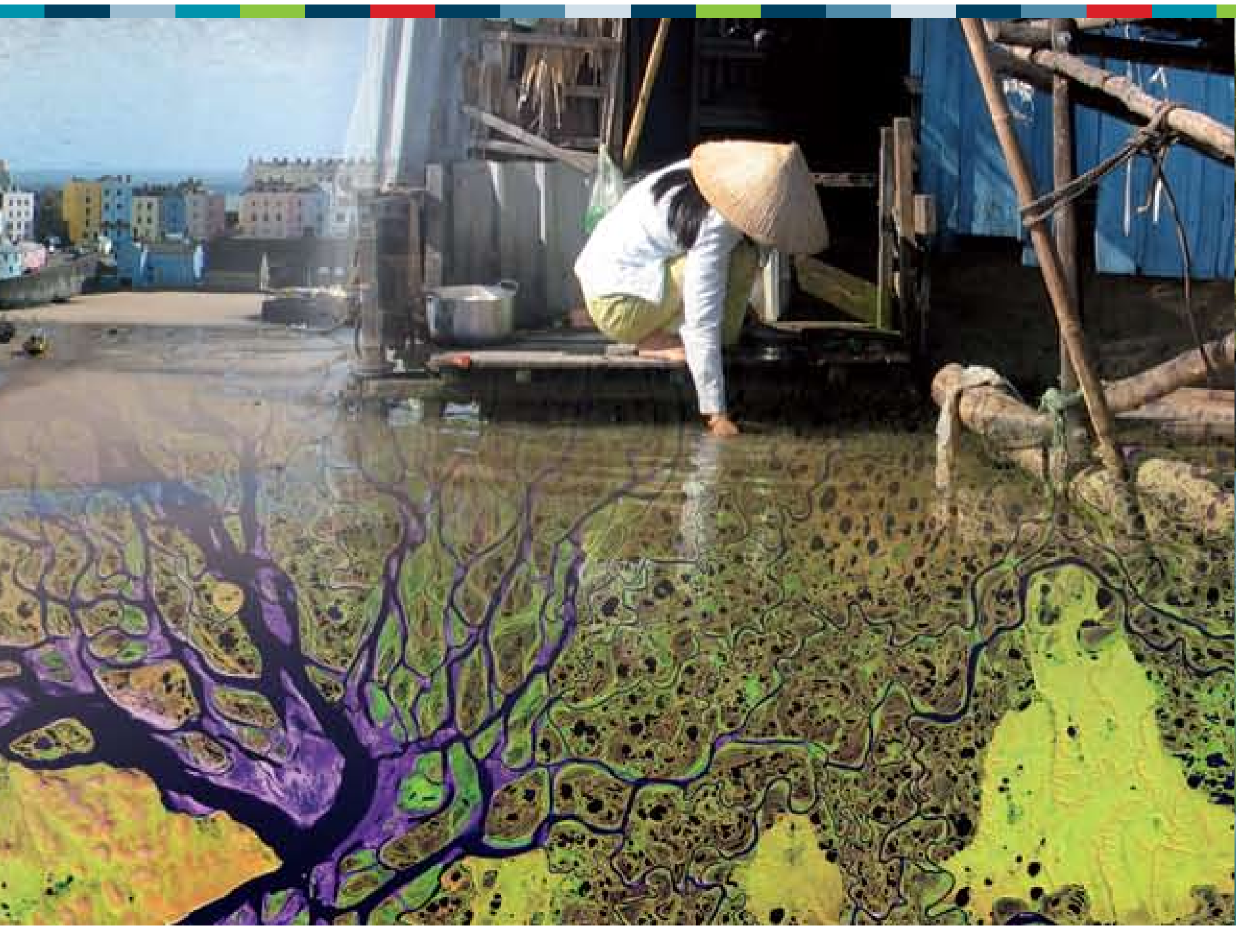

Innovative Solutions for the Delta

Adapting the Deltas of the World to Climate Change: "Inspiration from the Next Generation"

DeltaCompetition 2008

ROYAL HASKONING

thinking in all dimensions

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contents

Foreword

DeltaCompetition 2008: Inspiration from the Next Generation

International character underlined once again

Dear reader,

In the years ahead the world's population will be confronted increasingly by the direct and indirect consequences of climate change. Sea levels are rising, rivers will have to remove ever more water, and the severity of wet and dry seasons is increasing. These changes have a huge impact on the billions of people who live in densely populated, vulnerable delta areas. These are ideal places for people to live – vast, fertile agricultural areas and space for rapidly growing cities and profitable economies. The residents of delta areas have had varying degrees of success in learning to anticipate the hazards associated with living in such vulnerable zones, such as flooding, coastal erosion and hurricanes. The far-reaching and heartbreaking effects of Hurricane Katrina in the area around New Orleans are still burned onto our retinas. The urgent need for appropriate measures is becoming ever clearer.

Royal Haskoning wants to make a contribution to sustainable interaction between people and the environment, and provides consultancy services worldwide relating to enduring solutions so that we can adapt effectively to the changing climate. And Royal Haskoning is also providing a platform, through the DeltaCompetition, for young talent – the new generation of decision makers, who face the challenges of the 21st century with an open mind. We are asking them to join us in the quest for sustainable solutions to the problems – and also the opportunities – that arise due to climate change in densely populated delta areas.

The first biennial DeltaCompetition, which Royal Haskoning held in 2006, was a big success. Students from all over the world picked up the gauntlet we had thrown down. Our requirements were tough. Their articles had to be original, have a scientific basis and be realistic and practicable. A team of students from Delft University of Technology received the well-deserved first prize for their bold plan for 'The Floating City'. And now too, during the second edition of the DeltaCompetition, the international panel of judges – chaired by Professor Lord Hunt – has been pleasantly surprised by the unusual and scientifically underpinned plans.

A few of the many ingenious ideas: students from Ho Hai University (Hong Kong) presented an engineering concept for a double canal and a tidal power station in delta areas. They developed this concept based on a plan for the Chinese Pearl River Delta that was submitted during the first DeltaCompetition. A student from the University School of Engineering in Cardiff investigated the positive effect of mangroves as a natural defence against natural disasters. An article written by three students from the University of Toronto, Canada, was also very surprising. They developed a complete concept for self-sufficient communities with (floating) aquaponics systems in Bangladesh. A splendid example of a multidisciplinary, solution-focussed study. And then there was also Delft University of Technology with a new contribution. A team of students came up with a new approach to delta management, based on their project experience in New Orleans after Hurricane Katrina.

In Adapting the Deltas of the World to Climate Change: 'Inspiration from the Next Generation' you will find the five best entries for the Royal Haskoning DeltaCompetition 2008. I hope that you will get a great deal of pleasure from reading this book. And that the creators of the ideas described in it also inspire you, together with Royal Haskoning, to tackle the challenges facing our delta areas in a creative and sustainable way.

Jan Bout,
Chairman of the Board of Management
Royal Haskoning

preface

Report of the Panel of Judges

The Panel of Judges of the 2008 DeltaCompetition received and reviewed a total of 16 papers submitted by students from all over the world with great pleasure and interest. Compared with the DeltaCompetition 2006, this years' competition consists of a category for teams and a category for individuals. As set out in the DeltaCompetition Rules, the Panel of Judges reviewed the papers according to three assessment criteria:

- Sound scientific fact and reasoning;
- Original, innovative elements; and
- Presentation.

The criteria carried equal weight for the assessment. Points were assigned for each of these assessment criteria, where each criteria weighed equally.

Five papers, 2 individual and 3 team papers, out of those submitted to the DeltaCompetition clearly stood out. These five were nominated for the shortlist by the Panel.

In general, the Panel was very pleased with the range of subjects, the quality and the innovativeness of the papers. It was not an easy task to nominate a shortlist and to select two winning papers. Despite this, the Panel of Judges reached a verdict. The two winning papers, together with a summary, are provided below.

The winning paper for the Team Category of the DeltaCompetition 2008 is:

Design and deployment of Aquaponic Grid Communities
The Ganges-Brahmaputra Delta

By Duc Tung Nguyen, Karthik Ramanathan and Sameer Vohra – University of Toronto, Canada

In their paper, the authors argue that in the Ganges-Brahmaputra delta region, also a heartland of agriculture, society is conscious of the fragility of the delta. In their study, the authors have described a comprehensive concept for small-scale, self-sustaining communities that increase safety, improve the ecosystem, and benefit social-economic development. They have also outlined the detailed economic reality of developing such communities, whilst recognising the economics constraints in Bangladesh.

This paper is a good example of a multi-disciplinary, solution-oriented concept that shows both a mitigative and adaptive approach to climate change. What the Panel of Judges particularly likes about this paper was the novel approach of chemical clean up by vegetation, but also that the scheme can be applied to a range of different contexts, within a framework that provides choice to the local community. The quality of the writing and good presentation of the argument are particularly noted.

The winning paper for the Individual Category of the DeltaCompetition 2008 is:

Mangroves

Natural defences against natural disasters in model simulations

By Fang Yenn Teo – Cardiff University, United Kingdom

Many countries have experimented with the re-establishment of mangrove's to help serve as a natural barrier to tropical storms and tsunamis. In this paper, the author uses detailed calculations to describe the effect of the presence of mangrove habitats on the force of the waves and the level of potential damage of these waves. The author tested these calculations extensively in the test site of Merbok Estuary, Malaysia. The author also found that re-establishing mangrove habitats has a positive impact on the natural ecosystem, contributing to the restoration and rehabilitation of mangrove habitats.

The concept of an artificial mangrove shelter is very appealing to the Panel of Judges. The attempt at calculating the positive effect of the presence and re-establishment of mangroves in helping to protect the hinterland is an original concept that works well with the principles of resource economics. The quality of the writing and good presentation of the argument are particularly noted.

Unfortunately, there can only be two prize winners. However, the three remaining papers that were nominated raised much discussion amongst the Panel of Judges. These papers are acknowledged for their original and scientific reasoning.

Adapting to climate change and sea-level rise in deltaic regions

An enhanced framework for adaptation support initiatives

By Paula Posas – University of Liverpool, United Kingdom

The overall message of this paper sets the case for research and management of deltas into regional groups, due to their common features and high vulnerability. The author recognises that climate change adaptation in deltaic regions involves a number of variables that require integration into a conceptual framework. The paper presents five proposals that expand on existing conceptual frameworks: a user-friendly website with systematised deltas climate information; a delta adaptation handbook; a delta adaptation ideas bank; a delta translation fund; and a sister cities representative initiative.

Building with nature
Finding a balance between natural and human processes in deltas

By Marten Hillen, Jos Kuilboer, Pieter Nordbeck and Roald Treffers – Delft University, Netherlands

In response to the discovery of the deterioration of the Mississippi, the authors of this paper have suggested methods to increase the safety of the city of New Orleans, while at the same time, safeguarding natural processes, through delta restoration using large scale river diversion. The study builds on an extensive stakeholder analysis, extensive calculations and modelling. Although the authors recognise that there remain a number of uncertainties, building with nature in consultation with stakeholders, shows a positive land use management method for delta regions around the world.

Double-Channel and the Tidal Power Station
Structural interventions for deltas threatened by rising sea level

By Wang Fei, Han Bos and Li Yuan – HoHai University, Nanjing, China

The authors of this paper set out a concept of a double channel and tidal power station to address the impacts of sea level rise and salt water intrusion in delta areas. Their concept is supported by calculations, building upon their conclusion that the double channel and utilisation of the resultant tidal power could significantly contribute to the economic development of the area and reduce ground water extraction in the area.

The panel of judges wishes to thank and congratulate all participants in the DeltaCompetition. Not only has the DeltaCompetition inspired young students all over the world, but the solutions they have come up with are very promising indeed. We especially recommend reading these five papers to all experts, decision makers and other stakeholders involved. We believe that these contributions constitute a source of inspiration for urgent problems facing many densely populated delta areas throughout the world. And we encourage the students who have participated in the DeltaCompetition, and especially the prize winners, to contribute their work and maintain their inspirational and enthusiasm after they graduate and become professionals and decision makers themselves.

panel of judges CVs

Prof. Dr. Julian Hunt

Julian Hunt has been a Professor of Climate Modelling in the Department of Space & Climate Physics, and Earth Sciences, and Honorary Professor of Mathematics at University College London, since 1999. Formerly he was at the University of Cambridge where he was Professor of Fluid Mechanics. He is still a Fellow of Trinity College. He is also a J.M. Burgers visiting professor at the Delft University of Technology, Visiting Professor at Arizona State University, Pierre Fermat Visiting Professor in Toulouse, Academic Director of the Lighthill Risk Network and Deputy Director of the Lighthill Institute of Mathematical Sciences. He is a Fellow of the Royal Society. He has honorary degrees from Salford, Bath, East Anglia, Warwick, Grenoble, and Uppsala.

In 2001 he has been awarded the L.F. Richardson medal for non-linear geophysics by the European Geophysical Society. He was Director-General and Chief Executive of the Meteorological Office from 1992-1997, and was created a Baron in the House of Lords (with the title Lord Hunt of Chesterton) in May 2000. He is chairman of Cambridge Environmental Research Consultants Ltd., which is working world wide on air pollution modelling and forecasting; he helped found it in 1986.

In his research, he has developed new approaches to modelling turbulence, atmospheric flows around buildings and over mountains, and the dispersion of environmental pollution.

Dr. Chris West

Oxford University, Environmental Change Institute, Director of the UK Climate Impacts Programme

Chris West trained as a zoologist at Oxford University (BA, 1975), and has undertaken research on a variety of animals around the world, including gorillas in Rwanda (1972), foxes in Britain (1974-76) and microscopic soil animals on South Georgia (1976-79, PhD London University 1984). He worked at Jersey (1983-86) and Bristol (1987-90) Zoos on the management and genetics of captive populations. He joined the Natural Environment Research Council in 1991, working on marine science and on international research co-operation. Since March 2002, he has been Director of the UK Climate Impacts Programme.

The UK Climate Impacts Programme is a team of twelve that helps organisations assess how they might be affected by climate change, so they can prepare for its impacts. It was set up by the Government in 1997; it is funded by DEFRA and based at the Oxford University Centre for the Environment. It works by promoting stakeholder-led impact research and developing a range of common tools and datasets to help organisations adapt to the impacts of unavoidable climate change.

Prof. Dr. Hans Opschoor

VU University of Amsterdam, Professor in Environmental Economics

Hans Opschoor is Professor of Sustainable Development Economics at the Institute of Social Studies and Professor in Environmental Economics at the Free University of Amsterdam. Hans Opschoor has worked in the field of environmental and ecological economics since 1971. From 1978 onward he has specialised in international aspects of these fields, especially North-South ones. He has worked and lived in Southern Africa (Botswana) and been involved in projects in India and China. Recently, Hans Opschoor has focused on the economics of climate change, and environment and poverty. In addition to that, he has a strong interest in scientific/academic co-operation in research and capacity development in a North-South-South. Hans Opschoor has published 13 edited volumes and monographs and over 170 articles, mostly on environment and development, environmental economics, environmental policy, environmental policy instruments.

Prof. Dr. Ir. Pier Vellinga

Wageningen University, Director of the Knowledge for Climate Programme in the Netherlands

Pier Vellinga (1950) is professor in Environmental Sciences and Climate Change at Wageningen University Research and Vrije Universiteit Amsterdam. Originally he specialised in Coastal Engineering contributing to the Deltaplan of the Netherlands. In 1987 he became advisor to the Netherlands Environment Minister on Climate Change. In that period he helped to shape international climate policies and he was one of the initiators and first bureau members of the Intergovernmental Panel on Climate Change. In 1991 he joined the Vrije Universiteit as professor in environmental sciences and as director of the Institute for Environmental Studies. In 2007 he took up a position at Wageningen University Research as well, to lead the National Climate Change Research programma: Knowledge for Climate. Pier Vellinga is a board member of several research institutes and environmental organisations in the Netherlands and abroad.

Dr. Zef Hemel

Deputy Director of Spatial Development of the City of Amsterdam
Zef Hemel (1957) is Deputy director of the Amsterdam Spatial Planning Department.

He studied human geography and planning at the University of Groningen. In 1994 he obtained his PhD at the University of Amsterdam with a dissertation on 'The Landscape of the Ijsselmeer Polders. Planning, Layout and Design'.

In May 2002 he became director of the Rotterdam Academy of Architecture. Prior to that he worked as a senior planner at the Ministry of Housing, Spatial Planning and the Environment (VROM) in The Hague, first as secretary to the Board for Spatial Planning, then as editor of the Fifth Report on Spatial Planning in the Netherlands, and finally as a member of the Ministry of Housing, Spatial Planning and the Environment's think tank. Zef Hemel is a member of the executive board of the Forum for Urban Renewal.

He is Deputy director at the Spatial Planning Department (DRO) since September 2004. The DRO is the policy department of Amsterdam local authority that advises on the policy for spatial planning and open and public spaces. Employees from the department carry out planning research and make urban development plans. DRO works for Amsterdam and for partners in the region. Together with city districts and other local authority departments and businesses the DRO works on large-scale urban projects such as IJburg, the Zeeburgereiland, the IJ banks, the Centrumgebied Zuidoost, Parkstad, the WTCW Science Park and the Zuidas.

At the DRO, among other things, Zef Hemel is involved in repositioning the planning function, intensifying regional contacts and the research function of the department.

Mr. Tom Smit, LLM, MSc

Tom Smit is a senior management consultant with law degrees from the Leiden and Harvard Universities and extensive experience in the public and private sector. Tom has advised numerous governments in the Netherlands and abroad on water, environmental and spatial planning legislation and administration.

During his career at the Ministry of Spatial Planning and the Environment, he was responsible for the drafting and implementation of the Dutch Environment Law. In his capacity as Director of the Union of Water Boards, after serving as Director of Water Board Limburg, he was involved in the drafting and implementation of the Law on the Water Boards. After that, he joined Twynstra Gudde management consultants, ultimately serving as managing partner at this firm. In 1998 he joined Royal Haskoning. First as director of the Environment and Water Divisions, and currently managing the Spatial Development Division.

Recently Tom has been involved in the regional consultation process leading towards the formulation of the new National Water Plan and an international comparative analysis of (integrated) water legislation. Besides different evaluation studies and consulting assignments in the Netherlands, the past years he has also advised on water and environmental management capacity of governments in countries such as Romania, Bosnia-Herzegovina and Greece.

Since 2006, Tom is responsible within Royal Haskoning for the organisation of the DeltaCompetition and acts as a Secretary to the Panel of Judges.

Prof. Ir. Louis de Quelerij, MSc CivEng

Dean Faculty of Civil Engineering and Geosciences, Delft University of Technology, Netherlands
Director of Fugro Ingenieursbureau B.V. Leidschendam

Louis de Quelerij was born on 29th of July 1952 in Vlissingen, Netherlands. He studied civil engineering at the Delft University of Technology and obtained his Masters degree in 1976.

From 1976 till 1986, he was employed by the Ministry of Transport and Public Works at the Rijkswaterstaat Department. He had been involved as geotechnical engineer at the Deltaproject, the major flood control programme for S-W Netherlands.

From 1986 he has worked at Fugro Ingenieursbureau B.V. (FIBV), one of the operating companies of Fugro N.V. Fugro is a consulting firm with 12,000 employees in 80 offices worldwide collecting and interpreting geodata for purposes related to the oil and gas industry, the mining industry and the construction industry.

From 1998 till 2002 he operated as managing director of FIBV, being responsible for the on shore geotechnical services in the Netherlands. He has experienced for more than 30 years as geotechnical consultant in many infrastructure and building projects related to hydraulic works (dikes, dams, storm surge barrier), highways, railways and underground structures.

In 2002 he was appointed as Dean and professor of the of Faculty of Civil Engineering and Geosciences of the Delft University of Technology (DUT). The Faculty deals with research and education programmes (Bachelor, Master, PhD) in the areas of Hydraulic Engineering, Water management, Design & Construction, Geotechnology and Transportation & Planning.

Since his DUT appointment he continues to work at Fugro for 1day/week as director being involved at water services development.

He has been active in many national and international committees dealing with civil engineering research, regulations and symposia. At present he participates in the board of the DUT Research Centres Water, Earth, Transport and Construction, the interuniversity research schools Transportation, Construction and Earth sciences, the delta technology programme Delft Cluster, the Dutch Network Deltatechnology and the Knowledge Centre's Building Process Innovation and Geo-Engineering.

He is a member of the Dutch Royal Institute of Engineers KIVI/NIRIA, the Netherlands Society for Soil Mechanics and Geotechnical Engineering (NSSMGE) and registered engineer of the Professional Association of Dutch Consulting Engineers (ONRI).

Mangroves

Natural defences against natural disasters in model simulations

Winner of the Individual Category of The DeltaCompetition 2008

Fang Yenn Teo

Abstract

The hydrodynamic effects of mangroves as natural defences against natural disasters have been studied in this paper. Included in this study is a refined two-dimensional depth-integrated numerical model that includes both the effects of drag force induced by mangrove trees and the blockage effects on water flow through mangrove swamps. The model study focuses on investigating the influences of mangroves on tidal flow structure and the consequential impacts of mangroves as natural defences especially the potential of tsunamis propagating up the delta.

The model has been applied to one of the actual mangrove fringed deltas at the Merbok Estuary in Malaysia. Two locations along the main river, i.e. the downstream and upstream were selected for the study of hydrodynamic processes of mangroves in this delta. Simulations have been undertaken for both conditions, i.e. with and without mangrove trees. Comparisons of velocity profiles and water elevations for both cases have also been undertaken.

The results suggest that mangroves have a significant impact on the hydrodynamic processes in the deltas and, in turn, have a key impact on the natural ecosystem of mangrove swamps. The study shows that the model developed can be used as a useful hydro-informatics tool for the risk management and planning of natural disasters. As a result, an innovative and environmentally friendly system, namely, the 'Artificial Mangrove Shelter', has been introduced and modelled. This system works towards sustainable restoration and rehabilitation of mangroves in the deltas.

Keywords: mangroves; natural defences; natural disasters; hydrodynamics; numerical modelling

1 Introduction

The benefits of mangroves in deltas are now being recognised for their potential as natural defences against natural disasters, which could prevent significant loss of life and damage in the future.

Mangroves have already played an important role in natural coastal protection and flood defence. Protection provided by these dense trees which grow naturally in rivers, estuaries and coastal areas, appear substantial, not only against storm generated waves, winds, typhoons and surges, (Massel et al., 1999), but also against tsunamis, where the trees roots and trunks reduce wave energy as the wave propagates through the trees (EJF, 2006). Knowledge of these interactions with mangroves aids the better understanding of hydrodynamics processes on deltas. Although research has progressed over recent years, there are still major uncertainties concerning the impacts of these riparian forests on natural disasters, especially surrounding flood storage, mitigation and peak flood flow rate. To manage the risk of natural disasters in deltas more effectively, improved understanding is crucial. Therefore, further research that includes this feature is needed.

On 26 December 2004, a tsunami hit many countries surrounding the Indian Ocean, the Bay of Bengal and East Africa. It was caused by a 9.0 Richter-scale earthquake, centred near the north-west coast of Sumatra in Indonesia; this tsunami was one of the most significant catastrophes in history. Countries severely impacted included Indonesia, Sri Lanka, India, Thailand, Malaysia and Myanmar.

As results of this disaster, researchers and scientists have been able to appreciate the mangroves can play valuable role as ecological and geomorphic buffers against tsunamis. Blasco et al. (2005), Dahdou-Guebas et al. (2005), Danielsen et al. (2005), Ong (2005), Kathiresan et al. (2005), Siripong et al. (2005), Harada et al. (2005), Imai et al. (2005), and Mazda et al. (2007) have all studied and recognised the importance of mangroves in reducing the impact of tsunamis. On the other hand, Kerr et al. (2006) and Chatenoux et al. (2007) disagreed with this statement. Kerr et al. (2006) found no relationship between human mortality and the extent of forests fronting hamlets for coastal protection during tsunamis. The belief that mangroves had no attenuation effects was also supported by Chatenoux and Peduzzi (2007), where the distance of the tsunami penetrated was best explained by distance from the earthquake epicentre. Therefore, more quantitative support is needed to understand the impact of mangroves on tsunamis.

In Malaysia, the tsunami hit three states at the north-west coast of the Peninsular: Kedah, Penang and Perak as shown in Figure 1. Most lives were lost in Penang and many fishing boats and houses were destroyed, particularly along the Kedah coastline, north of Kuala Muda. The impact of the tsunami was far less severe in neighbouring countries.

The effect of the tsunami on Malaysia has led to an increased awareness of the value of natural barriers such as mangroves swamps, in reducing the impact of waves (Abdullah et al., 2005).This report has also strengthened the perception that in order for vulnerable coastlines to be defended, it is critical that mangroves are preserved, protected and set aside as green belt areas.

Previous research focused on modelling vegetation resistance in more detail and included the effects of depth-dependent vegetation, spatial distribution and hydraulic interactions between the vegetation elements (Wolanski et al., 1980, Kutija et al., 1996, Fathi-Mahagdahan et al., 1997, Mazda et al., 1997, Naot et al., 1997). It also considered the influence of the drag force introduced by mangroves on the flow structure, incorporating the effect on the vegetation into the Manning coefficient (Pertyk et al., 1975).

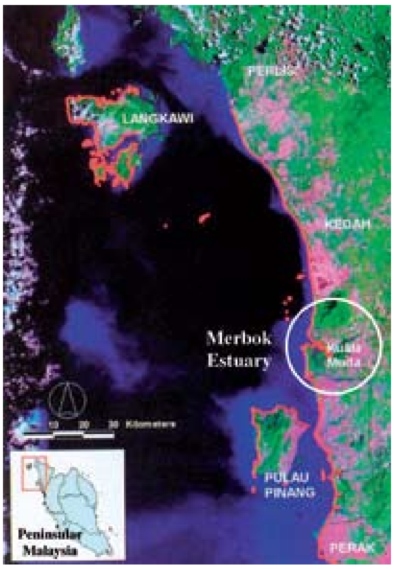


Figure 1. North-west coastline of Peninsular Malaysia and the Merbok Estuary, with the red line showing the region affected by the 26 December 2004 tsunami (after Komoo and Othman, 2006)

Furukawa et al. (1997) proved that mangrove trees were responsible for enhancing friction, with much of this enhancement being due to the vegetation presenting obstacles to flows. Wu et al. (2001) modelled the influence of mangrove vegetation on the cross-sectional area of the flow, by using a two-dimensional depth-integrated numerical model. This was refined to include effects of the drag force induced by the mangroves as well as the blockage effects they had. This additional resistance was also investigated by Struve et al. (2003), through experiments in a hydraulic flume and numerical modelling.

In this paper, a refined two-dimensional depth-integrated numerical model (described in detail by Falconer, 1986 and Wu et al., 2001), has been used. The model included the drag force and blockage effects on the water flow caused by mangrove trees and focuses on vegetation resistances, cross-sectional areas of tidal flow structure and the consequential impacts of mangroves. It considers these as natural defences against natural disasters, especially in regard of their potential for tsunami propagating up the delta of the Merbok Estuary in Malaysia.

2 Mangroves

Mangroves are found in low energy coastal areas of subtropical and tropical climates in countries such as Malaysia, Indonesia, South Africa, Vietnam and Australasia. Mangrove trees have specially adapted stilt roots, known as pneumatophores and salt-excreting leaves. Their extent and shapes vary among different species.

Their root and leaf structures enable them to thrive along sheltered coastlines and estuaries. Mangroves typically occur between spring low tide and spring high tide and have few other plant species associated with them. Different species appear dominant in different tidal inundation zones. Red mangroves (Rhizophora species) are often a pioneer, growing where the area is more continually flooded, with seedlings and small trees sprouting below water. These give way first to a full-grown Rhizophora species with prop roots, and then, towards the high tide zone, where taller black mangroves grow. Once established, the network of roots anchors the trees to the soft mud and traps more sediment, which contributes to soil formation and stabilises the coastline.

As well as acting as a natural defence, mangroves also create the effect of a natural breakwater which stops erosion. Mangroves act as a natural filter system for the run-off and enable ground waters to retain and recycle nutrients and remove toxins, including excess amounts of nitrogen and phosphorous, petroleum products, and halogenated compounds through a process called rhizofiltration. They also help to clarify adjacent open water, which facilitates photosynthesis in marine plants.

In addition, mangroves are valuable ecosystems, which provide habitat for migratory water birds, as well as shelter and food for growing fish populations and crustaceans and provide adjacent local communities with a plentiful supply of fish, crab, and prawns. The mangroves themselves provide wood for construction and the production of charcoal, which contributes to productivity.

Mangrove estuaries are widely used for aquaculture, such as the cultivation of mussels and oysters. They are important in terms of tourism as they promote public awareness of the natural habitat.

3 Numerical Model

Numerical Modelling of flow in coastal and estuarine waters is generally based on shallow water equations. These hold the principles of mass continuity and conservation of momentum. The shallow water equations are defined by the depth-integrated three-dimensional Reynolds equations for incompressible and unsteady turbulent flows, and include the effects of the earth's rotation, bottom friction and wind shear.

Mangrove trees have a significant impact on the velocity structure and therefore Wu et al. (2001) developed the following shallow water equations, which include both the effects of the drag force and blockage induced by the trees. Disregarding the Coriolis and wind forces, the model solves the continuity equation as:

(1) $$\theta \frac{\partial \eta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0$$

and the momentum equations in the x, y horizontal plane, including the effects of the drag force and blockage, can be respectively written as:

(2) $$+ \frac{\partial (q_x^2/H)}{\partial x} + \frac{\partial (q_x q_y/H)}{\partial y} = -gH\frac{\partial \eta}{\partial x} - \theta \frac{g q_x \sqrt{q_x^2 + q_y^2}}{H^2 C^2}$$
$$\frac{\partial^2 q_x}{\partial x^2} + \frac{\partial^2 q_x}{\partial y^2} \Bigg] - F_x$$

(3) $$\frac{\partial q_y}{\partial t} + \frac{\partial (q_x q_y/H)}{\partial x} + \frac{\partial (q_y^2/H)}{\partial y} = -gH\frac{\partial \eta}{\partial x} - \theta \frac{g q_y \sqrt{q_x^2 + q_y^2}}{H^2 C^2}$$
$$+ \nu \left[\frac{\partial^2 q_y}{\partial x^2} + \frac{\partial^2 q_y}{\partial y^2} \right] - F_y$$

Where t is time; η is the water surface elevation above (or below) the still water datum; q_x, and q_y are the depth integrated discharges per unit width in x, y directions respectively; H is the total water column depth; g is the acceleration due to gravity; C is the Chezy bed roughness coefficient, which can be determined from the Manning formula or Colebrook-White formula; and ν is the depth-averaged eddy viscosity; F_x and F_y are the drag force components induced by mangrove trees per unit area in x, y directions respectively; and θ = porosity of mangroves.

The drag forces induced by the mangrove trees per unit area have been included in the model in the following form:

(4) $$F_x = \frac{1}{2} C_D D_t \rho_t \frac{q_x \sqrt{q_x^2 + q_y^2}}{H}$$

(5) $$F_y = \frac{1}{2} C_D D_t \rho_t \frac{q_y \sqrt{q_x^2 + q_y^2}}{H}$$

where C_D = drag coefficient (dimensionless), which is approximately 1.0 for circular cylinders under turbulent conditions, though it depends on vegetation conditions (Mazda et al., 1997 and 2005) and Reynolds conditions (Schlichting, 1962); D_t = diameter of a typical tree, which is assumed to be a circular cylinder; and ρ_t = number of trees per unit area.

The blockage effects, induced by the mangrove trees on the flow, are taken into account by introducing the porosity θ of the mangroves (Wu et al., 2001), whereby:

(6) $$\theta = 1 - \frac{\pi}{4} D_t^2 \rho_t$$

4 Merbok Estuary

Merbok Estuary is situated in the state of Kedah, Malaysia (5° 409N, 100° 259E), at the north western entrance to the Malacca Straits (as shown in Figure 1). The estuary stretches for 35km, and is fringed by mangrove swamps in the inter-tidal zone, with the total mangrove area being about 50km². The width of the estuary at the mouth is about 2km, and it narrows to about 20m in the upper reaches. The depths vary from 3m to 15m, with a few 20m deep holes sited where tributaries join the main estuary.

The mean annual discharge is estimated to be 20m³/s, and the mean neap and spring tidal ranges are about 0.8m and 2.3m respectively. Further details of the estuary are given in Ong et al. (1991). Various physical aspects of this estuary are also described in Uncles et al. (1990 and 1992), Dyer et al. (1992), Ong et al. (1994), and Simpson et al. (1997). This estuary, which contains one of the highest recorded levels of species biodiversity in the world, is surrounded mainly by rice, rubber and oil palm cultivation. There is a fast growing town, namely Sungai Petani, sited contiguously with this estuary. From the early 1970s to the end of the last century, shrimp farming was actively pursued (Ong, 1982). Samarakoon (2004) also analysed the impacts of urbanisation in this estuary to the mangrove ecosystems. A satellite image of Merbok Estuary is shown in Figure 2.

The model discussed previously has been used to simulate the hydrodynamic processes in the Merbok Estuary. The model area was represented using a mesh of 243 x 265 uniform grid squares, with a grid size of 50m. Based on the observation made by Wu et al., 2001, the diameter of the trees used in this study was assumed to be 0.1m. The model was run for both conditions, i.e. with and without mangrove trees, and the density of the trees was set to 4 and 0 per m². The drag coefficient value of 1.0m was used for this study. Bed elevations of computation domain contour are illustrated in Figure 3.

5 Tidal Currents in Mangrove Swamps

The model has been set up and applied to simulate hydrodynamic processes of tidal flow structure in the mangrove swamps of Merbok Estuary. At the open seaward boundary, a sinusoidal wave, with the tidal range set to 1.5m, with the high water at 2.3m and low water at 0.8m and with the time step set to 12s. The model was run with and without mangrove vegetation.

Two locations along the main river, i.e. the downstream and upstream, were selected as shown in Figure 3 to investigate tidal currents in mangrove swamps. It was found that mangrove vegetation had a significant impact on the flow patterns. Figures 4 and 5 show time series plots of the velocities and water elevations at the downstream and upstream of the main river. Significant effects of the mangroves on the velocities are observed in Figure 4, thereby confirming the need to include the extra terms referred to previously in the numerical model. Due to the effects of those extra terms, and mangrove trees effectively reducing the area of flow along the river, the currents in the main channel were increased significantly. The significant increases in the velocities in the main river were much smaller at the upstream end of the river, where mangroves reduced the peak current and absorb the energy of tidal waves. There were slight influences of the mangrove vegetation on the water levels and these effects are shown in Figure 5.

6 Effects of Mangroves on Tsunamis

With the similar model, the study focused on investigating the influence of both the vegetation resistance and the reduction in the cross-sectional area of flow using mangrove trees and the consequential impact on tsunami currents. Based on observations from last tsunami at this coastal site, the near shore height of the tsunami was reportedly 2m to 3m (Abdullah et al., 2005). Hence the model was set to an idealised wave period of one hour with the low water at 0.5m and high water at 3.5m, and the time step set to 12s to drive the tsunami currents. Again, two locations along the main river section were selected to investigate how the mangrove trees affected the behaviour of the tsunami currents.

Figures 6 and 7 show time series plots of the velocities and water elevations at the downstream and upstream of the main river for both conditions. The significant effects of the mangrove trees on these velocities are observed in Figure 6. The results showed that the mangrove trees greatly affected the tsunami current. The influence of the mangrove trees on the water elevations and their effects along the main river channel are shown in Figure 7. As shown in Figure 7, the water elevation at the downstream of the main river, in the case of mangroves, is larger than the case without them, while this relation is the reverse at the upstream of the main river. The reason for this was the mangrove swamp along the main river functioned as temporary water storage rather than pass-ways.

Comparisons of velocity profiles and water elevations for both cases have been undertaken. The significant increases in the velocities and water elevations in the main river were much smaller at the upstream end of the river, where mangroves reduce the peak and potential to propagate up the estuary. The drag forces and blockage effects from the mangrove trees reduced the flow into the mangrove swamp and caused rising of water at the downstream of the main river. These results show that mangroves play a key role in wave attenuation, in reducing the effects of a tsunami in the main river and would also reduce the impact of flooding by such a wave on some major township at the head of the river.

Figure 2. Satellite image of Merbok Estuary (Google, 2008)

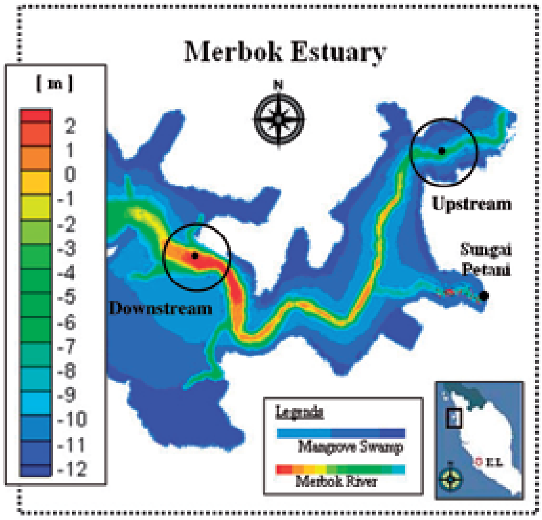


Figure 3. Merbok Estuary showing bed elevations of computation domain contour in m and selected locations

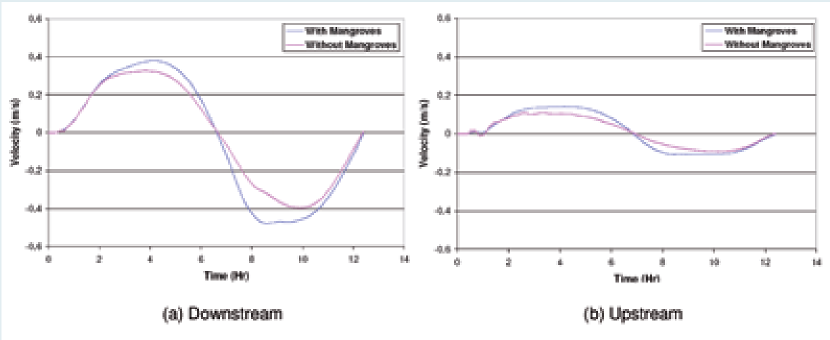


Figure 4. Time series of velocities at the selected locations: (a) downstream, and (b) upstream of river

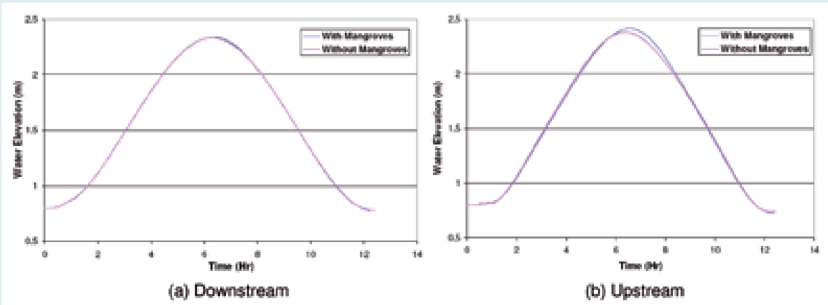


Figure 5. Time series of water elevations at the selected locations: (a) downstream, and (b) upstream of river

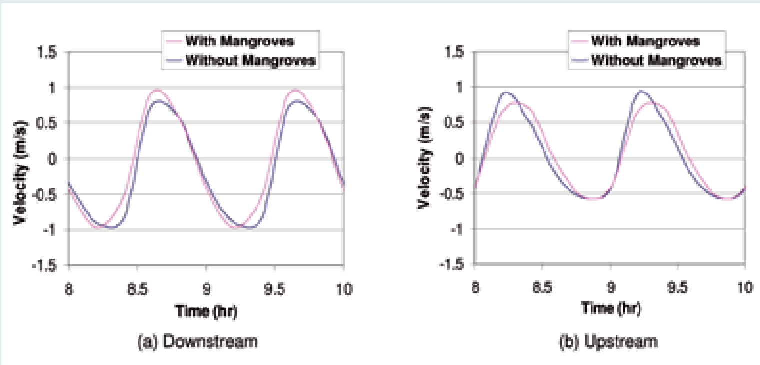


Figure 6. Time series of velocities at the selected locations: (a) downstream, and (b) upstream of river

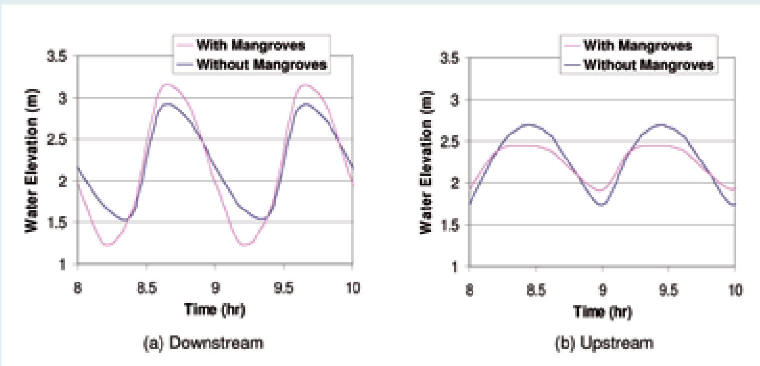
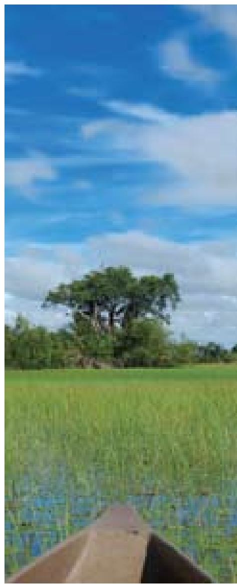


Figure 7. Time series of water elevations at the selected locations: (a) downstream, and (b) upstream of river

7 Sustainable Innovation



The restoration and rehabilitation of mangrove swamps as natural defences is one of the most important issues of natural disaster risk management and planning. This complex process is an essential tool in the campaign to restore, rehabilitate, protect, and increase mangrove habitats. It involves renewing natural mangroves that have been lost or degraded and reclaiming their functions and values as vital ecosystems.

In the presence of extreme natural events at deltas, such as tidal currents, waves, storm surges, and tsunamis, natural mangrove re-colonisation is compromised and becomes more complex. Clear cutting possibly exposes the site to erosion, which makes subsequent reforestation difficult, because seedlings are washed away. Mangroves have to withstand these actions, especially on exposed sites and where they colonise cleared or newly established mudflats.

Tidal currents will hardly be so large as to cause problems to mature trees, but the establishment of seedlings may be difficult in the presence of currents. Besides that, other problems encountered in the restoration of mangroves include barnacle infestation, inappropriate site selection which may result in seedlings being washed out, attacks by crabs, and dying out anchorage in the sediment, which is not sufficient to prevent seedlings from being washed out, and deep inundation could also adversely affect mangrove seedlings.

In general, the establishment of seedlings and young mangrove trees may be easier in the shelter of other mangrove trees as these also help to rehabilitate damaged mangrove ecosystems and to protect existing mangrove stands. At the exposed site where there is no shelter provided by other mangroves; there is a need to duplicate the real environment of this shelter for sustainable restoration and rehabilitation. Hence, the innovation of an environmentally friendly system, namely the 'Artificial Mangrove Shelter' is suitable for this purpose. The sustainable innovation of an 'Artificial Mangrove Shelter' will provide:

1. Artificial defences against natural disasters by absorbing, attenuating and obstructing the energy of currents and waves.
2. Artificial shelter to encourage restoration and rehabilitation of mangroves.
3. Artificial sediment traps for soil formation and stabilizing the coastline.
4. Erosion control and protection from strong waves and current action at exposed sites.
5. Flood mitigation and attenuation by increasing the storage capacity and reducing wave energy propagation.
6. Environmentally friendly with little change on the natural environment and habitat.
7. Enhancement of the aesthetic aspects of the natural environment for recreation purposes.
8. Enrichment and enhancement of the nature habitat.

As noted by Struve and Falconer (2001), "Mangroves are woody and adult trees are rigid, but young trees can bend with the flow. Adult trees and stems will always protrude above the water surface, whereas young trees and stilt roots may be submerged, in which case their effects are depth-dependent and stems are similar to straight cylinders." The 'Artificial Mangrove Shelter' system is designed by replicas of the mangrove stem configuration as shown in Figure 8. It consists of circular cylinders that make it easy to construct. Circular cylinders were used to represent mangroves in this study for simplification, though the vertical profile of mangrove trees is very complex. Setting up of the system is illustrated at Figure 8. The 'Artificial Mangrove Shelter' system plays a key role as defence and prevents seedlings and young mangrove trees from being washed away by strong waves and currents by the sea or river. Thus, the establishment of seedlings and young mangrove trees will be easier. Influence of the vegetation resistance and cross-sectional area of flow through simple circular cylinders were investigated with the similar model as discussed previously.

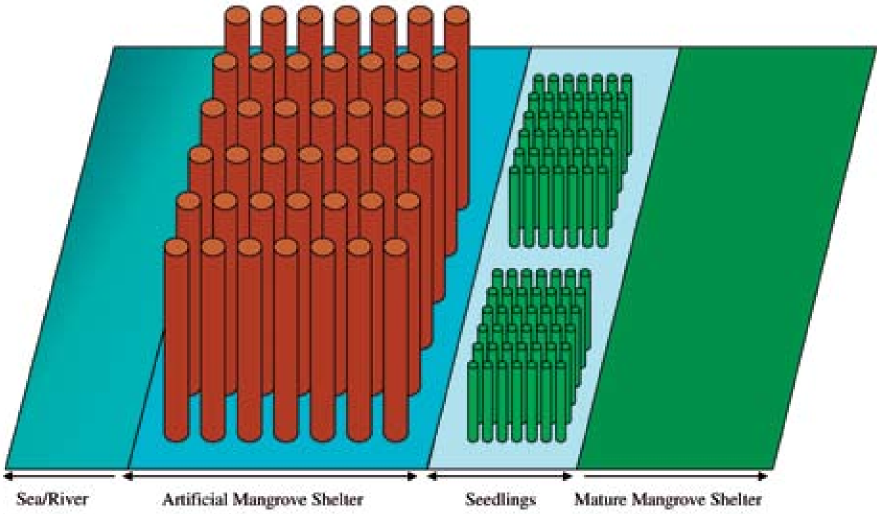


Figure 8. Setting up design for sustainable innovation of 'Artificial Mangrove Shelter'

Conclusions

This study has focused on investigating the influence of vegetation resistance and cross sectional areas of tidal flow arising from mangroves, and the consequential impact of these changes on the dissipation of tsunami currents.

Predictions were undertaken with and without the effects of mangrove trees on tidal and tsunami currents. These simulations were undertaken to investigate the effects of mangrove trees on the hydrodynamic and flushing processes in the deltas. It has shown that mangrove trees would have a significant effect on the water exchange behaviour within the deltas. Due to the drag force and the blockage effects induced by mangrove trees, the flow areas were reduced and concurrently the currents in the main river were increased significantly. These increases of water elevations in the main river were much smaller at the upstream end of the river. The study has been investigated to establish the significance of the trees effect on the attenuation of the current at the head of an estuary. Results show that mangrove trees would have a significant impact on the hydrodynamic processes of tsunami currents in a delta and, in turn, would also have a key impact on the ecosystem associated with mangrove swamps.

This study has proven that the model developed has the capability of being used as a useful hydro-informatics tool for the risk management and planning of mangrove swamps as natural defences against natural disasters in a proactive manner. Modern numerical model tools hold great promise for future applications. By working towards sustainable restoration and rehabilitation of mangroves, an innovation of an environmentally friendly system, namely the 'Artificial Mangrove Shelter' has been designed and modelled.

Acknowledgments

This paper is sincerely dedicated to all victims of the Indian Ocean tsunami which took place on 26 December 2004. The authors would like to thank the Government of Malaysia for the support and consent to this paper. The authors are very grateful to Professor J.E. Ong and Dr W.K. Gong of the School of Biological Sciences, Universiti Sains, Malaysia, for introducing them to the challenges associated with the management of mangrove swamps.

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Adapting to climate change and sea-level rise in deltaic regions

An enhanced framework and proposals for adaptation support initiatives

Runner up in the Individual Category of The DeltaCompetition 2008

Paula J. Posas

Abstract

Based on a literature review of the rise in sea-level and climate change in delta regions, three declarations can be made.

Firstly, there is a convincing case for research and thinking about deltas as a group or as a region of groups due to their common features and high vulnerability which are similar to the small-island states in the Intergovernmental Panel on Climate Change (IPCC) reports.

Secondly, climate change adaptations in deltaic regions involve a potentially unwieldy array of variables that need to be synthesised into a conceptual framework to guide deliberation and decision making. A framework of this type is essential for understanding which options are available and which core elements need to be considered over which time period. Existing frameworks could be made more powerful and informative if they addressed these aspects or were presented along with relevant supplementary information.

Thirdly, despite the existence of some valuable resources on worldwide deltas, climate change, and rise in sea-level, many of these resources are difficult to find by searching online. There is no specific area that holds, systemises or maintains information about worldwide deltas and climate change.

On this basis, and drawing on the best sources available following the literature review, this paper proposes expansions to existing conceptual frameworks and outlines five original proposals, namely:

- a user-friendly website with systematised deltas and climate change information;
- a delta adaptation handbook;
- a delta adaptation ideas bank;
- a delta translation fund; and
- a 'sister city' representative initiative.

Each of these proposals can contribute to public and private sectors in developed and developing country delta regions. In addition, each of the proposed initiatives would facilitate research and promote more effective distribution of ideas, best practice, and approaches to climate change adaptation in delta regions.

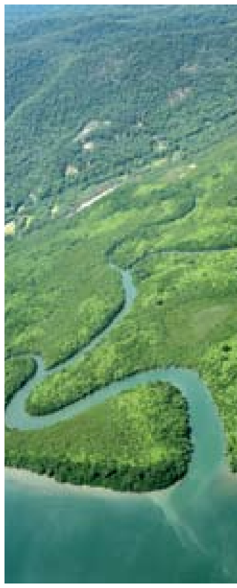
Introduction

This paper reviews current knowledge and new approaches to deltas and the pressures they face, together with climate change and its various impacts.

In this paper 'climate' is defined as 'the average weather in a particular location over a thirty year period' (UKCIP, 2008) and 'climate change' is understood as a change in climate over time, whether due to natural or human induced causes.

To provide context to the arguments and proposals for climate change, this paper will first present information about the geology and history of deltas, the reasons they are vulnerable, and how they are impacted by climate change. From this it will be easier to understand why greater attention needs to be paid to deltas as a group, the need for robust conceptual frameworks to aid decision making, and the critical need for systematised information and adaptation support initiatives.

Deltas, their geology and history



Deltas, which are landforms that develop at the mouths of rivers and streams, are created by deposit and build up of water-transported sediment which is unable to dissipate as it reaches a body of water, such as a sea, ocean, or lake.

Deltas consist of an upper deltaic plain, which is land above highest tide, a lower deltaic plain, which is occasionally covered by tidal water and a sub-aqueous deltaic plain. These deltas spread outwards, forming new land provided that the volume of sediment deposited is greater than waves, currents, and tides. Conversely, reduction in sediment deposits, and other factors such as excessive groundwater withdrawal and accelerated sea-level rise, can cause deltas to subside or retreat.

Since the last glacial maximum (about 18,000 years ago) sea level had slowed to a pace that allowed deltas to accrete, or gather vertically and build seaward (Stanley and Warne, 1994; Syvitski, 2008). Most modern deltas began to form between 8,500 and 6,000 years ago, when global sea levels stabilised within a few metres of the present level.

Greek historian Herodotus, who lived during 500BC, is credited with first recognising and naming deltas, noting that the sediment that accumulated at the mouth of the Nile River formed the shape of the uppercase Greek letter, Delta (Δ).

Though deltas are often triangular, or fan shaped, the shape and size of deltas vary widely and are determined by a complex, interacting set of factors. Syvitski and Saito (2007, p. 261) cite four main factors:

1. Sediment supply from a river's bed and suspended load, a reflection of drainage-basin characteristics, water discharge and sediment yield;
2. Accommodation space, as controlled by sea-level fluctuations, off-shore bathymetry, tectonics, subsidence, compaction, and isostasy;
3. Coastal energy, through the influence of waves and tides, longshore and cross-shelf transport; and
4. Density differences between effluent and receiving waters critical in defining the dynamics of discharge plumes.

On a more simplified level, it is also accurate to say that deltaic landforms are shaped by a combination of river, wave, and tide processes (Nicholls et al., 2007). Shapes and dominant influences on a selection of worldwide deltas are depicted in Figure 1.

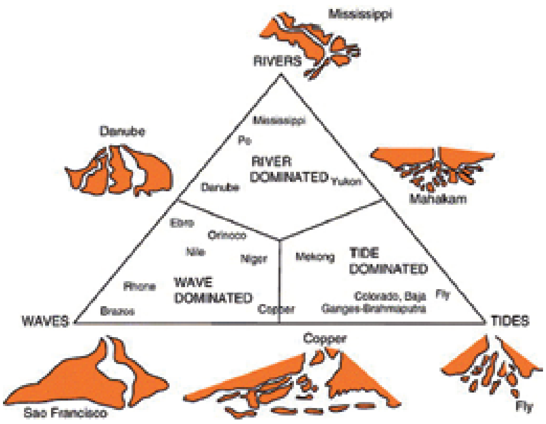


Figure 1. Morphodynamics of various worldwide deltas, from Syvitski and Saito, 2005, based on Galloway, 1975

Delta regions have long proved attractive for settlements, and early civilisations which built up around many river deltas, including the Tigris-Euphrates, Nile, and Indus. Part of the appeal of delta regions are their fertile soils for agriculture, the variety of natural resources, such as water, fish, wildlife, vegetation and their position along waterways which facilitate commerce and transport. Their attractiveness has resulted in 'disproportionately rapid expansion of economic activity, settlements, urban centres and tourist resorts' (Adger et al., 2007, p. 319).

An estimated 300 million people inhabit a sample of 40 deltas globally, with an average population density of 500 people/km^2 (Ericson et al., 2006). Syvitski (2008) reports 325 million people in a sample of 51 deltas.

Most countries with large populations situated in low elevation coastal zones, i.e. those situated in contiguous areas along a coast line that is less than 10m above sea level, are large countries with heavily populated delta regions (McGranahan et al., 2007).

The human population is heavily concentrated near coasts. 49 per cent of the 1994 population (some 5.62 billion people) lived within 200km of a coastline (Cohen et al., 1997) and population densities in coastal regions are about three times higher than the global average (Small and Nicholls, 2003).

60 per cent of the world's 39 metropolitan areas with population over 5 million are located within 100 km of the coast, including 12 of the world's 16 cities with populations over 10 million (Nicholls et al., 2007). Increasing utilisation of the coast seems a trend that is 'certain to continue in the 21st Century' as in the 20th (Ibid., p. 319), especially given that coastal populations are growing at twice the global average (Bijlsma et al., 1996). A striking illustration of these trends is that over the last 20 years in China, 100 million people have moved from inland to the coast (Nicholls et al., 2007).

Vulnerability of delta regions

All over the world, from the tropics to the circumpolar arctic, both human and climatic pressures are combining to substantially increase the vulnerability of deltas. (i.e. sea-level rise, increasing storm strength and frequency, etc.). Human pressures includes sediment starvation caused by water extraction, water diversion, and sediment entrapment behind dams; dredging of waterways for navigation, port facilities, and pipelines which exacerbate saltwater intrusion into surface and ground waters (Nicholls et al., 2007); and degradation of protective coastal ecosystems including mangroves and wetlands (Nicholls, 2004; Coleman et al., 2005).

These climatic and other pressures are continually putting delta functions and dependent populations at risk. Highly populated deltas which are vulnerable to climate change and other pressures are depicted in Figure 2, where vulnerability may be due to exposure and sensitivity, but mediated by resources and human capital (Yohe and Tol, 2002). Even the rivers that feed deltas are threatened by climate change; for example, the Indus which is threatened due to its dependency on glacier water and the Nile, due of high evaporation, which is likely to increase as temperatures rise (Wong et al., 2007).

Figure 2. Populated deltas vulnerable to climate change and variability and other pressures, from SURVAS website, 2008

Based on a study by Ericson et al. (2006), the Intergovernmental Panel on Climate Change (IPCC) identifies the deltas in Figure 3 as the most vulnerable or at risk, as a function of indicative population potentially displaced by current sea-level trends to 2050. 'Extreme' in Figure 3 refers to greater than one million people, 'High' encompasses 50,000 to one million people, and 'Medium' indicate between 5,000 to 50,000 people. While a significant contribution to acknowledge, it must be recalled that this widely disseminated image is based on a sample of 40 deltas, and as such, does not include every delta that might be vulnerable (there are at least 75 major world deltas according to World Delta Database, 2008).

Figure 3. Relative vulnerability of coastal deltas, from SURVAS, 2008, as cited in Parry et al. 2007, p. 858, based on Ericson et al., 2006

A recent study (Coleman et al., 2005) of 14 of the world's major deltas, namely the Danube, Ganges-Brahmaputra, Indus, Mahanadi, Mangoky, McKenzie, Mississippi, Niger, Nile, Shatt el Arab, Volga, Huanghe, Yukon and the Zambezi, found that 15,845 km^2 of deltaic wetlands had been lost over the past 14 years, with human development activities accounting for over half the losses. In the subsiding Mississippi River deltaic plain, sediment starvation and increasing salinity and water levels of coastal marshes due to human development, occurred so rapidly, that between 1978 and 2000 that 1,565 km^2 of intertidal and coastal marshes were converted to open water (cited in Nicholls et al., 2007).

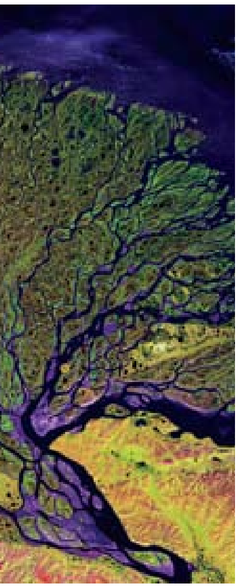
This is not just a problem of land and habitat loss. Wetland losses impact many sectors and functions, including: food production due to loss of nursery areas for fisheries; biodiversity loss (MEA, 2005); flood and storm protection, in that storm surges will penetrate further inland; and waste treatment and nutrient cycling functions (Nicholls et al. 1999). Hurricane Katrina in August of 2005 resulted in loss of a further 388 km^2 of wetlands, levees, and islands surrounding New Orleans in the Mississippi River deltaic plain (cited in Nicholls et al., 2007).

This example demonstrates that significant deltaic land loss can be both gradual and episodic. It also underscores the significance of human influence and climatic changes and/or events on delta dynamics, indicating that both need to be key considerations in sound decision-making about delta development and protection.

Climate change in perspective for delta regions

Deltas clearly face a complex set of challenges and pressures generally; climate change is acting as an overlay, amplifying existing problems and vulnerabilities. But, that statement should be made cautiously, because of the risk of oversimplifying the situation.

Climate change does pose novel risks, including the impact of drought, heat waves, accelerated glacier retreat and hurricane intensity (Adger et al., 2007, p. 719) and challenging trends such as increased flooding (Nicholls et al., 2008a) and sea-level rise which require an unprecedented long-term view and advance planning (Nicholls, 2004 and 2007).



Climate change is also considered distinctive due to three factors (Watkins, 2007): its cumulative nature (and system time lags), its urgency, with no obvious historical analogies, and its global coverage in the sense that impacts will be happening simultaneously worldwide, over a sustained time period and that the entire world community will have to work together to minimise and address its impacts.

The most recent United Nations Development Programme (UNDP) Human Development Report (HDR) (Watkins, 2007, p. 1) attributes particular urgency in addressing climate change, because of the danger that it 'will stall and then reverse progress which has built up over generations' in the areas such as poverty reduction, health, nutrition, education and others. The Report cites mechanisms by which this might occur, either singularly or as a combination, also have a particular relevance to delta regions:

- Agricultural production and food security, which will be impacted by changes in rainfall, temperature and water availability;
- Water stress or insecurity from changes in run-off patterns and glacial melt;
- Sea-level rise and increasing exposure to climate disasters;
- Ecosystem deterioration and biodiversity loss; and
- Human health challenges, including heat stress and the spread of diseases like dengue and malaria.

The HDR report (Watkins, 2007, p. 3) gives special focus to rural communities in major river deltas as those with today's 'real climate change vulnerabilities linked to storms and floods'. It also reiterates the urgency of climate change adaptation and mitigation for two main constituencies, those with a weak political voice and the world's poor and future generations.

Deltaic environments are highly sensitive to a rise in sea-level (Ericson et al. 2006; Woodroffe et al., 2006), and rise in sea-level associated with climate change presents extensive quantifiable risks to land and populations (Anthoff et al., 2006, p. 9; Nicholls and Klein, 2001, p.2).

Over the last 1000 years, sea level has been rising very slowly (≈ 0.1 mm/year); but since 1961 it has increased to 1.8mm/year and since the 1990s, has reached 3mm/year (Syvitski, 2008). Sea-level continues to rise (Nicholls et al., 2007). Around delta regions, relative sea-level rise can be much greater than that of the overall rise in sea-level. This is due to delta compaction and subsidence accelerated by large scale human activities (Syvitski, 2008).

Syvitski's (2008) research has found that accelerated delta compaction associated with hydrocarbon and groundwater mining 'can exceed natural subsidence rates by an order of magnitude,' thereby significantly increasing the relative sea-level rise. Threats associated with this are especially severe for highly-populated mega-deltas (deltas greater than 10,000km^2), such as the Ganges-Brahmaputra, Mekong, Irrawaddy, and the Nile, which are already subject to flooding from storm surges and seasonal river floods.

Climate change acts on coastal systems through the various drivers or risk factors (see Table 1). Among these drivers, the rise in sea-level has often been singled out for particular attention. This is understandable, given current trends and the fact that some have argued that 'there are no winners given the rise in sea-level, rather there are small losers and big losers' (Nicholls and Mimura, 1998, p. 14). While sea level is unquestionably of critical importance in thinking about climate pressures on delta regions, Nicholls et al. (2007, p. 345; 2008b) stress that the present strong focus on sea level needs to be broadened and balanced to include 'all the climate drivers in the coastal zone', such as temperature rise, extreme events, floods, salt water intrusion, biological effects etc., which are having and are anticipated to have further impacts on 'freshwater resources, agriculture and forestry, fisheries and aquaculture, health, recreation and tourism, biodiversity, and settlements and infrastructure' (Nicholls et al., 2007, p. 331).

Table 1. Main climate drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects

Climate driver (trend)	Main physical and ecosystem effects on coastal systems
CO_2 concentration (↑)	Increased CO_2 fertilisation; decreased seawater pH (or 'ocean acidification') negatively impacting coral reefs and other pH sensitive organisms
Sea surface temperature (↑, R)	Increased stratification/changed circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality; pole-ward species migration; increased algal blooms
Sea level (↑, R)	Inundation, flood and storm damage; erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change)
Storm intensity (↑, R)	Increased extreme water levels and wave heights; increased episodic erosion, storm damage, risk of flooding and defence failure
Storm frequency (?, R)	Altered surges and storm waves and hence risk of storm damage and flooding
Storm track (?, R)	
Wave climate (?, R)	Altered wave conditions, including swell; altered patterns of erosion and accretion; re-orientation of beach plan form
Run-off (R)	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply

(Trend:↑ increase; ? uncertain; R regional variability)
Source: Nicholls et al., 2007, p. 323

The IPCC reports a substantial increase since 2001 in the understanding of climate change implications for coastal systems and low-lying areas, a category which includes deltas. With very high or high confidence, the IPCC (Nicholls et al., 2007, p. 317) asserts that:

1. Coasts [meant to encompass 'coastal systems and low-lying areas' in this section] are experiencing the adverse consequences of hazards related to climate and sea level;
2. Coasts will be exposed to increasing risks, including coastal erosion, overcoming decades due to climate change and rise in sea-level;.
3. The impact of climate change on coasts is exacerbated by increasing human-induced pressures;
4. Adaptation for the coasts of developing countries will be more challenging than for coasts of developed countries, due to constraints on adaptive capacity;
5. Adaptation costs for vulnerable coasts are much less than the costs of inaction; and
6. The unavoidability of sea-level rise, even in the longer-term, frequently conflicts with present-day human development patterns and trends.

These six policy-relevant findings support this paper's three arguments and inform its five original proposals.

Three Propositions

What emerges from these messages is the **importance of adaptation** strategies and measures for vulnerable coastal areas, in this case, **delta regions**. The need to strengthen **adaptive capacity** in vulnerable regions, and the need for **ways to help grasp the spectrum of choices** involved in making 'human development patterns' more compatible with climate change and variability, unavoidable sea-level rise, and other exacerbating pressures.

Blending these messages with the findings of the remainder of the literature review, three key needs can be identified:

1. the need for research and thinking about deltas as a group, due to their common features and pressing needs;
2. the need for a more comprehensive conceptual framework to guide deliberation and decision making about adaptation strategies and measures in delta regions; and
3. the need for compilation, systematisation, and maintenance of information, research, and guidance on deltas and climate change adaptation in the context of existing pressures and future trends. Core reasons to address these needs are given in the diagram below.

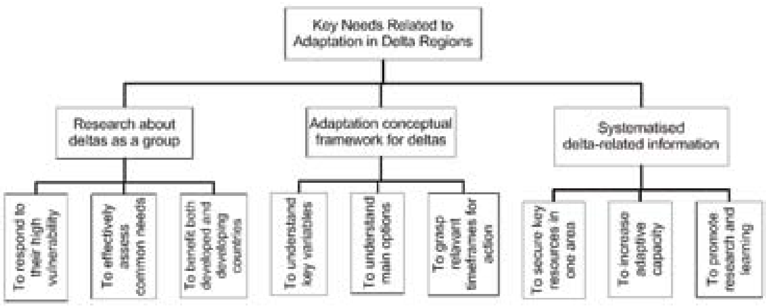


Figure 4. Overview of core propositions to be addressed

Research and thinking about deltas as a group

Many authors (i.e. Nicholls and Mimura; 1998; Woodroffe et al., 2006; Reker et al., 2006; Burkett, 2008; Tol et al., 2008) imply that it would be productive to treat deltas as a group or as regional groups for research and other purposes. The most recent IPCC report (Nicholls et al., 2007, p. 346) asserts definitively: 'While research is required at all scales, improved understanding at the physiographic unit scale (e.g., coastal cells, deltas or estuaries,) would have particular benefits, and support adaptation to climate change and wider coastal management.'

Dispersed networks around the globe, many of them regional, have already come to this conclusion (i.e. ADP, 2008; APN, 2008; DRAGON, 2008; EURODELTA, 2007; WDD, 2004). Groups who deal with wider coastal issues relevant to deltas, such as coastal erosion, also prove the potential synergies and benefits of working at a regional level (EUROSION, 2008; Salman et al., 2004). These group initiatives, even if sometimes short-lived or sporadically funded, work together on deltaic issues at regional or wider levels. This further underscores the validity and value of such an approach in the context of climate change and other pressures.

There are at least three readily apparent reasons to promote greater attention to deltas as a group. The first is their extreme vulnerability in terms of risk to large human populations and deltaic ecosystems. The IPCC (Nicholls et al., 2007, p. 317) emphasises: 'Populated deltas, especially the Asian mega-deltas), low-lying coastal urban areas and atolls, are key societal hotspots of coastal vulnerability, occurring where the stresses on natural systems' tend to coincide with low human adaptive capacity and high exposure.'

The second reason is that they face serious common challenges and struggles, independent of national income level (Stern, 2007). This is confirmed by studies of both developed and developing countries (Dasgupta et al., 2007 study of the impact of the rise in sea-level, on 84 developing countries; Nicholls et al., 2007 on Hurricane Katrina; Kabat et al., 2005 on Netherlands; Wong et al., 2007 on scope of loss of wetlands, floodplains, and forests along European Rivers; and Tol et al., 2008 on much of Europe's early-stage measures to adapt to sea-level rise).

Since learning that adapting to climate change is an ongoing process, it is logical to make the best use of existing resources and build on synergies relating to common issues, constraints, and opportunities, such as incentives and structures for cooperation, as illustrated in Woodroffe et al. (2006) and Tol et al. (2008).

A third reason to suggest looking at deltas as a group, to facilitate the transfer and sharing of research and knowledge between developed and developing countries. This sharing is in fact a duty of signatories to the United Nations Framework Convention on Climate Change (UNFCCC, 1992), whose Article 4.1 commits parties to promote 'full, open and prompt exchange of relevant scientific, technological, technical, socio-economic and legal information' and to 'cooperate in preparing for adaptation to the impacts of climate change; develop and elaborate appropriate and integrated plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas' among many other specific responsibilities. Such sharing gains further importance, value, and urgency given the unavoidability of further climate changes and variability, as well as the 'commitment to the rise in sea-level wherein sea level will continue to rise due to thermal lags in the ocean system, even after greenhouse gas emissions stabilise (Warrick and Oerlemans, 1990; Nicholls and Lowe, 2006).

As with the small island states in the UN and IPCC contexts, being identified as a group has strengthened opportunities for research, learning, and cooperation. It has also helped bring visibility to and international support for addressing present and future climate challenges (UNCSD, 2007 and IPCC report chapters on small island states from 2001 and 2007).

A conceptual framework for adaptation in delta regions

Both mitigation and adaptation are essential and complementary responses to climate change. 'Mitigation' refers to efforts to reduce greenhouse gas emissions into the atmosphere. In contrast, 'adaptation' refers to adjustment in systems in response to observed or expected changes in order to eliminate or reduce adverse impacts and take advantage of positive opportunities (UKCIP, 2008). In this paper, following Adger et al. (2005, p. 78), adaptation is understood to include 'activities, actions, decisions and attitudes that inform decisions about all aspects of life, and that reflect existing social norms and processes.' Since adaptations occur in a context of demographic, cultural and economic change, climate adaptations can, in fact, be difficult to distinguish from actions triggered by other social or economic events (Adger et al., 2005).

Adaptation in delta regions is imperative, as it is now recognised by numerous authors and researchers. However, it must be borne in mind that there are a number of reasons why climate change-related adaptation, knowledge and experience has not progressed further and faster. It played only a 'marginal part' in IPCC reports prior to 2000 (Metz et al., 2000, Section 1.8).

One of the reasons for this was two distinct schools of thought about climate change then. The 'preventionist' (must drastically reduce emissions) and 'adaptationist' (natural and human systems will adapt naturally to changes), neither of which encouraged attention to adaptation. That remained the case until people began to understand that climate change is a 'genuine threat' rather than a 'theoretical phenomena'. After this, the 'realist' school emerged, which considered adaptation to be a 'crucial and realistic response option, together with mitigation' (Metz et al., 2000, Section 1.8). This timeframe suggests that more systematic efforts toward adaptation on a worldwide scale have only begun to take hold and develop over the past eight to nine years.

Metz and co-authors (2000) provide excellent further discussion of the reasons adaptation has been relatively more neglected in the past and cite some of the strong incentives to adapt as:

1. adaptation technologies reduce vulnerability to anticipated impacts of climate change and to contemporary hazards associated with climate variability; and
2. since adaptation options must take into account site-specific natural and socio-cultural circumstances, they provide opportunities to strengthen capacities (technological, institutional, legal, economic, etc.) and raise awareness among key stakeholders.

Yet, it could be argued that there is still a gap to cross, surrounding understanding of adaptation in delta regions and to how to approach the issue with appropriate perspective. This paper argues, with others (Klein et al., 1999; Nicholls and Klein, 2000*; Nicholls et al., 2007), that a holistic view is necessary to be able to select appropriate measures for deltaic and coastal climate change adaptation. It is inaccurate to think that the only real responses to climate change are technical and engineering based adaptations, and it is simply not enough to know about the 'retreat-accommodate-protect' options.

While there are many alternatives within these three approaches, they are not intuitive and tend not to be presented (notable exceptions being Klein et al., 2000, Section 15.3.3 and NRC, 1987). Nevertheless, this is the model most often mentioned in the literature, and due to the way it is portrayed, is often likely to be perceived as the only one.

This situation highlights the need for frank portrayal of the subdivisions, along with the suite of other approaches that exist. This is so that informed decisions can be made and for many more people to become empowered to take part in developing adaptation solutions. For these reasons, a series of existing frameworks to understand adaptation in delta regions will be presented.

These reflect the author's perception of the most useful aids for addressing coastal and deltaic management for climate change, rise in sea-level and other pressures. They will be followed by this author's alternative adaptation approaches and a collection of insights for guidance, which concludes the conceptual framework sequence.

It would be the topic of another paper to describe what each of these subsequent frameworks and models imply, but within the constraints of space, they will simply be presented below with references for further information.

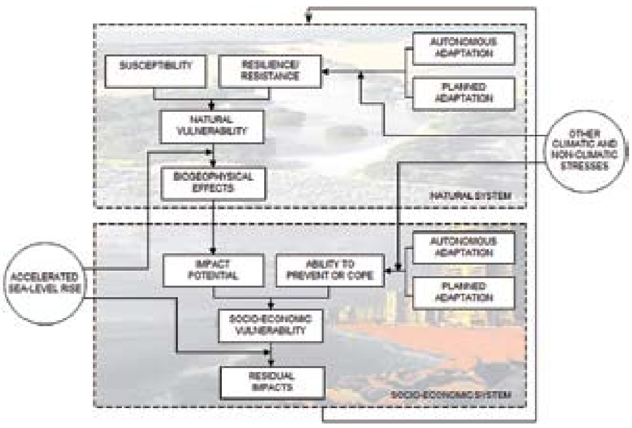


Figure 5. A conceptual framework for coastal vulnerability assessment, redrawn from Klein and Nicholls, 1999

The proposed enhanced framework comprises a cascade of different models and information. Starting from a basis in the information in Table 1 and Nicholls and Klein's (2000*) overall guidance, Figure 5 below illustrates how the rise in sea-level, climate change considerations, and other stresses should be factored into assessments of vulnerability.

Figure 6 below emphasises the iterative process that occurs in coastal adaptation, which, regardless of adaptation response selected, involves various stages including information gathering, planning, and monitoring in an overall integrated coastal zone management (ICZM) context.

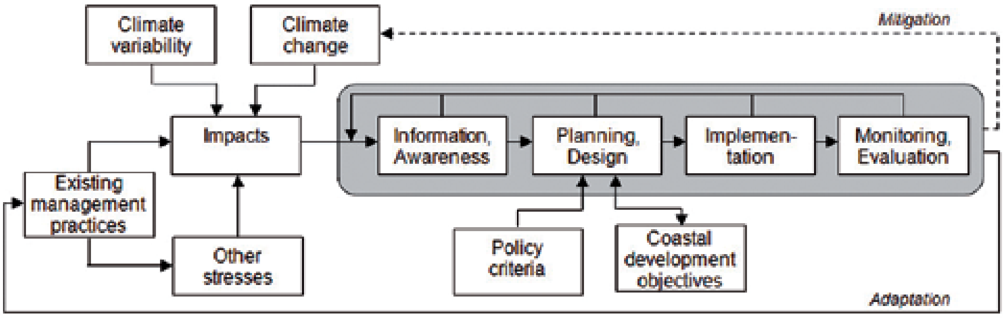


Figure 6. Conceptual framework showing iterative steps (in shaded area) involved in coastal adaptation to climate variability and change, redrawn from Klein et al., 1999, p. 245

Table 2 gives an overview of various ways to differentiate adaptation options; it may be used to guide thinking and gauge whether a wide enough set of options, considerations, and alternatives has been taken into account for making a confident decision. Tol et al. (1998) and Adger et al. (2007) provide further insight into adaptation costs.

Table 2. Bases for differentiating adaptations

General Differentiating Examples	Concept or Attribute of Terms Used	
Purposefulness	autonomous spontaneous automatic natural passive	planned purposeful intentional policy active strategic
Timing	anticipatory proactive ex ante	responsive reactive ex post
Temporal Scope	short term tactical instantaneous contingency routine	long term strategic cumulative
Spatial Scope	localised	widespread
Function/Effects	retreat - accommodate - protect prevent - tolerate - spread - change - restore	
Form	structural - legal - institutional - regulatory - financial -technological	
Performance	cost - effectiveness - efficiency - implementability - equity	

Source: Smit et al., 1999, p. 208

Figure 7 offers an alternative view of adaptation response options, going beyond the typical 'retreat-accommodate-protect'. It can be argued that a wider representation such as this (particularly in expanded form with elements clearly elaborated) will stimulate thinking that leads to more imaginative and stronger adaptation responses, and as a result, help build capacity and overall receptiveness to adaptation actions. In Figure 7, the two approaches without a citation can be followed up in Klein et al. (2003), and more in depth discussion of adaptive management can also be found in Nelson et al. (2007).

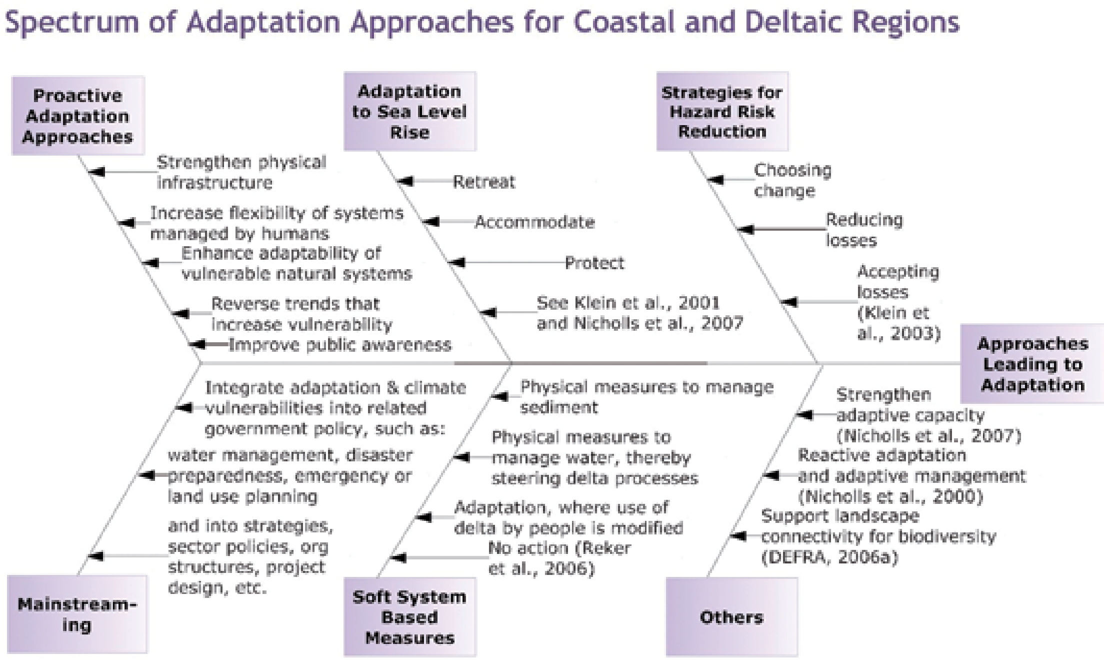


Figure 7. Spectrum of adaptation approaches for coastal and deltaic regions

Finally, Figure 8 synthesises key words of wisdom which were loosely strewn throughout reviewed documents. These may further direct thinking and approaches to adaptation, whether specific or blended approaches.

It is the interlinked nature of dynamics in deltas and along coasts that necessitates measures being designed within the context of ICZM (Nicholls et al., 2007). It is also worth emphasising that any of the approaches and measures adopted in Figure 7 will not only contain technical aspects, but will entail other views and processes as reflected in Figure 6. The capacity that can be implanted through in-depth understanding of the frameworks presented above would be a formidable aid to fostering sound decision making (see DEFRA, 2006b and Salman et al., 2004 for early examples). Short of further development of this proposed enhanced framework, in this author's estimation, the IPCC Chapter 6.6 (Nicholls et al., 2007) provides the best overall guidance and information for coastal and deltaic climate adaptation available at this time.

Key Questions1: Where to adapt? How to adapt? When to adapt? (Nicholls and Klein, 2000*) For what time period?
Key Questions2: Who or what adapts? Adaptation to what? (Smit et al., 1999)

Key climate change adaptation principles (for regions and local authorities)	Major impediments to the success of adaptation in the coastal zone	Defining successful adaptation
• Seek opportunities to incorporate adaptation into new and existing developments • Work in partnership with communities (households, public and private sectors) • Incorporate flexibility to deal with changing risks • Understand existing vulnerabilities to climate and identify critical thresholds • Identify key climate change risks using the latest climate change scenarios • Look for no regrets, low regrets, win-win and adaptable measures to manage climate risks • Adopt a sequential and risk-based approach to development decisions • Avoid actions that will make it more difficult to cope with climate risks in the future • Review your adaptation strategy regularly (From Shaw et al. 2007, p. 13)	• Lack of dynamic predictions of landform migration • Insufficient or inappropriate shoreline protection measures • Data exchange and integration hampered by divergent information management systems • Lack of definition of key indicators and thresholds relevant to coastal managers • Inadequate knowledge of coastal conditions and appropriate management measures • Lack of long term data for key coastal descriptors • Fragmented and ineffective institutional arrangements, and weak governance • Societal resistance to change (From Nicholls et al., 2007, p. 341)	• One cannot define success only in terms of effectiveness of meeting objectives, because... • An action successful in the short term might impose externalities at other spatial and temporal scales. • Adaptation to climate change can be evaluated through generic principles seeking to promote equitable, effective, efficient and legitimate action harmonious with wider sustainability. (From Adger et al., 2005, p. 80)

Timeframe Considerations: Anticipatory adaptation can be justified (1) when there are net benefits independent of climate change (win-wins) and (2) for high priority decisions due to: (a) possible irreversible catastrophic impacts of climate change, (b) long timeframe decisions concerning issues such as infrastructure expected to experience climate change, and (c) likely unfavourable interaction between climate change and other long-term trends without anticipatory action (Nicholls and Klein, 2000*). Cases where it is likely to be more cost-effective to implement adaptation measures early on include ones involving infrastructure with long economic life or if current activities may 'irreversibly constrain future adaptation to impacts of climate change' (Adger et al., 2007, p. 721). These criteria are not exclusive but can serve as an aid to thinking and decision-making.

Figure 8. Insights on climate change adaptation

Systematised deltas information

Despite the existence of some valuable resources on worldwide deltas, climate change, and the rise in sea-level, many of these resources are difficult to find using online searches, and there is no single repository where information about deltas and climate change is assembled, systematised or maintained. This means that efforts to develop adaptation strategies or devise coastal protection measures in a particular deltaic region are more likely to be attempted with limited prior information, understanding and knowledge available. If these systems were in place, work could take place, based on past knowledge, research, and experience.

Lack of access to systematised resources also means that building up individual, public and private sector capacity is hampered. Because of information barriers, people are more likely to continue with a compartmentalised thought patterns, perhaps thinking that delta adaptation strategies are confined only on the basis of 'retreat-accommodate-protect' and the only methods available are limited to hard engineering solutions.

If relevant information were more readily accessible, people would be able to understand and consider a wider spectrum of approaches, as presented in Figure 7. For those unfamiliar with deltaic issues and delta management, there is a significant need for information resources that can help people access information surrounding deltas and what needs to be done to make sound decisions and, climate-aware plans.

The following section describes five proposals to support climate adaptation in delta regions that respond to these identified needs.

Proposals

1. An easy to use website with systematised worldwide deltas climate and adaptation information

A website holding information about delta adaptation is needed to take advantage of all the useful resources and research already generated. These can help to build recognition of deltas across all sectors, help those working with deltas develop their knowledge and experience, and support the idea of bringing deltas together as a group, due to their high vulnerability and common issues.

Information about deltas is becoming increasingly available, such as in the World Deltas Database (WDD, 2004), Deltas on the Move report (Reker et al., 2006), and various scientific publications (i.e. Coleman et al., 2005; Ericson et al., 2006; Woodroffe et al, 2006; Syvitski and Milliman, 2007), but the 'how to' and education/capacity building side with guidance on how to use this information is still lacking. The goal at the core of the proposed website, is to build capacity and to converge scattered information into one place, (Dankers, 2008). It could direct people to some of the top resources relating to deltas, such as Nicholls et al. (2007) for the IPCC, Reker et al. (2006), Nicholls (2004), and Klein et al. (2000 and 2003). In later developments, the website might also host a deltas adaptation 'helpdesk' – where coastal managers or others could ask questions and receive a response within perhaps 1 week. If it were a general question, it could then be posted on the website. A helpdesk function would add immense value, helping individuals overcome barriers in the search for appropriate adaptation solutions.

It is true that delta-related websites already exist, but they tend not to stay updated due to projects ending (i.e. WDD, 2004), include only or primarily publications sponsored by their own institution (i.e. Tyndall Centre, 2008), be regionally rather than globally focused (i.e. APN, 2008; EURODELTA, 2007), or centre on only geologic or scientific aspects of deltas (i.e. DRAGON, 2008; WDD, 2004). The NCSP Knowledge Network (2008) is perhaps a close example of the type of on-line resource being proposed for deltas. Despite not meeting the proposed ideal, all the delta-related websites are important resources that can be used to formulate the type of website envisioned. This would be one that would compile all relevant information from the other delta websites and research, and systematise and maintain the information in user-intuitive and searchable categories, which no other website currently achieves.

2. A deltas adaptation handbook

Subsequent to a systematic collection of resources for the website, relevant information would be in place to prepare a delta adaptation handbook. Whether policymakers or individuals, finding time to research and understand relevant information on a new topic is a major barrier to effective action.

The author suggests an effective way to combat this problem is to create a delta adaptation hand or guidebook modelled on Surviving Climate Change in Small Islands: A Guidebook (Tompkins et al., 2005). This is an extraordinarily well prepared resource of 132 pages, divided into sections addressing why it is important to be concerned about climate change, understanding climate change risks, assessing vulnerability and structuring an adaptation plan, and developing and implementing a climate change adaptation strategy.

Creating a manual along these, or similar, lines would contribute greatly to strengthening capacity and knowledge of users and delta inhabitants. As has been demonstrated in this paper, there are many dimensions to consider in adapting vulnerable areas to climate change, other human influences and interacting pressures. A simply presented primer consolidating the most essential information would be invaluable. Such a practical, straightforward format, as is portrayed in the Tompkins et al. document, would also facilitate widespread understanding and strengthen communication between all stakeholders, policymakers, planners, coastal managers as well as governmental and non-governmental organisations, communities, and individuals. Even prior to a website compilation exercise, the references used in this paper could be used as the foundation of such a guidebook.

3. An adaptation ideas bank

The purpose of an adaptation 'ideas bank' or adaptation compendium would be to collect and organise, by characteristically different adaptation strategies and measures, and indicate where more information on each might be found, building on the work of Adger et al., (2007). Such a 'clearinghouse of adaptation technologies' (also advocated by Klein et al. in 2000 with similar and further parameters) would make ideas available and support the open exchange of information. All types of adaptation measures and support resources would be posted there, including: innovative strategies like the adaptation strategy in Finland (Dankers, 2008), innovations in the Netherlands (Kabat, 2005), flood strategy in UK (DEFRA, 2008), and UK resources such as its climate adaptation guidance organisation (UKCIP, 2008), policy guidance (DCLG, 2007), and easy to use adaptation manuals for local authorities and communities (Shaw et al., 2007).

It would include a description of what adaptation entails in different areas, from highly engineered flood defences and homes that can float on water, to artificial snow-making machines for the alpine ski industry, to bamboo flood shelters on stilts and mangrove planting to protect against storm surges (Watkins et al., 2008). It could be organised following the criteria in Adger et al. (2007, p. 720) relating to spatial scale, sector, type of action, climatic zone, etc. and further enhanced using specifications from Klein et al. (2000, Section 15.7.2). Such an 'ideas bank' would need to be hosted on a website, potentially the same website outlined in the first proposal. This might also be something the IPCC or United Nations could eventually foster, as it began to do in a survey of mitigation projects (UNCSD, 2007).

4. A deltas translation fund

This proposal is for a delta translation fund that would be used to finance the translation of key delta resources to make them more widely known and available. Approximately five or six delta experts could identify one publication or resource to be translated annually, that would be selected for its potential to contribute to furthering delta science and/or management solutions.

Ranking criteria for the selected publication could be: presence of important new information or insights; clear, understandable presentation; high degree of operational or planning utility; and relevance to more than one region or a large population within a region. The author would suggest the Deltas on the Move report (Reker et al., 2006) as the first candidate for translation. It provides a concise and thorough overview of delta issues and climate change, as well as presenting emerging trends in thinking surrounding systems-based delta management.

Furthermore, it presents new information, analysis, and resources on world deltas. The report could be translated into five languages and in order to reach those presently most in need of the information; perhaps these languages could be Chinese, Arabic, Burmese, Spanish, and French (which covers many African countries). All winning publication translations would be made available online for universal access.

If there were a year when no single publication stood out, the panellists might submit a grant or use the fund to have a synthesis of new knowledge written and translated. The panellists would allow any winning publications (and possibly shortlists too) to be put on a website, showing their estimation of the most important new contribution on deltas, coastal management, and climate change.

The panellists could accept nominations from around the world for translations that were eagerly sought. It would not always be translations from English into other languages, but the fund might also be used for translations into English, as a way to disseminate cutting-edge adaptation strategies (e.g. Finland), flood control strategies (e.g. Netherlands), or high quality adaptation practice manuals from South or East Asia.

Critical to the success of this initiative would be the nomination, participation, and awareness that this is being done as an effort of good will to support knowledge and capacity worldwide. It would be important to communicate that such an initiative would be for the transfer of knowledge between both North-South and East-West (and vice versa) as each region has perspectives, insights, and experience from which the others can benefit.

5. Delta sister cities programme

This final proposal moves away from information access and management to a more human perspective, as capacity building is not only about information, but about people.

What is envisioned for a delta sister cities program would be (1) assessing which cities or regions have most in common and (2) supporting individuals within those regions to participate in knowledge sharing events in neighbouring or 'sister' regions. The programme would provide annual grant support for travel costs associated with knowledge and technology transfer between deltas under similar conditions, or with similar pressures. Part of the purpose of such a programme would be to encourage cross-fertilisation of ideas and technologies between developed and developing countries.

Application eligibility would be open to both seasoned experts and individuals being 'groomed' for delta management and would favour those with limited means for such exchange (who could come from either developed or developing countries). As this proposal and the others show, deltas present an opportunity for shared learning, in such a way that can facilitate progress as a world community, rather than only as specific nations.

The daring aspect of all of these proposals is the idea of putting information in everyone's hands and investing in human capacity, not only of academics and coastal managers but also of all those who have a stake in the sustainable future of delta regions.

Conclusion

Though deltas come in all shapes and sizes, they share many features, issues and vulnerabilities due to their particular geography. This makes them suitable for study as a group or as regional groups, thereby facilitating knowledge and technology transfer in the face of climate and other pressures. In order to support capacity building, existing conceptual frameworks for deltas may need to be enhanced to show a larger piece of the coastal and deltaic management picture.

Included in this, it is necessary to show a wider portrayal of the diverse adaptation approaches that actually exist beyond technical options and 'retreat-accommodate-protect'. There is a growing urgency for information on deltas and climate change and other pressures to begin to be assembled, systemised, and maintained in order to optimally support research, capacity development, and design and implementation of adaptation measures. Finally, new adaptation support initiatives are required to address these findings and further build capacity at all levels. Such initiatives might include a website specifically for worldwide deltas and climate issues, a deltas adaptation handbook, an adaptation ideas bank, a deltas translation fund, and a sister city representative programme.

Kabat et al. (2005, p. 283), who advocates the development of hydro-metropolis or 'floating cities' in The Netherlands, suggests that 'climate proofing should be driven by opportunities for technological, institutional and societal innovations, rather than purely by fear of the negative effects of climate change.' This paper argues that the strengthening of capacity that would come about through enhanced conceptual frameworks, new presentation of adaptation approaches, and innovative adaptation support initiatives would do just that.

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Design and Deployment of Aquaponic Grid Communities

Ganges-Brahmaputra Delta

Winner of the Team Category of The DeltaCompetition 2008

Duc Tung Nguyen
Karthik Ramanathan
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Executive Summary

Figure 1. Map of Bangladesh – Ganges-Brahmaputra Delta visible lower centre of image [38]

In third world nations, there is often an understandable lack of focus on environmental concerns when they conflict with the development of industry and the quality of life [1]. However the situation in the Ganges-Brahmaputra Delta is different. As the heartland of agriculture in Bangladesh, the threat posed by global warming, population growth, and rise in sea level is a stark reminder of the fragility of the area. Human development, combined with encroaching ocean water has led to the subsidence of land at an ever-increasing rate [2]. Clear cutting tracts of land removes natural erosion barriers, while the continued damming of upstream areas slows down water flow which hastens the process of aggradation along river beds. This study proposes the introduction of an Aquaponic Grid Community (AGC) that is deemed to be the most efficient and economically viable solution to the aforementioned issues. It will be self-sufficient from both energy and food standpoints; will act as a new social catalyst; and will provide an increased income to the residents of the region. A detailed analysis of the steps that need to be taken to create, run, and maintain such an endeavour has been outlined to help turn this concept into a viable reality.

Introduction

The issues of global warming and environmental degradation are the driving factors towards the development of sustainable and energy efficient technologies. However up to this point, the implementation of such systems across any field has not been beneficial from an economic or productivity standpoint. Notable examples include wind farms and hydrogen based automobiles, which have both suffered from low power yields, and expensive start up costs [7].

The Ganges-Brahmaputra delta is located mainly in the country of Bangladesh and parts of West Bengal, India. It is formed by the combined entrance into the Indian Ocean of two of the largest rivers in South Asia, namely the Ganges and the Brahmaputra. The delta is approximately 350km wide at its largest point. It is home to over

140 million people. Over a third of a billion people are dependent on the agriculture and fishing provided by the delta [3]. The region is extremely prone to severe natural disasters mainly in the form of hurricanes (cyclones) and floods. These problems are exacerbated by the progression of global warming, which, though not proven, has been thought to contribute to the increased scope of the issues faced by the area. In addition rising sea levels, subsidence, river damming, aggradation, and increasing loss of forestry (please see glossary for definitions) are threatening the future of the delta as a productive farming region and thereby the livelihood of the individuals who are dependent upon it [7].

It is therefore the aim of this project to introduce a mechanism of directly maintaining the livelihood of the local populace of the Ganges-Brahmaputra delta while ensuring that any endeavours remain profitable for the users of the technology. To this end, the study introduces the concept of AGC facilities that allow the growth of food crops in a hydroponics environment while operating aquaculture fish farms in the surrounding waters. The main idea behind this proposal, is the design and deployment of these facilities so they can be transplanted into any deltaic region and have an immediate positive impact on the local community, (see Table 4).

Problem Definition

With the onset of rising sea levels (3.1mm/year) [5] and slowing down of sedimentation, the regions surrounding the Ganges-Brahmaputra delta are experiencing increasing levels of flooding, estimated to be at a rate of 4000 hectares per year [6]. In addition, these waterlogged areas have inadequate drainage, resulting in multi-decade loss of arable land [7]. Furthermore these sections become mosquito havens due to the presence of stagnant water.

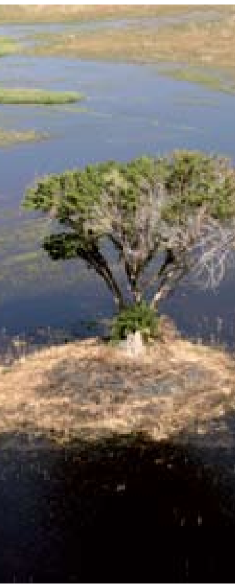
The traditional method of agriculture in the region involves clear cutting and draining an area, planting crops, drilling groundwater wells for irrigation and finally harvesting crops. In the event of a natural disaster, such as the rapid onset of flooding, all crops would be lost. However clear cutting and ground water sequestration leads to greater flooding in the future due to the loss of drainage gradient and subsidence, thereby starting a vicious cycle characterised by even greater losses in arable land [7]. Moreover these issues have been exacerbated by the tropical climate conditions present in Bangladesh. Monsoon flooding is an annual event that adds up to 3m of water. Cyclonic surges often batter coastal areas and cause excessive wind and water damage to crops and buildings. Finally, the use of fertilisers in agriculture often leads to runoff polluting local water supplies causing environmental problems such as eutrophication [8].

Therefore the major issue facing the Ganges-Brahmaputra region is the strain placed on local agricultural and fishing industries in supporting the population of the area. An innovation and/or technology expansion is required to directly increase the agricultural productivity of the area.

Constraints and criteria

Regardless of the implementation chosen to aid the area, there are a few items that need to be universally met before the idea can be considered useful. These can be broken down into the following groups:

1. Cannot exceed $50000 US dollars.
2. Allow a measurable increase in the agricultural throughput of the region.
3. Must be ecologically safe.
4. Generate power internally and thereby be self sufficient.
5. Should be low maintenance, defined by the technical abilities of a local villager.
6. Should be constructible by the local populace (not requiring foreign materials).
7. Assist in reducing the impact of relative sea level rise.



These constraints have been selected because they can be quantitatively measured to provide an accurate measure of the efficacy of the implementation. These quantitative yardsticks are as follows:

1. The total cost of a system can be measured easily by factoring in all sub costs such as labour, parts, and construction. Auditors assigned to the Bangladesh Government will conduct oversight of all matters.
2. The increase in agricultural and fish throughput of the region can be observed by looking at the relative change in the financial status of the local farmers and as well by observing the difference in food output per capita on a long term basis before and after implementation.
3. The ecological viability of the solution can be monitored and commented upon by the United Nations Department of Economic and Social Affairs, Division of Sustainable Development and the United Nations Food and Agriculture Organization, Department of Fisheries and Aquaculture. These groups are responsible for developing ideas and coordinating with governments on methods to improve local quality of life and are also able to generate reports on the status of projects [9,19].
4. The ability of the solution to be self sufficient can be measured simply by determining its reliance on outside power sources. By ensuring that no outside power is used, this metric is achieved.
5. The technical abilities of an average villager are a suitable heuristic to utilise when determining the potential complexity of a solution. Certainly some training will be required to operate the systems; however this can qualitatively be identified by the mantra 'Keep It Simple'.
6. The essence of having local materials and labour simply implies that in the event of damage to the system and/or required expansion, there will be no need for the expensive importation of supplies from foreign countries.
7. By measuring the relative rise in sea level before and after the implementation of the solution on a decade basis, one can determine the effects that such a system has had on the environment.

Analysis

Potential Solutions

Based on the problem definition and the accepted constraints several individual and amalgamated solutions were considered. These are listed in table 1. on the opposite page.

As mentioned in the table, the proposed ideas were evaluated based on their impact on the welfare of the local populace and their impact in alleviating regional and global factors such as global warming, rising sea levels, eutrophication and river delta degradation. Additionally, other critical factors such as political, economic and social implications were also utilised to appraise the solutions, as these issues are far more vital in the implementation and continuous development of large scale projects than the former issues.

As part of the constraints, all solutions were considered from the perspective that the solutions would be primarily implemented, developed and maintained by the federal and municipal government and supported by external institutions such as Universities, NGOs and development banks.

Table 1. Proposed Solutions and their respective merits

Solutions	Issues addressed	Advantages	Disadvantages
River degradation solution – self powered dredging via underwater turbines	Degradation, monsoon flooding, spring flooding, rising sea levels, annual loss of land to water logging	Natural energy source, Dredged soil used to grade land	Slow down of water leading to excess sedimentation, complex technology
Sea based – self contained aeroponic farms	Degradation, monsoon flooding, spring flooding, rising sea levels, annual loss of land to water logging, subsidence, eutrophication	Resistant to flood waters compared to land based irrigation methods	Susceptible to cyclones, large scale infrastructure project which isn't economically viable
Land grading – via natural techniques – damming flood waters	Degradation, monsoon flooding, spring flooding, rising sea levels, annual loss of land to water logging	Water drains easily. Stops sanitation problems caused by stagnant water	Requires purposefully flooding and draining lands to grade land, making land unusable for a certain time, relies on flood waters to carry significant amounts of silt, does not address local necessities of food and shelter
Symbiotic aquaponics grid – self contained hydroponic and aquaculture farms	Degradation, monsoon flooding, spring flooding, rising sea levels, annual loss of land to water logging, subsidence, eutrophication, cyclones	Addresses reliable food and shelter, as crops are semi resistant to floods as they are floating	Continuous effort to determine good combinations of fish and plants and optimise growing and planting periods
Delta degradation solution – Speeding flow of water using external wind based turbines to slow sedimentation and speed up drainage	Degradation, monsoon flooding, spring flooding, rising annual loss of land to water logging,	Environmentally friendly. Addresses loss of land by encroaching sea waters	Large scale infrastructure required to make a sizable increase in water flow, difficult to plan as water channels are constantly changing
River based hydroponics – River bank hydroponics via boats	Monsoon flooding, spring flooding, subsidence, eutrophication	Crops are semi-resistant to floods as they are floating	Farmers at the mercy of the river

Selection

The basic tenet of the selected idea was to create a low-tech, low-cost, self-sufficient village that utilises aquaponics to achieve these means, called an Aquaponic Grid Community (AGC). The idea involved developing small but scalable adjacent zones of hydroponics and aquaculture with water as the nutritional ether between the two systems. Although other solutions satisfied the technical constraints drafted above and were viable and innovative for the Ganges-Brahmaputra delta, AGC provided a means of large scale collaboration between locals and regional governments and the solution's simplicity made it more conducive to being accepted and further more, utilised on an ongoing basis. A visual representation of the AGC is shown below:

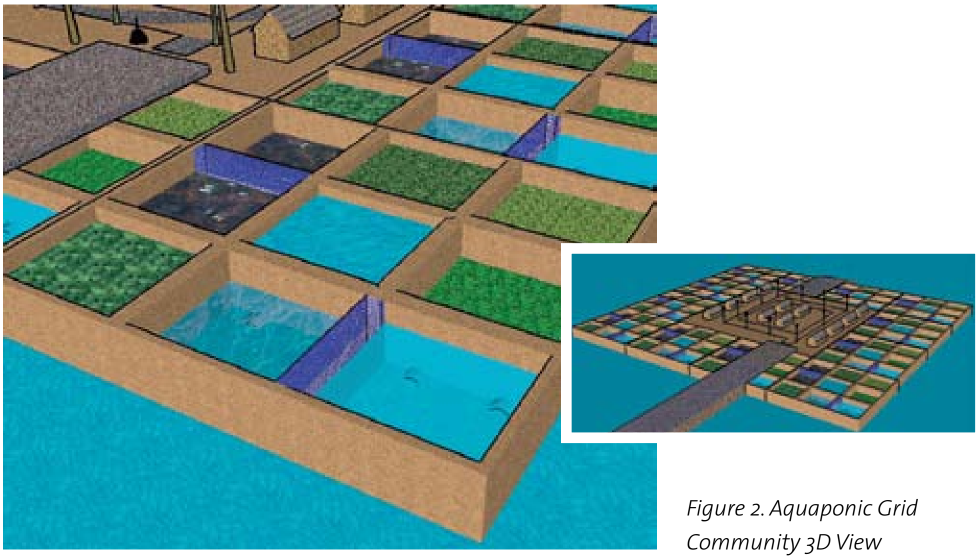


Figure 2. Aquaponic Grid Community 3D View

Technical Details

The Aquaponic Grid Community consists of utilising flooded and waterlogged lands as Bangladesh has the highest ratio of swamp land to land ratio in the world and loses 4000 hectares to flooding every year [6].

The land is to be divided into subsections of 50m by 50m known as units. A grid of 3 by 3 units forms a larger classification known as a zone. The units are divided by simple floating docks on the surface with nets below to prevent movement of aquaculture species across the barriers. The docks provide access to each of the units and provide a means of performing maintenance without having to enter the water. The zones are separated by large mud banks with embedded vegetation, such as grass and trees, to prevent bank erosion. There are a series of pumps and filtered channels embedded into the sides of the zones and units. These allow the transmission and movement of water and aqua-cultural material to move between areas.

In the event of a problem in one zone, material can be diverted to another. Additionally, this allows water and nutrient level imbalances to be modified easily. The large area of water surrounding an AGC implies that water can additionally be moved into and out of the system.

Agriculture

The continued population increase in the Ganges-Brahmaputra region, combined with the volatile and increasingly flooded regions of the deltaic plain, implies that an ideal method of cultivating crops is hydroponics. Hydroponics is the methodology of growing plants in a completely aqueous environment. This is because plants uptake nutrients solely through solution form and thus do not technically require a soil medium [10]. However to provide a firm base for the plants, they will be placed on beds constructed of weeds such as Water Hyacinths (Eichornia Crassipes) and Duckweed (Najas Graminea). These water weeds are extremely hardy and often grow in very dense quantities along waterlogged areas. Refer to the Construction section of this report for a more detailed overview of the process.

Modern aquaponic farms have successfully grown hundreds of varieties of crops and plants in enclosed and controlled environments [10]. Experiments in river hydroponics have shown that there is essentially no barrier to the type of food plant that can be grown as long as it is suited to the general climate present in the region [11]. There have been 23 confirmed experimental hydroponically grown vegetable varieties and five spice types in Bangladesh alone. A few direct examples are as follows: Okra, egg plant (aka aubergine), pumpkin, spinach, beans, tomato, potato, cabbage, turnip, radish, carrot, ginger, onion, chilli, and garlic [12].

Figure 3. Hydroponic Beds [12]

It is suggested that rather than select specific plants for the region, it be left up to the villagers and local governments to determine what the best selection and mix of crops would be. An experienced farmer can decide what would provide the easiest mix between ease of cultivation and generated revenue from specific crops.

During colder months, when water levels may recede, it is a viable opportunity to grow rice in the paddy like environment present in each zone and unit. Rice is a staple of the Bangladeshi diet and the worldwide demand of rice will continue to increase, especially with population growths projected to occur in the neighbouring regions and countries [3].

A sample implementation of the floating bed system can be viewed in Figure. Notice the hook and tether system attached to both the bed and the unit sidewalls. In the event of floods or other unforeseen natural disasters, the beds can be anchored so as not to be washed away or overturned. Furthermore one can see that on the sidewalls, mud banks, and outer rims of the zones, trees (mangroves) and grass has been planted. This is to aid in the prevention of erosion of the sidewalls and provide shelter in the event of storms. It also adds a level of aesthetic appeal to an otherwise barren landscape.

Aquaculture

Fish farming is a very profitable enterprise, considering the world fish trade industry is worth over $100 Billion US dollars, worldwide [37]. In fact total seafood consumption levels have risen from 11.5kg to an estimated 17.4kg per capita in the last 30 years [37]. Furthermore, fish farms can have high yield outputs in relatively small areas. The waste produced by the fish can be utilised to fertilise and enrich the nutrient content of the water for food crop use. Moreover, there are a variety of edible fish that are able to consume animal and human faecal matter and mosquito larvae, thereby considerably lessening the impact of the environment of the aquaponics farm. The primary organisms are to be divided into three distinct groups: Carp, Shrimp, and Crab. These provide an ideal balance between the consumption requirements of the local populace, while ensuring high demand by foreign importers.

The basic details of the organisms are as follows:

1. Carp – Family of Cyprinidae. High economic and nutritional yield. Native to Ganges-Brahmaputra region. Food sources include fishmeal, micro-organisms such as zooplankton, insect/insect larvae and any other organic matter [14,15,16].
   a. Rohu (Labeo Rohita)
   b. Catla (Catla Catla)
   c. Mrigala (Cirrhinus Mrigala)

Figure 4. Rohu Carp [14]

2. Shrimp – Family of Penaeus. Large scale worldwide consumption combined with low maintenance farming makes it ideal for aquaculture. Are generally scavengers and will consume most organic matter [17].
   a. Giant River Prawn (Macrobrachium Rosenbergii)

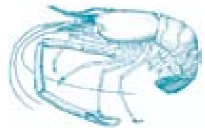


Figure 5. Giant River Prawn [17]

3. Crabs – Nutritionally rich and highly valued economically. Native to Ganges-Brahmaputra region. Extreme scavengers and can be cannibalistic if necessary. Diet consists of other small marine animals and occasional organic matter [18].
   a. Mud Crab (Scylla Serrata)

Figure 6. Mud Crab [18]

These species were selected not only for their nutritional and economic viability, but also because they are native to the Ganges-Brahmaputra deltaic plain. The introduction of foreign fish species could create unforeseen problems such as the accelerated decline of native species [37].

A sample implementation can be viewed in Figure 2. Rolled up netting present on the surface of the fish pond can quickly be deployed over the entire water surface in the event of floods or other unforeseen natural disasters, so as to prevent the aquatic organisms from escaping the unit.

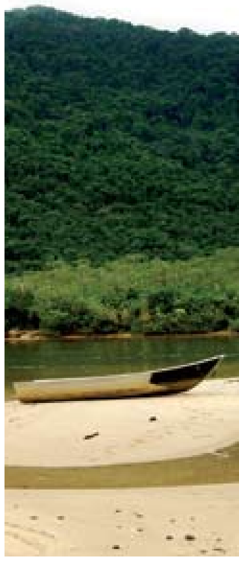
Integration, monitoring and replenishment

The main idea behind the entire farm is the combination of both the aquaculture and the hydroponics into a single system. Though the fish and plants will generally be separated into different units, the nutrients and water will be cycled through all zones. This allows a greater benefit because the waste matter of the fish can be utilised as fertiliser for the plants. Fish faecal matter has a high concentration of ammonia (NH_3- & NH_4) and nitrates (NO_2- & NO_3-), which are both essential to the survival of plants [11]. In classic aquaculture farms, the water would have to be constantly recycled to prevent a toxic build-up of the nitrogen compounds and resulting runaway eutrophication [8]. In classic hydroponic farms, there would be a requirement for constant nutritional replacement and chemical additives to the water, which is an expensive and time consuming process that requires the use of large scale pumps, filters and computer controlled equipment [37].

By combining both systems, a pseudo closed-loop system can be achieved where both groups of plants and animals can live symbiotically. The beauty of this aquaponic system lies in the fact that it does not have to be a completely closed-loop system, which most experimental research strives for [20]. By having a large open source of water in the surrounding region that acts as a buffer, water can be quickly moved and replaced to prevent toxicity. In addition, decaying plant beds and left over plant material can act as either fish food or fertiliser for a new generation of plants.

However for all these events to occur, daily water quality and organism health readings must be taken. It is foreseen that these would be conducted by the villagers. A nine test water quality kit is costs between $215 and $450 US dollars [21]. However, these systems can conduct up to 300 individual tests [21]. The data collected, such as pH levels, turbidity, salinity, nitrate/ammonia, dissolved oxygen, carbon dioxide, fish activity, and plant health, will be sent to universities for analysis.

These institutions will then respond with the steps that need to be taken to maintain a healthy farm and advise of any potential problems. An overview of the entire interaction can be seen in the oversight section of the report.



Sanitation

In most aquaculture and agricultural areas, human and animal manure is often added to the water or soil to provide nutrients to the organisms along the chain. The effluence is rich in items necessary for plant growth, such as ammonia and nitrites. However the waste material also contains significant amounts of harmful chemicals, such as phenols, heavy metals and chlorinated compounds [22]. To properly use waste material as an aquaponic nutrient source requires significant amounts of treatment, this would be virtually impossible in the confined space of an Aquaponic Grid Community [22].

Although there have been no extensive studies into the practice of using effluence as food for aquaculture projects, there is a general scientific consensus that the quality of fish is degraded and that there will be negative developmental effects. As such, the only viable proposition to deal with human and animal waste is to filter and store the effluent in large tanks to be hauled out and disposed of effectively, on a monthly basis, or thereabouts.

Potable Drinking Water

Potable water is a scarcity in Bangladesh despite the abundant rainfall and periodic flooding of rivers. Additionally, Bangladesh is the site of the 'largest case of mass poisoning in history' due to the lethal amounts of arsenic found in ground water sources, such as tube wells [23].

A clean source of drinking water is critical to the success and survival of both Bangladesh and the proposed AGC. To provide a stable source of water, we propose to utilise Pond Sand Filters (PSF) in conjunction with rain water harvesting. PSF units are sustainable filtering devices that manually filter water. The unit consists of several sections; the filtering section composed of sand, the pre-treatment chamber composed of gravel and/or brick chips which are separated by wire mesh and several small chambers before and after the two processing units for storing water [23]. Additionally, a cheap and sustainable method of extracting arsenic from the water will be utilised by means of a coal ash filter. Depending on the size of the community, complete zones will be allotted for the purpose of storing safe drinking water. These zones will be isolated by means of the mud banks from aquaponic units and contamination from surface water runoff. Water will pass through PSF units before being utilised. The filtering section will utilise two serial sand filter sections to prevent downtown time due to the process of re-sanding every two weeks and downtime to allow for the growth of the biological layer after the re-sanding process [24, 36].

During the rainy season, rooftop rain water harvesting units will be used to collect water. This water will be collected in small tanks that will be connected to the PFS. Once the tanks are full, excess water will be stored in the zones allotted for drinking water [36]. Utilizing these two combined practices, the most common sources of water contamination can be eliminated and a stable source of drinking water can be provided to the residents of the Aquaponic Grid Community.

Construction Details

Continuing our trend of promoting self sustaining development, our method of choice for implementing the AGC is by the two-pronged efforts of local citizens, who will eventually inhabit the communities together with members of the Bangladeshi army. A few members from each community will be designated as chief auditing and maintenance officers. As such they will be required to be closely involved in the planning and construction phases of the community so they can act initiate repair and maintenance work for the foreseeable future.

In addition to the abovementioned parties, there will be a requirement for design consultants, namely engineers, scientists and architects to be present in the development and construction stages to identify the most ideal locations for placing the community.

This will include addressing issues such as proximity to other communities and towns, availability of markets for produce, proximity to transport networks, planning of transportation linkups to highways and waterways. It would also involve determining and accommodating the needs of the community, such as the availability of schools and medical establishments. It would also need to take into consideration the feasibility of training the auditing and maintenance officers so that future revisions, repairs and maintenance can be carried out remotely. A more detailed plan is illustrated below in Figure 7.

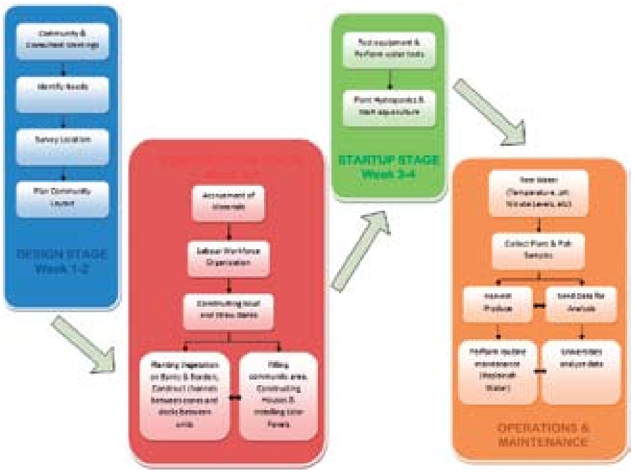


Figure 7. Design and Implementation Process

Validity of Use (Envelope)

Depending on the size of proposed community, the zones can be arranged in multiple configurations, making the solution highly applicable and scalable. Our intent is to develop and refine the concept of an AGC in the Brahmaputra-Ganges River and then subsequently deploy the initiative in neighbouring deltas which are illustrated in Table 4.

Our proposal intends to build elevated communities surrounded by zones. The zones will act as a buffer during the spring and monsoon floods (June/July/August [3]) by having additional water intake capacity and releasing water during winter months where there is low precipitation (lowest levels are during January [3]).

The ideal locations for the proposed communities are areas that were once arable but are currently waterlogged. This reduces the strain on the environment as this reclaimed land prevents further devastation in the form of deforestation for the purpose of agriculture. This indirectly reduces land degradation by preventing surface soil erosion due to deforestation and tilling of top soil layer in land based agriculture. Locating the communities within close proximity of the river delta provides a ready source of water that can be utilised and also purified and de-nitrified as a side process of the wetland based agriculture. We determined some areas that are ideal for commencing pilot projects based on their proximity to the river and susceptibility to flooding. One such area can be seen in the figure on the page opposite (23’25’58.90”N, 90’11’19.87”E [39] – North of Balakandi).

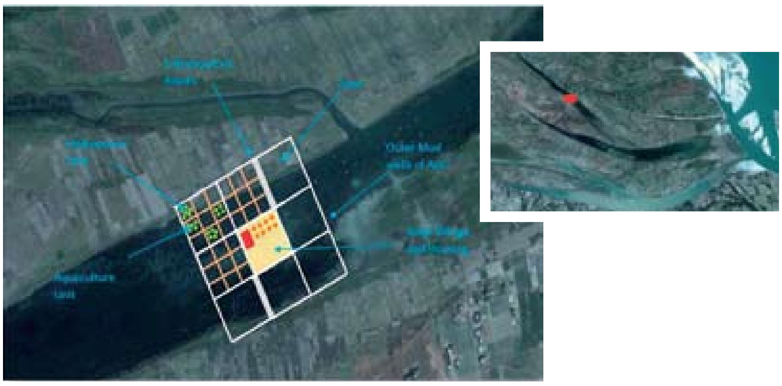


Figure 8. Birds Eye sketch of AGC in patch of flooded land

Political, administrative and financial details

This proposal creates ideal conditions for aquaponic growth and the continuous development and refinement of aquaculture based methodologies. At the same time it creates an infrastructure where local farmers provide good quality field based data to universities, in return for improved crop yields and less dependency on external factors.

The simplicity of this proposed solution lies in empowering the Bangladeshi people to turn their country's greatest weakness into its driving force, which could transform Bangladesh into a strong area of ecological, economical and energy sustainable agriculture and development. In fact, Bangladesh could lead in the promotion of hydroponic crops as a method for growing higher quality produce, over produce which is grown organically[25]. Hydroponic crops require less water and have higher yields per unit area than their organically grown counterparts [25].

Development funding and oversight

Development funding could theoretically be provided by a multitude of sources including, but not limited to, foreign investment, bank loans, and trade financing. However the goal of this project is to promote internal sources of finance and labour so that any eventual debt incurred, need not become debilitating due to stringent borrowing conditions or excessive interest rates [26].

Furthermore, no intensive land development can be effectively conducted by simply paying individuals to start shaping the land, especially considering the well documented corruption problems present in Bangladesh [27]. There is the requirement for an integrated top down organisational structure that consists of NGOs, local Universities, and municipal governments, formed under an umbrella organisation which is manned by the federal government. These groups will have their own specialisations for which they will be responsible. A possible scenario is as follows:

1. Government of Bangladesh: Primary method of funding for the project.
2. Bangladesh Ministry of Environment and Forest: Will be responsible for overseeing the entire project and implementation of farms and employ auditors and other investigators to ensure the reliability of the project. This includes making site visits and acting as the political front for the project when dealing with international attention and the national government [9].
3. Bangladesh University Department of Environment: Majority of responsibility will involve conducting studies on the environmental impacts and upkeep of the farms. Villagers will provide scientific data in the form of daily readings of pH, turbidity, salinity and water chemical content. This data will be analysed and updates will be sent back to the village farms. The primary goal will be to keep track of the progress achieved by the aquaponic farms.

4. United Nations Department of Economic and Social Affairs – Division of Sustainable Development and United Nations Food and Agriculture Organisation – Department of Fisheries and Aquaculture: Provide third party support for the project and independent verification of environmental goals and achievements. Will be responsible for working with the international community in expanding the scope of the project if successful.
5. Grameen Bank/Association for Social Advancement/Asian Development Bank/International Monetary Fund: Secondary source of funding for the enterprise. Directly involved with the Government of Bangladesh, and not the inhabitants of the villages. The micro-credit schemes provided by some of these organisations have been criticised for having excessive interest rates for some of the poorest inhabitants [26]. By having them deal directly with the Government, added security is in place to ensure the local community is not burdened with financial obligations surrounding any private investment in the project.

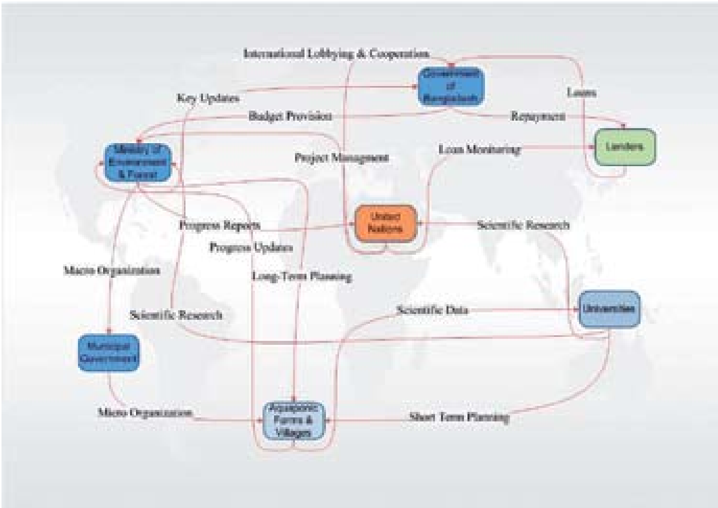


Figure 9. Oversight regulations and communication channels

Budget and revenue

The allowable budget for a single aquaponic farm composed of permaculture zones has been capped at $50,000 US dollars (approx 3,500,000 Bangladeshi Taka). This value was obtained by looking at the material and labour required to construct the farms, as well as to implement the various farming protocols. A breakdown of costs for the construction of a single farm can be seen in Table 2.

The second table (Table 3) deals with the revenues and costs associated with running an Aquaponic Grid Community for a period of one year. The conversion rate used by this report is 1 $ US dollar = 70 Bangladeshi Taka, which is a reflection of the average exchange rate during the month of July 2008 [28]. The labour values are educated guesses which are for the most part based on the average salaries for various professions as listed by the Bangladesh Bureau of Statistics.

It should be born in mind that any costing analysis is only valid for a given period of time and idealises the actual costs of the construction and manufacturing processes. The values indicated are educated guesses based on the general engineering experience of the authors and are simply provided as a framework for the readers to understand the intricacies of constructing any large scale project. They should not be taken as firm values and instead represent the absolute baseline. There are a variety of areas that have been glossed over, namely breakdowns of construction schedules and equipment rentals [33].

Table 2. Budgetary evaluation of proposed construction

	Price ($ USD)	Units (Avg. Farm)	Total
Materials [33]			
Straw	50/Ton	10	500
Cement	0.5/Kg	10000	5000
Clay	0.5/Kg	8000	4000
Asphalt	1/Kg	10000	10000
Mesh/Netting	0.25/m^2	10000	2500
Wood	0.5/Kg	5000	2500
Weeds	1/Bed	300	300
Construction [33]			
Bricks	0.02/Brick	20000	100
Roads	10/m	200	2000
Village housing	100/House	12	1200
Floating beds	1/Bed	300	300
Wooden dock	20/Dock	32	640
Mud excavation	4/m^3	500	2000
Labour			
Army [35]	200/Soldier	20	4000
Local villagers	150/Villager	20	3000
Supervising engineers	400/Engineer	3	1200
Machinery operators	300/Operator	4	1200
Aquaponics			
Pumps	30	32	960
Piping	7/m	30	210
Grates/Filters	2	80	160
Machinery			
Electrical generator – 4 KW	400	3	1200
'Always On' Solar power systems	350	10	3500
Heavy machine rental	1250	4	5000
Waste disposal tank	500	5	2500
Total	$54990		

Table 3. Operation revenues and costs of AGC for 1 year

Revenue/Cost	Projected Revenue/Cost ($ USD)	Quantity	Total
Hydroponics			
Winter Crops	0.15/Kg	15000	2250
Summer Crops	0.15/Kg	20000	3000
Rice	0.5/Kg	5000	2500
Aquaculture			
Fish	2.8/Kg	3000	8400
Prawns	4.2/Kg	2000	8400
Crabs	6.5/Kg	1000	6500
Maintenance			
University researchers	-350/Month/Researcher	12 Months, 1 Researchers	-4200
Government staff	-350/Month/Staff	12 Months, 1 Staff	-4200
Village support staff	-150/Month/Villager	12 Months, 1 Villagers	-1800
Fuel	-0.78/litre	10000	-7800
Estimated repair	-50/Month	12 Months	-600
Fish feed	-1/Kg	2000	-2000
Water Test equipment	-210/bi-monthly	12	-5040
Plant seeds	-1/Kg	100	-100
Seed fish population	2/Thousand	4000	-8
Profit	+5302		

Innovative future additions and expansion projects

Toxin Cleanup

Bangladesh is the world leader in the stripping of decommissioned ocean-going vessels. This industry employs a significant number of coastal residents, but provides meagre wages and exposes workers and the environment to toxic chemicals such as chlorine, oil and asbestos. There is growing concern within Bangladesh and the international community of the extreme dangers involved in this industry.

One of the primary concerns is that toxic chemicals such as trichloroethylene (TCE) and tetrachloroethylene (PCE) will leak into neighbouring water and contaminate it. These chemicals are two of the most common cleaning solvents [9].

This contaminated water has the capacity to kill local wildlife and seep into groundwater sources, which could potentially poison the local populace.

The Dehalococcoides Ethenogenes bacterium strain 195 is effective in consuming these two chemicals and converting them into metabolic ethene. This organism is often used effectively by both industry and government in western nations to clean contaminated water sources [29, 30]. However, one of the major problems involved with cultivating strain 195 is its lack of growth in a monoculture environment (meaning by itself), as it requires the presence of other bacteria and an organic environment to thrive. There have only been a few studies that explore the toxicity of strain 195 to humans and animals, but preliminary reports indicate no adverse effects [29]. As such, it is proposed that the Aquaponic Grid Community set aside a single contained unit for cultivating this bacteria to be harvested and transported to contaminated sites.

This process of using organisms to combat pollution is called bioremediation. Other potential bioremediation organisms that could be cultivated include 'Acinetobacter Calcoacetius' which is used for the removal of crude oil and 'Geobacter Metallireducen' which is used for the removal of toxic metals. Current research predicts the discovery of an esoteric bacteria that can aid in 'eroding' nuclear waste [31]. Another significant use of bacteria is the application of genetically modified E.Coli that can be added to effluent stored in tanks to speed up the breakdown of waste products. Future bacterial colonies may even be able to convert waste into usable materials, such as clean fertiliser or even fuel. The current manufacturing costs of these designer bacteria would be in the range of $20,000 US dollars and a time span weeks. If costs can be reduced, the effluent stored for extraction can potentially be used as part of the aquaponic system [32]. Using the Aquaponic Grid Community as to cultivate these agents will provide a great boost to the economy of the region.

Marine Environment Expansion

The Aquaponic Grid Communities by definition are composed mainly of freshwater. This limitation fundamentally reduces the amount of possible aquaculture that can be carried out. There is a variety of marine (saltwater) life such as fish, including tuna, halibut, cod and salmon, that would be beneficial to farm for aquaculture. These fish are very lucrative in the world fish trade and are consumed heavily by nations such as the United States, Europe, Canada, and Japan [19]. With the right set of barriers in place and a smarter network of pumps, it would be theoretically possible to have neighbouring marine and freshwater farm units. In addition, the Aquaponic Grid Community can be built closer to the ocean to take advantage of the naturally higher salt water concentrations.

AGC Version II (Aquaponic Grid CITIES)

There has been a resurgence in the discussion within the scientific community about expanding human civilization into the oceans [1], similar to the concept proposed by previous Delta Competition entrants. However, such a large scale project is not feasible for third world nations for a variety of reasons.

These range from the associated costs to the tremendous political initiative necessary. However by using the Aquaponic Grid Community's modular profile, expansions can be conducted with interlinking additions being made over a period of decades. It is theoretically possible to develop into a system being the size of a large town/small city. The individual units compromising this city need not all be aquaponic facilities. They can contain buildings or pasture for livestock, but by ensuring agricultural needs are completely met in such a sustainable fashion, many issues faced by conventional city structures can be avoided, namely the often complicated movement of food supplies between remote farmers and homeowners [25]. Moreover the entire city is based around water and as such, can deal with rising sea levels more easily.

Table 4. Neighbouring deltas where AGC can be deployed

Name	Major Issue Faced	Notes
Ganges Brahmaputra Delta	Erosion and Ocean Flooding.	Severe erosion that occurs due to regional topology.
Godavari Delta	Erosion caused by Dam Construction and Ocean Flooding.	Focus on ways to get rid of dams or maybe bring sediments in another fashion.
Krishna Delta	Ocean flooding.	Human land development and drilling causes water intrusion. Focus on constructing alternate clean water source.
Mahanadi Delta	1 in 5000 gradient means poor drainage into sea.	Ways of siphoning water have already been established. However, these pose their own issues that need to be addressed.
Red River Delta	Expansive agricultural development, poor water drainage, flooding, deforestation.	Super high population density which depends on rice production from region
Mekong Delta	Damming of river. Erosion, Flooding due to Poor drainage in some areas. Agricultural development damages delta.	Very high population. Depend on farming (plant and fish).

Shortcomings

There are certain areas that have been identified as potential bottlenecks in both the design and implementation of Aquaponic Grid Communities (AGC). They can be summarised as follows:

1. Flooding and Severe Weather: Although allowances have been made for particularly inclement climatic conditions, there is the possibility that cyclones and other dangerous weather phenomena can overcome the AGC defences. Pump bailing and buffer zones might fail. This is a risk that has to accepted and mitigated on a year to year basis.
2. Sanitation: There is no long term, currently viable, solution in place for disposing of human effluent. Using human effluent as fertiliser and/or feed, risks contamination and ill health of the aquaponic organisms. Moving it to proper facilities remains the only option at the present. Any unforeseen event may cause this system to fail, thereby severely affecting the functioning of the AGC.
3. Ecosystem Balance: Determining the right mixture of aquaculture and hydroponics and the location of their respective units is not an exact science. There will have to be manual trial and error, which will lead to lost productivity in the beginning stages of an AGC.
4. Bureaucracy and Infrastructure: This entire project is heavily dependent on the proper organisation of the key members (government, international, academic). Any form of bureaucratic slowdown or lack of infrastructure will dramatically delay the construction and operation of an AGC.
5. Diseases: Due to the close proximity of plants and fish life, there is the possibility of diseases spreading quickly between neighbouring zones and units. This can wipe out an entire farm population in weeks. Proper water treatment and testing needs to be maintained to ensure this scenario does not occur.

Conclusion

The purpose of this study was to present the potential for a system to maintain and improve the livelihood of individuals living in the Ganges-Brahmaputra Delta by the development of agricultural and aquaculture technologies.

We have proposed an ambitious and innovative solution, in the form of an Aquaponic Grid Community (AGC), to alleviate and address the major issues Bangladeshi' people have as well as those who live in low lying river delta regions around the world.

In our initiative, we have provided a complete and well examined framework upon which communities can develop and thrive in a sustainable environment without putting additional burden on global issues, such as rising water levels, eutrophication, and soil degradation. Construction, implementation, oversight and budgetary issues were resolved and a viable plan has been outlined to realise the project.

The AGC will not only be an amalgamation of plant and fish growth projects, but will more importantly present a new social dynamic in fighting the effects of global warming and deltaic degradation.

It will use only local supplies, be self sufficient in terms of food and energy, and most of all, engender the idea of coexisting in an environmentally clean fashion, with nature. The research conducted as part of this experiment will aid in the development of other aquaponic facilities in the world, while laying the groundwork for more esoteric projects in the future, such as the colonization of the oceans. As an additional benefit, the AGC's will be in a position to attract foreign currency through the process of exporting goods, thereby instigating the economic development of this particular deltaic region. Overall, it is believed that this project will contribute to the sustainable growth and preservation of the Ganges-Brahmaputra Delta while expediting the development of future technologies.

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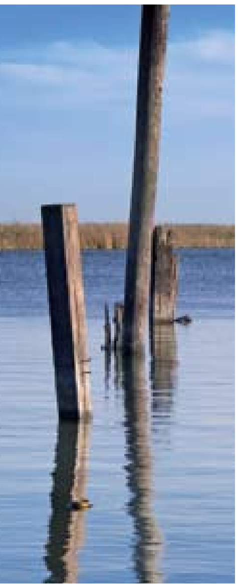
The Double-Channel and the Tidal Power Station

Structural interventions for deltas threatened by rising sea level

First Runner up of the Team Category of The DeltaCompetition 2008

Wang Fei
Han Bo
Li Yuan



1 Abstract

The world has been changing significantly since the Industrial Revolution, improving people's daily life with automatic machines, but at the same time threatening the future through climate change.

It is generally accepted that climate change is creating an increase in average global temperature that is directly and indirectly causing ice to melt, resulting in sea level rise. Climate change is also thought to be the cause of increased incidence of extreme weather which is occurring more frequently over the world, such as the extreme tropical storms and heat waves, particularly those across Europe in 2003.

Deltas, due to their low-lying coastal location and often high density human populace, are particularly at risk from rising sea level. This increases the flood risk and makes seawater intrusion a significant problem. This study applies a structural concept to the control of rising sea level that will in turn contribute to economic and technological development of the delta.

The aim is to build a structure applying engineering concepts that uses two channels (the Double-Channel) to raise the groundwater table. By utilizing two channels, the flow direction of sea water can be controlled and even used to produce a renewable form of energy. Further, it will use a tidal power station to help the system to produce even greater energy results.

The Double-Channel should be used at the head of the delta to protect it. This concept can be practiced in almost every delta. The Yangtze River Delta was chosen as an example in this study. In order to help implement the theory, some useful models are outlined at the end of this paper.

2 Introduction

The Yangtze River Delta is the largest region in China with a strong industrial base, continued economic investment, water and land transportation, and, is the country's largest export base. With Shanghai being the leader of the South African export base and Zhejiang the northeast industrial economic zone, this delta has been China's growing economic development area with the fastest and largest total economic output. Statistical data shows that the Yangtze River Delta region is 1% of the country's total land, 5.8% of the nation's population, and has created 18.7% of GDP, 22% of the national fiscal revenue and 18.4% of exports.

The Yangtze River Delta is under the influence of climate change and is paying the price. As we all known, climate change brings a series of problems, such as sea level rise and increased flood risk. Also, the Yangtze River Delta is of high economic and geographic importance. Its high investments and population density have made this area highly vulnerable to the risk of climatic impacts.

Firstly, the Yangtze River Delta faces the problem of reduced land as the result of sea water intrusion and sea level rise. Yangtze River Delta's rapid economic development has resulted in significant capital, labour and land investment. The socio-economic activities together with natural processes continue to exert pressure on the amount of land available in the delta, land will become an increasingly scare resource. Obviously, this presents a huge obstacle to the development of the region's economy.

Secondly, sea water intrusion will reduce the levels of fresh water. We need to take immediate action in order to prevent this happening. Fresh water is in increasing demand as industry develops and without action, progress will be severely restricted. The Qiantang River Estuary, an estuary of the Yangtze Delta, was selected for study as a typical example of its kind. We believe the ideas and solutions presented in this paper could be introduced to many other deltas to help deal with the sea-level-rising problem.

3 Analysis

Today, nearly all land near sea is experiencing the terrible problem of soil erosion. Moreover, this situation will become worse due to the impacts of climatic change predicted by many scientists.

Land and water are such precious resources, in delta areas where people depend on the area physically for living and for their economy; it will be necessary to find solutions in order to survive. In our area of study, the Qiantang River Estuary is an example of one of the many endangered places.

3.1 How erosion happens

Soils in coastal aquifers often turn saline due to the intrusion of saline water underneath the groundwater table. If the groundwater is extracted below a certain limit (depending on the wedge thickness as in Fig3-1), saline water can begin to pollute the land mass. Coastal areas are often inundated by sea waves. This is also responsible for turning soilalkaline. [1]

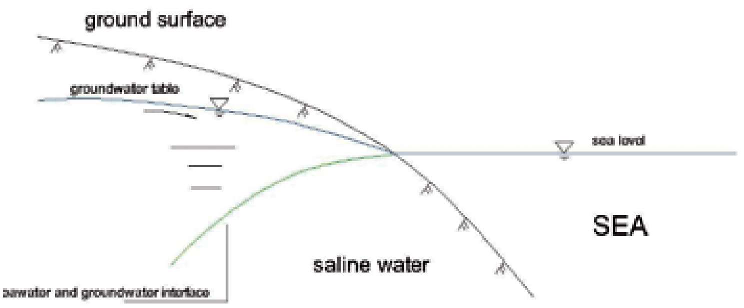


Figure 3-1. Sea water intrusion in coastal aquifer (SKMAZNDER, 1983)

In its Fourth Assessment report (2007), the Intergovernmental Panel on Climate Change (IPCC) claim, that temperature is to rise at the rate of 0.1 degree every ten years – even if remedial measures are taken. Recent research undertaken for the UK Government suggests that sea levels could be between 26 and 86cm above the current level in southeast England by the 2080s. At some sites this means that, by the 2080s, sea level has the probability of 1/50 of rising between 10 and 20 cm by the 2080s. The inevitable rise of the sea-level and the groundwater table's continuing decline both lead to more and more serious soil erosion as explained above. [2]

3.2 Current interventions

Figure 3-2. Dikes along the riverside of Macao [3])

3.2.1 Building dikes by riverside

Along a river delta, long-dikes are the most common method used to prevent rising sea level from coming into contact with the vulnerable soil. The weaknesses of this method are acknowledged but the dikes are not considered to be a long-term solution because sea level will continue to rise and erosion could occur by other means such as seepage. Also the dikes' construction is limited by the economic investment.

3.2.2 Building benthal dikes

The creative idea of building benthal dikes was carried out in Dalian (a costal area northeast of China), however, the results were not positive. The paper reported the apparent effects and claimed that it was the cause of some serious outcomes such as increased alkaline content.

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大连斥资打造3段地下长城 为何仍难阻挡海水入侵

news.longhoo.net 2004-12-10 10:19:24 推荐本稿 短信订阅

【龙虎网讯】据千龙网转引新闻晨报消息：目前，大连市国土资源和房屋局地矿处副处长王欣军向记者透露，为了防止海水入侵，大连市目前主要采用的办法是修建"地下长城"——即在地表下浇注水泥墙体。据悉，到目前为止，大连市已经修建了3段"地下长城"，而且还打算将来修建更多。然而采访结果却显示，仅靠"地下长城"单独阻击海水入侵似乎有些勉为其难。

Figure 3-3. The news reported in 2004, about the benthal dikes (Longhoo, 2004)

3.3 Solutions

Study and research show that erosion is caused by saline intrusion which takes place in two ways. The first way is when raised seawater seeps through to groundwater. The second way, called 'seawater encroachment', is caused by everyday tides. Knowing the causes and existing preventative measures, it is clear that the problem can be dealt with in two ways.

The first principle is to raise the groundwater table. It's been a long time since the Chinese government allowed legal exploration of groundwater in order to prevent it descending. It is impossible to monitor whether or not businesses are sticking rigidly to the policy. Thus, along with the soft policy, we also need something tangible, i.e. structural intervention. The soil-erosion theory tells us that seawater invades because of the broken balance of interface. While the interface just exists at the end of the riverbed, then why not partially raise the groundwater table merely by the sea since we lack fresh water? We will present a structural intervention in Section 4 from this perspective.

Meanwhile, tides should be contained within a permitted range. As research shows that rising seawater is inevitable, it's unwise to build innumerable dikes without considering economic factors. Also rising sea level is not always a negative consequence as long as we make effective use of the excess seawater and tides to create energy.

4 Strategy and concept

Based on the analysis, a strategy should contain two key elements: raising the groundwater level and controlling the tidal water. The structural interventions work in a combined system which can provide additional benefits such as using controlled seawater to build power tidal stations. The solutions are described below.

Double-Channel

4.1 Definition

Double-Channel can be simply described as two rivers, one of which runs along the bank of river while the other is more like an inland fond flowing almost parallel to the first channel.

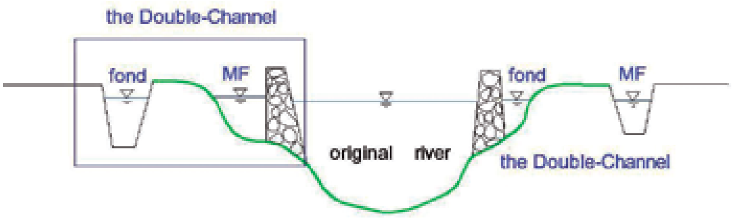


Figure 4-1. The Double-Channel and original River

4.2 Function

Since two channels are presented as a colligation, it is preferable to use them sympathetically from both the engineering aspect and the economic aspect.

4.2.1 Static Compensation

As nearly all the research papers predict that rising sea-level is inevitable, the simplest solution to prevent erosion is to raise the groundwater table to impede seawater from invading the groundwater level. We believe that this is the most effective method and key to successfully managing the situation.

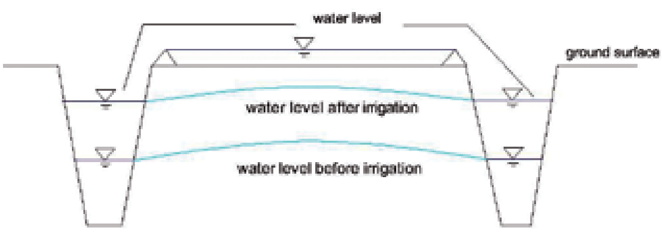


Figure 4-2. Alternate Furro Irrigation (Wei Yongchun,1979)

In the strategy, we propose building a Double-Channel. The idea is inspired by the Alternate Furrow Irrigation [5] method created some years earlier (Fig 4-2)

In the reference, the significant effects are reported as both raising the groundwater table and reducing soil erosion. Because of the notable influence on rising water-level, we advise building a Double-Channel on each side of the Qiantang River (as Illustrated in Fig 4-3)

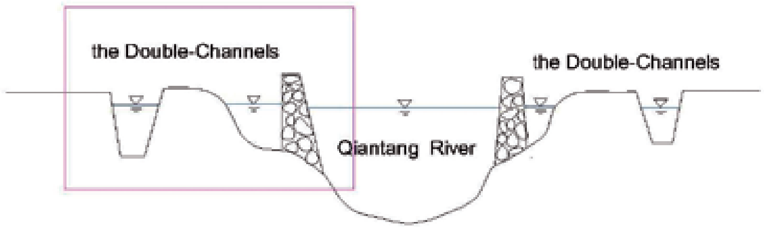


Figure 4-3. New engineering measurements of Qaingtang River

The illustration (Fig 4-3) is a section of the Qiantang River Estuary. We chose the left bank at random (Fig 4-4) to explain how the Double-Channel works.

The lower curve represents the original groundwater table and the higher one is formed by constructing the Double-Channel. Both trend lines of the water table has been proved by many scientists and experiments, but the actual difference between the two lines may be not as significant as the illustration indicates. A computer model can be used to calculate exactly how much the sea level will rise.

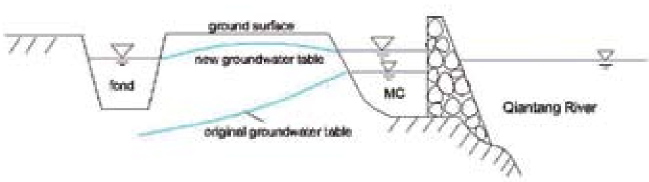


Figure 4-4. The Double-Channel

When it comes to each individual channel, the function needs to be specific. Of the Double-Channel (Fig 4-4), the left channel could be the fond, as suggested by the second place paper of 2006 DeltaCompetition, and the right channel the Multifunction Channel (MF), as it has more functions.

Fond

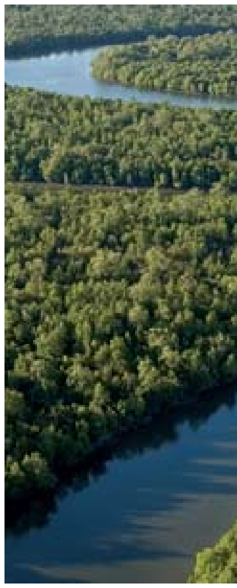
We utilise an additional channel rather than taking advantage of the more popular wells, because we believe that this increases the development of agriculture and recreational activities. In the 2006 DeltaCompetition, one paper named *'The opportunities of a geographical approach to the Pearl River Delta'* demonstrated a very worthwhile example.

As G. Van. Ren wrote in the paper: *'Fish ponds are a combination of fish farms with agriculture on the surrounding dikes. Especially the combination of fish with mulberry trees for silk production on the dikes has a very high cultural historic value and would strengthen the green image of the city, since silk worms are sensitive to air pollution and can therefore only exist in clean ('green') areas. Next to the cultural historic value and the high agricultural yields the fish ponds can fulfill another important part of the requirements. They can limit the extremes of rainfall and drought.'* [6]

The fond in our strategy is expected to be newly constructed inland and derive water resources upstream of the Qiantang River, Xinan River or Fuchun River. The fond would have the same function as outlined above, although its primary function is to work as part of the Double-Channel to increase the groundwater table by a reasonable and controlled amount.

The Multifunction Channel

Since raising the groundwater table is the main function of the right channel, it is not technically a multifunction channel. It could be described as a liner reservoir which can save and release water by using water sluices at the reservoir's beginning and end.



The MF is used to conserve water in order to raise the groundwater table with a fond nearby. The MF is a store for fresh water, and such a design has two side effects. Firstly, by saving water at the riverside, dikes and fresh water would naturally play a protective role, by preventing soil from coming into contact with seawater immediately. Alternatively, such a design can also reduce the area of secretions causing the water level of the middle river to rise which helps to keep seawater from encroaching. By using the Chezy and Manning equation:

$$Q = \frac{A}{n} R_n^{\frac{2}{3}} S_0^{\frac{1}{2}} = \frac{A^{\frac{5}{3}} S_0^{\frac{1}{2}}}{n X^{\frac{2}{3}}}$$

on computer models, the elevation of the middle river can be accurately calculated.

This needs to be further studied to enable engineering designers to calculate the actual size of the structural work to be done. [7] The purpose of this paper is to present an outline of the strategies and solutions rather than the specific and detailed calculations.

In addition to the minor functions, the MF also plays another important role in our strategy. In the next section we will discuss the idiographic function of the MF in detail.

4.2.2 Dynamic transfer

When it comes to dynamic use, transition is the core value. By designing and building some interventions, we can transfer seawater by using MF. We can predict tides to an exact amount and therefore we can take sufficient preventative measures to keep seawater from flowing into fresh water, diagram Fig 4-5 to 4-7 illustrates this.

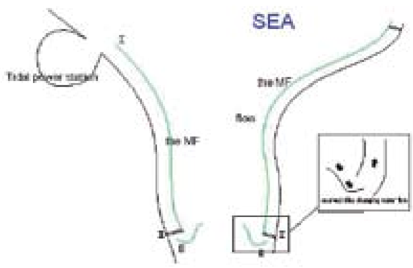


Figure 4-5. The overview of the MF and its sluices

From the illustration, you can see that we set two sluices at the beginning and end of the MF to control water freely. Meanwhile, we put a curved dike with a sluice before the MF; we believe this can change the flow's direction by hydraulic knowledge.

The curved dikes are highlighted in the red square in the right corner of Fig 4-6. We can predict that the seawater will change its original flow and flow in the direction of the curve. This prediction will need to be verified further by computer and practical models.

Below is a guide:
All the sluices are shut to converge water in order to raise the groundwater table which has been explained in Section 4. A tidal time-table is required.

Before incoming tides, fresh water in the MF should be discharged (open SI, close SII, no work on SIII).

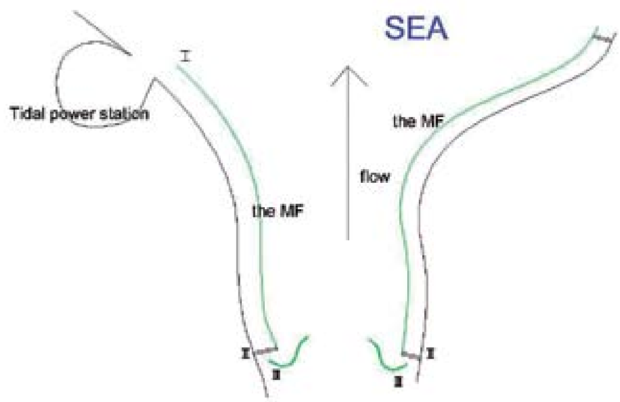


Figure 4-6. Normal condition (no tides)

Such a measure has a clear aim: to create space for the incoming tide. However, further study is needed to look into the effect of the lowering of the freshwater level which may cause the groundwater table to fall. This side effect can be studied in the Double-Channel model outlined in Section 6.

Then, when the tide flow's in, we close SIII and open SI and SII. This will cause the tide flow to change direction as it meets the curved dike to flow into the MF. The seawater is released either back to the sea or to an alternative place where better use can be made of it, such as at a tidal power station. Therefore, the end of the MF will reach the storage area of a tidal power station.

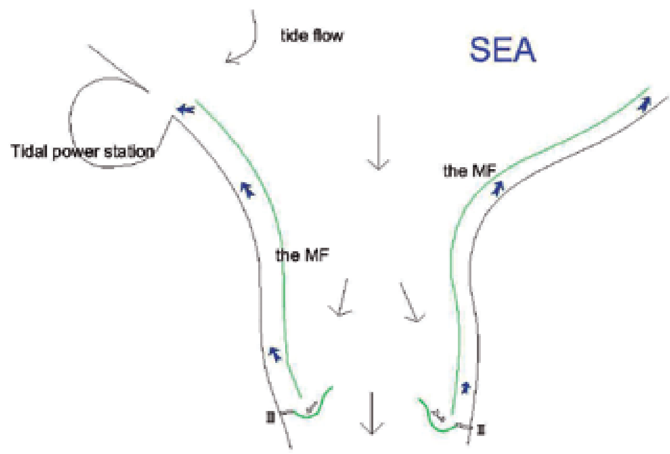


Figure 4-7. Tide coming (induce water into the MF)

The effect of the tidal power station on the level of seawater will be discussed in the next section.

5 Tidal power stations

Building tidal power stations at the river mouth may have the effect of lowering the sea water level suitably, reducing sea water encroachment, and adjust the energy structure.

Assuming the tide lasts one hour and the average discharge is 3000 cubic metres per second, then the volume of seawater induced into the power station is about V=3000*60*600=12,960.000 cubic meters. This is a significant volume of sea water.

5.1 Reducing the Seawater encroachment

5.1.1 The Theory of Tidal power generation

Tidal energy is used to generate power using the potential energy created by the tide's rise and fall. Its principle is similar to the hydroelectric power. This plan adopts the tidal power plant of a single reservoir and unidirectional electricity generation, as shown in Fig 5-1. There is evidence of tidal power generation from as early as the 10th and 11th centuries in Western Europe. Research by the US Army Corps of Engineers and other distinguished tidal specialists shows that tidal power generation may be one of the most economic way to obtain energy.

The principle is as follows:

1. On the rise of the tide, turn on the penstock, until the tide reservoir is full;
2. When the descending sea water level is equal to the rising reservoir water level, close the penstock;
3. When the head of water is high enough, the electricity generation starts immediately;
4. In the process of power generation, tide level rises, and the reservoir water level drops, so the water head is decreasing. When the water head is low enough than the smallest water level which is the requirement of head power generation and hydraulic turbine efficiency, the hydraulic turbine shut down. Therefore the waiting working condition appeared;
5. When the sea water level is equal to the reservoir water level again, turn on the penstock and another cycle begins. Then turn on the strobe again to begin another circulation.

In the operational process, the electrical energy provided is interrupted. The power generation time window for each tide is approximately 5-7 hours. Fig 5-2 show's storage-, waiting- and generating- electricity of the three operational conditions.

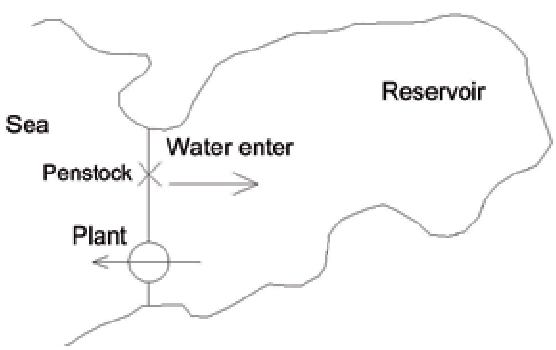


Figure 5-1. The principle diagram of single reservoir and undirectional tidal power station

Below we can see the 3 stages: storage, waiting and generating electricity

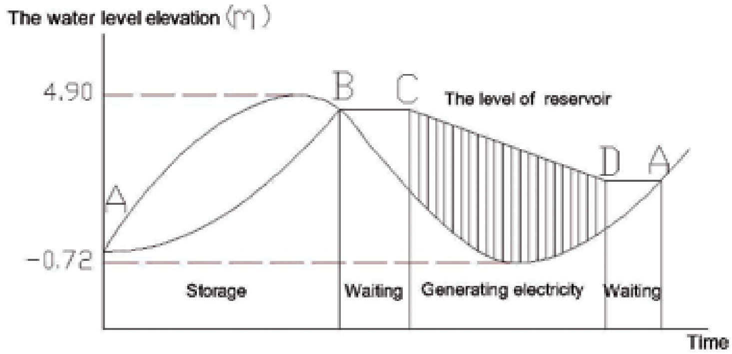


Figure 5-2. The working stages diagram of a single reservoir unidirectional tidal power station

5.1.2 The theory of reducing the seawater encroachment

From Fig 5-2, in the waiting working stage, we can see we need to turn on the penstock. The sea water enters into the reservoir and fills it. The reservoir is located near the mouth of the river and the storage capacity is large, thus it may bring down the sea water level at the mouth of the river accordingly and reduce the amount of seawater encroachment.

5.2 Adjusting the energy structure

The tidal power station uses the renewable energy source to generate electricity, which reduces the amount of coal, petroleum and other non-renewable energy source used; it also reduces the amount of greenhouse gas discharged.

In comparison to the hydroelectric power station, there are no submergence and immigration problems for the tidal power plant. The tidal power station provides an efficient method of renewable energy.

5.3 The design of Hangzhou Wan tidal power station

5.3.1 Design data

In order to design a tidal power station, we must obtain the following design data:

1 Local tide data

1. The maximum and minimum tidal range;
2. Stage hydrograph of rising and ebb tide; and
3. The tidal gradient.

2 Terrain data

A bay or a section of river must be chosen for gradient and flow control. Its topographic diagram needs to be mapped so that the water surface area and the storage volume to carry out the hydro-energy computation can be calculated. Then the relationship curve of reservoir's water level and the volume can be calculated.

The data of Ganpu in Hangzhou Bay

Tide level data: The statistical data from the years 1953-2000 is used.
The average tide level in one day is shown in Fig 5-3. High average water level is 4.9m, and low average water level is 0.72m. Average range is 5.62m. [9]

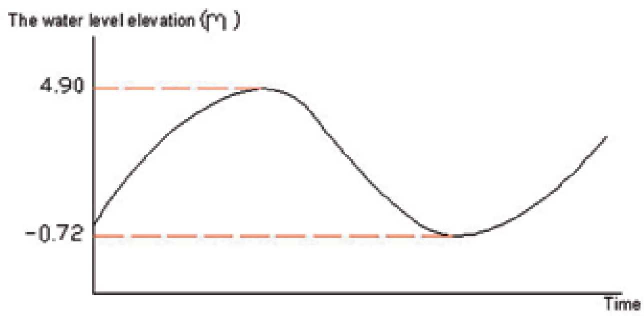


Figure 5-3. The tidal level diagram in Ganpu

5.3.2 Parameters calculation

The tidal energy is in direct proportion with tide quantity, tidal range and the area of the reservoir. From this, the installed capacity and annual power generation of the tidal power station can be calculated.

After the preliminary estimate, if the large-scale tidal power plant was constructed in Ganpu, the installed capacity would be 2,490,000kw, and the annual power generation is 6,850,000,000kw/hour. This could lower the sea water level by some cms accordingly. The maximum water level in reservoir is 4.9m.

6 Discussion and recommendations for further research

6.1 Quantitative analysis

In this paper, the Double-Channel is presented by qualitative analysis without further quantitative calculus. Even though the Double-Channel is inspired by the successful irrigation method, many specific calculations still need to be carried out to verify whether it could raise groundwater as significantly as irrigation does. In other words, we need to know how much higher the ground water table can be raised. This is a very worthwhile area for further research.

It is necessary to look at the following computer-generated models:

- the Double-Channel model to study the rising groundwater table problem
- the MF channel to study how much seawater can be directed to the tidal power station
- the curved dike model to study how to change the seawater's direction.

The Double-Channel Model

The purpose of this model is to determine how much the man-made channel effects the rising ground water table and whether it would influence the seawater and ground water interface.

The main function of the specifically constructed fond is to support the Double-Channel. However, its economic benefit is also recognised and it is recommended that this is also assessed in order to fully determine the full potential outcome of the project.

Curved dike model

It is necessary to develop the most effective and economic method to construct a curved dike. Further hydraulic knowledge is required in this aspect.

Mixed system model

In this system both the Double-Channel and tidal power station operate together. This is a very complicated process and by using the model we can optimise the performance.

7 Conclusion

The aim of this study is to develop a system of structural interventions to combat the rising sea-level and its side-effects: seawater encroachment and soil erosion.

Further, these solutions will contribute to further the economic and technological development of the deltas.

A combination of analysis, strategy and concept development has been applied. How sea level rises and how soil erosion happens have been explained.

Today's technology provides a better understanding of the urgency needed in order to deal with such a problem. A management approach using controlled structural intervention is recommended.

The Double-Channel was examined. This is a combination of two channels which raise the ground water table thereby raising the seawater and ground water interface. This ensures the seawater does not go through into the ground water system and pollute the internal lands and fresh water. Moreover, one of the channels is a fond which may also provide some economic benefits and other functions. The other channel, known as the Multifunction Channel is a liner reservoir which could save and discharge its water freely. At the beginning of the MF, a curved dike is built to induce seawater, specially the tide flow, to flow into the empty MF which heads to the tidal power station thus making use of precious energy.

In addition to engineering benefits, this system aims to give some energy saving initiatives which would contribute to climate change mitigation. Tidal energy is one of the important resources for the future because it is a clean and renewable resource.

The Double-Channel is a physical means to protect the deltas from the intrusion of sea water. It partially raises the groundwater to resist the rising sea level. Also, with the addition of a tidal power station the inner and external tides can be utilised to produce significant quantities of renewable energy.

Overall, the Double-Channel contributes to the development of solving seawater encroachment and soil erosion in the predicted future.

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Building with nature

Finding a balance between natural and human processes in deltas

Based on a Mississippi delta case study

Second Runner up of the Team Category of The DeltaCompetition 2008

Marten Hillen
Jos Kuilboer
Pieter Nordbeck
Roald Treffers

Finding a balance

This entry for the 2008 DeltaCompetition aims to provide a new approach towards delta management.

Currently many of the world's major deltas are out of balance and clear solutions are yet to be formulated. We experienced this in the spring of 2007, by a research project based in New Orleans (USA). This city was hit hard during the 2005 storm season, but it was also found that the Mississippi delta as a whole, is deteriorating at high speed. During the project this was discussed with many stakeholders and work was undertaken with a variety of people involved in these problems. This DeltaCompetition paper is a by-product of our project, but illustrates a more general method, based on the Mississippi delta.

Abstract

Deltas are currently under a lot of stress. Pressure is placed on deltas from the cultivation of rivers, protection against flooding from both the river and the ocean, subsidence due to geophysical processes and fluid withdrawal, climate change and a rising sea level. A classic classification of delta processes is given by Galloway (1975) and makes a distinction between fluvial, wave and tide-dominated characteristics of a delta. Increasingly, deltas are also influenced by human activities.

The introduction of human influence in delta areas asks for a renewed, integrated view on their development. This research suggests an alternative classification, based on Galloway, which serves as an experimental framework for all deltas and includes human influence. Using a case study, the feasibility of a concept based on 'building with nature' will be illustrated in this paper. The case study describes a solution which restores deltas by controlled natural processes in a human-influenced delta. The example concerns a large-scale diversion in the Mississippi River designed to reintroduce natural sediments to stimulate marsh growth and preserve the delta plain. Calculations are made and then verified with the use of a small-scale physical model of the lower Mississippi delta.

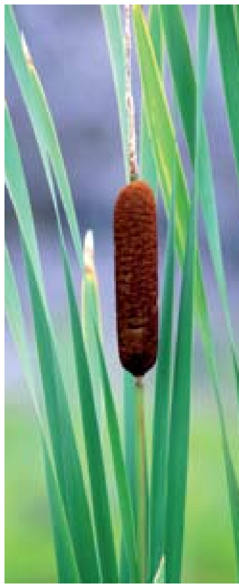
The results of the calculations on a large scale Mississippi River diversion show that it is possible to reintroduce sediment input into the delta. This case study demonstrates that it is possible to shift from a mainly human-influenced Mississippi River delta, towards a more nature-dominated delta.

However, delta restoration is a gradual process that takes several decades requiring a large diversion., In the long run this will provide benefits for all stakeholders. Valuable areas all over the world are under threat and will be lost if no action is taken. 'Building with nature' is a unique solution to many of these problems!

Introduction

A delta develops where a river debouches in a standing body of water. The mass of sediment deposited around the river mouth forms the delta plain. This is an area where complex and interesting interaction between water and land takes place. Deltas are fertile and resourceful, but also vulnerable environments of the earth. Some of the world's most interesting ecosystems can be found in deltas. These characteristics, the river and the proximity to the ocean, make it a good place to settle from an economic point of view; the majority of the world's population lives in densely populated delta areas.

Currently, deltas are under a lot of stress as human impact takes its toll. The cultivation of rivers, protection against flooding from both river and ocean, subsidence due to geophysical processes and fluid withdrawal, climate change and a rising sea level place a lot of pressure on them. The effects are believed to cause major problems but are not yet completely understood.



The vulnerability of delta areas to extreme climate conditions has been witnessed recently. Natural disasters in New Orleans (2005), Bangladesh (2007) and Myanmar (2008) demonstrated this and also the extreme impact they can have on society.

Stakeholders

Over the years, deltas have been changed and modified for many different purposes. Human cultivation of these areas has disturbed the natural processes. Many different interests are presented in deltas, such as housing, ecology, transportation, recreation, tourism and many more. In Table 1 a global view of different stakeholders, their interests and goals are shown.

Table 1. Stakeholder analysis

Stakeholders	Interests	Goals
Central Governments	To provide healthy and safe living areas and stimulate economic development	Improve living standards Increase wealth of inhabitants Increase economic activities Exploiting full potential of the delta
Inhabitants	To maintain and improve living standards	Provide income Safe place to live Exploiting delta economy
Environmental agencies (e.g. WWF)	To maintain biodiversity and healthy flora and fauna	Improve biodiversity Reducing environmental damage due to economic activities Stimulate natural processes
Transportation (e.g. port of Rotterdam)	To provide goods to the hinterland	Increase profits Increase shipment of goods Increase of tradable goods
Recreation and Tourism	To provide a positive environment for leisure activities	Increase recreational area Increase amount of tourists
Industry (e.g. fishery)	To exploit profitable opportunities in the area	Increase profits Increase trade Expansion of business in delta area
Agricultural	To exploit the fertile land	Increase yield Increase profit Increase trade

Due to these different functions a variety of stakeholders are involved and all their interests have to be taken into account. This calls for new adaptation strategies. A balance has to be found which maintains these different functions, keeps all stakeholders satisfied and preserves the delta itself. A realistic approach is needed which considers them all.

This plan tries to find a long-term sustainable and integrated solution for large delta areas. The focus is on knowledge already available but applying it from a different perspective. Moreover, it is a long-term solution that can be applied alongside the conventional cultivation measures already established. This study proposes working with nature in a controlled manner; it supports a gentle transition to make it effective and to maintain the many functions of a delta and the interests of the different stakeholders.

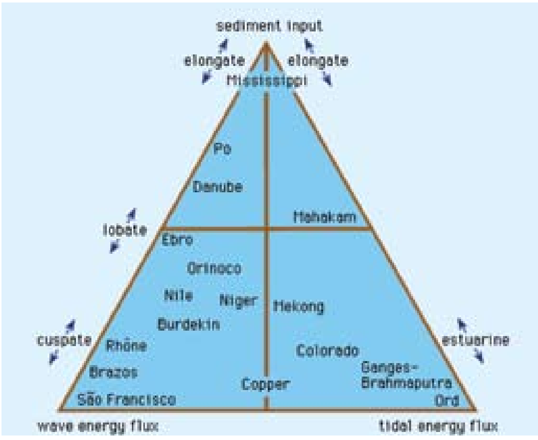


Figure 1. Galloway triangle (Brittanica)

Delta classification

A lot of research has been conducted on deltas, their formation, the dynamic processes and the changes due to human involvement. The fact that every delta is unique makes it difficult to define a general framework that is a perfect fit for all deltas.

Breakthroughs in delta research came in the 1970's. Coleman and Wright (1971, 1973) described delta characteristics based on studies of 50 different modern deltas and Galloway (1975) classified deltas by fluvial-dominance, wave-dominance and tidal-dominance characteristics (see Figure 1). This categorization has been adapted to more refined definitions by Hayes (1979), Dalrymple et al (1992) and Orton and Reading (1993), but Galloway's triangle remains the most used classification.

Due to the complex processes in delta areas, human influence is hard to define and many features are still barely understood. Although knowledge of delta evolution, hydrodynamic processes, and the influence of cultivation increases by the day, no clear management and development solutions for deltas are recorded. Even when processes are well understood it is very difficult to find a balance between a delta's many functions.

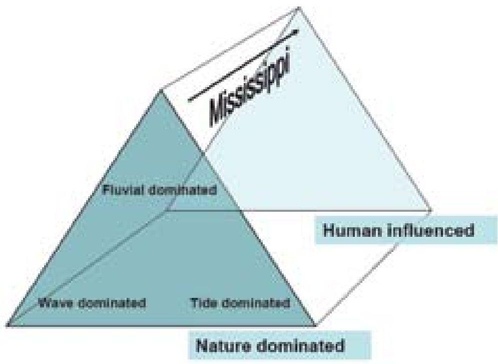


Figure 2. Human influence (Hillen, Kuilboer, Nordbeck & Treffers)

Hypothesis

Today, deltas are largely influenced by human activities. For example, the construction of the Three Gorges Dam in the Yangtze River, which blocks enormous amounts of sediments, but also the cultivation of the Mississippi River by constructing large-scale level systems. Human intervention is becoming an increasingly dominant process in the development of deltaic areas.

The introduction of human influence asks for a renewed integrated view on their development. As a result the general framework provided by Galloway needs another dominant force. This research suggests an alternative triangular framework, which includes human influence and can serve as an experimental framework for all deltas, (see Figure 2).

Figure 2 shows the shift of the Mississippi delta from nature-dominated to human-influenced. Any delta in the world can be positioned in this framework. For example, the Irriwaddy delta would be positioned towards the more traditional nature-dominated side, the Rhine-Meuse delta towards the human-influenced side and the Niger delta in between these two.

Some deltas that are predominantly human-influenced, such as the Rhine-Meuse delta and the Mississippi delta, are deteriorating at high rates. Hence, the redistribution of influencing factors also demands a new way of delta management to fit these characteristics. In order to keep up with relative sea level rise, delta management nowadays should focus on a balance between human and natural processes. In order to restore the balance where human-dominance is too strong, natural processes need to be reintroduced. This can be achieved by 'building with nature'.

Using a case study, the feasibility of the 'building with nature' concept will be illustrated in this paper. The study describes a solution that restores deltas by using natural processes in a controlled manner in a human-influenced delta. The example uses a large-scale diversion in the Mississippi River to reintroduce natural sediments, thus stimulating marsh growth and preserving the delta plain. It may also help to decrease the risk against flooding in New Orleans. This case is based on an extensive study that also takes human stakeholders into account, such as fishing and shipping industries. In this paper the focus is on the possibilities of reintroducing natural processes in order to preserve the deltaic plains of the Mississippi River delta.

Mississippi delta

The Mississippi delta in Louisiana (USA) is one of the world's major deltas (see Figure 3). This delta functions as the case study area for the 'building with nature' strategy outlined in the previous sections.

The Mississippi delta has a receiving basin with a small tidal range and limited wave action and is a classic example of a fluvial-dominated delta. The Mississippi River drains 41 per cent of the United States with a catchment area of 3,225,000km^2. The river is of great importance for the United States because of its shipping industry and the Mississippi delta is an important area for the oil and gas industry, port and fishing industries.

The city of New Orleans was founded in 1718. To protect the city from inundation by the Mississippi River, levees were constructed. In the 18th century the lower Mississippi River was canalised and shortened by 230km. In addition, its natural floodplain has been reduced by approximately 90 per cent in area due to levee construction. The lower Mississippi River contains 2,700km of levees along both sides of the river (Baker et al, 1991). In 2005, hurricanes Katrina and Rita both had devastating effects on Louisiana showing the vulnerability of the delta. A significant number of people and properties were hit by the hurricanes which also caused substantial damage to the delta environment (Day et al, 2007).

This delta has been selected as the case study for this paper for the following reasons: the Mississippi River delta displays many of the dilemmas common to other deltas, it is important to the world's largest economy, there is high pressure on the area due to the many and varied stakeholders, it has recently been the focus of worldwide attention.

Figure 3. Topography Mississippi delta (Google Earth)

The delta has been subjected to some major changes. The driving processes for these changes are natural, such as subsidence, saltwater intrusion and erosion of wetlands, but also human-induced effects such as cultivation of the river and the oil and gas industry. Most of these processes interact with and reinforce each other. For example, initially wetland loss is largest internally, but as the wetlands open up, wave-erosion will become more significant.

Since 1930 the coastal wetlands in the Mississippi delta have decreased significantly, a total loss of 4,800km^2 of wetlands (Day et al, 2005). Loss of marshes in one area was originally compensated for by marsh creation in another area. This came as a result of channel switching and sediment deposition by the Mississippi River and since the stabilization of the sea level rise, approximately 4000 years ago, there has always been an overall net growth of the Mississippi deltaic plain. However, human intervention caused a net overall loss of deltaic plane. As a result of the cultivation of the Mississippi River, the wetlands were excluded from riverine sediment input and therefore the decay of the Mississippi delta increased. Currently the marshes in the Mississippi River delta deteriorate at a rate of 115km^2 per year (Day et al, 2007). With this rate of loss of marshes, critical energy infrastructure may be affected and other facilities, such as housing and other structures will be exposed to the open water of the Gulf of Mexico. Shipping will be similarly affected, because as wetlands erode, it will become more expensive to maintain waterways and ports in south-eastern Louisiana (USGS, 1994).

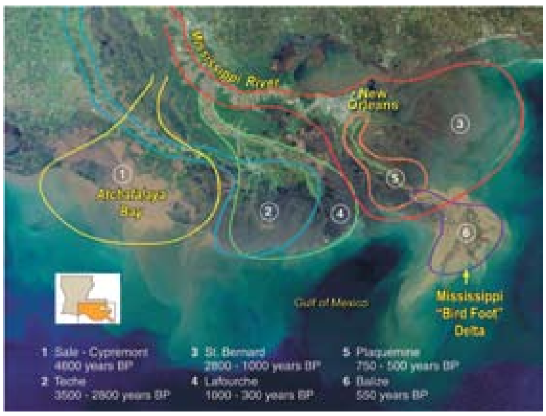


Figure 4. Geological history of Mississippi delta (Day et al, 2007)

Atchafalaya delta

According to Reading and Collison (1996), where a coastline is fed from a contemporary river, which supplies sediment more rapidly than basinal energy can distribute, a discrete shoreline protuberance develops that is called a delta. This is how the Mississippi delta was formed over thousands of years. The delta switching process of the Mississippi delta is well studied and is illustrated in Figure 4. However, today the Mississippi River does not supply the amount of sediment it should do 'naturally' and is forced to stick to its current delta lobe by the levees.

The Mississippi transports an average of 159 million tons of sediment a year (Templet and Meyer-Arendt, 1988). Throughout Louisiana, the levees that protect the inhabitants of the delta are assisted by diversions that divert Mississippi River floodwaters into the Gulf of Mexico via the Atchafalaya River or Lake Pontchartrain.

The Old River Control Structure, 507km up the river from the Gulf of Mexico, distributes 70 per cent of the Mississippi water through the Mississippi River and the remaining 30 per cent to the Atchafalaya Bay. The structure was completed in 1963 and was constructed to control the discharge of the Mississippi River. It prevents the delta from switching into the Atchafalaya Bay. The Atchafalaya River has a shorter course to the Gulf of Mexico and thus there is a natural tendency for the water to flow through that river.

The formation of a delta in the Atchafalaya Bay, by the diversion of 30 per cent of the Mississippi River, is a clear example of the available building blocks presented by nature. The on-going life cycle of the Atchafalaya delta is a product of normal geologic processes for the Louisiana coast with some human influence Shlemon (1975) named four stages of delta formation. From the initial flocculation of suspended sediment (1) to a 20 year period of slow subaqueous growth (2), which is directly followed by rapid sub-aerial expansion (3), the final phase is one of subsidence and compaction (4). All stages are evident in the Mississippi delta plain.

The first three steps of this pattern can be seen very clearly with the formation of the Atchafalaya and Wax Lake birdfoot deltas (see Figure 5). In the Atchafalaya Bay two bifurcating type delta lobes are formed with the sediment from 30 per cent of the Mississippi River water.

Despite cultivation of the catchment area, the 2,700km of levees and the Old River Control structure, the river still carries enough sediment for land-building. This means great possibilities for 'building with nature' since much of the subsidence of the delta plain could be combatted by restoring natural flooding and overbanking processes to deposit sediment over the delta.

Figure 5. Wax Lake delta and Atchafalaya delta (Google Earth)

Large river diversion

Natural processes need to be restored in order to combat deterioration of the Mississippi delta. The separation of the Mississippi River from its floodplains is the major cause of the loss of marshes. These natural processes are well documented and understood and this knowledge can be applied in order to restore them in a controllable manner. This way it does not conflict with the many other functions of the delta or the safety of the inhabitants, further, the economy of the area is ensured. Thus, it was decided to conduct an investigation into a large scale controlled river diversion set up in order to restore sediment deposition in the delta using controlled natural flooding events whilst maintaining most of the current functions.

Caernarvon diversion

The Caernarvon freshwater diversion (see Figure 6) was constructed to the south-east of New Orleans. This diversion is used as a reference project for marsh restoration. Although it is a small diversion and not originally constructed for diverting sediment, its effects are well documented. Therefore it serves as a good source of information for relations between sediment transport and marsh restoration.

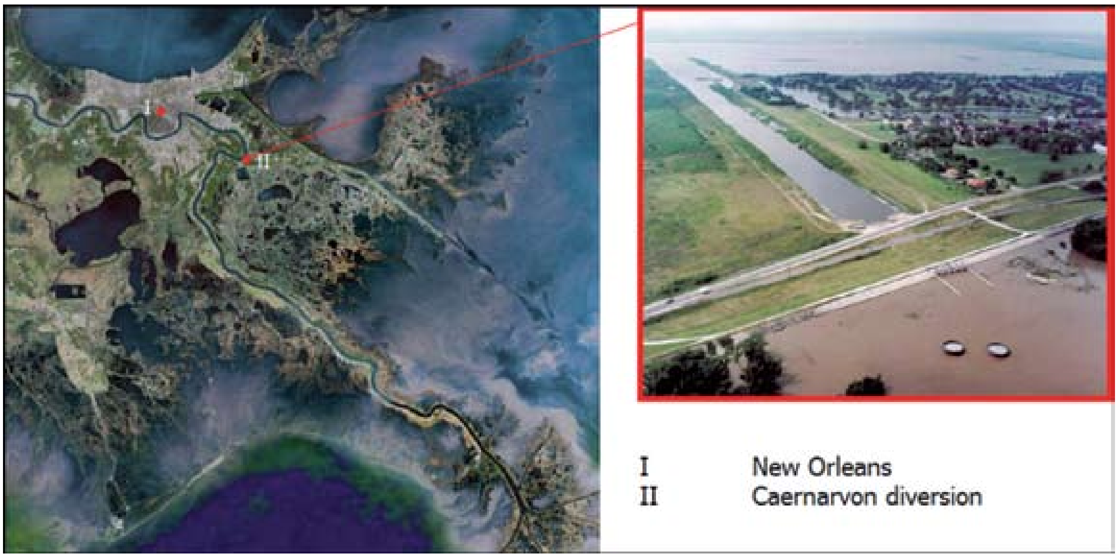


Figure 6. Caernarvon diversion (USACE)

The primary function of the Caernarvon diversion is to divert fresh water into the Breton Sound Estuary. Mineral sediments are also diverted into this area. There is an annual deposit of mineral sediments of 1,230 g/m^2/y in the Breton Sound area due to the Caernarvon diversion (Wheelock, 2003). Wheelock also refers to personal commentary from Paul Templet (2001) who states that a growth rate of 2,500g/m^2/y is needed for land-building marshes in Breton Sound Estuary. Nyman et al (1990) estimated that to vertically accrete at 1 cm/y saline marsh requires 1,800g/m^2/yr of mineral sediment per year. Sediment deposit in Breton Sound lags behind – given the 2,500g/m^2/y and 1,800g/m^2/y growth rate. The required amount of sediment is diverted, but not all sediment is deposited in the marshes. Wheelock suggests that better land building will occur when more coarse grained sediment is diverted. She also stresses the importance of good transport to spread the sediment over the area.

The Caernarvon diversion also shows that pulsed diverted discharges are necessary for a good sedimentation process, but in order to have a good effect they need to be large pulses. These controlled flooding events should coincide with the discharge and sediment peaks in the Mississippi River. Diverting water this way will have the least impact on navigability and also the highest concentrations of sediment. Adequate timing and planning of the outflow of sediment load is important for sustainable marsh growth. The case of Caernarvon shows that the diverted volume of sediment is sufficient, but the transport mechanism is not. Most sediments flow directly through the channels to the Gulf of Mexico. Therefore large pulses, exceeding 100m3/s, are needed to ensure that there is sediment deposit on the marshes. Combined with additional sediment trapping methods this could counter the subsidence.

Calculations large river diversion

To determine if large river diversions are technically feasible calculations were carried out and verified with the use of a small-scale physical model and further numerical calculations. The loss of marshes occurs when vertical soil accretion fails to keep up with relative sea level rise (RSLR). The goal is to reverse this process and establish growth of marshes. In the calculations this growth is defined as preserving the marshes, thus keeping up with the relative sea level rise. RSLR rise is assumed to be 10mm/y over the entire Mississippi deltaic plane (Day et al, 2007).

The RSLR in the Mississippi deltaic plane is one of world's highest. RSLR consists of sea level rise due to climate change, expansion of the oceans and melting of ice on top of Greenland and the Antarctic (1-2mm/yr) (Church et al, 2001) and subsidence, mainly due to oil extraction (8-9mm/yr) (Snedden et al, 2007).

To determine the amount of sediment needed for this marsh growth the results of the sediment deposition thesis by Wheelock (2003) are used as a basis. The first investigation is the amount of sediment deposition. Next, the bathymetry of the receiving bays that the diversion will affect is determined. The next step is then to determine the percentage of diverted sediment that will settle in the influenced area. Again, the experiences of the Caernarvon freshwater diversion are used to determine a relationship between the diverted sediment and the sediment deposited in the area. With these three steps the amount of sediment that needs to be diverted can be calculated. Finally, this is checked against the available amount of sediment in the lower Mississippi River.

Amount of sediment

Reintroducing water from the Mississippi River into the Breton Sound Estuary clearly increased the rate of vertical marsh accretion, DeLaune (2003). According to Lane (1999) almost all of the suspended sediment would be deposited in the marshes and Hyfield (2007) states that mineral sediments form the basis of vertical accretion in marshes. Sediment deposition usually forms the mineral soil layers. These layers have high availability of nutrients and are therefore good for marsh growth.

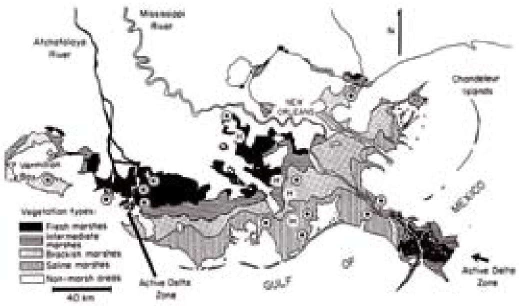


Figure 7. Different marsh types in the Mississippi delta (Nyman et al, 1990)

Nyman et al (1990) studied the relationship between the mineral and organic matter in different marsh types found in the Mississippi deltaic plane estimating sediment requirements in these marshes to various subsidence rates. The results of Nyman's study give the combination of mineral and organic matter required to maintain the marsh surface-water relationship in g/m^2/yr. As can be seen in Figure 7, in the area near Port, sulphur saline marshes can be found. Nyman found the following relationship:

- Organic matter = 923 + 601x
- Mineral matter = 1,798x

Where x is equal to the rate of subsidence per year (in cm/yr).

This means that for a 10mm/yr subsidence-rate in the Mississippi delta birdfoot area the amount of sediment that is needed to cope with the subsidence equals for mineral matter 1,798g/m^2/yr and for organic matter 1,524g/m^2/yr.

The amount of mineral sediment deposited by a diversion is relatively easy to determine, compared to the organic matter deposited. Mineral sediment that is transported from a river into an estuary will be suspended by waves and carried by wind-driven or tidal current onto the marshes. This will cause aggradations, an increase of height in relation to the mean sea level.

This added sediment is also beneficial for the growth of marsh plants on the deposited surface, which also leads to an increase of land elevation (CLEAR, 2004). For the calculation of sediment deposition, it is assumed that only the building of mineral soils is relevant. The accretion will be higher when organic accretion is also taken into account. Wave activity on marshes and the advantages of fresh water are left out of the early estimations.

Influenced area

A diversion location halfway between New Orleans and Head of Passes (Mississippi River mouth) is selected. The diversion will divert water to the east, the west or both sides of the Mississippi River to establish marsh growth. On the west side, water will be diverted into Barataria Bay and on the east side, into the Breton Sound Estuary. The east side of the diversion has a small area of marshes adjacent to the Mississippi River. The west side of the diversion has a marsh system, which is deteriorating; channels and lakes are forming that stimulate the marsh deterioration.

The size of the influence of the diversion (see Figure 8) is determined by experiences taken from the Caernarvon diversion, and also by the fact that the discharge diverted is larger. The influenced area at each side is divided in two different parts. This division is based on depth and the presence of existing marshes. The first part (I) is the area that will be directly influenced by the diversion and where on a short time period marsh restoration should be visible. The second part (II) is the area with a larger depth and located further from the diversion.

Figure 8. Influence area Port Sulphur diversion (Google Earth)

Assumptions

The basis of the calculation is to determine how much sediment is needed to fill the area where marshes are desired. Assumptions have been made on the following aspects:

- Marshes start to grow at a depth of 0.5m and the retention rate of sediments is 15 per cent. This is based on data of the Atchafalaya River flowing into the Gulf of Mexico, LCA Report, (2004).
- The benefits of input from fresh water and organic matter is not taken into account. Only mineral sediment as the main contributor to marsh growth, is taken into account.
- The influenced area is arbitrarily chosen with the reduction of the effects of a storm surge on New Orleans in mind.
- The sediment distribution through the diversion is assumed to be equal. This means that the sediment that flows through the diversion will be distributed evenly over the influenced area.
- Only suspended sediment is taken into account. Suspended sediment is relatively easy to trap with the use of a diversion. Therefore only the total suspended sediment load is used to determine the needed discharge for marsh growth.
- The whole influenced area needs to be filled with river sediments. Natural marsh areas consist of marshes, small distribution channels and lakes. For the first calculations it is assumed that there are only marshes and no distribution channels and lakes. The concentration of the sediment is taken to be the same as the sediment concentration in the Mississippi River. As a first estimate for the deeper area (part II) 35 per cent of open water will exist. This open water has an average depth of 1.5m (van Heerden, 1983).

- Sea level rise in the area of the diversion is 10 mm/year. 1-2mm/year due to climate change and 8-9mm/year due to subsidence.
- Wave erosion is discounted. Since the impact of waves on marsh erosion in a complex process, it is not taken into account for the basic calculations. However, wave force is relatively low in the Gulf of Mexico.
- The severe impact of a hurricane is discounted. Since hurricanes are extreme forces and are very irregular and unpredictable it is too complex to take them into account.
- Variability in discharge and sediment concentration is discounted. The influences of pulsed events are important for the growth of marshes. For the basic calculations only the average discharge and average sediment concentration is used. With pulsed events the results will be more advantageous.

Results

The required discharge, for three different scenarios, is determined using the data of suspended sediment concentrations in the Mississippi River (see Table 2).

For a 50-year time period, the annual average diverted discharge in the east direction should be 3,404m^3/s and in the west direction it should be 1,221m^3/s. Combined diverted annual average discharge through the Port Sulphur diversion should then be 4,625m^3/s.

For a 40-year time period, the annual average discharge in the east direction should be 4,227m^3/s and in the west direction it should be 1,438m^3/s. Combined diverted annual average discharge through the Port Sulphur diversion should be 5,665m^3/s for a 40 year period.

For a 25-year time period, the annual average discharge in the east direction should be 6,695m^3/s and in the west direction it should be 2,090m^3/s. Combined diverted annual average discharge through the Port Sulphur diversion should then be 8,785m^3/s for a 25 year period.

Table 2. Summary suspended sediment load lower Mississippi River at Tarbert Landing (USACE)

	Total Measured Suspended Load	Sand Silt Ratio				Water Year Discharge	Avg. Sed. Concern.
		Sand		Silt			
Oct-Sep	(1000 TONS)	(1000 TONS)	%	(1000 TONS)	%	(1000 DSF)	(PPM)
1990-91	157,029	52,209	33	104,82	67	228,833	253
1991-92	115,115	36,549	31	81,07	39	170,358	259
1992-93	205,054	78,133	38	126,881	62	266,722	285
1993-94	135,537	57,854	43	77,683	57	227,398	221
1994-95	107,028	18,349	17	88,101	83	184,186	204
1995-96	117,233	28,008	21	91,384	79	180,105	241
1996-97	156,751	32,918	21	123,833	79	245,435	237
1997-98	171,267	39,391	23	131,678	77	211,282	302
1998-99	167,622	33,201	21	132,411	73	190,967	315
1999-00	72,649	13,603	19	56,846	61	117,497	229
2000-01	133,388	22,676	17	110,713	83	165,163	297
2001-02	114,428	24,029	21	90,397	79	200,03	212

Conclusions

To have marshes on both sides of the Mississippi River a significant discharge is needed. Depending on the time period about one third, increasing to half the yearly average, Mississippi River discharge needs to be diverted in the embayment. To have marsh in the total influenced area within a shorter time period, a much higher discharge is needed. The effects of the freshwater input in Caernarvon contribute considerably to marsh preservation, and the nutrients of the river water are not taken into account. With sustainable marsh management focused on improving the sediment retention rate, improved sedimentation can occur. The retention rate in area II is an influential parameter. Therefore management of navigation channels, oil and gas subtraction, and good vegetation management can improve this rate. Also restoring barrier islands, or by artificially creating barrier islands by using dredged material, will increase the retention rate.

Diverting water of the Mississippi River with pulses when there is a high sediment concentration present and discharge available will help divert an increased amount of sediment. This results in more and better sediment deposition. Taking the considerations above on board, a sound estimate of the discharge is calculated, this can be checked against the physical model of the lower Mississippi River and more detailed numerical calculations.

In order to verify the conclusion of the previous section i.e. that large marsh areas can be restored with the use of a large-scale diversion, a qualitative physical model and a quantitative 3D numerical modelling program have been used. These are outlined below.

Physical model

To qualitatively check the effects on land formation by reintroducing the natural processes in the delta, tests were made using the small-scale physical model of the Louisiana State University (LSU) in Baton Rouge (see Figure 9).

Using the physical model different concepts of diversions were tested. This gives insight on the area of influence and the effects of a diversion regarding its size, location, angle and the sedimentation characteristics in the river. The model has two key features which are advantageous for this study:

1. It gives a qualitative illustration of the sedimentation processes and helps to show the impact of different diversions.
2. The model sedimentation time-scale currently reproduces two years in 33 minutes. Therefore several hours of testing can represent decades of sedimentation.

The model was constructed and tested in Grenoble, France, by Sogreah consultants under the supervision of Coastal Restoration Consultants. The model is a qualitative model of the lower 122km of the Mississippi River and its surrounding coastal delta area, constructed to study coastal restoration programs. According to Sogreah, energy gradients and sediment transport characteristics in the river and marshes are well simulated despite the fact that it is a qualitative model river flow. The model dimensions are 8.46m x 7.41m (62.69m^2). It has a 1:12,000 horizontal scale and a 1:500 vertical scale and represents an area of 9,027km^2. Despite the distortion, the model is still considered to be quite accurate for flows in the river bends and thus represents the modelled area sufficiently.

The model was designed and built according to the Froude similarity law. Turbulent flow was simulated with the minimum Reynolds number and sediment transport with suspended sediment particles. The model also satisfies Shields law for incipient sediment particle entrainment. The sediment in the model represents sand particles with a size between 62μm and 300μm. The sediment materials in the experiments are synthetic particles and have a density of 1,050kg/m^3. The run time of the model is based on this sediment deposition time-scale.

These particles account for 20 to 25 per cent of the total sediment load of the Mississippi River. The deposition of the smaller particles, silt and clay, are made visible by dye injections. Both processes are captured by time-lapse photographs at regular intervals (see Figure 9) and is analysed together with the sediment balance of the model. The results provide useful information on the effect of the reintroduction of natural processes in the Mississippi River delta. The sediment supply and discharge of the model are tuned to represent an average annual discharge curve of the Mississippi River.

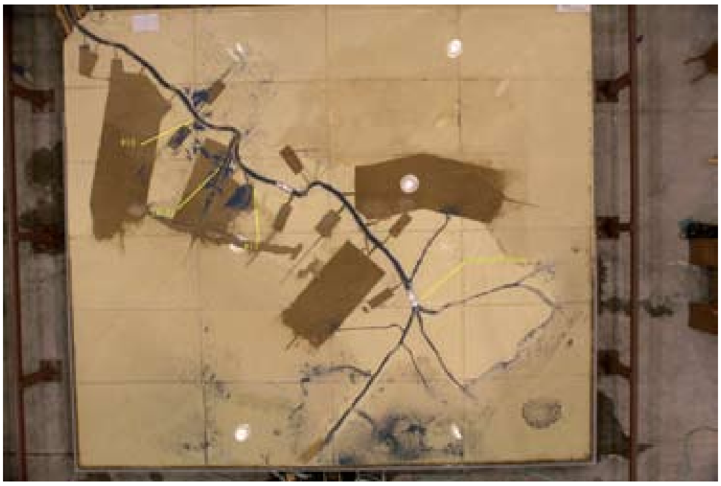


Figure 9: Small scale physical model of the lower Mississippi River (LSU)

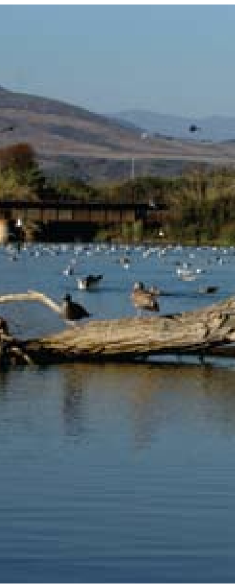
For this research, runs were made for a total time-frame of 30 years, 10 years for each of the three different diversions.

Although it is difficult to simulate the complex sedimentation and marsh restoration processes the results obtained were quite similar to what was expected based on the available theories on sediment movement. Figure 10 gives an example of the results and how to interpret them.

Figure 10: sediment settling and interpretation

The amount of deposited sediment is about 170 million tons. The model only represents the coarse sediments (sand). According to Brown, Cunningham and Gannuch, (2004), 90 per cent trap efficiency is taken for sand, for the suspended sediment transport (silt-clay) that is 40 per cent. The percentages of sand and suspended sediment transport are respectively 20 per cent versus 80 per cent If the deposited sand is also representing the deposited suspended sediment, the total amount of deposited sediment over 30 years is:

170 million tons + ((170 million tons / (90% * 20%)) * 40% * 80 %) = 472 million tons
This is an average of 472 / 30 = 15.75 million tons per year.



In the previous section it was determined that a yearly average discharge of 4,625m³/year is needed to create marshes over a time period of 50 years. This corresponds to a requirement of 14.6 million tons of sediment per year to sustain marsh growth. The amount that was deposited during the tests using the physical model corresponds to this amount. However, the average diverted discharge by the three diversions in the physical model is probably slightly higher, nevertheless the amount of deposited sediment is similar to the amount required. With the qualitative character of the SSPM in mind, one can conclude that diverting a large discharge in combination with a large quantity of sediments is possible and that it does have the marsh restoration land-building capacities.

Numerical modelling

The creation of marshes using a diversion can result in a reduction of storm surge. The opinions of experts on the extent of this reduction vary. To get an impression of these effects, runs were made with help of Delft3D software, a numerical model developed by Deltares. With the use of Delft3D the effects of marshes on storm surge were determined. The increased roughness and vegetation parameters were submitted in a special vegetation (marsh) module.

The results clearly show that land growth in the wetlands does have a positive impact on surge reduction and that surge heights depend on the direction of the flow and obstructions it encounters. In other words, the safety of a typical area depends highly on the location of the restored marshes and the path of the hurricane. Overall, the majority of outcomes from the numerical calculations showed reductions in peak water levels in the order of 1/6 to 1/12 of the Katrina surge levels. The area influenced by the restored marshes is limited however and stresses the importance of a large area of restored marshes.

Conclusion

The results of the calculation on a large scale Mississippi River diversion show that it is possible to restore sediment input in the delta. A check with a physical model supports these findings and a basic numerical calculation shows that it has positive effects on the safety of the area. With these results the case study shows it is possible to shift the Mississippi River delta in the experimental triangle of the hypothesis (Figure 2) from mainly human-influence towards a more nature-dominated delta. Thus establishing a better balance between these two components.

'Building with nature' is possible for the Mississippi delta. It is a gradual process with a time span of several decades requiring a large diversion to obtain the desired results for the delta. The marsh areas would recover and the city of New Orleans would become safer against wave action, such as those produced by Hurricane Katrina.

By understanding the natural processes and their potential, a step towards 'building with nature' can be taken. This is possible using controlled diversions as shown in the case study. Since using controlled diversions will preserve the delta in the long run, they will provide benefits for all stakeholders. In the short-term some stakeholders might endure greater negative effects due to the diversion, but pursuing the present course will lead to increasing loss of the delta and negative effects for all stakeholders. The use of a controlled diversion and its gradual effects enhances the ability to reduce or even eliminate negative issues for certain stakeholders. This is necessary since a realistic solution is needed for most deltas. Going completely back to a nature-dominated delta is not an option, but going gradually and in a controlled manner in that direction is very favourable. Especially with the many threats such as climate change, sea level rise and increasing urban pressure it is now necessary to establish a new balance between human and natural processes.

Discussion

There continue to be many uncertainties in managing a deltaic environment successfully and to ensure that the interests and goals of all, or at least most of the, stakeholders are met.

However, this paper shows that 'building with nature' and reintroducing a more natural cycle with sediment and nutrients, is a serious management option that can ensure high quality of life for all stakeholders in a deltaic area.

One has to look to the future and realise that by 'building with nature' harmony between stakeholders and the deltaic environment can continue and develop.

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Royal Haskoning, Consultants, Architects and Engineers organises the DeltaCompetition – an international competition for students – every two years. Through the Delta Competition, Royal Haskoning provides students from all over the world – as individual or team – with a backdrop against which they can come up with scientifically underpinned, innovative and sustainable solutions for the inhabitants of vulnerable delta areas.

It is often the vast fertile deltas, such as those of the Rhine, Ganges and Mississippi, which are densely populated regions with highly developed economies. The people who live there are becoming increasingly aware of the urgency of taking appropriate measures to counteract the disastrous effects of climate change and the associated rise in sea levels. This book presents the five best entries in the DeltaCompetition 2008. Each and every one of them is an innovative report that contains the promise of sustainable solutions to the challenges that changing climatic conditions are confronting us with.

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