes in the delta. The embankments built in recent time, sectioning off large parts of the Ukrainian flood plain and most of the islands in the northern distributary, have completely halted the growth process.
- Filtering of the river water. When the waters of the Danube reached the immense reed beds and lakes of the vast flood plain over a four-month period each year, at least some of the water was filtered by the flood plain: silt particles were removed and nutrients supported the luxuriant reed growth. No filtering has taken place in the reed beds since the construction of embankments.
- Formation of river banks. During flooding, silt particles in the water were deposited on the riverbanks and in the adjacent stretches of reed beds. In the present embanked situation, there is virtually no sedimentation except for the narrow strips of land not encircled by dikes.
- Development of islands. Islands in the river developed in the same way as the riverbanks but in a distinctive form. This is the reason for their saucer-like shape, high at the outer edges and lower in the middle. Nowadays the islands are embanked, sedimentation is absent and the center of the islands subsides due to consolidation;
- Growing in line with the sea. The water level in the oceans and seas has risen by about 30 cm over the last two centuries. The siltation rate of the Danube flood plain has apparently kept pace with the rising water level in the Black Sea, despite being quite slow. The riverbanks remained dry, while insufficient sediment reached the main area of the delta plain, the extensive reed beds and the shallow lakes to keep them completely dry, although they were not flooded by the sea either.

It is predicted that the sea level will rise at a faster rate in the near future, at an estimated 50–90 cm this century alone. In order not to become completely submerged, the area must be accessible for the available sediment. This should allow it to keep pace with the sea level.

The outer delta

The quantity of sediment that reaches the outer delta, which lays completely in Ukraine, is very important for the growth of this most dynamic part of the delta system. The quantity of sediment increased during the 19th century when a larger

area of land in the catchment area was brought into cultivation. On the other hand, the influx of sediment decreased sharply after the construction of the Iron Gate dams in the mid-20th century. The isolation of the flood plain from the (rest of) the delta by the embankments further increased the influx of sediment.

A number of important processes take place in the outer delta:
- Formation of sandbars. The sediment carried by the river to the sea is subjected to the forces of the waves and currents, along with sand originating from the sea. The force of the waves creates sandbars in the coastal area. These sandbars develop parallel to the coastline in a north–south direction. At the same time, the sea currents transport the sand southwards, hence the asymmetric fan-like form of the outer delta. Locally, the sandbars develop into dunes.
- Formation of numerous outlets, reed beds and the filtering of silt and nutrients. The sandbars block the river mouths at the point where the river meets the sea. Behind the sandbars, the dunes, and the shallow river mouths, the water stagnates. The discharge of the Kiliya branch flows through many small distributaries towards the sea, and seeps through the reed beds in places. The outer delta therefore has a bowl-like shape: a series of ever-renewing sandbars at the outer edges of the delta with behind them an area where silt is deposited, reed beds develop, and many branches bifurcate.

Neither dikes nor embankments have been constructed on the outer delta, so the area has retained many of its natural qualities. However, some of the larger river branches used to be dredged for shipping, providing an easy artificial outlet for the water, sediment and nutrients. Both the filtering capacity and the growth of the delta have been negatively affected by the dredging.

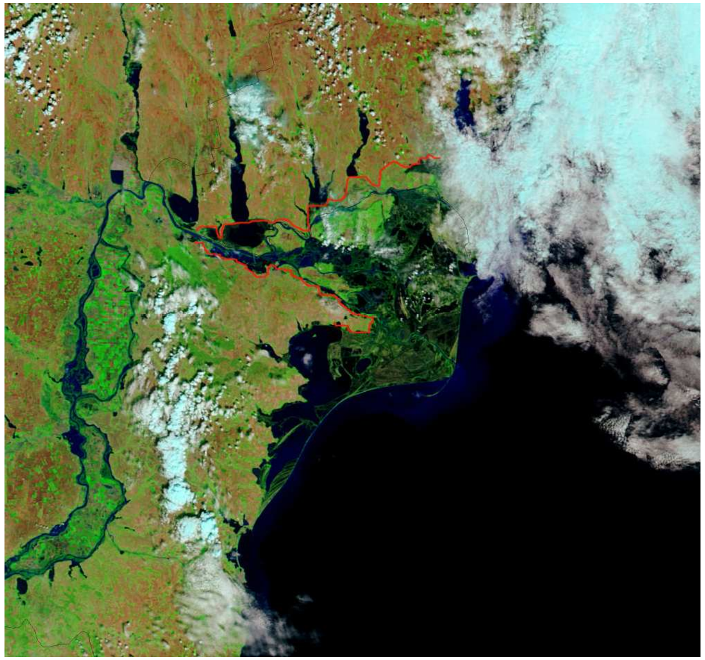
Potential for a natural system

In order to restore the ecology and functioning of the delta, a choice needs to be made as to whether the problems in the area should be solved by means of technology or by making use of the natural processes as far as possible. The first option involves numerous technical solutions for isolated problems. Some problems, however, would be too large for technical solutions; for example, the filtration of the water of the Danube, sedimentation on riverbanks and in the reed beds at a rate that would allow the delta as a whole to grow in line with the expected rise in the sea level.

The second method implies the restoration of the natural system as a whole. The re-establishment of the natural morphological system by reconnecting the flood plain and the islands to the river by removing the dikes (as far as possible) will solve many of the problems with which the delta flood plain is now confronted. Due to the embankments, almost the entire natural system of the flood plain is currently in a state of hibernation. Restoring the annual flooding would bring most of the natural processes to life again.

A transition zone from river to sea, from freshwater to salt water, and from clay to sand can be found near the sea. This part of the delta has proven its ability to maintain its rich and healthy state to date. It is continually changing in time and space, and will follow the major climatic changes of our era, i.e. the rising of the water level in the Black Sea.

Figure 7.1: During the march 2006 floods large parts of the Romanian part of the Danube delta were flooded (black and dark blue in this false color image). The Ukrainian part in the north wasn't flooded, due to embankments. The red line shows the border of the whole flooded area before construction of the embankments.



7.2 Water management and flood restoration

Intervention measures targeting the water management of a delta generally take up a lot of space. This is why it is mainly deltas with plenty of space and a large delta plain that are suitable for this type of system-based measure. The surface area of natural wetlands is also a good indicator, as this is also a measure of the space available within a delta (see 6.4). These natural areas could be used for water storage measures, for example.

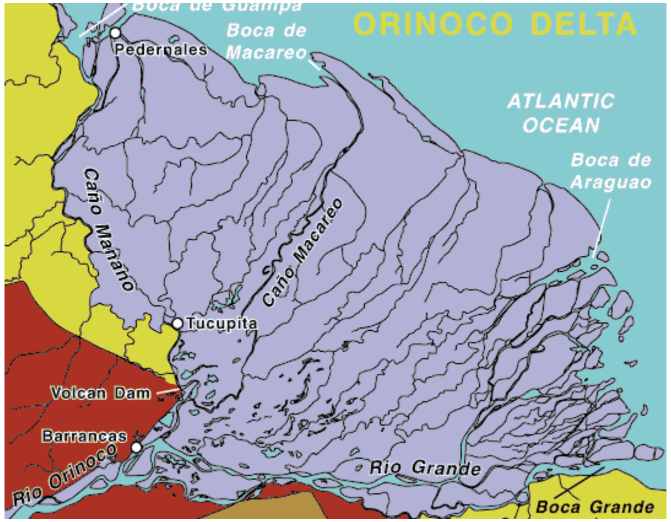
Examples of deltas that could potentially be considered for water management and flood restoration measures include the Mississippi, Orinoco, Irrawaddy and Huang He deltas. In these deltas a large area of natural wetlands is present and they have a large delta plain.

Orinoco delta

The Orinoco River is one of the larger river systems in South America. It has its source high up in the Guiana Highlands, meanders its way through the dense rainforests of Venezuela and discharges into the ocean (WDD). The upper Orinoco delta is fundamentally controlled by river discharge and lies generally 2,7 to 7 m above mean sea level (AMSL). It is seasonally flooded and naturally covered with deciduous forests (although much has been cleared by humans). The middle part of the delta is a result of complex interaction between river discharge, tides and local rainfall. The middle delta plain is <1 to 2.5 m AMSL, is flooded for most of the year and is covered by evergreen and palm forests.

Human activity has had a profound impact on the ecosystem of the Orinoco delta. The construction of the Volcán Dam (Figure 7.2) has significantly influenced the hydrology and ecology of the north-western Orinoco Delta by reducing the water and sediment discharge. In addition, the clearing of forests in the upper delta for agriculture, grazing, and human habitation has also had a significant impact upon the delta ecosystem (Bureau of Economic Geology, 1998). The Orinoco delta covers an enormous area between 0 and 2 m AMSL. Despite the lower population density, the number of people potentially at risk of flooding (in 2000) as a consequence of climate change is greater here than in the Nile delta, for example. Due to the large area covered by natural wetlands and the large delta plain, the Orinoco delta appears to be suitable for the implementation of water storage measures such as the controlled flooding of wetlands during floods and the creation of retention areas.

Figure 7.2: Map of the Orinoco delta with the Volcán Dam (Bureau of economic geology 1998, Texas University)



7.3 Adaptation

Adaptation measures can be implemented in deltas where it would not be effective to take physical measures regarding sediment and water management. This may be the case in deltas where:

- physical measures are simply not possible, for example because there is no physical space or sediment available;
- the costs of physical measures are out of proportion with the damage and/or losses that would be suffered as a result of flooding.

In these deltas, measures tackling or compensating for the consequences of flooding are much more effective than physical measures that aim to prevent that flooding. Some indicators for deltas where this is the case include (see 6.4):

- the size of the coastal plain and the amount of space available: wider delta plains offer more options for adaptation measures such as the relocation of people and industries, the restriction or directing of land use types etc;
- GDP: in places with a low GDP, it will be cheaper to pay out compensation for losses than to take physical measures. This can be determined by means of a cost-benefit analysis.

The Ganges-Brahmaputra delta

The Ganges and Brahmaputra rivers form one of the largest river systems on Earth. The delta is also one of the largest in the world, covering some 105.640 km^2 (see photo). The main area of abandoned deltaic plain lies to the west and is home to one of the largest mangrove regions in the world, the Sundarbans. The site of active deltaic sedimentation lies to the east. Wave energy in the delta is relatively low and, as a result, few beaches are present along the shoreline and muddy tidal flats are common. The coastline is extremely irregular as a result of the large number of tidal channels that dissect the coast. Broad mud and silt flats border the coast. The offshore slope in front of the delta is extremely low. The Ganges-Brahmaputra delta is subsiding by more than 1.5 mm per year.

Lower Deltaic plain of the Ganges-Brahmaputra delta (Hart & Coleman, 2004).

The Ganges-Brahmaputra delta is one of the world's most densely populated deltas. Humans therefore have a major impact on the delta. The inland part of the tidal plain is now protected by dikes, and the former saline lands have been converted into various agricultural and marine farming areas. Originally, the entire surface of the abandoned delta formed a vast expanse of mangrove forests, but large areas of the original wetlands have been converted for agricultural use. The only areas in which agricultural expansion has not taken place are those areas where saline tidal waters intrude into the delta plain, such as the Sundarbans. Yet even here, agricultural land is being expanded by means of the construction of levees to prevent salt water intrusion.

Fishermen at the Sundarbans (Left: www.zipcon.net/~beckyd/grapefruit - archives/fisherman_sunderbands.htm, right: www.grandpoohbah.net)

Due to the high population density in the coastal area, the situation in a subsidence zone and the expected significant rise in the sea level, the number of people potentially at risk of flooding as a result of climate change is high. There is therefore a great necessity to take measures.

Physical measures in the Ganges-Brahmaputra delta in terms of sediment and water management would appear to be virtually impossible now, despite the enormous supply of sediment. Due to the high population density, there is hardly any space left for any intervention measures. Even an adaptation measure such as the relocation of people from the most vulnerable areas of the delta would be difficult as there is so little suitable and available land beyond the delta plain.

Due to the low GDP, it would therefore probably be more cost-effective to take adaptation measures, which could consist of:

- the construction of hills and refuge mounds to limit the consequences of floods;
- offering financial compensation for losses resulting from flooding;
- setting up an early warning system to warn the inhabitants in case of disasters.

7.4 Do nothing

Taking no action may be the best strategy for some deltas. Such deltas are those in which so few people live and where the economic interests are so minor that coastal erosion and flooding as a consequence of climate change will cause little damage. There is therefore no necessity to take measures.

Fly delta

The Fly (see photo) is the world's 23rd largest river. It flows almost entirely through Papua New Guinea and originates high in the island's Central Mountains. The high peaks and high rainfall create a fast-flowing, gorge-cutting, landslide-producing river, turning into an aggrading and meandering river closer to the sea. It discharges into the Gulf of Papua via a 40-mile wide mouth. The Fly River delta displays a classic funnel-shaped geometry of a tide-dominated system. The area of the delta is 6.230 km^2. Mid-channel islands, covered by mangrove vegetation, are common in the distributary system. Tidal mudflats abound at low tide (www.vims.edu/margins/fly.htm).

Fly river delta (Hart & Coleman, 2004).

Unlike most large rivers around the world, the Fly River drainage basin has been relatively undisturbed by humans. There is little economic activity, besides a number of coconut plantations, and only a few people live along the course of the Fly river course and on the delta. There are copper and gold mining operations upstream, in the Ok Tedi and Strickland (tributaries of the Fly), but otherwise urban development is essentially absent in the 75.000 km^2 catchment area.

Calculations show that this delta will be greatly influenced by climate change. The 1/100yr surge height is large. However, so few people live on the Fly delta – the coastal population is less than 2 people per km^2 – that there are no people potentially at risk of flooding. The economic interests in the delta are relatively minor. There is no need for any measures to be taken to combat the consequences of climate change or to reduce the damage.

8. Conclusions and subsequent steps

Conclusions

Deltas are complex sedimentary structures, built from sediment and water. There are several natural factors that control the processes in a delta, and their influence varies from delta to delta. It is important to gain a good overview of the dominant processes at work in a delta, as these form the basis for system-based measures.

Intentionally and unintentionally, humans have a great impact on deltas. They change the natural processes within the delta in order to be able to live and work there. Most human interventions disturb the equilibrium between the supply of sediment and erosion processes. As a result, affected deltas are no longer able to respond to modified circumstances such as climate change.

Four strategies of system-based measures can be distinguished: physical measures aimed at the management of sediment and at the management of water, adaptation and no action. The extent to which measures could contribute to the continued existence of deltas is greatly depending on the space and scope available within a given delta. Which measure can best be taken depends on local geomorphological, ecological, economic and social circumstances.

It will not be possible to save an entire delta with a single type of "soft" intervention. System-based measures will not be sufficiently effective to completely exclude the need for technical measures. However, on a smaller scale and locally, system-based measures can be adequately effective.

Data used have been extracted from available worldwide databases. These data have their constraints in the worldwide nature of the databases used: local detail can often not be offered, and not all deltas of the world could be included.

Three simple, generic indicators provide a first, quantitative glance of vulnerability, stocks at risk and the potential for system-based measures. These are: 1/100 yr surge height, people potentially flooded in 2000 and area of the coastal plain between 0 and 2 m above mean sea level. In addition to these generic indicators, a range of specific indicators is provided that can offer detailed informed on specific aspects of vulnerability, risk and the potential of system-based measures.

The world's deltas are quite diverse, and so will be their responses to climate change and the potential for soft measures to accommodate or counteract this. Different deltas are suitable for different 'soft' system-based approaches. Looking at a single indicator simplifies the complex reality. The real diversity can be visualized and studied using the DELTAS system for innovative delta management.

System-based measures as described in the present report will be applicable beyond deltaic coasts. Site-specific conditions and prevailing natural processes will determine suitability on other coastal types such as estuaries and sand-bar systems.

One of the objectives of phase 1 was to come up with a list of deltas that might be interesting for the next phase. Taking the 4 highest-ranking deltas for all individual indicators mentioned in section 6.4 gives a list of the following list of 20 deltas:

Chao Phraya	Godavari	Mekong	Parana
Danube	Krishna	Mississippi	Po
Fly	Lena	Niger	Shatt el Arab
Fraser	MacKenzie	Nile	Yangtze-Kiang
Ganges-Brahmaputra	Mahakam	Orinoco	Yukon

The deltas that score three or more times with the best 4 are Lena (4), Ganges-Brahmaputra (3) and MacKenzie (3). For further interpretation, a subset can be created from these 20 deltas by applying several criteria. That is, however, also a more context-dependent (subjective) approach.

The deltaic complex of Rhine, Meuse and Scheldt has a particular position. It was not included in the present study, since it did not feature in the data bases used. Since system-based measures are equally applicable on delta-similar coastlines, this complex of river mouths will be included in the subsequent phase of this project. Because system-based measures have been applied here, we presume that the area is potentially promising.

Subsequent steps
This study includes an inventory of deltas that will be confronted with the effects of climate change in the future. This was looked at on a global scale and on the basis of existing knowledge. The next step consists of the selection of a number of deltas (with the aid of DELTAS) with good potential for system-based measures. We will then look more closely at these deltas, or even just at parts of the deltas. The following aspects will feature in the next phase:
- the further study of the ecological, morphological, economical and social functions of these deltas;
- the collection of supplementary information;
- the mapping of the effects of future climate changes on these deltas;
- the mapping of the way in which system-based measures can be used to anticipate climate change;
- the mapping of the opportunities that arise with regard to social and economic aspects.

After using the system, phase 2 should comprise contacting local experts and key informants for subsequent steps to be taken as well as searching local partners and institutions cooperating with the development and realization of system-based measures in the selected deltas.

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Annex 1

Testing and selecting indicators to assess vulnerability and potential for system-based engineering of deltas

1 WDD indicator testing

The WDD could provide various indicators for vulnerability and potential for system oriented engineering. Potential WDD indicators were explored by plotting potentially causal relationships. The form of the delta could be important for e.g. accommodation space. Parameters that describe this form could therefore be important vulnerability indicators.

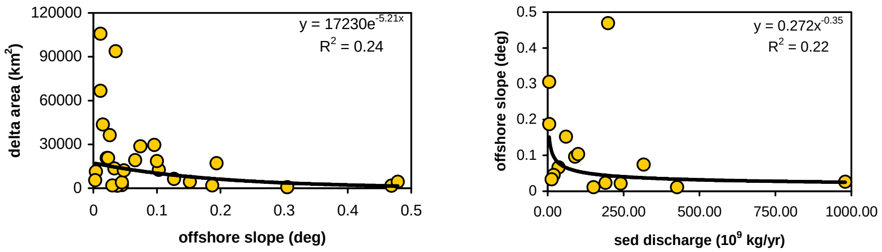
Going one step further, the form of the delta could be related to both the amount of available sediment, and the forcing processes that should transport this sediment. Particularly delta area, subaerial/subaqueous and shoreline, and to a lesser extent also the number of river mouths and the offshore slope, describe the form of the delta. River water discharge, tide, and wave power and height determine transport of the available sediment. Sediment discharge, subaerial/subaqueous and offshore slope determine the potentially available amount of sediment. We analyzed whether the data sets were correlated (R2 in the figures below), and performed a two-tailed significance testing (p in the figures below). Table 1 gives an overview of tested variables.

We realize that such an overview can appear rather abstract. Therefore, we show some relationships between variables in following figures. Some figures also illustrate that potentially meaningful relationships may fail to be significant at $p<0.05$ due to often only a single outlier. Delta area could be an important parameter for accommodation space, and is correlated with another description of form, offshore slope. The latter is amongst others correlated again with river sediment discharge. This relationship however is not significant ($p > 0.05$) and is therefore not mentioned in Table 1.

Table 1: Overview of potential WDD indicators tested for causal relationships. Presented are the level of significance and the coefficient of determination (R2) for at most three independent variables. When a correlation has a negative sign, this is indicated with [-].

Variable	correlates with variable	R^2	variable	R^2	variable	R^2
Process (enabling the transport of sediment) v form (built with sediment)						
Annual av discharge	delta area (<0.01)	0.41	# river mouths (<0.05)	0.18		
Max discharge	delta area (<0.01)	0.47				
min discharger	# river mouths (<0.01)	0.46				
spring tide	# river mouths (<0.05) [-]	0.15				
wave power shoreline	subaerial/ subaqueous(<0.01)	0.53	offshore slope (<0.01)	0.69		
Transport of water v transport of sediment						
annual av. discharge	sed. discharge (<0.01)	0.45				
max discharge	sed. discharge (<0.05)	0.27				
Form as a descriptor of sediment availability v form as a result of the available sediment						
offshore slope	delta area (p<0.01) [-]	0.24	subaerial/ subaqueous (p<0.01)	0.53	river mouths (p<0.01) [-]	0.27

Figure 1: Exploring delta area in its relation to sediment availability at the offshore slope and a driving process sediment discharge.



An example of process (enabling the transport of sediment) versus form (built with sediment) can be explored by looking at the variable wave power. It is correlated with many form parameters, such as shoreline ($p > 0.05$), offshore slope, and subaerial/subaqueous. The latter is not surprising because offshore slope and subaerial/subaqueous are also correlated themselves.

Figure 2: Wave power is correlated with several form parameters. The number of river mouths is another interesting WDD variable that is related to offshore slope, and sediment discharge ($p > 0.05$).

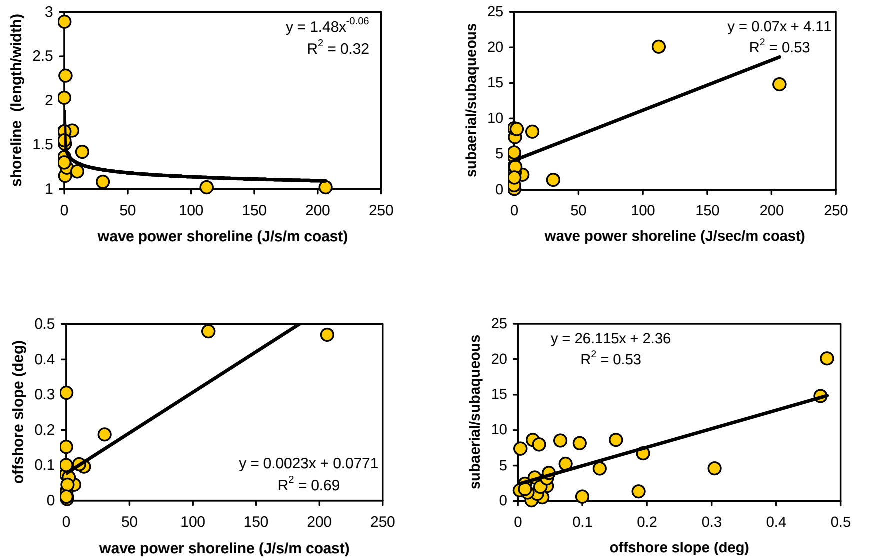
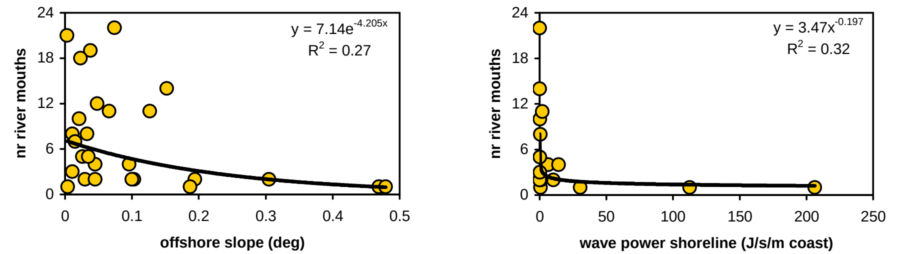
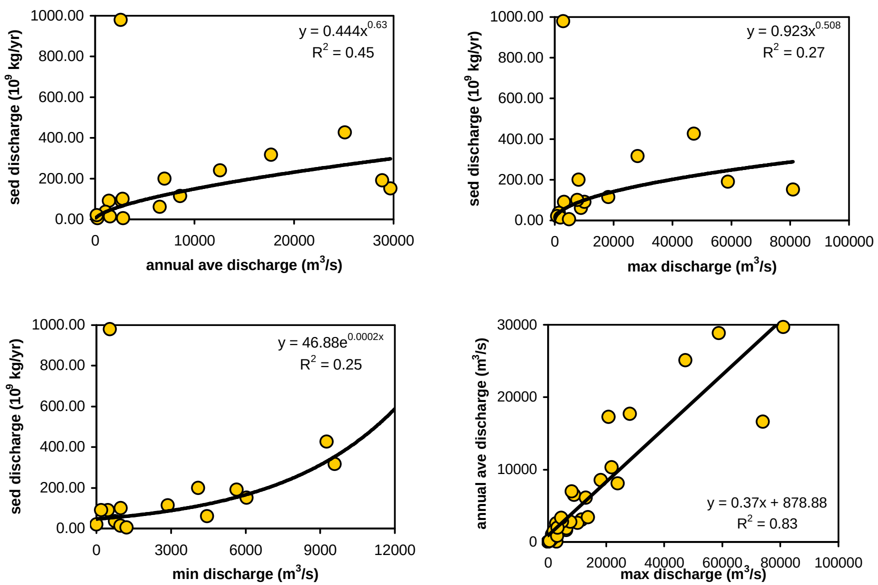


Figure 3: The number of river mouths and offshore slope and wave power are correlated.



For the river we explored the discharge of water versus the transport of sediment. In deltaic environments, the discharge of river water can also be important as a variable potentially related to flooding. The seawater related variables in WDD (spring tide and wave power and height, that were elaborated before) could be combined with, e.g., height of the dikes from Diva (sections 2 and 3 in this Annex) for further analysis of probability of flooding by the sea. The outlier responsible for decreasing the correlation coefficients is Huang He (Yellow River), which seems to have an extremely high sediment discharge (980 x 109 kg/yr) for its water discharge.

Figure 4: Correlations of river water discharge and sediment discharge.



Finally, a principal component analysis was performed. Principal components analysis (PCA) is a statistical technique that can be used to simplify a dataset (cf Jongman et al., 1987). It is a linear transformation that chooses a new coordinate system for the data set such that the greatest variance by any projection of the data set comes to lie on the first axis (also called the first principal component), the second greatest variance on the second axis, and so on. PCA can be used for reducing dimensionality in a dataset while retaining those characteristics of the dataset that contribute most to its variance, by keeping lower-order principal components and ignoring higher-order ones. The idea is that such low-order components often contain the most important aspects of the data. However, this is not necessarily the case, depending on the application.

This analysis was performed on a selection of the WDD dataset as described in Table 5.3 without sediment discharge and wave power, because of a relatively low number of available observations for these variables. For the WDD dataset:

- The first axis comprises annual average discharge, maximum discharge, minimum discharge and delta area and shoreline. It explains 37 % of the total variation. This component describes river-form relationships.
- The second component comprised subaerial/subaqueous and offshore slope, and explains 18.5 % of the variation. These describe sediment availability and form.
- The third component comprises spring tide, rms wave height and number of river mouths, and explains 14.5 % of the variation. It seems to describe marine forces versus a form relationship number of river mouths (Number of river mouths is higher on a gently sloping delta).

In total 70% of the variation in the (tested part of the) WDD dataset was described with these 3 axes. Using only one separate variable from each axis would already allow characterizing the form of the deltas from causes related to river, sediment availability, and marine forces.

2 DIVA indicator testing

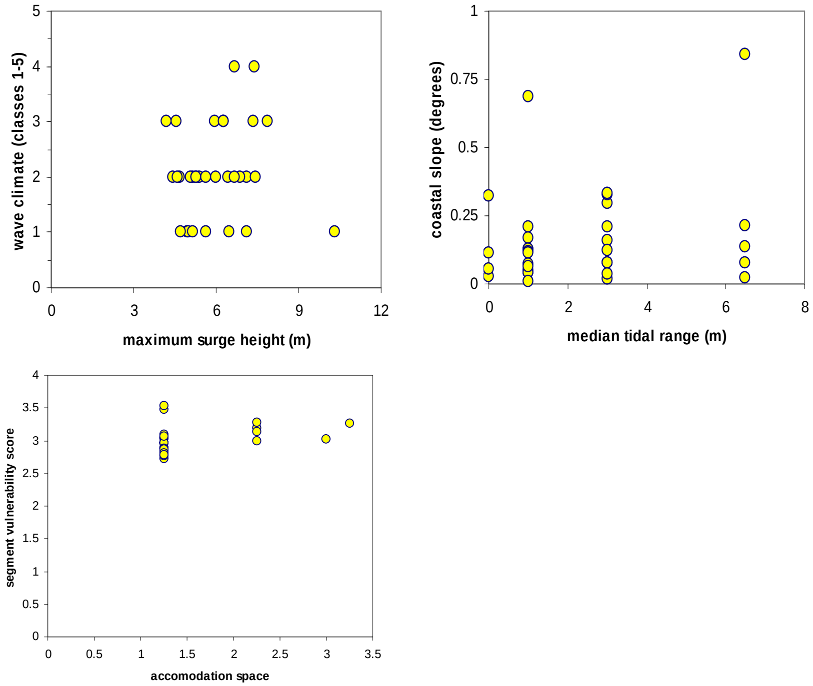
Combining of the 43 WDD deltas with the 115 rivers available in DIVA did not result in a complete match. Several rivers end up in lakes (e.g. Amu Darya in the Aral Sea and the Salenga in Lake Baikal), some deltas are not covered in the DIVA river set (e.g. Baram, Colville, Grijalva, Klang, Ord). Many DIVA rivers obviously have no clear delta. This led to a coupled set of 34 rivers.

Physical vulnerability

Two major compound indicators available in DIVA are the segment vulnerability score (CSVS) and accommodation space (ASPACE). The deltas studied here appear to vary only slightly in CSVS. This scaled, categorical indicator varies between 2.5 and 3.5 only (Figure 5). In contrast, accommodation space shows a wider span. It must be noted that a high score in DIVA indicates high vulnerability, thus a high value for ASPACE suggests that there is little room for accommodation in the adjacent hinterland. Apparently, the bulk (28 of 34) of the deltas is estimated to have substantial accommodation space for inland migration of the present coastline.

The two outliers are the Niger in Nigeria and the Mangoky in Madagascar. One of the constituent variables of the CSVS is sediment supply (SEDSUP). This again is a categorical indicator with 5 classes and class 1 indicating high sediment supply thus low vulnerability, whereas 5 indicates high vulnerability. All 34 deltas and 115 DIVA rivers, however, have been classified as belonging to category 3 (moderate) or 4 (high to moderate vulnerability), limiting the usefulness of this indicator. Wave climate, maximum surge height, tidal range and coastal slope all span a substantial range: clearly hydrodynamic conditions in adjacent coastal waters differ among deltas.

Figure 5: Scatter plots of potential indicators of physical vulnerability for 32 deltas in DIVA.



Deltas combining high surges with a high tidal range and an overall rough wave climate are probably more vulnerable to erosion, land loss and flooding. Examples of deltas that may experience a maximum surge over 7 m are the Zambezi, Red River, Mekong, Ganges, Fly, Fraser and Lena. High tides (5-8 m) are experienced at the Zambezi, Mangoky, Shatt al Arab, Ganges and Burdekin, whilst deltas in the Mediterranean and Caribbean experience little to no tides. Sea level rise appears highly variable among deltas, and the direction of future world development appears to make a distinct difference (Figure 6).

Figure 6: Sea level rise according to DIVA in the 32 deltas in 2100 related to sea level rise in 2000, all expressed as meter change after 1995.

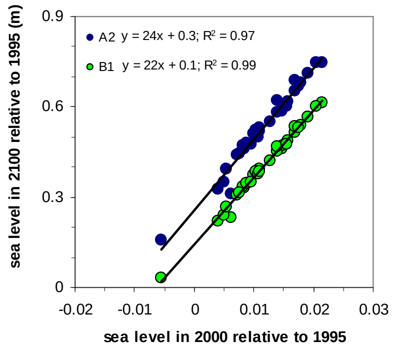


Figure 7: A range of socio-economic DIVA indicators.

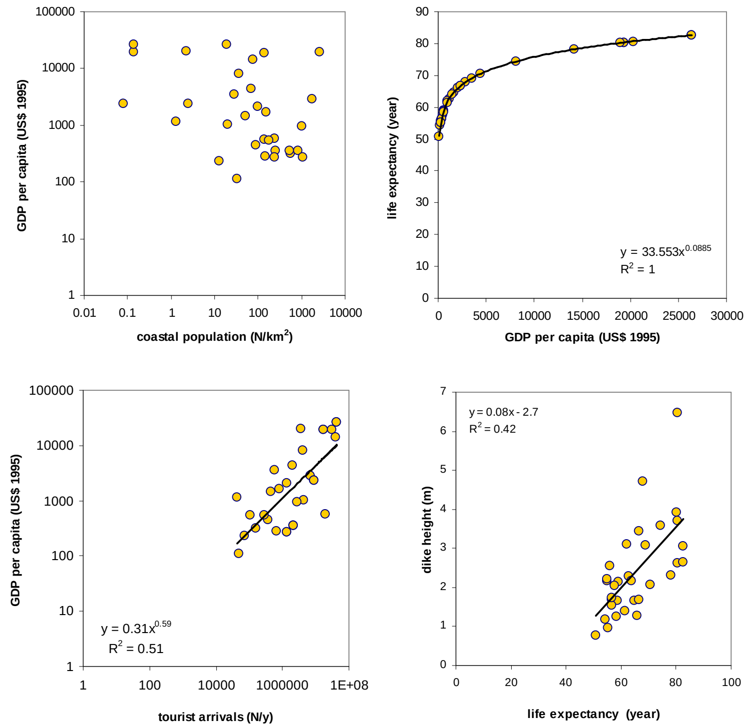
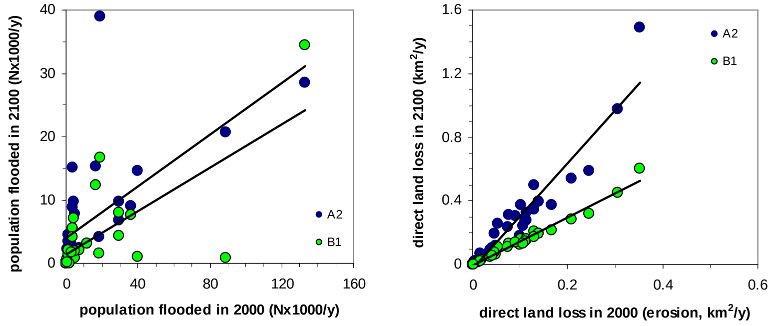


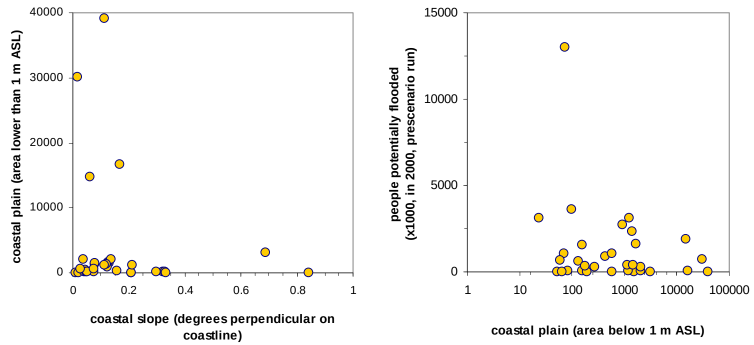
Figure 8: Population at risk and land lost in 2100 as a function of two scenarios according to DIVA simulations.



Stocks at risk

The DIVA indicators of coastal population density and economic activity value (as GDP) show substantial variability among the deltas covered (Figure 7). Life expectancy appears to be extrapolated straight from GDP in DIVA, since the explained variance of our subset was 100%. Dike height and tourist arrivals (in 1995) show clear co-variability with GDP (and hence life expectancy). Whereas estimated land loss in 2100 correlated well to land loss in 2000, the estimated population flooded and hence people estimated to suffer serious losses did not covary well across time: overall, less people were estimated to be flooded in 2100, probably because DIVA assumes that economically feasible measures will be taken or land will be evacuated when submerged in sea. The overall pattern when comparing the two scenarios is that under A2 sea level rise will be more serious and hence all consequences as well. Overall, it can be concluded that the following socio-economic variables from DIVA offer useful variability among deltas: coastal population, GDP, dike height and possibly tourist arrivals. The distinction in future development according to scenarios also makes a sensible difference.

Figure 9: DIVA indicators that can be used to assess the potential for soft engineering measures



Potential for soft engineering

Several possibly useful indicators have been sorted to allow a detailed check-up (see below). Obvious variables were sediment supply and accommodation space (SEDSUP and ASPACE), but only accommodation space was found to differentiate between deltas (Figure 5). Other variable should be the area of low coastal plains (for example < 1 m above sea level), and the slope across the coastline. Both display substantial variation among deltas (Figure 9). Steep coastal slopes generally have less coastal plains, but the scatter remains substantial. The highest number of people potentially flooded occurred in Bangladesh (Figure 9 right panel, the outlier) in a comparatively small coastal plain.

DIVA- indicators combined

A principal components analysis of all DIVA indicators combined for these 34 deltas suggested that three major axes together explained a significant part (52%) of the total variation. The first axis correlated to storm surge indicators, and explained 21%. The second axis (additional 19%) was related to lowland areas in the coastal plain characteristics, and the third axis related to the population that was potentially flooded (additional 12%). Further components added little to the explained variance and were not strongly correlated to any of the underlying individual variables. Notably, the population that would actually be flooded in 2100 under scenario A2 correlated strongly to PCA-axis 1. Thus, physical (axes 1, 2) and socio-economic indicators (axis 3) do span across different dimensions in the DIVA database. This justifies a separate inclusion of these types of indicators and supports our initial distinction in three categories of indicators.

Single linear correlations among the many variables used here support the overall pattern of the PCA: several clusters of variables exist. Table 2 only reports the most outstanding and significant (p>0.05) correlations. Most projections for scenarios A2 and B1 also correlate well with the values estimated for 2000. This confirms the pattern of Fig 8. Lowland areas available in deltaic coastal segments correlate well, so when there is a large area below 1 m AMSL, then the same holds for 2, 3 and 4 m elevations. Since scenario-based indicators of stock at risk were found to covary closely, we propose to use the estimates for 2000, and maybe use the B1 and A2 scenario outcomes as an indicator of possible band with of future developments. It is noteworthy, that indeed the B1-scenario, geared towards a sustainability-oriented world, would lead to lower mortality estimates and lower sea level rise.

3 Combining WDD and DIVA indicators

WDD gives an accurate physical description of deltas and the processes that are building and continuously changing their form. DIVA incorporates and produces a much larger set of variables. Where the two datasets provide similar variables (mean annual discharge, tidal regime), these correlate well, which is a comforting observation. We chose to keep such pairs of variables, as well as most others that might be useful for potential future users. Therefore the indicator database is rich in variables.

Possibly interesting correlations between WDD and DIVA are listed in Table 3. For example, delta area in WDD was found to correlate to the set of surge height indicators of DIVA, as well as to the indicator ‘people potentially flooded in 2000’ (ppf200). Further, offshore slope correlated negatively with surge height and with dike height. The PCA of the combined dataset largely confirmed the pattern observed in the DIVA-set: two major geophysical axes (correlated closely with, e.g., surge height and coastal lowland area available) explain most of the total variation, together with one socio-economic axis (correlated to people potentially flooded). These three axes should thus guide our choice of priority indicators. We propose surge height (probably surgeh100y is a best compromise) and area of coastal lowland (areaunder2) as main indicators of geophysical vulnerability and potential for soft engineering measures, respectively. Stock at risk then would best be indicated by the variable ‘people potentially flooded in 2000’ (ppf2000).

Other indicators than the three priority ones suggested above can be useful, when more detailed questions are to be asked. For example, maximum river discharge (WDD) was not found to add substantially to an axis of the PCA, but may well be crucial to determine the flood height of a river entering a delta, and hence the flooding risk for the local population. This could not be ascertained from the present database.

Table 2: Summary of significant linear covariability among DIVA variables for 34 deltas. Presented are the level of significance and the coefficient of determination (r2) for at most three independent variables. When a correlation has a negative sign, this is indicated with [-].

scale	variable	correlates with variable	R^2	variable	R^2	variable	R^2	notes
country	sdikecost	GDPpc (0.03) [-]	0.14					
	GDPpc	areaunder1m (0.01)	0.20					area under 1 m forms a cluster with those under 2, 3, 4 and 5 m, see below
	tourarr	areaunder2 (0.001)	0.35	mediantide (0.033) [-]	0.14			
admin unit	potfloodplain2000	avgdisch (0.02)	0.17	wavclim (0.04) [-]	0.13			potfloodplain in 2000 and 2001 following A2 or B1 are all closely correlated (r-squared often 0.99)
	potfloodplain2100A2, potfloodplain2100B1							
	potlandlosserosion2100A2	mediantide (0.03)	0.14	wavclim (0.03)	0.14			the two scenario-based estimates of potential landloss due to erosion closely correlate
	potlandlosserosion2100B1							
	ppf2000	upsub (0.01) [-]	0.19	surgeh1000y (0.001)	0.98			ppf2000, as well as the ppf and paf for 2100 and both scen.are all closely correlated (r-squared often 0.99)
	ppf2100A2, ppf2100B1							
	paf2100A2	surgeh1000y (0.002)	0.37					
	paf2100B1							
	rslr2100A2	upsub (0.001)	0.29					these two scenario-based estimates of relative sea level rise are closely correlated (r-squared 0.997)
	rslr2100B1							
	sumnaturalwetlands	areaunder2m (0.001)	0.44	rslr2000A1 (0.004)	0.25			

scale	variable	correlates with variable	R^2	variable	R^2	variable	R^2	notes
coastal segment	areaunder1m	areaunder3m (0.01)	0.20					these area estimates fall into two classes : under 1-5, and 6-8, 9-12, 13-16; within these two groups the correlations are higher. Only one example is presented here
	area1316	waveclim (0.01) [-]	0.49					
	avgdisch	areaunder1m (0.012)	0.24					avgdisch of DIVA is closely correlated to that of WDD
	copop	copopd (0.001)	0.50					obviously copop and copopd are correlated.
	copopd	wavclim (0.04)	0.13					
	dikeht	surgeh1000y (0.011)	0.19	GDPpc (0.001)	0.30			
	rivimpact	avgdisch (0.001)	0.61	areaunder1m (0.012)	0.24	slope 0.048) [-]	0.12	rivimpact and salintru are very closely correlated (r-squared = 0.99)
	surgeh1000y, surgeh100y, surgeh10y							all estimated surge heights are very closely correlated (r-squared 0.92 or higher), only one is given as an example
	surgeh1yr	mediantide (0.005)	0.23	upsub (0.026) [-]	0.15	surgeh10 y (0.001)	0.96	
	aspace	slope (0.001)	0.86					note that aspace and csvs are DIVA-vulnerability indicators: high values indicates high vulnerability, so low accomodation space
	csvs	avgdisch (0.001)[-]	0.27	surgeh1000y (0.004) [-]	0.13	aspace (0.05)	0.12	csvs also correlated with slope, directly

Table 3: Linear correlations between WDD and DIVA variables. Further as Table 2.

Variable	Correlates with var.	R^2	variable	R^2	variable	R^2	notes
Delta area (n=31)	Pff2000 (0.001)	0.40	Surgeh1000 (0.009)	0.21	Salintru (0.03)	0.14	Correlations also with other surgeh, with paf2100A2, paf2100B1, ppf2100A2, ppf2100B1, and with rivimpact
Shoreline (n=23)	Tourarr (0.01)	0.27					
N river mouths (n=24)	Rivimpact (0.005)	0.30	Areaunder1 (0.03)	0.19			Also other areaunder2, 3; and salintru
Offshore slope (n=23)	Surgeh100y (0.004) [-]	0.34	Dikeht (0.009) [-]	0.27			Also other surgeh
Springtide 9n=26)	Median tide (0.001)	056	Surgeh1y (0.001)	0.38	Tourarr (0.009) [-]	0.25	Also other surgeh
RMS waveh (n=25)	Potfloodplain 2000 (0.02) [-]	0.21					Also rslr200A2 and pff2000A2
Subaerial/subaqueous (n=24)	Surgeh10y (0.04) [-]	0.17					Also surgeh100y, surgeh1000y

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