The Effects of Climate change on World Aquaculture:
A global perspective

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Executive summary

1. Climate change and global aquaculture

Outline of global climate change and climate prediction

- It is now widely accepted that observed changes in the earth's climate are at least in part a result of human activities.
- Models for future climate prediction are continually growing in sophistication with the current generation of General Circulation Models linking both ocean and atmosphere components. The resolution of global climate models is relatively low and considering their theoretical nature they are better suited for predicting long term changes in variables such as temperature and precipitation over larger areas than more localized and variable phenomena such as cyclones.
- Temperature is predicted to increase more at higher latitudes compared with equatorial areas. Maximum and minimum temperatures at a given point will vary and there may be an increase or decrease in the range of temperatures seen at the diurnal, seasonal and inter-annual time scales.
- As a global average precipitation levels are predicted to increase although southern Africa, Australia and Central America will most likely see a decrease. Changes in seasonal variation will also be important and may lengthen or shorten growing seasons in relation to water availability or increase the risk of flood damage at certain times of year.
- Mean sea level is predicted to increase between 10 and 90cm during the 21st century with most predictions falling within the 30 to 50cm range although some uncertainty remains in relation to land based ice in Antarctica and Greenland.
- Changes in climate variability and extreme events are considered harder to predict although increases in the intensity of precipitation events, risk of drought and peak cyclone wind intensities are considered likely in some areas.
- Changes in ocean currents as well as having a substantial influence on the worlds climate may have significant direct effects on aquaculture through changes in temperature, primary productivity and hence food availability, and the distribution of disease, toxic algae blooms and predators.

An overview of global aquaculture

- The global aquaculture industry in continuing to grow, accounting for an increasing share of total fisheries production.
- Asia and particularly China accounts for the majority of the worlds aquaculture production.
- While aquaculture plays an important role in the livelihoods of people from a wide range of areas it is again Asia the greatest numbers can be seen. There are an estimated 9.5 million aquaculturists in Asia and it is likely that many more people will be involved in supplying a range of goods and services to the sector.

- Although the average rate of growth in the aquaculture sector appears to have slowed in recent years compared with the rapid growth seen during the 80's and 90's, continued expansion is predicted for the coming decades as a result of an increasing demand for fish and the limited production capacity of capture fisheries.
- As a result of economic pressures and the increased development and spread of aquaculture technologies, it seems likely that a general trend towards more intensive culture practices will occur.

Impacts of climate change on aquaculture production systems

- Climate change impacts on aquaculture are considered in the current study as either direct e.g. changes in water availability, temperature or damage by extreme climatic events, or indirect such as in the case of increased fishmeal costs and its consequences for aquaculture feeds.
- Potential direct impacts on aquaculture are outlined here in table 1.7.
- The particular sensitivities of aquaculture related livelihoods to different aspects of climate change will be linked to the type, scale and intensity of aquaculture taking place as well as the environment in which it is being conducted. There has been a considerable amount of work focusing on the different aspects of aquaculture dependant livelihoods, but little that deals directly with the potential effects of climate change. The sustainable livelihoods approach can be useful in assessing how climate change may impact on the natural, physical, economic, human and social capitals necessary for aquaculture.

2. GIS based assessment of aquaculture related vulnerability to climate change

A Geographic Information System (GIS) based model is used to indicate areas where livelihoods are likely to be vulnerable to climate change impacts on aquaculture. The model used the concept that vulnerability (V) is a function of exposure to climate change (E), sensitivity to climate change (S) and adaptive capacity (AC).

$V = f\,(E, S, AC)$

The concept of climate trends, such as gradual changes in mean temperature and precipitation levels, compared with climate shocks, for example; floods and cyclones, is considered important when assessing potential impact pathways. The categories of fresh, brackish and salt water culture are used to give some indication as to the location and type of aquaculture likely to be taking place within a country. It is considered that the type and location of the aquaculture environment will influence its vulnerability to particular climate related impacts.

The indicators used in the vulnerability model along with its basic structure are shown in figure 2.1. All layers are reclassified on a scale of 1 – 5 and layer combination is by Multi Criteria Evaluation (MCE) using weighted linear combination. Different levels of significance/weightings can be assigned to layers being combined in the sub and main model.

Decisions regarding weightings were maid by the authors after obtaining a consensus of expert opinion from a focus group and guided questionnaire.

Eight combinations of component layers are used to assess vulnerability in relation to a range of issues, culture environments and climate factors. Table 2.23 highlights countries which score at least 4 out of 5 for at least part of their area under the different combinations.

Asia featured highly in the vulnerability assessment with the large aquaculture producing countries such as; Bangladesh, Cambodia, China, India, The Philippines and Vietnam indicated as vulnerable under most of the layer combinations used.

Aquaculture production in Africa as a whole is low when compared to Asia. However many African countries are considered to have a very low adaptive capacity and are therefore considered vulnerable in some instances.

A number of Central and South American countries are considered vulnerable with Nicaragua and Guatemala being the areas of most concern.

3. Case study - Bangladesh

Introduction

Bangladesh is one of the world's most densely populated countries with nearly half of the 138 million population being considered bellow the poverty line. Bangladesh is recognised as being very vulnerable to climate change and sea level. Approximately 85% or the countries poor live in rural areas, and it is estimated that around 61.5% of the countries employed people are connected to agriculture. With estimates of over 3 million fish farmers aquaculture is highly significant within Bangladesh both in terms of food security and economic income.

The physical geography, climate and weather of Bangladesh

Bangladesh is an extremely flat and low-lying deltaic country (Fig. 3.1) with a large proportion of its area comprising of the floodplain of three converging rivers; the Ganges, the Brahmaputra-Jamuna and the Meghna (GBM river system). Bangladesh experiences a cooler dry winter period and a summer monsoon season during which it is forced to drain a large quantity of cross boarder runoff and as a result an average of 20.5% of the country floods annually. Peoples livelihoods are typically well adapted to the average annual flooding, however during extreme flood events such as in 1998 up to 70% of the country can be inundated. Such events are typically associated with synchronisation of peak flow within the GBM river system and cause widespread damage.

Bangladesh is also vulnerable to cyclones and associated storm surges which can inundate the flat low lying coastal areas.

Current state of aquaculture in Bangladesh

Traditionally aquaculture in Bangladesh has taken the form of extensive pond culture of freshwater fish species such as carp species, and often relied on natural stocking of fish seed during flood periods. The current trend is towards more intensive methods and deliberate stocking of select species. A greater range of fish species are now cultured along with high value crustacean species such as *Penaeus monodon* and *Macrobrachium rosenbergii.*

Future potential for aquaculture in Bangladesh

Bangladesh's population is predicted to expand from its current level of 138 million to between 190 and 222 million by 2030. Aquaculture has an important potential role in providing food for this increasing population in a country where malnutrition is currently common.

There are a large number of nongovernmental organisations within Bangladesh that are helping to promote aquaculture. It is hoped that through micro credit schemes and provision of appropriate information and training that poorer people will be able to participate in small scale aquaculture, providing both additional food and income.

The culture of high value species such as shrimp is seen as having the potential of generate substantial export earnings and is been promoted.

Potential future climate change in Bangladesh

Sea level rise is a major concern due to the low elevation of much land in Bangladesh with inundation estimates of 2500 km^2 (2%), 8000 km^2 (5%) and 14000km^2 (10%) for 0.1, 0.3 and 1.0 metre rises respectively.

Increased salination of ground water may alter the range of species that can be cultured at a given location.

Loss of natural coastal defences may increase the risk from storm surges.

The Bengal delta has a high level of subsidence with an estimated effective sea level (the combination of actual sea level rise and the subsidence of land) or more than 10mm per year under current conditions.

Storm surges represent a serious threat to aquaculture in the countries coastal areas. A relationship between sea surface temperature and cyclone intensity has been suggested. Estimated maximum surge height under conditions similar to the 1991 cyclone is 7.6m with a predicted increase to 9.2m and 11.3m under 2°C and 4°C surface temperature increases respectively.

Temperature increases within the Bangladesh region are predicted to be greater during the winter period compared with the summer. Precipitation levels are predicted to be greater during the summer monsoon period with possible decreases during the winter months. These predictions suggest a potential increase in the risk of flooding during the monsoon season as well as a limited water supply during the winter period. The potential for greater variation as well as a greater likelihood of synchronised peak flow in the major rivers and consequent increases in flooding should also be considered.

Summary – vulnerability of aquaculture in Bangladesh and potential adaptation

Within Bangladesh sea level rise with its associated land loss and salination of ground water as well as risk from storm surges and inland flooding would appear to represent the greatest potential climate related risks to aquaculture. The potential for water shortages during winter as a result of decreased precipitation combined with an increasing population should also be considered.

The promotion of suitable culture methods and species within a given area in relation to both people's socio economic situation and changing environmental conditions will be important in helping gain the maximum benefit from aquaculture. Further research should be encouraged with the following areas seen as especially significant:

- Awareness of latest climate predictions for the Bangladesh area, especially those involving precipitation regimes, sea level rise and if possible tropical storms.
- Organisation and availability of historic data and research.
- Analysis of site suitability for aquaculture based on:
    - Predicted changes in climate and consequent environmental factors: Water availability, Salinity and temperature.
    - Risk from extreme events notably riverine and storm surge floods.
    - Social and economic evaluations and predictions.
    - Resource availability e.g. Seed, inputs and support networks.
- Continued improvement and development of aquaculture practices for a broad range of species in order to maximise production where possible.
- Production and distribution of quality seed.
- Cost benefit analysis for a wide range of species and culture methods in relation to climatic and environmental variables.

4. Conclusions

- The current study provides a strong starting point and a useful guide for further investigations both at more local level and with a focus on more specific issues.

- More focused case studies will be very important not only in guiding policy decisions for the areas concerned, but also for the increased understanding of the ways in which climate change impacts will take place along with possible adaptive measures to counter them. It may then be possible to apply the knowledge and working methods gained from one area to others with similar characteristics.
- Ability to adapt to climate change will be strongly linked to adaptive capacity making economic predictions an important part of vulnerability assessment.
- The promotion of suitable species and culture methods at a given location in order to maximise production and profits in the face of a changing climatic, socio economic and environmental variables will be important. The use of Geographic Information Systems (GIS) are seen as providing powerful tools in this area.
- The efficient organisation, distribution, and where possible free availability of data and literature will greatly assist future work and help determine what can be achieved with the limited time and resources available.

1. Climate change and global aquaculture

Outline of global climate change

It is now widely accepted that at least part of the earth's 0.6°C warming during the 20th century is due to emissions of greenhouse gases caused by human activities (Figure 1.1). Use of proxy temperature records suggests that the spatial extent and duration of warming during the middle to end of the twentieth century in the northern hemisphere makes it the most significant climate anomaly of the last 1200 years (Osborn & Briffa, 2006). Throughout the 20th century sea level has risen, with average global tide gauge data showing average increases of between 0.1 and 0.2 metres (IPCC, 2001a). Observations of sub-surface ocean temperatures that are suitable for analysis have been available since the late 1950's, and since this period ocean heat content is shown to have increased (IPCC, 2001a). Warm episodes of the El Niño-Southern Oscillation (ENSO) which are known to have regional impacts on temperature and precipitation over many areas ranging from the tropics to mid latitudes, have been recorded as more frequent, and of greater intensity and persistence during the last 30 years compared with the rest of the 100 year period for which suitable records are available. In general climate changes observed at the regional level are often a consequence of variability at the inter-decadal or multi-decadal time scale. There are however regions in Asia and Africa where an increase in the intensity and frequency of droughts has been seen during recent decades (IPCC, 2001a).

Box 1.1 Key references for climate change information

Two references appear frequently in the text in relation to a variety of climate change information:

IPCC, 2001a. Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., & Johnson, C.A., eds. (2001). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

IPCC, 2001b. McCarthy, J., Canziani, O.S., Leary, N., Dokken, D., & White, K., eds. (2001). *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

The Intergovernmental Panel on Climate change aims to "assess scientific, technical and socio- economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation".

The IPCC is structured around three working groups; Science, Impacts and adaptation, and Mitigation, which all contribute to an assessment of available information. As many climate change issues contain much uncertainty, with opinion and experimental results for many topics being varied, a consensus of expert opinion and summarization of information is therefore highly valuable in the case of a project such as the current one.

During the last few years, scientific consensus has moved to an acceptance that climate change is 'real' and that we are now experiencing its early stages. In 2001, the Intergovernmental Panel on Climate Change (IPCC), stated that "new and stronger evidence that most of the warming over the last 50 years is attributable to human activities" and suggests that the way in which the climate continues to change during the 21st century will be a result of both natural changes and the response of the climate system to human activities.(IPCC, 2001a).

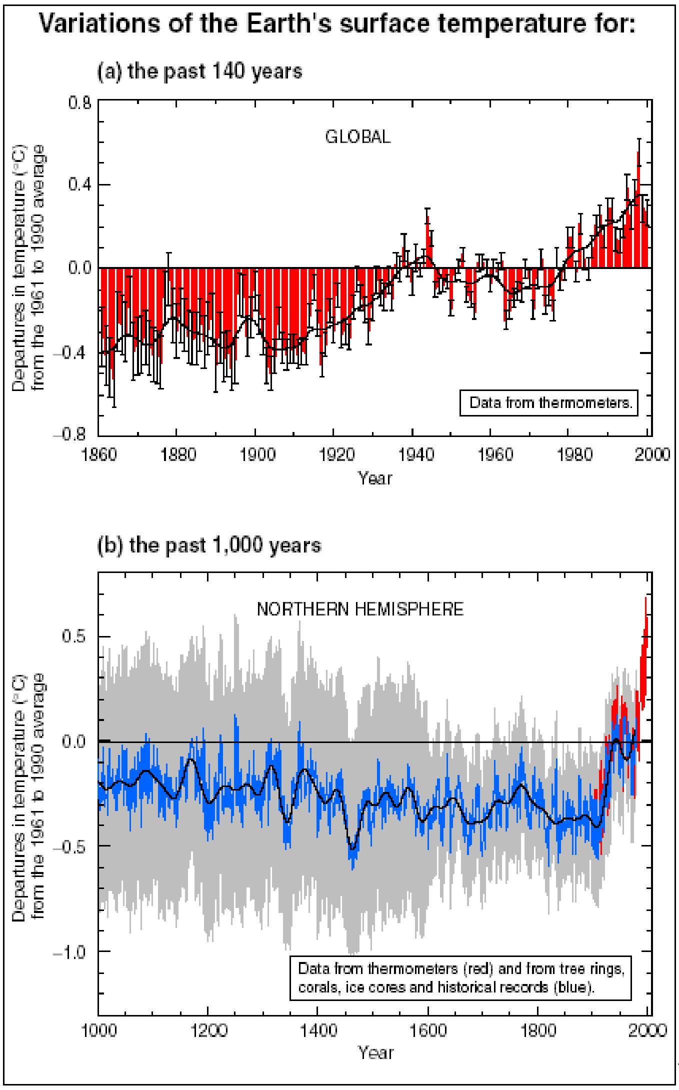


Figure 1.1 Variations of the Earth's observed surface temperature over the last 140 years and estimates for the last millennium (source: IPCC, 2001a).

Climate prediction

Models and scenarios

Climate prediction models are gradually growing in sophistication due to better understanding of climate variables and increased computing power. The current generation of models known as General Circulation Models (GCM's) link both atmosphere and ocean variables. The models consist of a number of cells covering the globe both horizontally and vertically.

GCM's require input dictating levels of climate forcers such as greenhouse gases and aerosols. This is done by the production of emissions scenarios which predict different levels and inputs of greenhouse gases and other climate forcing components in relation to future social, economic and technological development. The Special Report on Emissions Scenarios (SRES) produced by the Intergovernmental Panel on Climate Change (IPCC) produces a range of Scenarios which are typically used in association with the current generation of GCM's. The results of a number of commonly used scenarios can be seen in terms of temperature increase in Figure 1.2. A recent critique of the SRES in Nature (Schiermeier, 2006) highlighted the view of many economists that the current scenarios are flawed and based on outdated economic theory. In particular, there are doubts over assumptions on the speed at which the economies of developing countries will develop and converge with currently more developed nations. There is also concern over how predicted economic development is linked with technological development and energy use. The IPCC is currently considering new scenarios which may be developed for use with the 5^{th} assessment report scheduled for 2013. In the case of the 4^{th} assessment report due in 2007, the current SRES scenarios will be used although other projections will also be considered (Schiermeier, 2006). However, the current set of SRES scenarios do cover a broad range of atmospheric greenhouse gas concentrations so should still be considered highly useful in terms of predicting a range of future climates.

Strengths, weaknesses and uncertainties in relation to climate models and prediction

Some aspects of future climate change such as average temperature changes can be predicted with greater confidence than others, for example increased storm events and the effect of El Niño-Southern Oscillation (ENSO) variations.

Sources of uncertainty affecting climate prediction include: future emissions and atmospheric concentrations of greenhouse gases; incomplete knowledge about how the global climate system will respond to greenhouse gas forcing; natural variability due to the tendency of a system to be sensitive to its starting conditions and feed back from the systems themselves. It is also worth considering the resolution of current GCM's which operate with cells that equate to hundreds of square kilometres on the earths surface, and therefore have a limited capacity to predict small scale events such as thunderstorms and tornadoes (IPCC, 2001a). Current GCM's do model cyclones but there is some uncertainty about the results produced. While there is no doubt that GCM's are very useful tools in the prediction of many planetary climate trends there is currently a lack of confidence in results at the detailed spatial and temporal scales sometimes required by planners and managers.

Variations between models and an incomplete knowledge of how the climate system will react to rapid changes in the levels of greenhouse gases will create additional uncertainty. Further uncertainty comes from not knowing how changes in climate that do take place will impact on clouds, grasslands, forests and in particular oceans, and how these will feed back into the system as a whole.

Analysis of inter-model variability shows that the level of agreement between models for climate variables such as temperature and precipitation may differ spatially even at large geographical scales. For example, there is strong agreement between models for a much greater than average warming at high northern latitudes during winter months, while there is much less agreement on the level of warming expected in Central America.

Predicted climate changes

The limitations and abilities of climate models are fully reviewed in IPCC (2001a). Predicted climate change is summarised here and is based on IPCC (2001a) unless otherwise referenced.

Temperature

- Average global temperature, using all 35 SRES scenarios, is predicted to rise between 1.4 and 5.8°C between 1990 and 2100 with change most likely to be in the 2 to 4.5°C range (figure 1.2).

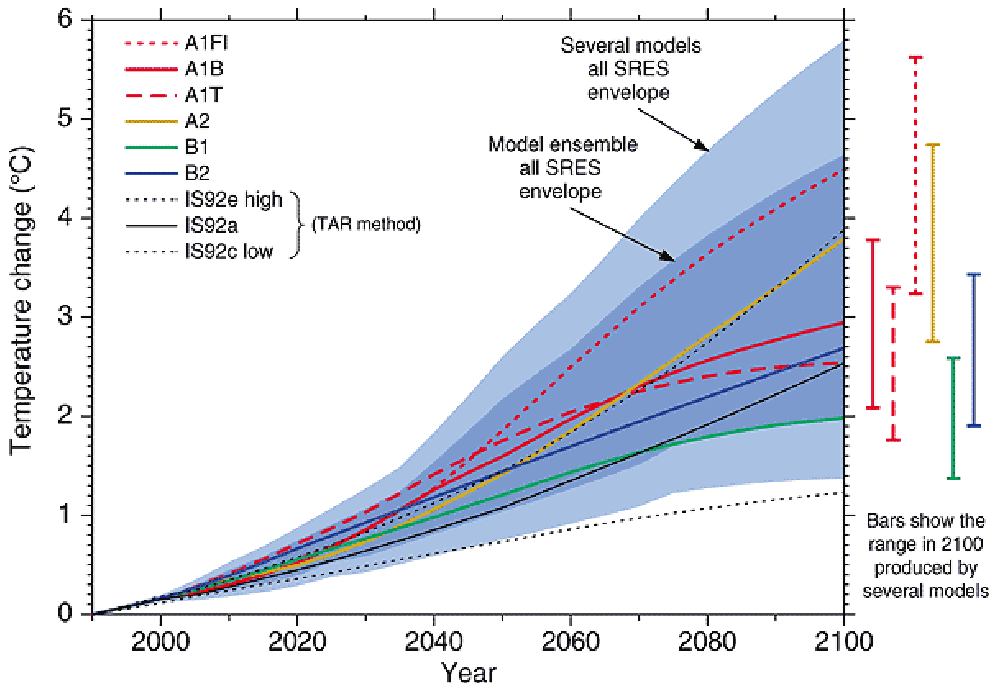


Figure 1.2 Predicted average global temperature increase using a simple climate model tuned to 7 GCM's (source: IPCC, 2001a).

- Temperatures at higher latitudes are predicted to increase more than those near the equator.
- Changes in global mean temperature are likely to come to a greater extent from higher minimum temperatures rather than maximums.
- Higher winter temperatures at high latitudes will be more significant for the global average than higher summer temperatures
- Diurnal temperature range may be reduced in some areas with a higher minimum night time temperature accounting for a greater proportion of mean temperature change than the daytime maximum.

Precipitation

- As a global average, water vapour, evaporation, and precipitation are expected to increase although at a local level drier as well as wetter areas will be seen. For example increases in precipitation are predicted for higher latitudes while Central America is expected to see a decrease in precipitation throughout the year.
- Changes in precipitation at the local level are likely to be linked to seasonality with winter (December, January & February) increases predicted for regions such as tropical Africa and some mid latitude areas in Asia and North America. Summer (June, July & August) increases are predicted for areas such as Saharan Africa and South Asia. Winter decreases are expected in Australia and South Africa.
- It is expected that for areas that receive an increase in mean precipitation then inter-annual variability will also increase.
- It has been suggested that atmospheric pollution in the form of sulphate aerosols produced mainly by Europe and the US may have reduced temperatures at northern latitudes and as a result shifted the tropical rain belt further south. This process may have contributed to the reduced rainfall and consequent droughts experienced by the Sahel region of Africa since the 1960s (CSIRO, 2002).

Sea level rise

- Figure 1.3 shows predictions for average global sea level rise between 1990 and 2100. The area with dark shading shows the average of 7 climate models and 35 SRES scenarios while the area with lighter shading represents the range of the predictions by the models and scenarios. The area within the outermost dark lines includes the range of all models and scenarios as well as uncertainty over inland ice, permafrost, and sediment deposition changes. Changes relating to the West Antarctic ice sheet are not included.

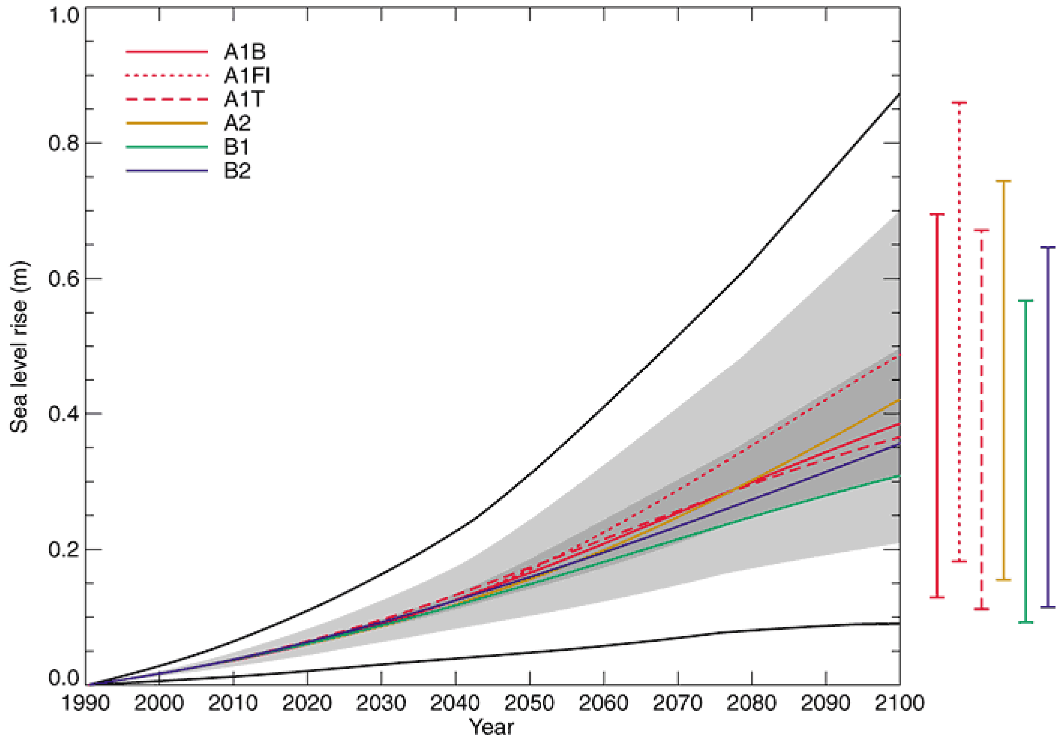


Figure 1.3 Predicted global average sea level rise from 1990 to 2100 using mean values from 7 GCM's (source: IPCC, 2001a).

- The main factors contributing to the increase in sea level predicted in figure 1.3 are:
  - Thermal expansion of sea water: 0.11 to 0.43m with an accelerating rate expected throughout the 21st century.
  - Glacial contributions: 0.01 to 0.23m.
  - Contributions from Greenland: -0.02 to 0.09m.
  - Contributions from Antarctica: -0.17 to 0.02m.
- The 2001 IPCC assessment report suggests extreme sea level rise due to the melting of the west Antarctic or Greenland ice sheet are considered very unlikely during the 21st century. Current ice dynamic models predict a maximum contribution of 3mm per year from the west Antarctic ice sheet. If the scenarios predicting higher stabilisation temperatures are used then nearly complete melting of the Greenland ice sheet could occur over the next millennium with a contribution to sea level rise of about 6 metres. The east Antarctic ice sheet is considered more stable with its total disintegration requiring warming far greater than anything predicted by current models. Recent data from the Pine Island and Thwaites glaciers suggests that the Antarctic may be making a greater contribution to sea level rise than was previously thought although it is currently unclear if this is the result of recent or ancient climate change, or part of a short term variation (BAS, 2005a; 2005b).
- Regional variation in actual sea level rise is predicted although agreement between models is generally poor.
- Consideration of relative sea level rise, the sum of actual sea level rise and changes in land elevation due to isostatic and tectonic processes, may be relevant to some areas.
- The effect of weather on extreme high water levels may become more pronounced if severity or frequency of storms increases. The combined effect of a mean increase in sea level with potential storm surge events also needs consideration.

Extreme events

Changes in the frequency, intensity and location of extreme climatic events can be predicted with more certainty for some variables than others. For example, in the case of tropical cyclones which are highly significant to aquaculture in areas such as Asia, there is currently little agreement between models regarding predicted areas of formation and frequency, although there is some indication that peak intensities could increase. Table 1.1 shows potential changes in extreme climate phenomena along with confidence in observations and predictions relating to these changes.

Table 1.1 The likelihood of changes in the frequency or severity of extreme events in relation to climate change. Produced by a combination of observational and modelling studies as well as a consensus of expert opinion (adapted from IPCC, 2001a).

Confidence in observed changes (latter half of the 20th century)	Changes in Phenomenon	Confidence in projected changes (during the 21st century)
Likely[a]	Higher maximum temperatures and more hot days over nearly all land areas	Very likely[a]
Very likely[a]	Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely[a]
Very likely[a]	Reduced diurnal temperature range over most land areas	Very likely[a]
Likely[a], over many areas	Increase of heat index over land areas	Very likely[a], over most areas
Likely[a], over many Northern Hemisphere mid- to high latitude land areas	More intense precipitation events[b]	Very likely[a], over many areas
Likely[a], in a few areas	Increased summer continental drying and associated risk of drought	Likely[a], over most mid-latitude continental interiors (Lack of consistent projections in other areas)
Not observed in the few analyses available	Increase in tropical cyclone peak wind intensities[*c]	Likely[a], over some areas

a. Likely = 66 – 90% chance, Very likely = 90 – 99% chance (consensus or expert opinion from IPCC working group 1).
b. For other areas there are either insufficient data or conflicting analyses.
c. Past and future changes in tropical cyclone location and frequency are uncertain.

Climate variability

- Variability in Asian monsoon precipitation is considered likely to increase.
- An El-Niño type response is predicted by many models for the tropical areas of the Pacific. Sea surface temperatures are predicted to increase more in the eastern and central equatorial areas than in the west which will create an eastward shift in mean precipitation.
- There has been considerable study of long-term observed changes in the El Niño Southern Oscillation (ENSO) during the 20th century (see for example Trenberth and Hoar, 1996 and subsequent discussion, e.g. Wunsch, 1999). Some argue for real changes in ENSO frequency and severity while others argue that changes are just part

of natural variability. Climate models are limited in their ability to simulate ENSO events but suggest little change or a small increase in amplitude. Even if the amplitude of ENSO events doesn't increase, the associated droughts and floods may become more severe in association with global warming. Figure 1.4 shows general warm episode (El Niño) impacts, while figure 1.5 shows impacts during the cold phase (La Niña).

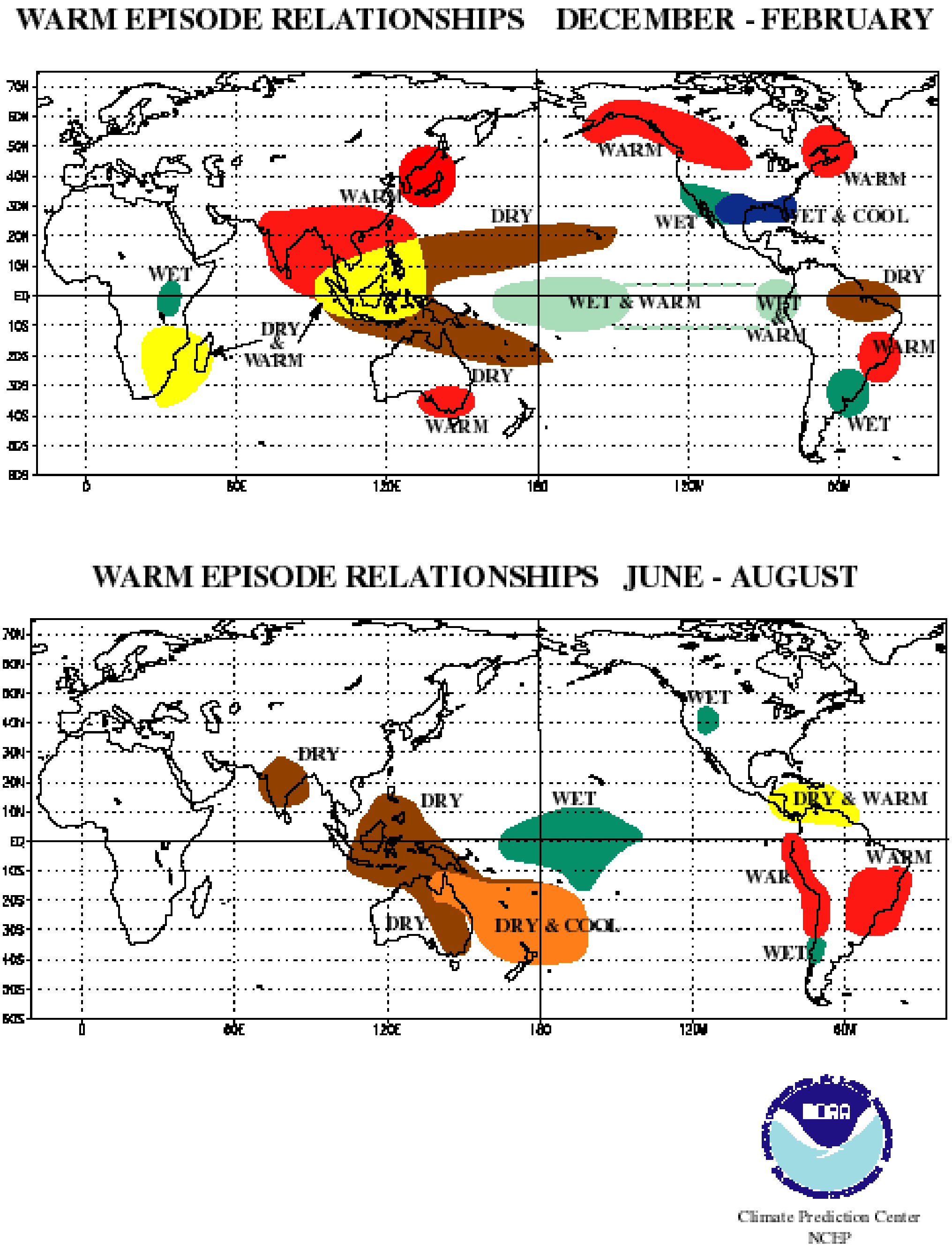


Figure 1.4 Climate impacts seen in relation to ENSO warm episodes (El Niño). Source: NOAA (2005).

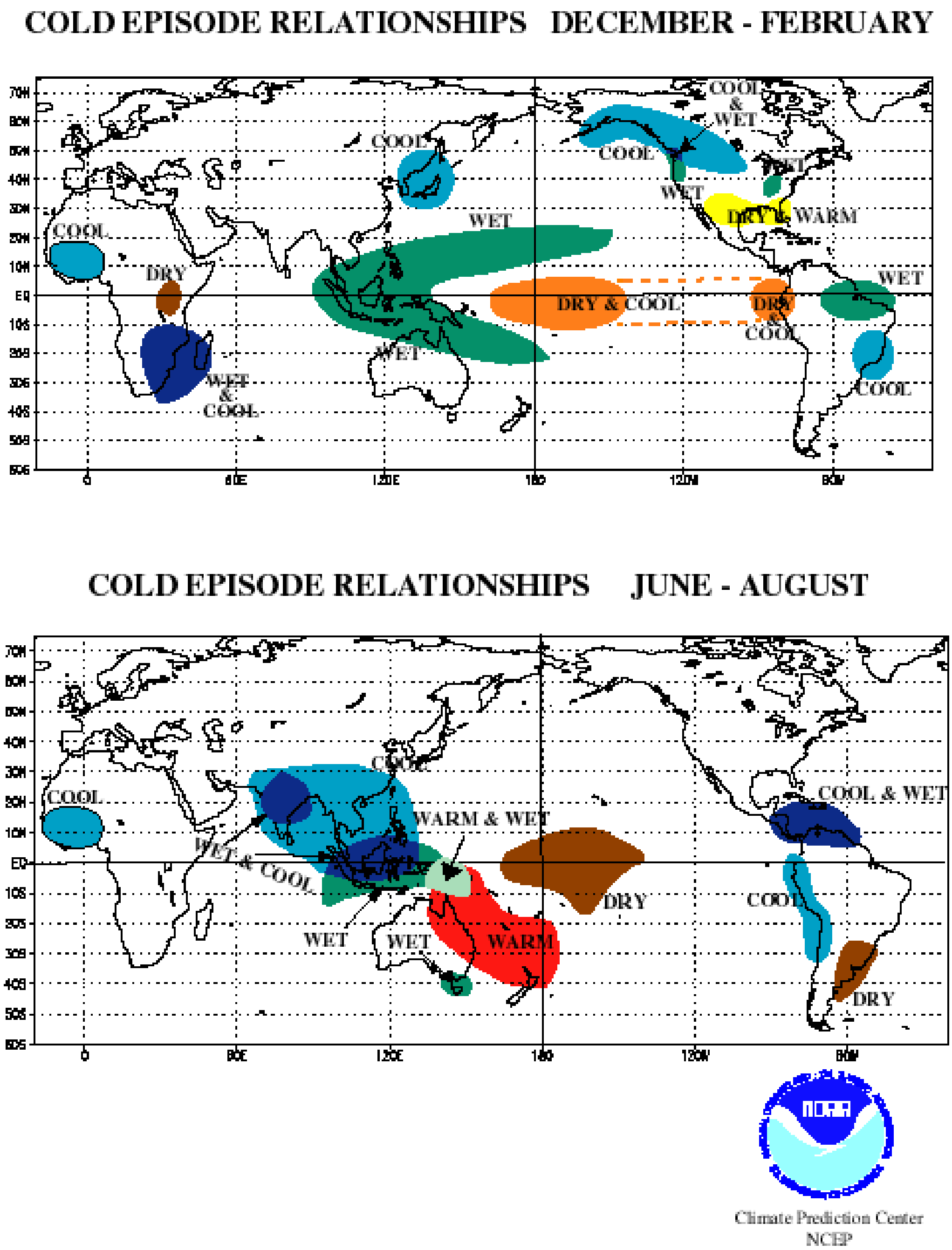


Figure 1.5 Climate impacts seen in relation to ENSO cold episodes (La Niña). Source: NOAA (2005).

Ocean currents and circulation

- Most current climate models indicate a weakening of the thermohaline circulation (THC) in the northern hemisphere. It is considered too early to say with much confidence if a complete collapse is likely and what the thresholds for this may be, but a shut down may be possible if radiative forcings change fast enough and are applied for long enough.
- A complete shutdown of the THC would have severe consequences in terms of the global heat budget, climatic changes and marine nutrient distribution. None of the

current models predict this complete shutdown during the 21st century although a reduction in THC may make it less resistant to future perturbations.

All these climate changes related to global warming may impact on aquaculture operations and production systems through a range of processes. Before identifying these pathways and impacts, the aquaculture sector and its recent development is reviewed.

An overview of global aquaculture

Box 1.2 Notes on the availability of production data

The Food and Agriculture Organisation of the United Nations (FAO) is currently the most complete source of data for aquaculture and fisheries production statistics at the global level.

The FAO defines aquaculture for the purposes of data collection as the ”farming of aquatic organisms, that is some form of intervention is implied in the rearing process to enhance production, (such as regular stocking, feeding, protection from predators), plus individual or corporate ownership of the stock is implied” (FAO, 2005).

FAO statistics and the associated windows database utility Fishstat Plus (version 2.3) was used extensively during the current project.

When considering production figures used in the following sections in relation to the aquaculture industry it is worth bearing in mind that the quality, and frequency, of record keeping and reporting may well vary between countries. Yields from fisheries are typically underreported, this is especially likely to be the case with subsistence fisheries. Some estimates suggest actual yield may be around twice that of reported figures (Kapetsky, 2000).

Production systems and trends

The global aquaculture industry continues to grow and gain an increasing share of total fish production, producing 29.9 percent, by weight, of fish, crustaceans and molluscs in 2002 compared with 3.9 percent in 1970 (FAO, 2004a). The average rate of growth for aquaculture since 1970 is 8.9 percent per year compared with 1.2 percent for capture fisheries (FAO, 2004a). Table 1.2 shows aquaculture production in 2000 and 2002 along with annual growth rates for the top ten producing countries in terms of production weight as well as the ten countries that experienced the fastest growth in the industry during the same period. The table also helps indicate the significance of Asia in terms of aquaculture production with China producing 69.7 percent of the world’s aquaculture products (excluding aquatic plants) in 2002 (FAO, 2004a).

Table 1.2 Production quantities (thousands of tonnes) and annual growth rate of production for the worlds 10 largest producers. Adapted from (FAO, 2004a)

Producer	2000	2002	APR (percent)
China	24580.7	27767.3	6.3
India	1942.2	2191.7	6.2
Indonesia	788.5	914.1	7.7
Japan	762.8	828.4	4.2
Bangladesh	657.1	786.6	9.4
Thailand	738.2	644.9	-6.5
Norway	491.2	553.9	6.2
Chile	391.6	545.7	18.0
Vietnam	510.6	518.5	0.8
United States	456.0	497.3	4.4
Top ten sub total	31318.8	35248.4	6.1
Rest of the world	4177.5	4550.2	4.4
Total	**35496.3**	**39834.6**	**5.9**

The type of species cultured, the conditions in which they live, and resources they require may be highly significant in relation to climate change. For example; culture of carnivorous species is likely to be influenced by the availability of fishmeal and fish oil while species cultured in coastal areas may be most at risk from storms and species cultured inland may be more prone to impacts of drought and flood events.

Table 1.3 shows the average rate of growth for different sectors of aquaculture in terms of species groups. In assessing vulnerability, the divisions of fresh, brackish, and marine culture are used as an indication of the type of aquaculture being conducted. It is also considered that to some extent these divisions may help indicate location (e.g. inland, coastal areas, or marine), and the relative value of the products produced. The percentage of production from fresh, brackish and marine culture is shown in Figure 1.6 for the top ten aquaculture producing countries in terms of quantity, while Figure 1.7 shows production value. The graphs demonstrate differences between different types of aquaculture with brackish and marine culture products generally having a higher per unit value. Figures 1.6 and 1.7 are based on total production but if aquatic plants and seaweeds were omitted then the differences would probably be more pronounced. Shrimp and carnivorous fish species are good examples of high value products from brackish and marine environments while tilapias and carps are common lower value species often associated with inland pond culture.

Table 1.3 Average rate of growth for different species groups within the aquaculture industry. Adapted from (FAO, 2004a)

Time period	Crustaceans	Molluscs	Freshwater fish	Diadromous fish	Marine fish	Overall
1970 – 2002	18.1	7.8	9.6	7.4	10.5	8.9
1970 – 1980	23.9	5.6	6.0	6.5	14.1	6.3
1980 – 1990	24.1	7.0	13.1	9.4	5.3	10.8
1990 – 2000	9.9	5.3	7.8	7.9	12.3	10.5
2000 – 2002	11.0	4.6	5.8	6.7	9.5	5.9

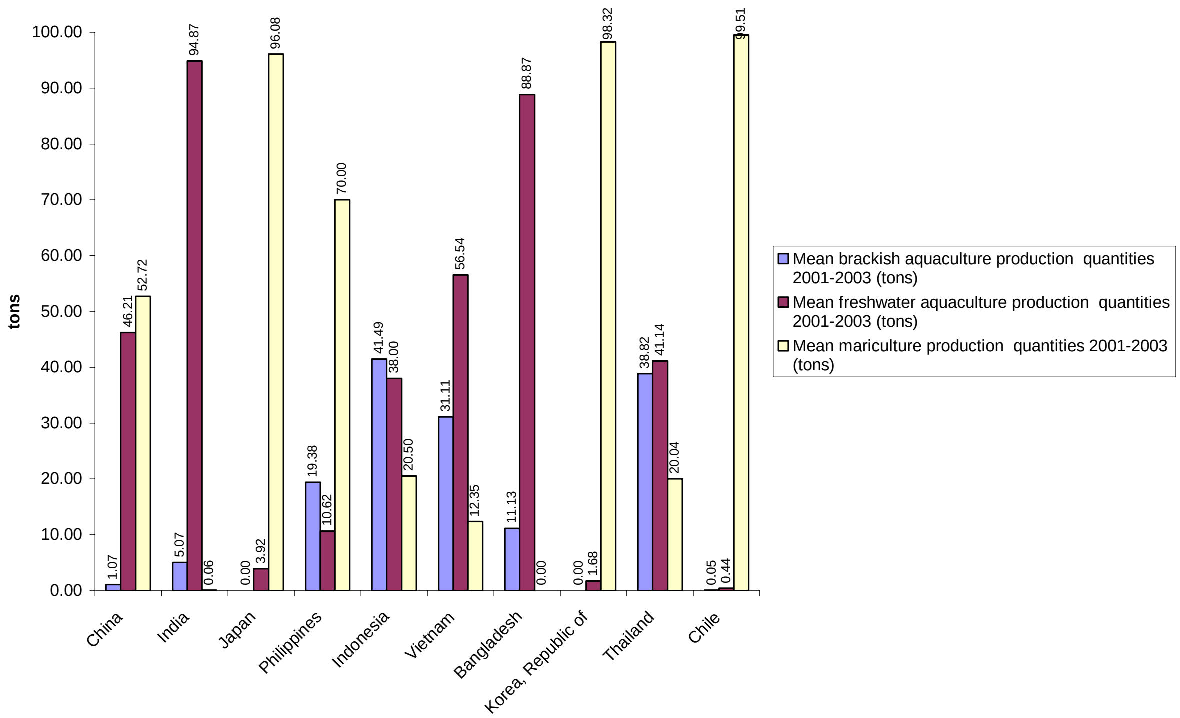


Figure 1.6 Mean production quantities (tons) for years 2001 to 2003 from freshwater, brackish, and marine aquaculture systems, shown as a percentage of the mean of a countries total aquaculture production for the same period.

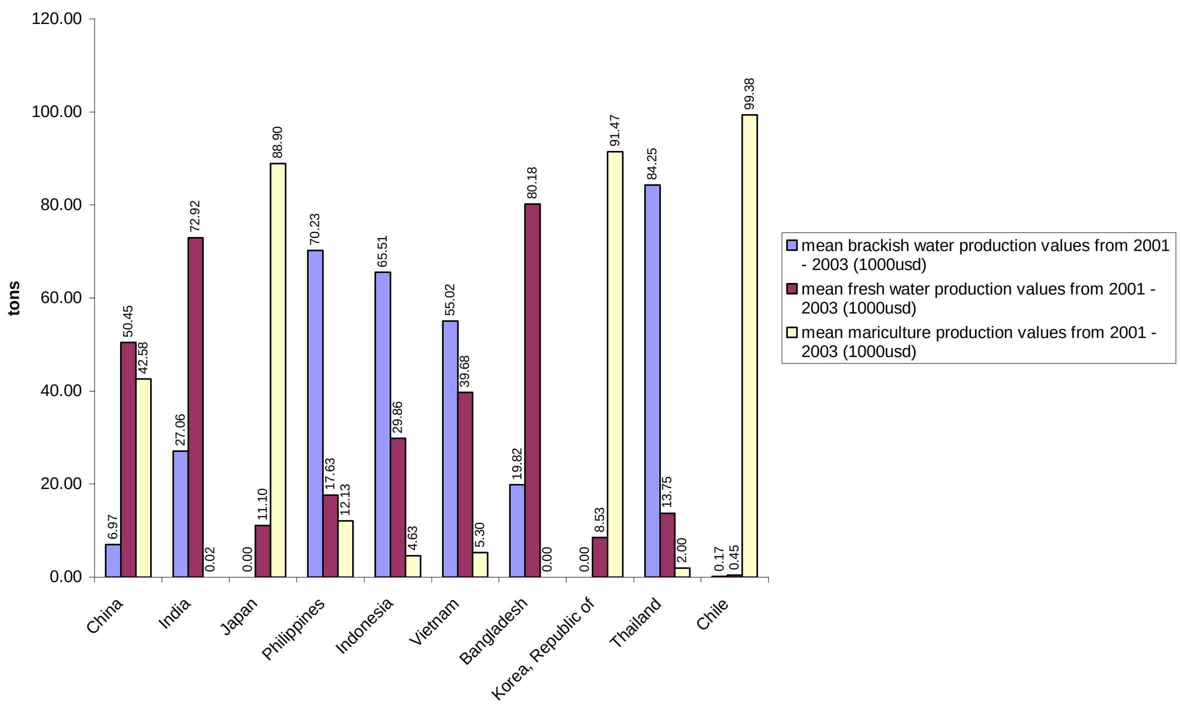


Figure 1.7 Mean value of aquaculture products from years 2001 to 2003 from freshwater, brackish and marine systems, shown as a percentage of the mean value of a countries total aquaculture production for the same period.

Overview of the significance of the aquaculture industry to livelihoods

Aquaculture systems range from small low intensity operations such as small family-owned ponds that require little in the way of inputs and which supply supplementary protein to a few individuals, to large-scale high-intensity systems such as shrimp and marine fish cage farms that are dependant on, and support a number of other industries.

Currently, complete data indicating the number or people employed in aquaculture world wide is unavailable (FAO, 2004a). Statistics that are available suggest an increase of around 8 percent per year since 1990 although some of that increase may be due to improved reporting. Table 1.4 shows the estimated number of people employed within the aquaculture sector at the continental level. Asia's aquaculture sector is highly significant with an indicated 9,502,000 people employed in 2002. China and Indonesia make up 3,960696 and 2,270,164 of this figure respectively. Figures for much of the world suggest a levelling off in the number of aquaculture employees since the year 2000 with this typically being the case in many developed countries (FAO, 2004a).

Table 1.4 Number of fish farmers by continent (x 1000). Adapted from (FAO,2004a)

Region	1990	1995	2000	2001	2002
Africa	No data	105	112	115	111
North and Central America	53	74	74	69	65
South America	19	88	92	92	93
Asia	3698	6003	8503	8720	9502
Europe	11	36	37	39	39
Oceania	negligible	1	5	5	5
World	3778	6307	8823	9040	9815

It is difficult to estimate the economic and social importance of aquaculture in countries where it plays a smaller role in the economy as there is a reduced emphasis on record keeping and reporting. This does not necessarily mean aquaculture is unimportant. It may play a significant role in certain areas and communities and in many developing countries the contribution to food security and rural economies may be substantial (FAO, 2004a). In the case of capture fisheries it is well known that estimates of the number of fisherfolk typically do not include those who fish seasonally or as a supplement to a more diverse livelihood. It seems likely that a similar situation may apply to aquaculture, especially in the case of inland aquaculture, where fish are integrated within farming systems, and people are likely to identify themselves as agriculturalists in censuses and socio-economic surveys. For marine aquaculture, the extent of under-estimation may be less due to the investment of resources needed and the identifiably different nature of the occupation from either farming the land or fishing in the sea. With the above information in mind the estimated figures may well represent a lower threshold.

As well as direct involvement in the primary production of aquaculture products a number of people will be dependant on industries that to a greater or lesser extent will be linked to aquaculture such as building of facilities, transportation, ice making, feed production and marketing. As demand for fish continues to increase in relation to supply in many areas fish is becoming a 'cash crop' with higher value species being sold to provide money that is then used to obtain more affordable food items (Sugiyama *et al.*, 2004).

For some counties aquaculture is a significant contributor to the national economy (Figure 1.8). At the sub national level aquaculture will generally be of far greater importance to certain regions and communities than others. Understanding where and why aquaculture is significant at the local level and giving consideration to issues such as food security compared with economic gain is likely to be of key importance in assessing livelihood vulnerability in relation to particular climate change impacts (see sections; *Impacts on aquaculture production* and *Impacts on aquaculture dependant livelihoods*).

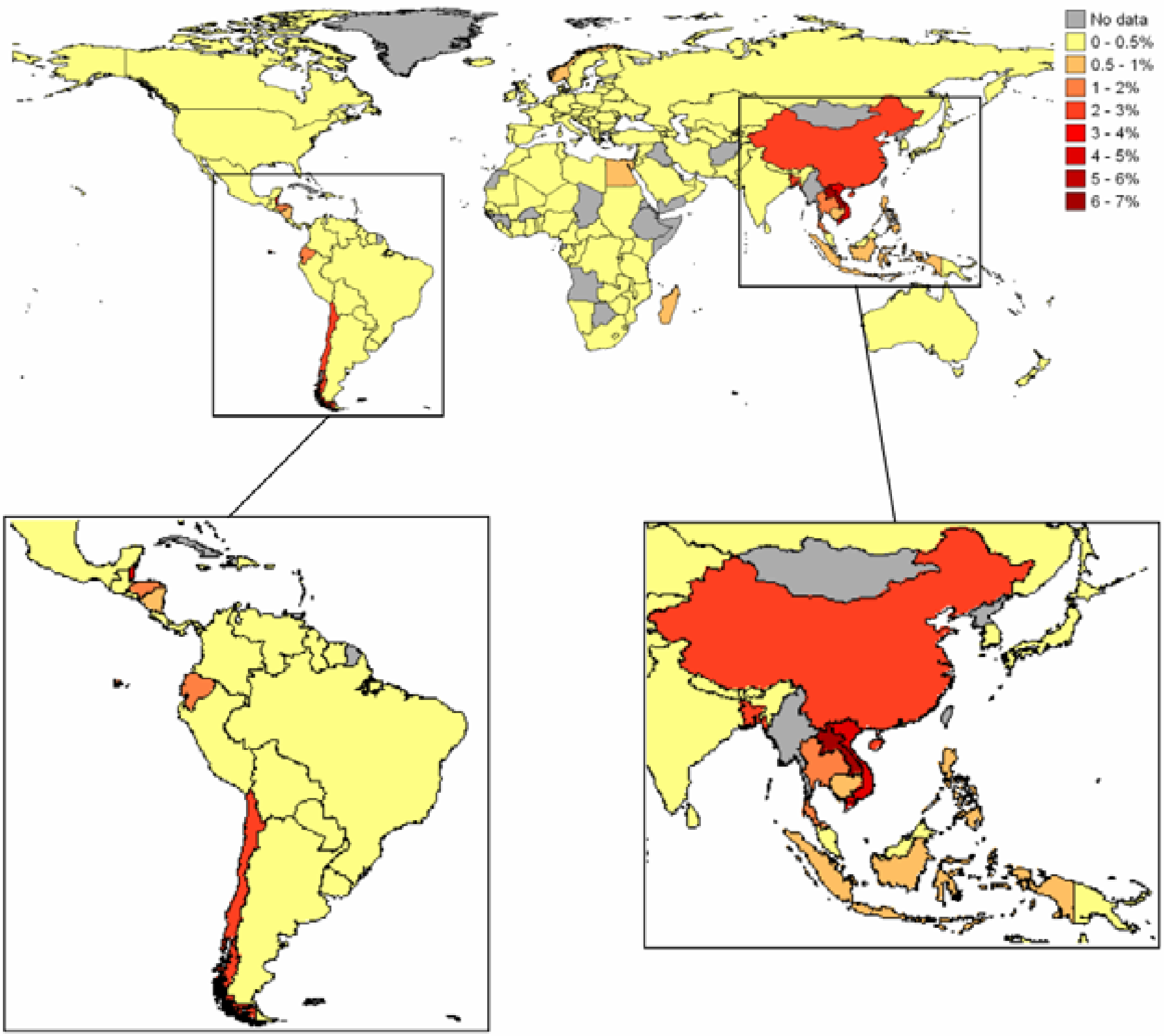


Figure 1.8 Aquacultures contribution to national economies as a percentage of GDP.

Aquaculture in the coming decades

Demand for fish products is predominantly dictated by price, demography, living standards and urbanization (Brugère & Ridler, 2004). In many areas human population and in some cases living standards are increasing resulting in an increased demand for fish, while in some developed countries fish consumption may be near saturation (Delgado *et al.*, 2003). The real price of aquaculture products will be influenced by production costs while relative price in relation to alternate products will also influence demand. The fate of capture fisheries as a supplier of fishmeal and fish oil for aquaculture feeds, and as an influence on availability and hence price of fisheries products may be a significant mechanism for climate related impact (see section on *indirect impacts* page 40).

Table 1.5 shows the results of a number of studies predicting future global demand for fish. It is worth noting that the Ye and Wijkström models are based only on demand and do not include real or relative price. The International Food Policy Research Institute (IFPRI) model does include prices and predicts an increase in both real and relative prices. An increase in the real price of fish will reduce demand with price elasticity estimated at -0.8 to -1.5. Increased relative prices are also predicted to reduce demand with substitutions being made for foods such as poultry (Delgado *et al*., 2003). Brugère & Ridler (2004) suggest that with a supply elasticity coefficient greater than that for capture fisheries, an increase in the real price of fish may provide aquaculture with an incentive.

Table 1.5 Projected demand for food fish (source: Brugère & Ridler, 2004)

Forecasts and forecast dates	**Price assumption**	**Global cons. per capita(kg/year) by forecasted date**	**Food fish demand(million tons) by forecasted date**	**Calculated quantities required from aquaculture by the forecast date[4]**				
				Growing fisheries		**Stagnating fisheries**		
				Total output (million tons)	**Growth rate (percent)**	**Total output[5] (million tons)**	**Growth rate (percent)**	**Average annual increase (million tons)**
IFPRI (2020)	Real and relative prices are flexible							
Baseline		17.1	130	53.6[3]	1.8	68.6	3.5	1.7
Lowest[1]		14.2	108	41.2	0.4	46.6	1.4	0.6
Highest[2]		19.0	145	69.5[3]	3.2	83.6	4.6	2.4
Wijkström (2010) (2050)								
	Constant	17.8	121.1	51.1[3]	3.4	59.7	5.3	2.4
	Constant	30.4	270.9	177.9[3]	3.2	209.5	3.6	3.5
Ye (2030)	Constant	15.6	126.5	45.5[3]	0.6	65.1	2.0	1.0
	Constant	22.5	183.0	102.0[3]	3.5	121.6	4.2	2.9

[1] Assumes an "ecological collapse" of capture fisheries.
[2] Assumes technological advances in aquaculture.
[3] Assumes a growth of output of food fish from capture fisheries of 0.7 percent per year to the forecast date.
[4] From 2000; (35.6 million tonnes, three-year average of aquaculture output).
[5] Assumes zero growth in food fish from capture fisheries after 2001. *Sources*: Calculated from Delgado *et al.*, 2003 (hereafter referred to as "IFPRI" - International Food Policy Research Institute); Wijkström, 2003; Ye, 1999.

Brugère & Ridler (2004) suggest that the output from aquaculture will have to continue increasing in order to meet fish consumption demands, especially considering most capture fisheries are probably operating near, or at their limit (Delgado *et al*., 2003). If the predicted requirements for fish shown in Table 1.5 are compared with historic growth rates for aquaculture, then meeting these requirements seems possible with the required highest annual growth rate of 5.3% being lower than that achieved by aquaculture since 1970. However, there are indications that the growth rate of aquaculture is starting to slow down as outlined in Table 1.3. Based on current trends, and using published figures for production, much of aquaculture's potential to meet future requirements will depend on China being able to maintain the increase in aquaculture seen during the 1990s (Brugère & Ridler, 2004). However there are doubts over the accuracy of China's statistics and it is suggested that production of aquatic products may be substantially overestimated (Lu 1998; Delgado *et al*., 2003). If China has over-reported then average global production will be lower than claimed and the outlook in terms of meeting global requirements is less favourable (Delgado, 2003).

It seems likely that economic pressures will lead to the gradual intensification of aquaculture at the global scale (Delgado *et al*., 2003; NACA/FAO, 2001). Different aquaculture systems operating at different intensities will be vulnerable to climate change in different ways. The implications of this are discussed further in the sections covering impacts on aquaculture dependant livelihoods, indirect impacts, and vulnerability assessment.

A region's plans and potential to expand and/or intensify aquaculture production will be relevant when considering vulnerability to future aquaculture related climate change impacts. Brugère & Ridler (2004) analysed aquaculture strategies, plans and other relevant information from major aquaculture producing areas as part of an investigation as to whether regional production targets could be met. Their results are summarised in Box 1.3. Areas predicted to have, or anticipating a large growth in their aquaculture industry may be worthy of special attention in relation to how climate change may affect this expansion.

Box 1.3 Regional aquaculture development.

Africa

- No quantified production targets except the non-governmental sources in Egypt.
- Average fish consumption is fairly low at 8 kg per person per year, and the IFPRI predict that this will fall still further by 2020 except under the most favourable scenario whereby aquaculture production increases considerably. This low per capita consumption indicates low overall animal protein consumption due to poverty, rather than lack of importance of fish in the diet – fish contributes a higher proportion of animal protein to the diet than the global average (FAO, 2006)
- Aquaculture has been seen by many countries as a valuable means of providing food security and has been given a high priority in fisheries policy and development agendas.
- So far Egypt stands out as Africa's most successful aquaculture-producing country with a annual growth rate of 17.3% from 1990 to 2000. This rate appears to have slowed recently, to 10% from 2001 to 2002.
- Export of aquaculture products to Europe has been seen by many countries as an important source of income, with tilapia currently being exported from Zimbabwe. Egypt's plans to export large amounts of sea bass and bream have met problems due to failure to conform to hygiene regulations.
- Aquaculture in Madagascar had a very high annual growth rate between 1992 and 2001 of 19% largely due to increases in shrimp farming after foreign investment.
- A lot of problems with aquaculture development in Africa are associated with poor governance. Many input costs are high including the cost of credit which constrains the development of aquaculture in many situations. Aquaculture needs to be commercially orientated in Africa if it is to expand at the forecasted rate.

Asia

- China, Bangladesh, India, Indonesia, the Philippines, Thailand and Vietnam have projections for aquaculture growth (table 1.6). These countries are also in the top 12 in terms of world production

Table 1.6 Forecasted and historical aquaculture production in Asia excluding aquatic plants (Adapted from FAO, 2004b).

	2000 output (tonnes)	Actual growth rates (percent)		Forecast growth rates (percent)
		1980 - 1990	1990 - 2000	
China	24473553	17.1	33.8	3.7 [2000 - 2010]
Bangladesh	654745	7.9	12.8	4.1 [2001 - 2010]; 3.5 [2001-2020]
India	2093216	11.4	6.8	8.2 [2000 - 2005]; 8.5 [2001 - 2010]
Indonesia	800682	9.9	5.1	11.1 [2003 - 2009]
Philippines	393695	6.3	0.3	13.4 [2001 - 2004]
Thailand	71651	10.2	9.0	1.8 [1996 - 2010]
Vietnam	498774	11.8	8.5	10.0 [2001 – 2010]

- Aquaculture in China has increased rapidly and now account to 60% of the global market.
- Although according to current growth rates China should be able to meet the requirements of the IFPRI baseline scenario by 2020 it does have some constraints on aquaculture growth such environmental concerns in coastal areas.
- India, the world's second-largest aquaculture producer, and therefore crucial when considering global aquaculture projections, has optimistic projections for the expansion of aquaculture. Projections by the government-sponsored Indian Council of agricultural research suggests that only 1/5 of available coastal land for shrimp farming is currently being used. Areas such as West Bengal look like they have a lot of land available. There are also inland brackish water areas that could be used farming shrimp or tilapia.
- A large and fast-growing domestic market in India is creating demand.
- Bangladesh predicts future aquaculture production based mainly on supply factors. Aquaculture expansion is predicted to come from both increasing per unit area yields as well as expanding the actual area used. The accuracy of previous predictions are evaluated and although historically Bangladesh has overestimated production the accuracy has been improving. Recent data suggests current targets may be met.
- Indonesia sees the aquaculture sector is an area of economic growth and potential for export earnings. It has a very ambitious plan where aquaculture is doubled between 2003 and 2009, reaching 2.3 million tons. Export earnings are predicted to increase nine-fold by 2009 earning Indonesia almost 7 billion dollars. Based on historic data the ability of Indonesia to achieve its ambitious targets seems unlikely.
- Marine culture is seen as the area with the greatest potential for expansion in Indonesia
- The Philippines planed to produce 663,000 tonnes of farmed fish by 2004. By 2002 production was only 433,000 tonnes. Data is not currently available but it seems unlikely that the target will have been met.
- Thailand had a growth rate of 2.6% between 1996 and 2002. This is higher than the forecasted 1.7% despite shrimp production being reduced by 11% between 2000 and 2002
- Vietnam has 300,000 ha of unexploited water and sees aquaculture is a source of food security and foreign exchange. The period 2000 to 2002 saw very little growth and meeting the target of 2 million tonnes by 2010 may prove difficult.

South and Central America and the Caribbean

- Brazil and Chile are the main aquaculture producing countries in South America accounting for 70% of output.
- Both Chile and Brazil have plans to promote aquaculture and has been demonstrated in China this can be important.
- Annual growth in aquaculture in Latin America is significantly above the global average and very

diverse with over 80 species being cultured

- Latin American and the Caribbean are currently considered to have great aquaculture potential because of the very favourable climate. This is a point worth bearing in mind in relation to climate change.
- Countries with large populations such as Brazil and Mexico are likely to be able to support a significant domestic market. Some smaller countries such as Costa Rica are close to the US and have good trade agreements allowing for potential export markets.
- An examination of the plans for aquaculture development in Brazil and Chile suggest that that IFPRI predictions may be underestimates.

Europe

- Historical data suggest aquaculture growth in Europe is slower than in the rest of the world, and some countries have actually seen a decline in aquaculture in recent years, notably Denmark which produced 23% less in 2001 compared with 2000.
- Salmon and trout account to 80% of European aquaculture output with Norway being the largest producer of Atlantic salmon both within Europe and globally.
- Growth in Southern Europe/Mediterranean???
- Salmon production appears to be growing steadily in Norway (FAO, 2005).
- In southern European countries such as Greece and Spain production of Marine fin fish, especially sea bass and bream increased considerably during the 90's but growth appears to have levelled off in recent years (FAO, 2005).
- Aquaculture in inland Eastern European countries is typically dominated by carp, and here again production seems to be steady during recent years (FAO, 2005).

Impacts of climate change on aquaculture production systems: a review

The impact of climate change on aquaculture production in socio-economic terms is difficult to assess due to uncertainty regarding the extent and rate of predicted changes as well as in some cases a limited knowledge of the possible biophysical impacts on farmed systems. There appears to be a limited amount of research on the possible impacts of climate variables on aquaculture, possibly because the climate change issue has not really been considered a priority by the industry. Nevertheless, understanding the mechanisms through which climate change may influence aquaculture production systems is essential for the appropriate design of policies and management strategies in the aquaculture sector, particularly when the future of the fisheries sector is conceived largely in terms of increasing support for aquaculture development.

Climate change impacts may be significant at a number of different scales ranging from global down to the local community level. By combining national or global level indicators with case studies at the district or local community level it may be possible to highlight and better understand a broader range of impacts (O'Brien *et al.*, 2004). For example, while a large area may be exposed to the risk of flooding or drought, the adaptive capacity of different communities within that area may vary greatly. Another example would be a situation where the local effects of reduced production as a result of climate change are compounded by reduction in the price of the product, or increases in the price of inputs such as feed, as a result of changing national or international policy and world markets.

Arnason (2003) suggests that climate change impacts on fisheries may be viewed in at least two different ways: as altering the availability of fish to fishermen (direct impact) and as changing the price and availability of fish products and fisheries inputs (indirect impact). Here a similar distinction is made for aquaculture with direct and indirect impacts being discussed separately in order to try to bring more clarity to the pathways involved although it is acknowledged that it is an interaction of both these components through multiple pathways that ultimately determines livelihood vulnerability to climate change. Climate change will impact across a wide range of sectors and is likely to have synergistic effects with a number of socioeconomic or environmental stresses (IPCC, 2001b; O'Brien *et al.*, 2004). Additionally, the interaction between different systems and the potential for processes in one system to directly or indirectly affect those in another should be considered. (Brooks, 2003). This concept is investigated in the current study by considering how changes in capture fisheries production systems might indirectly impact on aquaculture.

While aquaculture has been assuming increasing importance during the last twenty years in terms of food production and food security, and research on the impacts of climate change has been increasing, little research has been undertaken to link the two. A combination of peer-reviewed-papers and general media articles were reviewed, as well as grey literature from national governments and international organisations. Some studies were observational and qualitative in nature, looking at past and current climate variability (often used as a proxy for climate change) effects on the aquaculture sector, while a few looked at future climate change scenarios and predicted impacts for the aquaculture industry. It is worth noting that number of peer-reviewed papers focusing on the issue is limited, highlighting a research gap.

Impacts on aquaculture production

Drivers of climate related change in aquaculture production systems can largely be grouped as: changes in air and inland water temperatures, changes in solar radiation, changes in sea surface temperature, changes in other oceanographic variables (currents, wind velocity and wave action etc.), sea level rise, increase in frequency or intensity of extreme events, and water stress. These changes will in turn create physiological (growth, development, reproduction, disease), ecological (organic and inorganic cycles, predation, ecosystem services) and operational (species selection, site selection, sea cage technology etc.) changes.

The difference between gradual mean changes in climate variables as opposed to extreme events (shocks and trends), as well as the type, scale and intensity of the culture system are all considered here as important general concepts when considering climate impacts. The potential impact pathways of climate change on aquaculture are summarised in Table 1.7.

Table 1.7 Impacts of climate change on aquaculture systems and production

Drivers of change	Impacts on culture systems	Operational impacts
Sea surface temperature changes	• Increase in harmful algal blooms that release toxins in the water and produce fish kills • Decreased dissolved oxygen • Increased incidents of disease and parasites • Enhanced growing seasons • Change in the location and/or size of the suitable range for a given species • Lower natural winter mortality • Enhanced growth rates and feed conversions (metabolic rate) • Enhanced primary productivity (phostosynthetic activity) to benefit production of filter-feeders • Altered local ecosystems - competitors and predators • Competition, parasitism and predation from exotic and invasive species	• Changes in infrastructure and operation costs • Increased infestation of fouling organisms, pests, nuisance species and/or predators • Expanded geographic distribution and range of aquatic species for culture • Changes in production levels
	• Damage to coral reefs that may have helped protect shore from wave action – may combine with sea level rise to further increase exposure	• Increased chance of damage to infrastructure from waves or flooding of inland coastal areas due to storm surges
Change in other oceanographic variables (variations in wind velocity, currents and wave action)	• Decreased flushing rate that can affect food availability to shellfish • Alternations in water exchanges and waste dispersal • Change in abundance and/or range of capture fishery species used in the production of fishmeal and fish oil	• Accumulation of waste under pens • Increased operational costs
Seal level rise	• Loss of areas available for aquaculture • Loss of areas such as mangroves that may provide protection from waves/surges and act as nursery areas that supply aquaculture seed • Sea level rise combined with storm surges may create more severe flooding. • Salt intrusion into ground water	• Damage to infrastructure • Changes in aquaculture zoning • Competition for space with ecosystems providing costal defence services (i.e. mangroves) • Increased insurance costs • Reduced freshwater availability
Increase in frequency and/or intensity of storms	• Large waves • Storm surges	• Loss of stock • Damage to facilities

	• Flooding from intense precipitation • Structural damage • Salinity changes • Introduction of disease or predators during flood episodes	• Higher capital costs, need to design cages moorings, jetties etc. that can withstand events • Negative effect on pond walls and defences • Increased insurance costs
Higher inland water temperatures (Possible causes: changes in air temperature, intensity of solar radiation and wind speed	• Reduced water quality especially in terms of dissolved oxygen • Increased incidents of disease and parasites • Enhanced primary productivity may benefit production • Change in the location and/or size of the suitable range for a given species • Increased metabolic rate leading to increased feeding rate, improved food conversion ratio and growth provided water quality and dissolved oxygen levels are adequate otherwise feeding and growth performance may be reduced	• Changes in level of production • Changes in operating costs • Increase in capital costs e.g. aeration, deeper ponds • Change of culture species
Floods due to changes in precipitation (intensity, frequency, seasonality, variability)	• Salinity changes • Introduction of disease or predators • Structural damage • Escape of stock	• Loss of stock • Damage to facilities • Higher capital costs involved in engineering flood resistance • Higher insurance costs
Drought (as an extreme event (shock), as opposed to a gradual reduction in water availability)	• Salinity changes • Reduced water quality • Limited water volume	• Loss of stock • Loss of opportunity – limited production (probably hard to insure against)
Water stress (as a gradual reduction in water availability (trend) due to increasing evaporation rates and decreasing rainfall)	• Decrease water quality leading to increased diseases • Reduce pond levels • Altered and reduced freshwater supplies – greater risk of impact by drought if operating close to the limit in terms of water supply	• Costs of maintaining pond levels artificially • Conflict with other water user • Loss of stock • Reduced production capacity • Increased per unit production costs • Change of culture species

Temperature changes will have an impact on the suitability of species for a given location. There are also likely to be influences on other factors such as oxygen levels, toxic algae blooms and the prevalence of pests, diseases and predators (2WE Associates Consulting LTD, 2000). In temperate areas increasing temperatures could bring the advantages of faster growth rates and longer growing seasons. McCauley and Beitinger (1992) predict that for every 1^{o}C rise in temperature the optimum range for the culture of channel catfish will shift approximately 240km north. Channel catfish provide a good illustration of some of the costs and benefits of higher temperatures. Growth rate and hence per unit area production will increased with increased average water temperature, but above 30^{o}C feeding is reduced and growth slows (McCauley and Beitinger, 1992), a situation that may bring increased yields to farmers in cooler areas while those in warmer areas may lose out.

If temperature rise causes increases in metabolic rates of fish greater than increases in food supply then there will be a negative impact on growth performance. This has been demonstrated in natural systems such as lake Toolik, Alaska, where primary productivity has not been observed to increase with increased temperature while bioenergetic modelling involving the lakes resident trout species predicts reduced first winter survival rates if current productivity trends continue (McDonald *et al.,* 1996). The example of Lake Toolik concerns a natural system from a cold climate that is highly nutrient limited and thus is not easily comparable to typical aquaculture systems where warm water species are often being cultured, and with the animals being fed or ponds fertilised. For aquaculturists aiming to maximise profit the relationship between temperature, ration size, bioenergetic performance, and feed conversion ratio is an important one with different species having different ranges in which they function most efficiently. Adaptive strategies for coping with increased water temperatures may include changes in feed formulation and feeding regimes as well as substitution for alternate species.

Temperature increases predicted over land areas from climate change models are typically in the form of air temperature. Increases in mean air temperature will not necessarily equate to increases seen in the temperature of aquaculture ponds. The main climatic factors influencing water temperature in an inland environment are solar radiation, air temperature, wind speed and humidity, in combination with the size and shape of the pond, and its water conditions. Turbidity and water colour also influence the amount of solar radiation absorbed and hence water temperature. As aquaculture ponds are typically shallow and turbid, solar radiation is likely to be an important influence on temperature (Kutty, 1987). It may be that the increased water vapour levels predicted to accompany a warmer climate will reduce the amount of solar radiation reaching ponds due to increased cloud cover offsetting some of the effect of increased air temperature (IPCC, 2001a). Accurate modelling of water temperatures using climatic data is extremely difficult and modelling using predicted future data is likely to be even more so. Making the distinction between changes in mean values as opposed to variability and extremes is likely to be useful in understanding impact pathways. In terms of temperature it may be that the greatest impact comes from an increase in climate variability and the number of extreme hot days and heat waves. As for increases in average temperature trends it would seem likely that most problems involving heat will come as a result of reduced water quality, oxygen levels, increased stress and associated disease, and reduced feeding and growth performance rather than by directly exceeding the thermal tolerances of animals involved.

Increases in sea surface temperatures due to global warming and changes in ocean currents may again enable lengthened growing seasons. Primary productivity may also increase which could in turn enhance production of filter feeding organisms such as molluscs (Johannes, 2004). A decrease in sea-ice cover could broaden the area available for the cultivation of valuable marine species providing new opportunities for areas previously not suitable for such development (IPCC, 2001b). Negative impacts of elevated sea temperatures include; reduced water quality, increased risk of disease and increased risk of toxic algae blooms which may destroy stock or make it unmarketable (Mudie *et al*., 2002; Harvell *et al*., 1999). As with freshwater systems, changing temperatures would shift the optimum area for the location of certain species. The distribution and/or abundance of wild fish stocks could also be affected. This may have local, national and international effects as fisheries are reduced or moved outside the area typically fished by a country or community. The resulting effect on aquaculture due to changes in fisheries product prices or through the supply and demand of resources such as fishmeal used in aquaculture feed are discussed in the section dealing with indirect impacts.

Aquaculture will have to compete with agriculture as well as industrial and domestic users for a limited water supply which may often be supporting a growing population. The relative value of aquaculture products in relation to non fish alternatives will be significant, as will the productivity of capture fisheries (Brugère & Ridler, 2004). Water stress due to decreased precipitation and/or increased evaporation may limit aquaculture in some areas. This may take the form of increased risks associated with a reduced water supply on a continual basis, or by reducing the length of a routine growing season. Increased variation in precipitation patterns and droughts may increase the risk and costs of aquaculture in some areas as provision for these extremes has to be made.

A study of perennial drainage density as a function of precipitation in Africa suggests a non linear relationship with 2 thresholds (de Wit & Stankiewicz, 2006). Areas with annual precipitation of less then 400mm/y have virtually no perennial drainage except in mountainous regions. Between 400 and 1000mm/y perennial drainage density increases linearly with increasing precipitation. Above 1000mm/y drainage density shows a slight decrease with increased precipitation. This highlights the range of the precipitation regime under which greatest climate change impact might occur. The effects of a 10 and 20% reduction in precipitation were investigated. Areas with annual precipitation near the lower end of the regime are shown to be most affected with a 50, 30 and 17 percent decrease in drainage density for areas receiving 500, 600 and 1000mm/y precipitation respectively. In terms of aquaculture the impact on communities dependant on water from rivers and streams, especially those of high stream order, could be highly significant both in terms of direct water availability for aquaculture or through increased competition with other water uses. In the case of the African study de Wit & Stankiewicz (2006) use a number of GCM's to investigate what areas are likely to be most affected in terms of drainage density reduction. Parts of southern Africa are shown to be affected with possible consequences for the Orange river which supplies water to the otherwise very dry south west Africa. The Sahel region that stretches from Senegal to Sudan and separates the Sahara from central Africa also appears to be at significant risk.

Increased precipitation can bring its own problems in the form of flooding. Floods may damage facilities, cause stock to escape, affect salinity, and introduce predators or disease. Increase in monsoon intensity has been predicted over some Asian regions (IPCC, 2001a), while changes in the timing of the monsoon pattern and increased inter annual variability could also be significant (Mirza, 2001; 2002). In Bangladesh flooding is common during the monsoon period. Particularly severe floods, such as in 1988 and 1998, occur when the Ganges, Brahmaputra and Meghna rivers all peak simultaneously. Currently the peak monsoon period over the catchments of these rivers is normally at different times but it has been speculated that this may change resulting in more frequent simultaneous peak discharge of the three rivers and consequent flooding (Mirza, 2001; 2002; Islam & Sado, 2000).

Sea level rise will have gradual impacts due to loss of land via inundation and erosion. Areas such as mangroves and salt marshes, which act as nursery grounds supplying seed for many aquaculture species and provide some coastal protection, may be lost as they are overcome by either the speed of rising sea levels or by being unable to retreat as they are sandwiched between rising sea and developed land behind them (IPCC, 2001b). Salination of ground water may occur, especially in low lying island areas, reducing the availability of freshwater for aquaculture and other uses (IPCC, 2001b). Other climate change factors may interact with sea level rise to cause increased impacts. Sheppard *et al*. (2005) suggest that in the Seychelles damage to coral reefs due to warmer sea temperatures along with elevated sea levels will result in deeper water over the top of reefs and significantly increased coastal erosion.

Some climate models predict an increase in peak wind speed and precipitation intensity associated with tropical cyclones, although not with the same confidence as for predictions of mean temperature and precipitation increases. While there is little in the way of consistent evidence for an increase in cyclone frequency (IPCC, 2001a) there is often speculation that this may happen along with a general increase in climate variability. A combination of low atmospheric pressure and strong winds can create storm surges that inundate low lying coastal areas causing damage to aquaculture. Bangladesh, a very low lying country with a substantial aquaculture industry, typically experiences storm surges of between 3 and 6 meters, with theoretical predictions of up to 7.5m (Salam, 2000). Future predictions for Bangladesh in association with increased sea surface temperatures of 2°C and 4°C suggest maximum storm surge heights of 9.2 and 11.3 metres depending on the extent of sea level rise (Ali, 1996). The distance that storm surge water travels inland is a function of land elevation, surge intensity and a friction factor relating to the type of terrain. The impacts of storm surges may be increased due the effects of mean sea level rise and the loss of natural defences such as mangrove areas and coral reefs.

High winds and waves may damage marine structures used for the cultivation of shellfish and finfish such as cages and platforms resulting in loss of stock and damage or loss of facilities. Inundation of coastal areas is likely to be greatest over flat low lying land which is also of the type suited to the culture of brackish water species such as shrimp. The impacts or storms and cyclones on aquaculture may be severe in financial terms as marine and brackish water species likely to be affected are often of high value.

Impacts on aquaculture dependant livelihoods

Climate change will result in social changes. There are likely to be new business opportunities while other industries may be lost. Demographic, market and infrastructure changes may be experienced along with both the creation and loss of a range of jobs (2WE Associates Consulting LTD, 2000). When considering how climate change may impact on aquaculture dependant livelihoods attention will need to be given to the type and scale of the aquaculture taking place as well as potential impacts in the area in question. For example a fairly low intensity small scale system providing food and/or income at the household or community level may be seriously affected by an extreme event such as a flood, resulting in an immediate reduction in the availability of food and money. In such a situation people may not have the financial resources to repair the situation, causing immediate problems. The same system, due to its low intensity, may be less sensitive to the impacts of gradual climate trends such as warming, with less chance of water quality issues or disease outbreaks being important issues. With inputs generally being cheap and locally derived, and with markets being local and the species being produced being of low value, there is also likely to be less impact from changes in market prices of both goods produced and resources. This contrasts with a high intensity farm producing carnivorous species. Such a setup may well have the insurance and/or financial capital to cope with an isolated extreme event but may be at risk over a longer term due to increases in insurance costs, loss of opportunity and changing market prices of products and inputs such as fishmeal.

Climate related changes to resource flows can affect livelihood security, particularly among the poor (SEI *et al.*, 2003). There is a need to improve the understanding of what makes fish farmers vulnerable to events and factors that result in poverty and what makes it difficult to improve livelihoods, as well as what adaptive strategies and potential solutions exist in the context of climate variability and change. In the climate change literature the concept of livelihoods is employed to understand the vulnerability context of communities (Adger, 1999; Elasha *et al.*, 2005; Morris *et al.*, 2002; SEI *et al.*, 2003; Ziervogel & Calder, 2003). Climate related work on fisheries typically focuses on climate variability, fluctuating stocks and livelihoods systems (Allison, Ellis, Mvula & Mathieu, 2001; Sarch & Allison, 2000). While there is a considerable body of work focusing on aquaculture dependant livelihoods (Bunting, 2004; Pérez-Sánchez *et al.*, 2005; Ross & Martinez Palacios, 2004; Tien, 2005; van Brakel *et al.*, 2003b) there has been little done directly in relation to climate change. There is however useful research focusing on aquaculture's requirements and site suitability which encompass environmental and climatic variables such as water availability, salinity and temperature (Aguilar-Manjarrez & Nath, 1998; Kapetsky & Nath, 1997; Salam, 2000; Salam & Ross, 1999, 2000; Salam *et al.*, 2003; 2005; van Brakel, 2003a). These studies will prove very useful when assessing aquacultures potential under future climate scenarios.

Using the sustainable livelihoods approach climate change impacts on fish farming communities can be linked to 5 assets that make up the livelihoods framework: human, natural, financial, social and physical (Box 1.4). The following sections give examples of how these assets may be affected by climate change and variability, based on the literature surveyed and knowledge of aquaculture systems. Primary results obtained suggest that the framework can be a useful tool in understanding the impact of climatic stresses in the aquaculture sector and in the provision of a typology of impacts at a range of scales.

Box 1.4 Livelihood assets

Natural capital – the natural resource stocks (soil, water, air, genetic resources etc.) and environmental services (hydrological cycle, pollution sinks etc) from which resource flows and services useful for livelihoods are derived.

Physical capital – physical assets comprise capital that is created by economic production processes. It refers to the basic infrastructure and producer goods needed to support livelihoods.

Economic or financial capital – the capital base (i.e. cash, credit/debt, savings, and other economic assets) which are essential for the pursuit of any livelihood strategy.

Human capital – the skills, knowledge, ability to labour and good health and physical capability important for the successful pursuit of different livelihood strategies.

Social capital – the social resources (networks, social claims, social relations, affiliations, associations) upon which people draw when pursuing different livelihood strategies requiring coordinated actions.

Source: (Badjeck, 2004) adapted from (DFID, 2001) and (Scoones, 1998)

Changes in natural capital

Changes in natural capital involve changes in sea surface temperature, water quality etc. that can affect production costs and incomes.

In Japan eel breeders on lake Hamana have blamed global warming for changing salinity levels in the lake which they say has affected production (Growfish, 2004c). In Tasmania warmer currents believed to be linked to climate change are said to affect salmon in fish farms by slowing growth, and increasing the presence of algae blooms and gill amoeba – a parasite on the fish which can lead to increased mortality. It was suggested that a partial solution to the problem of slower growth may come from studying how temperature affects salmon and adjusting feed formulations accordingly (Paine, 2003). In the United States droughts which are linked to higher average temperatures, are causing slower growth of catfish and increased possibility of disease outbreaks. In order to harvest the catfish at marketable sizes producers are having to maintain them for longer periods which significantly increases production costs (AgJournal, 1999).

Due to increased sea surface temperatures attributed to global warming, the mollusc *Haliotis*, also known as abalone, are now present in England's West Country. The region is thus becoming a suitable habitat for abalone farming and the local government is promoting this new industry to rejuvenate the failing fishing sector (Brown & Sutton, 2002).

Fluctuations in sea temperature off the coast of Ecuador correspond to fluctuations in the recruitment of shrimp at both seasonal and interannual time scales (Cornejo-Grunauer *et al.*, 1997). As a result prices of wild broodstock can vary greatly. For example in 1991 in association with positive temperature anomalies prices ranged from US$ 15 to 30 per adult, while in 1995 with negative temperature anomalies prices were in the US$ 130 to 160 range (Cornejo-Grunauer *et al.*, 1997).

With warmer temperatures and larger brackish water areas created by heavy rain, the increased availability of wild shrimp seedstock along the pacific coast of South America will create competition for hatcheries which may have to lay off staff at least on a temporary basis (Rosenberry, 2004). In the case of Ecuador the decrease in catches of small pelagic species affected fish meal production for feed which in turn led to imports of fish meal at higher prices due to increased demand over supply with the end result of increased production costs (Cornejo-Grunauer, 1998b; Cornejo-Grunauer *et al.*, 1997). There may also be water quality issues during cold La Niña periods due to reduced rainfall, and hence water availability, leading to reduced production. In terms of aquaculture production ENSO can be seen to have both positive and negative impacts within the region (Rosenberry, 2004).

Reduced water supply, and decreases in water quality, leading to increased incidence of disease also affects countries like Panama and Costa Rica where production of tilapia and trout have been affected (CRRH, 2002).

Over much of Asia El Niño events result in dryer conditions (NOAA, 2005) and this may have a negative impact on species such as shrimp. For example the 1991 – 93 El Niño contributed to drought in areas of Thailand, Indonesia and the Philippines which in tern led to a reduction in shrimp production through reduced water quality and associated disease, as well as reduced availability of wild seed and broodstock (Rosenberry, 2004). Fish production from ponds may also be affected, with reports from the Philippines of reduced production of species such as tilapia in relation to El Niño related drought (Yap, 1999).

Impacts on physical capital and the influence of financial capital

Loss of physical capital is often associated with the impacts of extreme events such as floods, storms and droughts. The result of a loss of assets and farming capacity is economic loss which small fish farms in particular may be unable to cope with.

In 2004 the Florida department of Agriculture estimated that hurricanes Frances and Charley caused and estimated $8.7 million loss to clam and oyster farmers within the state, with this figure only accounting for stock losses and not including infrastructure such as boats, buildings and hatchery facilities (Bierschenk, 2004).

In Bangladesh the 2004 floods caused damages to the aquaculture sector: ponds overflowed and in the Chandpur district most of the 13, 000 fish farms lost part of their stock which translated into economic losses of around 3.5 million dollars (Growfish, 2004b). In the Sobulia village in Fulpur, fresh water shrimp farms on some 30 acres or land were washed away by floodwaters (Hague, 2004). The Bangladesh Small Fishermen Association estimated that fry and growing niches in 80% of water bodies in 45 flood-hit districts had been washed away causing significant losses to cultivators (Growfish, 2004a). Most fish farmers did not have the financial resources to repay some of the loans they contracted to enter the fish farming business and made an appeal to the government to supply interest-free loans and supply of fish fry free of cost from government hatcheries (Growfish, 2004a).

In the south of England the floods in the summer of 2004 also affected fish farmers. In Boscastle one owner lost 40, 000 fish ,including brown trout and salmon (Growfish, 2004d).

In Latin America climate variability (ENSO events and extreme events (i.e. hurricanes) have a significant impact on the aquaculture industry as the examples below illustrate:

In Ecuador large El Niño events such as in 1997 – 98 tend to result in reduced profit for shrimp farmers despite the potential for increased production typically associated with El Niño conditions in this area (Rosenberry, 2004). Primary causes are difficulties in transportation due to damage and losses in infrastructure such as highways and bridges (Cornejo-Grunauer, 1998b), as well as damage to hatcheries which may have a delayed impact on the industry as a whole (Rosenberry, 2004).

In Honduras about 10% of shrimp farm infrastructure was damaged by hurricane Mitch in 1988 with an estimated losses in production of $23 and $4 million in 1998 and 1999 respectively, and an $8 million loss in equipment, facilities and infrastructure. (Rosenberry, 1999). While storms of this nature can not be directly linked to climate change the suggestion that they may increase in either intensity of frequency needs careful consideration in relation to potential damage, related cost and hence the feasibility of future aquaculture activities.

Reduced human capital and impacts on social capital

This section focuses on climate change effects on employment in the aquaculture sector and the possible resource-use conflicts related to aquaculture that climate variability and change might cause.

The 1997-98 ENSO event significantly affected employment in the aquaculture sector in Ecuador with the collapse of shrimp hatcheries (approximately 300) which employed around 6000 people and provided shrimp larvae as the "seed" for shrimp ponds (Cornejo-Grunauer, 1998b).

Climate variability and change might increase current conflicts over scarce resources like freshwater and coastline space as the examples below illustrate:

Intensive shrimp farming in Thailand and Taiwan has led to the use of large quantities of groundwater which has lowered the water table and caused salinity issues for local land and waterway (Braaten & Flaherty, 2001; Dierberg & Kiattisimkul, 1996; Primavera, 1998 p. 263). Salinization not only reduces water availability for agriculture but also for other domestic and industrial uses (Primavera, 1998 p. 263). Under climate change scenarios which increase the frequency of droughts, the availability of fresh water might be a source of conflict between the aquaculture sector and other sectors (like rice agriculture), or at the least become an impediment to the full development of aquaculture. Aquaculture can cause habitat modification by affecting such ecosystem services as coastal protection and flood control by removing mangroves (Naylor *et al.*, 2000). Conversion to shrimp ponds has been the main cause of mangrove loss in the last few decades in Bangladesh and Sri Lanka, while in Vietnam a total of 120 00 ha of mangroves has been cleared for shrimp farming from 1983 to 1987 (Primavera, 1998 p. 264). In the context of increased extreme events driven by climate change there is an incentive to reclaim mangrove areas which could in the long run could lead to conflicts between aquaculture producers and other users of the coastal zone.

Indirect impacts - the influence of capture fisheries

Ways in which climate change indirectly impacts on aquaculture may be subtle, complex and hard to identify or quantify. Impacts may take place at a range of scales from local to global and in many cases community level studies will probably be needed to unpick the pathways involved. Effects on availability and/or cost of inputs will influence production costs and methods, while the relative price of aquaculture products in relation to alternatives will also constrain aquaculture production. Bearing these points in mind the role of capture fisheries has to be seen as highly significant both in terms of competing with aquaculture products in the market place, and supplying inputs, typically in the form of fishmeal and fish oil. Other types of agriculture will also have a significant role, supplying feeds and fertilizer as inputs, and by producing competing products such as poultry (Delgado, 2003).

Table 1.8 shows projected changes in price of various fisheries and agriculture commodities under a number of economic scenarios for the period 1997 - 2020. Comparing the faster and slower aquaculture expansion scenarios with the baseline scenario shows the influence of an increasingly more significant aquaculture sector. The ecological collapse scenario is based on a one percent annual decline of all capture fisheries products including fishmeal and fish oil. While the ecological collapse scenario is currently way beyond what is considered likely by fisheries analysts (Delgado, 2003) it does highlight the potential consequences of damage to capture fisheries on the price of fish as a whole. High fish prices would reduce demand and hence fisheries production. Estimates of fisheries production for the year 2020 are given in Table 1.9. The relatively small 17 percent average decrease in production for all areas under the ecological collapse scenario is explained by production responses to price increases by both aquaculture and capture fisheries (Delgado, 2003).

Table 1.8 Projected changes in the price of various between 1997 – 2020 under different production scenarios (adapted from Delgado, 2003)

	Scenario					
Commodity	**Most likely (baseline)**	**Faster aquacultur e expansion**	**Lower China production**	**Fishmeal and fish oil efficiency**	**Slower aquacultur e expansion**	**Ecological collapse**
Low-value food fish	6	-12	6	5	25	35
High-value finfish	15	9	16	14	19	69
Crustaceans	16	4	19	15	26	70
Molluscs	4	-16	3	3	25	26
Fishmeal	18	42	21	-16	0	134
Fish oil	18	50	18	-5	-4	128
Beef	-3	-5	-3	-4	-2	1
Pig meat	-3	-4	-2	-3	-1	4
Sheep meat	-3	-5	-3	-3	-1	2
Poultry meat	-2	-5	-2	-3	0	7
Eggs	-3	-5	-3	-4	-2	3
Milk	-8	-10	-8	-9	-8	-5
Vegetable meals	-1	3	0	-7	-4	16

Table 1.9 Projected production of food fish in 2020 under a range of scenarios (adapted from Delgado, 2003)

Region	Scenario						
	Actual 1997	**Most likely (baseline)**	**Faster aquacultu re expansion**	**Lower China production**	**Fishmeal and fish oil efficiency**	**Slower aquacultu re expansion**	**Ecological collapse**
China	33.3	53.1	61.7	45.7	53.3	46.1	47.7
Southeast Asia	12.6	17.5	19.5	17.5	17.6	16.2	13.5
India	4.8	8.0	9.8	8.0	8.0	6.7	6.8
Other South Asia	2.1	3.0	3.5	3.0	3.0	2.6	2.5
Latin America	6.4	8.8	9.4	8.8	8.9	8.5	6.1
West Asia and North Africa	2.2	2.8	2.9	2.8	2.8	2.7	2.1
Sub-Saharan Africa	3.7	6.0	6.0	6.0	6.1	6.0	3.0
United States	4.4	4.9	5.1	4.9	4.9	4.8	4.2
Japan	5.2	5.2	5.1	5.2	5.2	5.2	4.8
European Union 15	5.9	6.7	7.0	6.7	6.8	6.5	6.0
Eastern Europe and former Soviet Union	4.9	5.0	5.0	5.0	5.0	5.1	4.2
Other Developed countries	4.8	5.8	6.1	5.8	5.8	5.5	4.7
Developing world	68.0	102.5	116.2	95.1	10..0	92.0	84.3
Developing world excluding China	34.6	49.4	54.5	49.4	49.7	45.9	36.6
Developed world	25.2	27.6	28.3	27.6	27.8	27.1	23.9
World	93.2	130.1	144.5	122.7	130.8	119.1	108.2

Climate change effects on capture fisheries are likely to be regional and impact on some species far more than others. The effects of climate change may combine with those of fishing pressure to reduce stocks of some species. For example recruitment of Atlantic cod has been shown to be affected by climate variability caused by the North Atlantic Oscillation (NOA) only when the spawning stock is low (Brander, 2005), and as a result of fishing in the North Sea cod recruitment is now predominantly from a limited number of year classes meaning that one or two warm years has a greater impact on the fishery (Cook *et al*.,1997).

Changes in ocean temperatures may cause a shift in the distribution of some fishery species, such as tuna, outside of a country's or regions traditional or legal fishing areas (Lehodey *et al*., 1997; Loukos *et al*, 2003) having potential consequences for export markets and the price of fish (Aaheim & Sygna, 2000).

For freshwater fisheries change in precipitation is likely to be a crucial factor. For example fish recruitment and hence subsequent catches have been correlated with annual variation in floodplain coverage of the Magdelena River, Colombia, and Kafue River, Zambia (Welcomme, 1985; Kapetsky, 2000). In Lake Tanganyika links have been suggested between ENSO events, local climate and fishery yields (Pilsnier, 1997).

While aquaculture may derive some benefits and incentive from higher fish prices due to climate-impacted capture fisheries, there are likely to be negative impacts related to costs of inputs, notably the much debated use of fishmeal and fish oil by the aquaculture sector.

Fishmeal and fish oil

Fishmeal and fish oil production is largely dependant on small pelagic species such as Peruvian anchovy, Chilean jack mackerel, Atlantic herring, chub mackerel, Japanese anchovy, round sardine, Atlantic mackerel and European anchovy (Naylor *et al*., 2000). Approximately two thirds of fishmeal comes from specialist fisheries which are equipped for and based around fish meal production (New & Wijkstrom, 2002). Tables 1.10, 1.11, 1.12 and 1.13 show production and consumption figures for fishmeal and fish oil giving an indication of where the fisheries and aquaculture sectors may suffer as the consumers in the event of impacts on fishmeal and fish oil production (data from the Fishmeal Information Network (FIN). The proportion of a country's total fishmeal and fish oil consumption used by the aquaculture sector will vary between nations. Those where a greater proportion of fishmeal and fish oil use is currently for sectors other than aquaculture, such as other livestock feeds may have a greater capacity for substitution with alternate protein sources if faced with increasing fishmeal and oil prices.

Delgado *et al*. (2003) suggest that excluding China, it is generally more developed countries that consume large quantities of fish meal and fish oil, and this reflects the intensive nature of livestock and aquaculture production in such areas along with a tendency towards carnivorous fish species. Delgado *et al*. also suggest that that the above situation results in a general trend for a net flow of both fish meal and fish oil from the developing to the developed world. This trend is not easily seen in the data presented in tables 1.10, 1.11, 1.12 and 1.13 but consideration should be given to the fact that the tables are not a complete representation of all countries, and that the level and accuracy of reporting and record keeping between countries may also vary.

Table 1.10 Fishmeal production for top 16 countries (Source: Fishmeal Information Network (FIN))

'000 tonnes	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Peru	1972	1740	815	1904	2309	1844	1941	1251	1983
Chile	1376	1195	642	957	842	699	839	664	933
Thailand	382	386	410	398	387	381	387	397	403
China	359	534	693	707	806	723	460	420	400
USA	329	394	294	355	335	342	337	318	353
Japan	406	363	379	409	387	227	225	230	295
Denmark	297	341	324	311	318	299	311	246	259
Norway	214	253	301	241	264	216	241	212	215
Iceland	265	279	220	234	272	286	304	279	204
South Africa	65	55	94	84	109	111	93	113	114
Spain	65	93	93	84	120	115	117	119	103
Ecuador	110	44	72	51	78	89	59	79	85
Russian Fed	207	177	163	155	126	98	95	68	70
Faroe Islands				25	24	44	37	42	68
Morocco	75	70	55	59	53	55	61	64	63
Mexico	68	63	45	48	65	61	65	65	55
UK	55	51	52	53	50	47	48	52	51

Table 1.11 Fishmeal consumption for top 16 countries (Source: Fishmeal Information Network (FIN))

'000 tonnes	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
China	882	976	416	673	1241	984	976	797	1147
Japan	412	437	330	346	338	478	480	388	402
Taiwan	373	320	172	294	299	295	242	239	238
Germany	290	293	252	233	304	197	120	198	183
Norway	106	128	100	143	183	143	127	150	162
UK	242	285	239	221	241	233	192	184	143
Denmark	107	87	94	139	131	130	135	167	132
Spain	63	97	63	94	123	116	89	95	105
USA	61	64	57	33	36	51	67	55	71
Indonesia	134	121	40	77	118	113	67	57	70
Greece	33	36	40	40	53	77	84	74	69
Italy	87	87	48	68	76	87	67	66	64
Netherlands	114	82	64	50	73	52	73	64	63
Canada	65	77	62	66	98	102	80	68	61
Vietnam	-	-	-	14	15	29	20	60	61
Russia	59	144	95	73	40	167	133	99	55

Table 1.12 Fish body oil production for top 16 countries (Source: Fishmeal Information Network (FIN))

'000 tonnes	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Peru	422	330	123	515	593	300	221	205	352
Chile	11	8	7	188	171	145	146	130	138
USA	113	128	101	130	87	118	96	80	81
Denmark	142	131	136	129	98	80	86	71	68
Japan	48	52	58	68	70	63	64	61	68
Iceland	137	130	88	102	95	96	70	104	49
Norway	77	85	98	69	83	56	72	52	37
Morocco	14	15	18	14	18	31	20	29	25
Spain	19	17	20	20	20	21	20	21	22
Turkey	4	5	5	5	5	6	9	14	14
Ecuador					6	10	7	8	14
China	11	8	7	10	24	27	27	30	13
Mexico	10	11	6	7	7	7	8	9	12
UK	12	9	10	12	10	10	11	11	12
Faeroe Is.	10	7	9	10	9	9	10	10	11
Russian Fed	6	2	8	12	12	11	11	11	4

Table 1.13 Fish body oil consumption (Source: Fishmeal Information Network (FIN))

Country	1997	1998	1999	2000	2001	Average
Chile	172	124	180	245	236	191
Norway	156	154	181	214	213	184
Peru	132	80	160	178	64	123
Japan	114	107	107	122	142	118
UK	80	58	57	54	69	64
Netherlands	73	11	47	66	24	44
Denmark	60	47	55	53	99	63
Germany	44	12	16	19	14	21
Canada	30	34	38	24	52	36
France	26	21	27	24	32	26
Spain	21	36	31	35	42	33
Italy	21	19	28	29	22	24
Belgium	18	1	1	4	1	5
China	13	10	38	49	30	28
Finland	9	6	5	3	4	5
Ireland	6	4	6	5	5	5
Poland	2	1	1	1	2	1
Sweden	1	0	0	4	4	2
Austria	1	1	1	1	1	1
Portugal	0	1	1	1	1	1
Czech	0	0	0	0	0	0
Other	282	205	273	297	192	250
Total	**3,258**	**2,930**	**3,252**	**3,428**	**3,250**	**1,225**

The type of species being cultured and the culture system will largely determine the level of dependence on fishmeal and fish oil. Carnivorous marine and diadromous species of finfish typically have higher requirements for highly unsaturated fatty acids, and consequently fishmeal and fish oil, than omnivorous freshwater species such as carps and tilapias. The amount the fish are directly fed on manufactured feeds as opposed to naturally occurring food items is obviously significant and here the level of intensity of the system will play a role. Systems range from extensive ponds with no additional inputs through to gradually more intensive systems using fertilization then supplementary feeding and finally to highly intensive systems where the fish are entirely dependant on compound feeds.

Table 1.14 shows estimated levels of fishmeal and fish oil inclusion used in formulated diets, the percentage of cultured fish being fed on such diets, and the food conversion ratio for a range of species. These figures give an indication of the differences seen between species groups and were originally used in a study investigating potential future use of fishmeal and fish oil by aquaculture (New & Wijkström, 2002). The study indicated that based on historical levels of fishmeal production and with predicted aquaculture growth, aquaculture would be using around 70% of globally produced fishmeal by 2015. The case for fish oil is worse with demand outstripping supply by 2010. While these figures are estimates they, along with spikes in the price of fishmeal in relation to past ENSO events, hint at the potential seriousness of any climate impacts on the fisheries concerned.

Table 1.14 Projected use of fishmeal and fish oil by a number of aquaculture species (source: New & Wijkström, 2002)

SPECIES GROUP	YEAR	AFCR	% FED ON AQUAFEEDS	INCLUSION RATE IN FEEDS (%)	
				FISHMEAL	FISH OIL
COMMON CARP	1999	2.0	25	5	1
	2015	1.5	50	2	1
	2030	1.3	80	0	1
TILAPIA	1999	2.0	40	7	1
	2015	1.5	60	3	1
	2030	1.3	90	0	1
CATFISH	1999	1.6	85	3	1
	2015	1.4	90	0	1
	2030	1.2	95	0	1
SELECTED FRESHWATER FISH	1999	2.5	50	50	10
	2015	1.8	80	25	15
	2030	1.5	100	15	15
EELS	1999	2.0	80	50	10
	2015	1.5	90	40	8
	2030	1.2	95	20	8
SALMON	1999	1.2	100	40	25
	2015	1.0	100	25	15
	2030	0.8	100	15	15
TROUTS AND STURGEONS	1999	1.2	100	30	15
	2015	1.0	100	20	15
	2030	0.8	100	15	15
MILKFISH	1999	2.0	40	12	3
	2015	1.5	60	5	2
	2030	1.3	80	5	2
OTHER DIADROMOUS FISH	1999	1.8	60	40	10
	2015	1.5	80	20	10
	2030	1.2	95	20	10
SELECTED MARINE FISH	1999	2.0	60	45	10
	2015	1.8	80	35	10
	2030	1.4	90	25	10
REDFISH	1999	2.0	80	45	20
	2015	1.8	100	35	15
	2030	1.4	100	25	10
JACKS AND YELLOW TAILS	1999	2.0	80	45	20
	2015	1.8	100	35	15
	2030	1.4	100	25	10
FRESHWATER PRAWNS	1999	2.0	85	20	1
	2015	1.6	95	15	2
	2030	1.4	100	15	2
CRABS AND LOBSTERS	1999	1.8	80	25	2
	2015	1.6	90	15	3
	2030	1.4	90	15	3
MARINE SHRIMP	1999	1.8	80	25	2
	2015	1.6	90	15	3
	2030	1.2	95	15	3

Compared with other agriculture sectors currently using fishmeal, aquaculture has considerably less elasticity between price and demand. This is largely due to the relative inability to switch to alternative protein sources such as soymeal compared with say the poultry and pig farming sectors which currently consume considerable quantities of fishmeal. It is likely that as fishmeal prices rise an increasing proportion will be used by the aquaculture industry for the culture of carnivorous species. Delgado *et al*. (2003) suggests that by 2020 fishmeal prices will be largely de-linked from that of soymeal, and that the aquaculture of carnivorous finfish will be particularly sensitive to changes in capture fisheries supplying fishmeal and fish oil.

Improvements in feed formulation and feeding techniques may help offset some of the effect of increased fishmeal and oil prices by reducing the inclusion rates in formulated diets, and through better food conversion ratios (New & Wijkström, 2002) .They also suggest that currently less exploited fisheries such as krill and mesopelagic species may provide alternative sources of fishmeal and oil, although a considerable increase in fishmeal and oil prices would be needed before investment in the development of the fishing and refining infrastructure for these new fisheries becomes viable. It seems that without current alternatives, and with large amounts of the global fishmeal and fish oil supply coming from a limited number of sources, the potential for climate change to indirectly impact on aquaculture of carnivorous species needs to be taken seriously.

The Peruvian fishmeal industry as an example

Peru is the largest producer of fishmeal and fish oil with neighbouring Chile also a large producer. Annual production has been fairly constant in recent times except during the 1998 El Niño period (Pike & Barlow, 2002) (Figure 1.9).

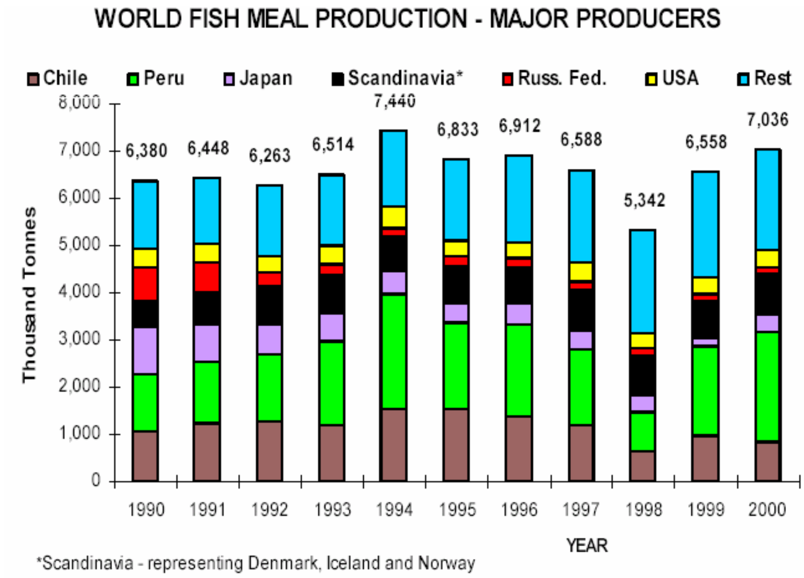


Figure 1.9 World fish meal production - major producers 1990-2000 (source: Pike & Barlow, 2002)

Historically the harvest of Peruvian anchovy has been extremely variable in relation to the warming of the ocean during El Niño events and a consequent reduction in coastal up welling, nutrient supplies, primary production and ultimately food for planktivorous fish species such as the anchovy (Delgado *et al.*, 2003).

In 1970 Peru was catching 12 million tonnes of fish for fish meal production (anchovy and sardines). During the period of the severe El Niño from 1972-73 production dropped significantly and while a recovery has been observed, it was very slight, with sardines becoming the main species caught (Figure 1.10). The El Niño in 1982-83 also reduced production but the 1998 event caused a more dramatic drop. As would be expected trends in fishmeal production and export follow those in fish catches and are shown in Figure 1.11.

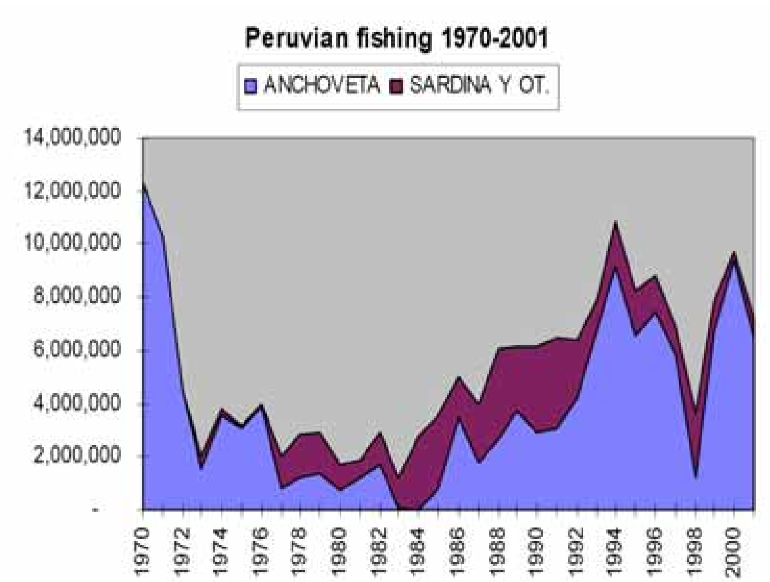


Figure 1.10 Catches of Anchoveta and Sardina from 1970 to 2000 in tonnes (source: Pike & Barlow, 2002)

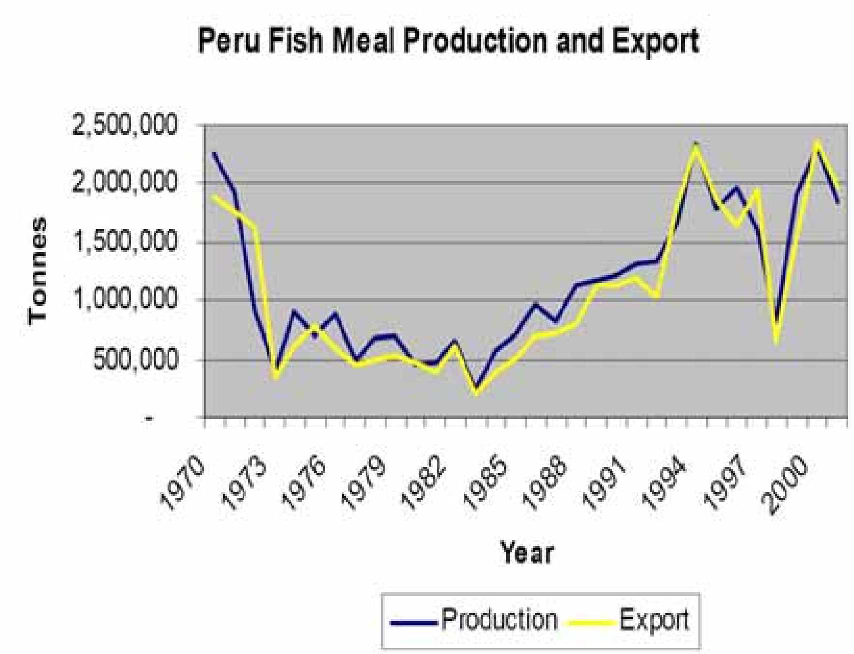


Figure 1.11 Peruvian fishmeal production and exports for 1970-2000 in tonnes (source: Pike & Barlow, 2002)

Figure 1.12 shows the increase in the price of fishmeal in Europe associated with shortages caused by the 1998 El Niño. The price ratio against soya is also shown, with soya production remaining fairly constant during the period of increased fishmeal prices (Barlow, 2002). The price of fishmeal is seen to drop in 1999 as the anchovy fishery starts to recover but there is then a steady increase which is attributed to increased aquaculture demand (Barlow, 2002).

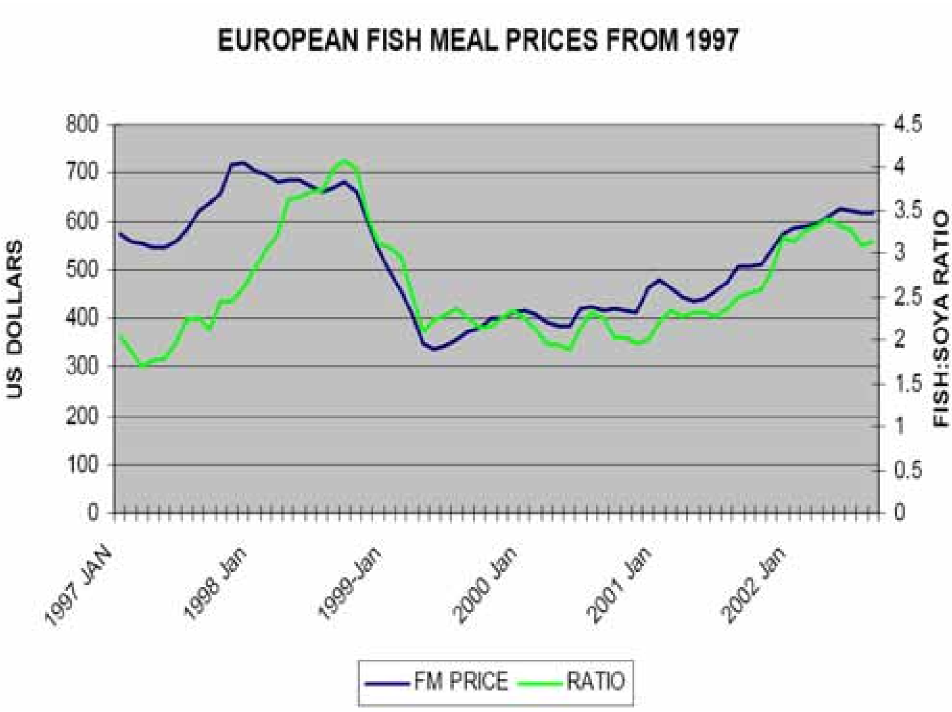


Figure 1.12 European fish meal prices and price ration against soya bean from 1997 to 2002 (source: Pike & Barlow, 2002)

As fishmeal prices increased due to reduction in supply there was substitution to less expensive plant-based meals with substitution being greatest among pig and poultry feeds and only to a limited extent in aquaculture (Delgado *et al.*, 2003 p. 90). As a result aquaculture became the largest end-user of fishmeal in 1998 (Delgado *et al.*, 2003 p. 90).

Without adaptation through improved technology and production methods aquacultures demand for fishmeal and fish oil will probably continue to increase resulting in higher prices and potentially further increases in pressure on wild fish stocks (Delgado *et al.*, 2003).

Aquaculture's relatively inelastic and increasing demand for fishmeal and fish oil combined with supply variability related to climate variability and shocks could be responsible for increased frequency of price spikes which will lead to greater production costs, especially in the case of carnivorous species (Delgado *et al.*, 2003).

Climate variability and climate change impacts on wild fish stocks (especially small pelagic ones) at the regional level will thus create an indirect impact on aquaculture production systems around the world. Predicted climate change impacts might be an incentive for fish farmers to farm low trophic level species (Naylor *et al.*, 2000). Feed is often the largest production cost for commercial aquaculture and therefore improving feed efficiency is already seen as a priority (Naylor *et al.*, 2000 p. 1021), but climate change might bring further impetus for greater development (Hew & Fletcher, 2001 p. 192). In this context for many countries the role of government policies and international aid agencies is crucial in order for the aquaculture sector to adequately adapt to future climate change.

2. GIS based assessment of aquaculture related vulnerability to climate change

Introduction

Direct assessment of potential impacts of climate change on aquaculture are not possible, due to the multiple possible pathways involved, their interaction with each other and with other non-climate related changes in the sector and with climate-related changes in other, interacting sectors. Given this complexity, the key tasks when assessing the vulnerability of aquaculture to climate change are to identify those areas and people that are most exposed to climate-related risks, whose livelihoods and economies are most sensitive to the impacts of that exposure, and who are least able to adapt to impacts and changes.

The IPCC provides a useful working method for assessing vulnerability (V) by describing it as a function of exposure (E) to climate change, sensitivity (S) to climate change, and adaptive capacity (AC).

$V = f\,(E, S, AC)$

This approach in terms of definition of vulnerability is similar to a number of recent studies (Metzger *et al.*, 2005; O'Brien *et al.*, 2004; Schröter *et al.*, 2004; Allison *et al.*, 2004). The method is adapted in the current study to be used in association with a geographic information system (GIS) to try to highlight areas where livelihoods are most likely to be affected.

The decision to use a GIS as opposed to a simple numerical index at the country scale is based on the following:

- Data can be incorporated at its maximum spatial resolution. Data was available at a variety of resolutions ranging from 2.5 arc minutes to whole country (see Spatial and temporal scales)
- The database can be updated and expanded as resources become available. This allows for further development and improvement of the modelling process.
- Once the database is established it is a relatively quick and easy process to manipulate and combine data in a large number of combinations to address a range of questions.
- Graphical representation of results, as well as individual components of the model, make is easier to see trends and patterns not easily visible when using numeric indices.

Vulnerability to climate change will be affected by a wide range of socioeconomic factors as well as biological and physical ones (O'Brien *et al*, 2004). Aquaculture encompasses many different processes and environments and not all will respond equally to a given change. For example while a rise in mean temperature could be potentially detrimental to inland pond culture in the tropics due to reduced oxygen levels and water quality, a temperature increase at higher latitudes could bring potential benefits in terms of longer growing seasons and increased production. The concept that the effect of climate change on aquaculture can not be modelled as a whole and that different components require separate investigation is considered important in this study. When assessing vulnerability in the following sections consideration should be given where possible to the differences between climatic shocks and trends, scale and intensity of culture systems, and whether aquaculture is taking place in fresh, brackish or marine environments.

Figure 2.1 gives an overview of the model used to assess vulnerability in the current study. Each of the components (sensitivity, exposure and adaptive capacity) are represented here as sub-models which themselves can be used to investigate particular effects of climate change before being combined in the main model to give an overall indication of vulnerability. The components of the sub models, and the sub-models themselves, can be included/excluded and combined with different weightings in a number of combinations to ask different questions of the database. The aim of the vulnerability assessment is to highlight areas that are likely to be vulnerable and hence require further investigation. The use of spatial data and GIS will give some indication of areas affected within countries and specific issues involved beyond what can be achieved with a numerical index, but as presented here still needs to be considered as an indicative tool. Limitations on what can be achieved are largely linked to data resolution, quality and availability.

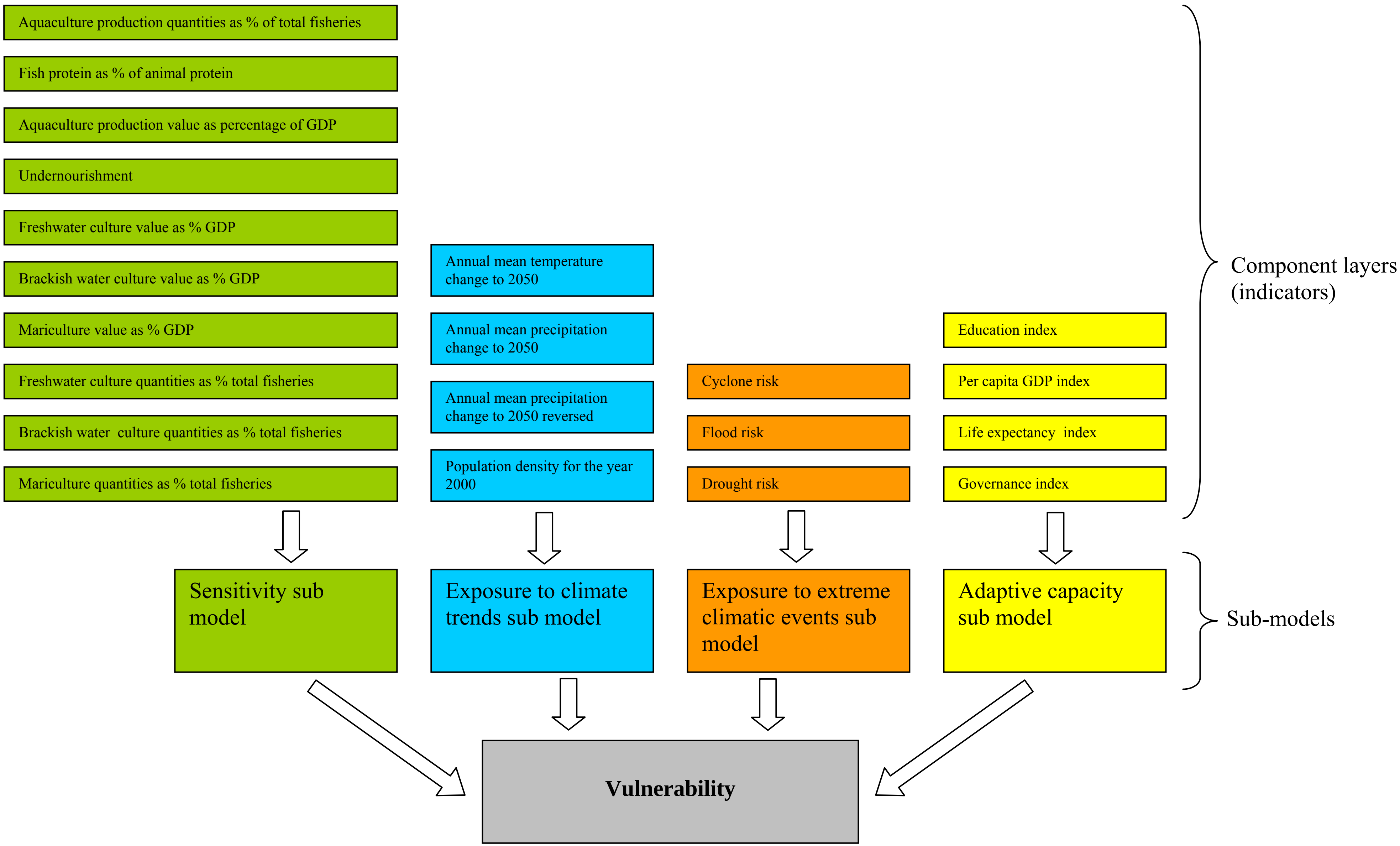


Figure 2.1: Schematic representation of the vulnerability assessment model.

Note: The complete range of component layers (indicators) available for use in the model are shown although not all will be used at any one time. The choice of layers and weightings (significance) used in their combination will vary depending on the issues being investigated.

Spatial and temporal scales

Data at a variety of resolutions was used in the current model. A priority for data selection was availability for as broad a range of countries as possible to allow comparisons across the globe. This, in turn limits the range, and hence resolution of data available for use. Extreme events, climate variables and population were represented at various higher resolutions, while the rest of the data (social, economic and political) were represented at the national level. For the purpose of combining data by multi criteria evaluation (MCE) all data were converted to raster images with a resolution of 2.5 arc minutes which equates to the highest original resolution of any of the data sets used.

While national level processes may influence vulnerability at the sub-national scale (Adger *et al.*, 2004), higher resolution data is generally considered preferable. Countries can vary greatly over their range both in terms of physical and human geography, with aquaculture typically having varied importance and consequences for different communities. As part of a broader assessment local case studies could use a similar modelling approach to the current study but with data that is both at a greater resolution and more focussed on the issues relevant to the area and communities in question. For example socioeconomic data similar to that used in the current study may be available at the district level, and historic data for extreme events may be available with detail of severity as well as spatial distribution.

Apart from predicted changes for temperature and precipitation levels which are based on future predictions by climate models, all indicators used were based on current data, hence current vulnerabilities in aquaculture are being assessed against future climate trends. It may be possible in the case of more localised studies, and with suitable data and careful consideration, to use predicted values for a wider range of indicators. In the case of the current global assessment and available data, the argument is accepted here that current vulnerability is still the best proxy, reducing uncertainty relating to indicators, and is appropriate for identifying means of increasing adaptive capacity (Adger & Kelly, 1999; Vincent, 2004)

Model construction and presentation

Box 2.1 Parameters of raster layers used in vulnerability model.

Reference system:	latitude / longitude
Number of columns:	8640
Number of rows:	3264
Min X	-180
Max X	180
Min Y	-56
Max Y	80
Resolution:	2.5 arc minutes

IDRISI (version 14) was used for all spatial modelling and data presentation. All data used in the modelling process were prepared in the form of raster Images (see box 2.1 for parameters). Raster is a term used to describe an image which consists of small uniform cells (pixels) arranged in a grid. These cells can all represent a unique numeric value e.g. temperature or population density. The image is georeferenced so that cells correspond accurately with points on the earth's surface. It is then possible to combine data layers (images) using a number of mathematical operations on cells that occupy the same grid location.

Reclassification

All layers used in the model were reclassified to have a scale ranging from one to five with five representing greatest impact or significance. In each case details are given in tables 2.4, 2.10, 2.12 and 2.14 which outline the method of construction and function of each layer used in the four sub models. Due to the varied nature of the data used within the model as a whole it was not possible to use one standard method of reclassification. In all cases objective reclassification decisions were made by the principal author based on information provided in literature accompanying the data, and on the author's knowledge of the data and issues involved.

Layer combination

Data layers were combined in the sub models and main model by multi criteria evaluation (MCE) using weighted linear combination. In this process different weightings (levels of significance) were assigned to each input layer which in turn controls their level of influence in the layer produced (output). The process is described in more detail in box 2.2.

Box 2.2 Combination of data layers by MCE using weighted linear combination.

Each layer is assigned a weighting, or level of significance, that determines its influence on the layer produced as a result of the combination. In the current study weightings were assigned by the author based on knowledge of the factors involved as well as consensus of expert opinion obtained from a focus group and group questionnaire.

Weightings are assigned so that when they are combined they have a total value of 1.

e.g. for a combination of 3 layers:

Layer 1 = 0.5
Layer 2 = 0.25
Layer 3 = 0.25

The value assigned to each cell in each data layer is then multiplied by the weighting given to that layer. Corresponding cells in each layer are then added together to produce a final combined image. An example of the process using 3 layers and the weightings described above is given in figure 2.2.

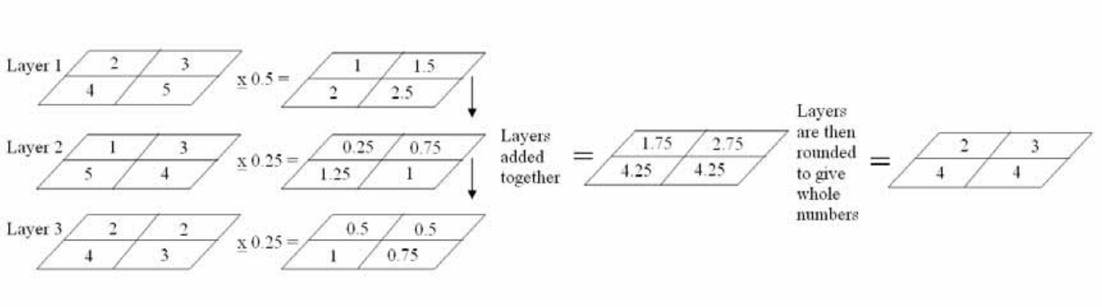


Figure 2.2: Example of layer combination using MCE and weighted linear combination

Weighting of components – use of expert opinion

The weightings used when combining data layers are obviously crucial to the outcome of the model. A focus group of 6 individuals from the Institute of Aquaculture, Stirling, with a broad range of expertise relating to aquaculture, livelihood issues and development, and environmental science were asked to complete a guided questionnaire to give their views on weightings to be used when combining data layers and sub-models. It is accepted here that a larger focus group would have be beneficial, providing a broader range of experience as well as allowing for more statistically robust results.

The group were asked to fill in a series of matrices (see example in Table 2.2) for the different layer combinations used in the models using scale described in Table 2.1. It was suggested that in each case they rank the layers in order of importance before filling in the matrix. Care was taken to explain the process fully and examples were used to help the group understand the weighting system and the use of the matrix as fully as possible.

Table 2.1: Scale used for assigning weightings using the pair-wise comparison matrix (Saaty, 1977).

1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9
extremely		very strongly		strongly		moderately		equally		moderately		strongly		very strongly		extremely
Less Important									**More Important**							

Table 2.2 Example of a pair-wise comparison matrix (developed by Saaty, 1977) used to assign weightings or levels of significance to a group of factors. The example given here is for the adaptive capacity sub model which combines 4 layers; Per capita GDP (PPP), Education, Governance and Health. The left hand column is compared with the top row, so in the example here education is considered 1/2 as important as per capita GDP, health is considered 1/3 as important as education, and so on. Weightings are derived from the scores given using the Weights module found in IDRISI GIS software, and are shown in the right hand column.

	Per capita GDP	Education	Governance	Health	Weightings
Per capita GDP	1				0.435
Education	1/2	1			0.286
Governance	1/2	1/2	1		0.182
Health	1/4	1/3	1/2	1	0.097

Consistency ratio = 0.02

Evaluation and analysis of questionnaires - assigning of weights used in the vulnerability model

Weightings were calculated from the scores given in the matrices using the Weights module in IDRISI software. Along with the weights a consistency ratio is calculated which indicates the consistency of logic between values in the matrix i.e. to what extent do the values given in the matrix contradict each other. In the case of the example given in Table 2.2 the consistency ratio is 0.02 which indicates a very good agreement between the values used. Saaty (1977) recommends a consistency ratio of 0.1 or less. This threshold has been used in a number of studies (e.g. Salam, 2000; Aguillar-Manjarrez, 1996) and is adopted in the case of the current model.

Table 2.3 Results of the Adaptive capacity matrix from the 5 successfully completed questionnaires. Weightings are shown and are also ranked in order for the purpose of analysing agreement between decision makers using Kendall's coefficient of concordance.

Component	Decision maker A		Decision maker B		Decision maker C		Decision maker D		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Education	0.2836	2	0.5	1	0.1342	3	0.1728	3	0.0879	3	0.236
Governance	0.1343	3	0.25	2	0.2622	2	0.0618	4	0.2862	2	0.199
Per capita GDP (PPP)	0.4992	1	0.125	3	0.5119	1	0.5656	1	0.5791	1	0.456
Life expectancy	0.0828	4	0.125	3	0.0866	4	0.1998	2	0.0468	4	0.108

Box 2.2 Equation for the calculation of Kendall's coefficient of concordance W (from Siegel & Castellan, 1988).

$$W = \frac{\sum_{i=1}^{N} (R_i - R)^2}{N(N^2 - 1)/12}$$

Where: N = Number of items being ranked.
R_i = Average of the ranks assigned to the *i*th item.
R = The average of the ranks assigned across all items.

Table 2.3 gives an example of the results obtained from the focus group, in this case for adaptive capacity with education, governance, per capita GDP at purchasing power parity and life expectancy as variables. The weightings produced by each decision maker using the pair wise comparison matrix are shown along with the order in which these weightings rank in each case. Where a sufficient number of decision makers (*k*) and variables (*N*) are involved Kendall's coefficient of concordance (*W*) is used to measure the level of agreement between different rankings based on the equation given in box 2.2. *W* can range from 0 (no agreement between rankings) to 1 (total agreement between rankings). The null hypothesis (H_0) that the rankings are not related can be rejected for values of W that are above a critical value. In the current study critical values for the rejection of H_0 at the 95% confidence level were taken from (Siegel & Castellan, 1988). It should be noted that in the current study only those decisions involving 4 variables and at least 4 decision makers had a sufficient sample size for the reliable use of *W*. For example in cases where 3 variables are used then 8 or more decision makers are needed before a critical value with a probability of occurrence of less than 0.05 is available (Siegel & Castellan, 1988).

SPSS statistical software was used to calculate values for W. In the case of the adaptive capacity example used in table 2.3 W was calculated at 0.579 which is just above the given critical value of 0.501 indicating an agreement between decision makers (Siegel & Castellan, 1988).

The results from the focus group questionnaires, including values for W where appropriate, are shown and discussed separately for each combination of layers in the following sections that describe the construction and outputs of the four sub models. Ultimately decision making regarding weightings was undertaken by the author while using the output from the focus group as a guide. In each case the contribution of the focus group, including comments made, is discussed along with the rational behind the eventual weightings used.

Care was taken not to influence the focus group in relation to individual weighting decisions, and it was considered important to discuss the concepts and ideas behind the model with the group in as much detail as possible. It was hoped that a good understanding of the models design and principals would allow for informed decisions regarding weightings. The group were also encouraged to give constructive criticism on any aspect of the model where they felt it appropriate.

In general there was a fair amount of disagreement between the weightings assigned by the decision makers and there were a number of comments on the difficulties of modelling at the global scale and the significant differences that exist between countries in relation to how they are affected by the variables used. The general consensus of the group was that it was best to think in terms of developing countries rather than developed ones. This matches the views of the authors and ideas in relation to the design and use of the model. Another comment that was made related to the potential differences in priority depending on whether the decision maker is thinking at the level of the individual, or the country. Decision makers were advised that it was best to consider the individual where possible as although the model outputs were largely at country level the models intention was to highlight regions where an individuals aquaculture related livelihood was most likely to be at risk.

Data not incorporated in the main model

Figure 2.3 shows the value of aquaculture products in US$ per kg. The average value obtained from global aquaculture as a whole is $1.21 per kg. French Guiana stands out in particular as supposedly having aquaculture products worth an average of $78.66 per Kg. This seems extremely unlikely under any circumstances, and even more so considering the majority of French Guiana's aquaculture is in the form of freshwater fish species. The next highest values come from Guadeloupe and the Solomon Islands with $17.27 and $14.00 per Kg respectively. As the aquaculture industries of these two countries is based mostly on high value prawn species these figures are perhaps more reasonable. As well as reporting errors such as those that may have been responsible for the figure for French Guiana, genuine differences in the values attributed to products by different countries and the relative value of the products within countries needs consideration when drawing conclusions from this data in relation to other data sets.

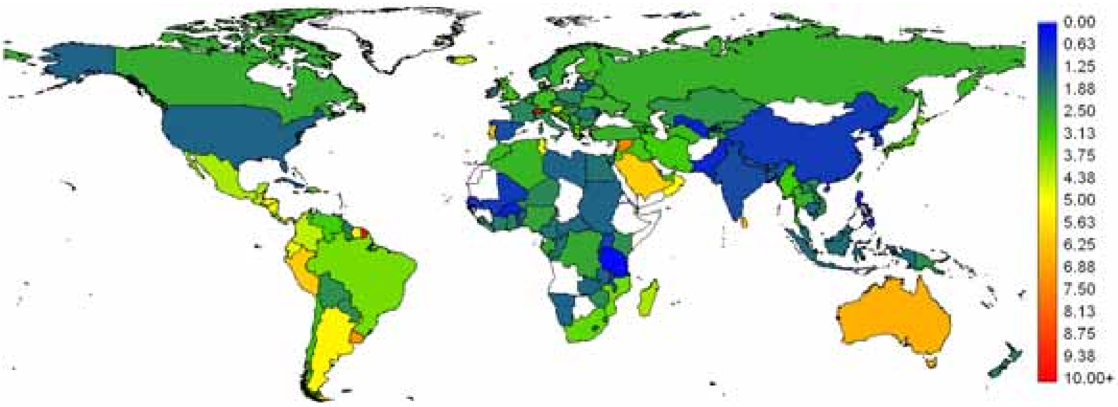


Figure 2.3: Aquaculture production value in US$ per kg.
(Based on FAO Fishstat data and FAO (2005).

Although further investigation at the country level would definitely be necessary, and bearing in mind the issues highlighted in the previous paragraph regarding comparison between countries, product value data may be useful when considering the following points: Areas where high value products are produced but overall production/economic contribution is low may represent specialist production of a few species and perhaps involving a small number of people. Low value species are likely to play an important role in areas where aquaculture is an important component of food security.

The use of product value per kg data in the construction of the layer representing sensitivity in terms of food security was investigated but eventually rejected. It was felt that due to the low value of aquaculture products in countries such as the US and Spain where food security is not considered a problem, and the wide potential variation of culture species and systems within countries with medium average values, that the overall clarity of the model may be reduced.

Sensitivity sub-model

Table 2.4 shows the data layers used in the construction of the sensitivity sub models. Sensitivity in the context of this study is indicated at the country scale and aims to describe the relative importance of aquaculture to livelihoods via its food security, economic and employment contributions. This is done via indicators of aquacultures significance to the country and people, as opposed to attempting to directly quantify impacts on aquaculture systems themselves, although the two issues are obviously linked. Data on the number of people involved in aquaculture and the amount of trade, both national and international, would be very useful in assessing the importance of aquaculture in terms of livelihoods. Unfortunately availability and quality of data in these areas is not sufficient to be included and allow for comparison of countries at the global level.

Table 2.4 Data layers used in the sensitivity sub models along with details of their construction and significance.

layer	**Data sources, reclassification and resolution**	**Description and significance**
Aquaculture production quantities as % of total fisheries	Data sources: Fishstat plus (FAO, 2005). A mean of the values from 2001 – 2003 is used in an attempt to even out some possible irregularities in reporting. Reclassification: 1 = <2%, 2 = 2–10%, 3 = 10-25%, 4 = 25-50%, 5 = >50%. Spatial resolution = whole country	Shows aquaculture production by weight as a percentage of total fisheries production giving an indication of the relative importance of aquaculture in terms of the fisheries sector as a whole.
Fish protein as % animal	Data sources: FAO food balance sheets (FAOSTAT data, 2004). Reclassification: 1 = <2%, 2 = 2–10%, 3 = 10-25%, 4 = 25-50%, 5 = >50%. Spatial resolution = whole country	Shows the percentage of fish protein that makes up the total animal protein intake in the diet. A high proportion of animal protein coming from fish may be due to a cultural preference or through necessity. It is hoped that when combined with the *aquaculture production as a percentage of total fisheries* and *undernourishment* layers, this layer will help indicate the importance of aquaculture in terms of food security.
Aquaculture production value as percentage of GDP	Data sources: aquaculture production values from Fishstat plus (FAO, 2005). GDP values from world bank development indicators (World Bank, 2003). A mean value from the years 2001 – 2003 is used in order for comparison with the mean values used for aquaculture production value over the same period.	Shows the value of aquaculture production as a percentage of total GDP to give an indication of the importance of aquaculture to the economy.

	Reclassification: 1 = <0.05%, 2 = 0.05–0.2%, 3 = 0.2–0.5%, 4 = 0.5–2%, 5 = >2% Spatial resolution = whole country	
Undernourishment	Data source: FAO. The Hunger Map (FAO, 2004c) - Prevalence of undernourishment in the world. Spatial data developed as part of the state of food insecurity in the world (SOFI) reports. Reclassification: Classifications used are the same as those in the original FAO/SOFI hunger map (FAO, 2004c). 1 = <2.5%, 2 = 2.5-5%, 3 = 5-20%, 4 = 20-35%, 5 = >35% Spatial resolution = whole country	Shows the percentage of people who are undernourished and is used when investigating aquacultures significance in terms of food security.
Freshwater culture value as % GDP Brackish water culture value as % GDP Mariculture value as % GDP	Data sources: aquaculture production values from Fishstat plus (FAO, 2005). GDP values from world bank development indicators (World Bank, 2003). A mean GDP value from the years 2001 – 2003 is used in order for comparison with the mean values used for aquaculture production value over the same period. Reclassification: 1 = <0.02%, 2 = 0.02–0.1%, 3 = 0.1–0.5%, 4 = 0.5–1%, 5 = >1% Spatial resolution = whole country	The value of aquaculture production from freshwater, brackish and marine environments is shown individually as a percentage of total GDP. Separating aquaculture into different environmental categories may help indicate the type of species being cultured and to some extent location e.g. inland, coastal areas or in the sea. This can then be combined with data on specific climate variables to highlight areas at risk from droughts, floods etc.
Freshwater culture quantities as % total fisheries Brackish water culture quantities as % total fisheries Mariculture quantities as % total fisheries	Data sources: aquaculture and total fisheries production quantities from Fishstat plus (FAO, 2005). A mean value from the years 2001 – 2003 is used. Reclassification: 1 = <1%, 2 = 1-5%, 3 = 5-20, 4 = 20-50%, 5 = >50% Spatial resolution = whole country	As above except these layers show aquaculture production, by weight, from freshwater, brackish and marine environments as a percentage of total fisheries production.

Outputs

In all figures, areas for which there is no data for one or more of the data layers used are shown in black. Certain data may not be relevant in some areas, such as in the case of mariculture and landlocked countries. It is also likely that some countries are failing to report or are under reporting data that would be relevant, and will therefore be under represented in terms of sensitivity and ultimately vulnerability. This is an accepted limitation of the assessment and while higher quality and more complete data sets would be of great benefit, the data currently available are still considered highly useful.

Layer 1: Sensitivity (Fig 2.4)

Constructed by MCE using layers:	Weighting
• Aquaculture production quantities as % of total fisheries	0.25
• Fish protein as % animal	0.25
• Aquaculture production value as % GDP	0.25
• Undernourishment	0.25

Layer purpose

This layer is designed as a broad and general assessment of sensitivity encompassing as many issues as possible and not giving greater preference to any particular issue or area. It is intended that this layer will be used along with similar general layers for exposure and adaptive capacity to give an all-round, non issue specific, indication of vulnerable areas.

Weighting of components

Table 2.5 shows the results obtained from the questionnaires completed by the focus group. The focus group were advised that in the context of this study and vulnerability modelling process that sensitivity could largely be seen as the sensitivity of people to climate change via impacts on aquaculture i.e. how important aquaculture is to peoples livelihoods. Therefore the sensitivity sub model is aiming to give a spatial representation of where aquaculture features heavily in people's lives.

There was a very low level of agreement between decision makers (W = 0.037). Notably individuals A, B and E indicated undernourishment as very important while C and D scored it as fairly insignificant. There was also a relatively wide range of values given for the other three variables making up the Sensitivity layer. Discussion with the focus group indicated that different individuals were approaching the problem in different ways and tended to focus on specific issues, areas or categories of people in the limited time they had available.

While it is agreed here that undernourishment is a highly important issue where aquaculture can play an important role, highlighting areas of undernourisment by themselves says little about the significance of aquacultures role in relieving the problem at those locations. By combining the undernourishment and fish protein as a percentage of total animal protein layers, an indication of the importance of fish in the diets of people in areas of low food security can be gained, although it is still unknown to what extent this fish comes from aquaculture as opposed to capture fisheries. Adding the layer showing aquaculture production quantities as a percentage of total fisheries production will help address the last problem by indicating the relative importance of aquaculture. The layer representing aquaculture production value as a percentage of GDP will also give a general indication of the importance of aquaculture to a region while specifically focusing on its economic importance. In many areas aquaculture products, particularly those of higher value, may be sold as a cash crop generating money for the purchase of cheaper foods. The sale and perhaps export of aquaculture products will also provide an income for a range of people not directly involved in production but who provide a range of goods and services to the aquaculture industry, again here the contribution of aquaculture to the general economy may appear as an important indicator.

It was felt that due to the interacting nature of the layers used, and considering the large number of complex issues being represented by a relatively simple model that it was important not to weight any section too weakly and potentially exclude certain issues. Bearing the last point in mind, and considering the very varied weightings given by the focus group, the decision was taken that none of the component layers could be justified as significantly more important than any of the others and consequently equal weightings were used.

Table 2.5: Weighting of components by the focus group for the general sensitivity layer.

Component	Decision maker A		Decision maker B		Decision maker C		Decision maker D		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Aquaculture production quantities as % of total fisheries	0.1267	3	0.1518	3	0.3462	1	0.278	2	0.0838	4	0.197
Fish protein as % animal	0.1864	2	0.0759	4	0.2094	2	0.5135	1	0.2323	2	0.244
Aquaculture production value as % GDP	0.0847	4	0.3549	2	0.3462	1	0.1325	3	0.1337	3	0.210
Undernourishment	0.6023	1	0.4175	1	0.0982	3	0.076	4	0.5462	1	0.348

$W = 0.037$

Results

As expected, Asia with its high aquaculture production is shown to rank highly in terms of sensitivity and hence the importance of aquaculture to peoples livelihoods (figure 2.4). No area achieved the maximum value of 5, which would have required 3 out of 4 of the equally weighted component layers to score the maximum value.

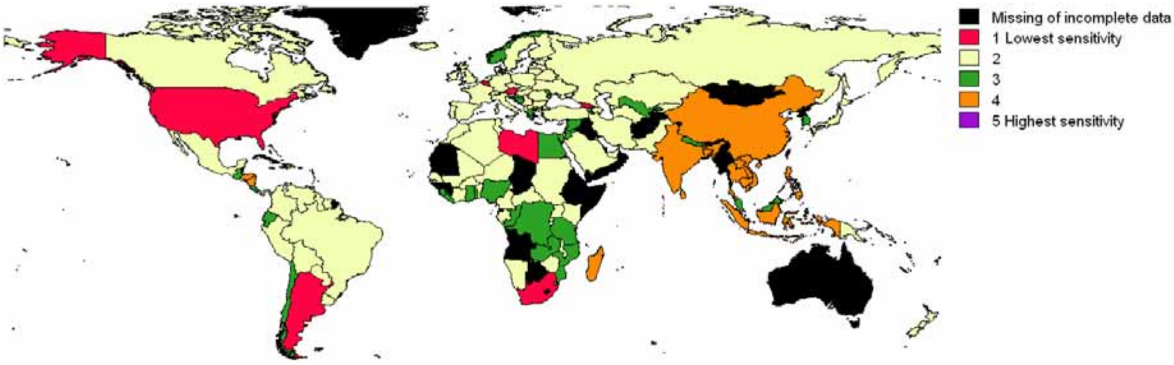


Figure 2.4: Sensitivity - a general non issue specific assessment.

Layer 2: Sensitivity - food security (Fig. 2.5)

Constructed by MCE using layers:	Weighting
• Undernourishment	0.5
• Aquaculture production quantities as % of total fisheries	0.25
• Fish protein as % animal protein	0.25

Layer purpose

This layer was designed to investigate the significance of aquaculture in terms of food security by combining data on the percentage of undernourished people with indicators showing the importance of fish and aquaculture products to the diet.

Weighting of components

All the decision makers agreed that undernutrition was the most important component when investigating sensitivity in terms of food security (see Table 2.6). Opinions were varied as to which of the other two factors was most significant but taking an average of all 5 decision makers results in aquaculture production as a percentage of total fisheries production and fish protein as a percentage of animal protein being given very similar scores. It is agreed here that undernourishment is the most important component but for the reasons given in relation to the same components in the previous (Sensitivity) layer the other two components also play a significant role. It was decided to set the final weighting for undernourishment at 0.5, slightly lower than the focus group average of 0.591, and then give even weightings of 0.25 to the other two components.

Table 2.6: Weighting of components by the focus group for the layer representing sensitivity in terms of food security.

Component	Decision maker A		Decision maker B		Decision maker C		Decision maker D		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Undernourishment	0.5396	1	0.4934	1	0.5396	1	0.7471	1	0.637	1	0.591
Aquaculture production quantities as % of total fisheries production	0.297	2	0.3108	2	0.1634	3	0.1336	2	0.1047	3	0.202
Fish protein as % animal protein	0.1634	3	0.1958	3	0.297	2	0.1194	3	0.2583	2	0.207

Results

The Sensitivity in terms of food security layer is shown in Fig 2.5. Asia again features highly with North Korea being the only country to achieve the maximum value. While in general aquaculture does not play such a significant role in Africa compared with Asia, parts of Africa are still classed as significant due to the high prevalence of malnutrition in some countries.

Case studies at the country or probably regional level will be needed to assess more accurately aquacultures role in local food security, where factors such as the type of species produced and its relative cost and availability when compared with other locally available alternatives can be considered. Details of imports and exports will also prove useful. Knowing the types of species cultured will also be relevant when assessing the implications of particular climate variables such as temperature rise.

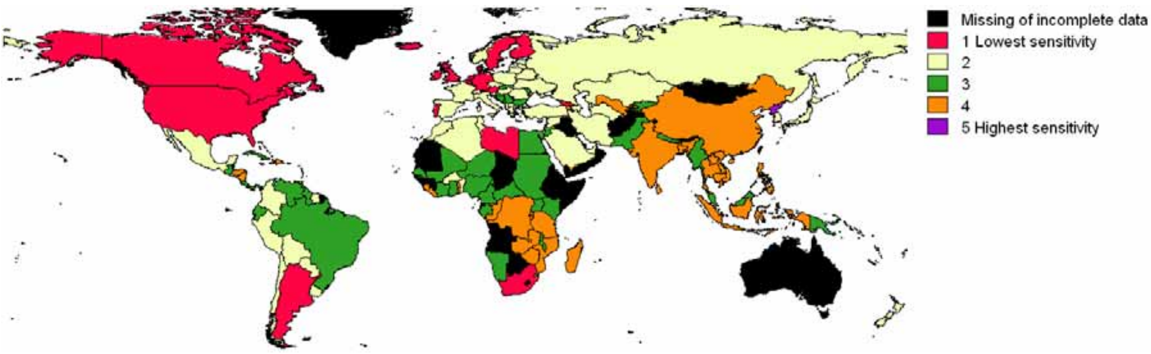


Figure 2.5: Sensitivity – food security

Layer 3: Aquaculture production value as % of GDP (Fig 2.6)

Figure 2.6 shows aquaculture production as a percentage of a country's GDP with the intention of indicating economic sensitivity to impacts on aquaculture. A link will exist to some extent between the size of the economic contribution and the proportion of a country's population that are stakeholders in aquaculture, although this will depend on the range of culture being undertaken and associated scales, intensity and degree of automation involved.

Although more detailed country level analysis would be needed there may be links between aquaculture's economic contribution and the attention it receives from investors and policy makers. This, combined with the extent of national resources, is likely to be a contributing factor to aquaculture's capacity to adapt to climate change.

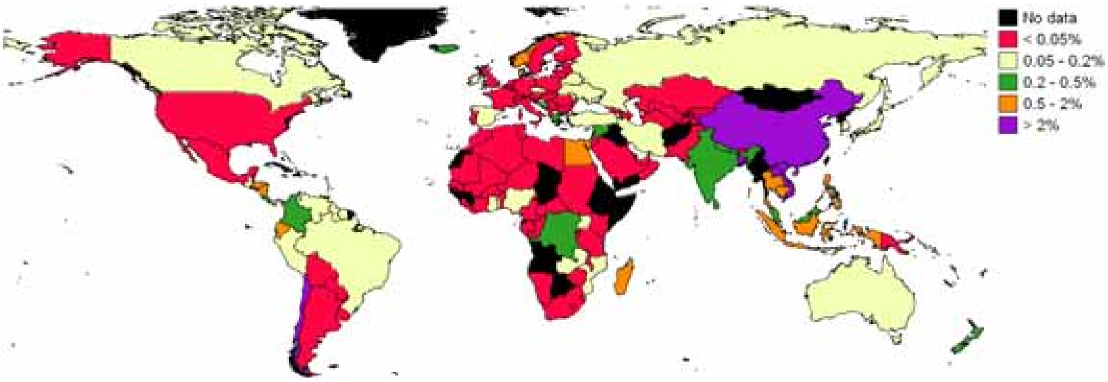


Figure 2.6: Aquaculture production value as a percentage of GDP (layer 3).

Layer 4: Sensitivity - freshwater aquaculture (Fig 2.7)

Constructed by MCE using layers:	Weighting
• Freshwater aquaculture production value as % of GDP	0.33
• Freshwater aquaculture production quantities as % of total fisheries	0.66

Layer purpose

This layer aims to compare the importance of freshwater aquaculture between different countries by combining data on production values from freshwater as a percentage of the GDP and production quantities of freshwater aquaculture as a percentage of total fisheries. Separating aquaculture into different environmental categories may give a rough indication of the type of species being cultured and to some extent location e.g. inland, coastal areas or marine. This can then be combined with data on specific climate variables to highlight areas at risk from droughts, floods etc.

Weighting of components

The weightings given by the focus group are shown in Table 2.7 with a strong agreement that production quantities from freshwater aquaculture as a percentage of total fisheries are more significant than the production value of freshwater aquaculture as a percentage of GDP. It is agreed here that production quantity as a percentage of total fisheries should be given greatest significance, and will better represent the large volume low value freshwater aquaculture often associated with developing countries. However this component alone does not indicate the size of the total fishery and consequently the actual size of the freshwater aquaculture sector within it. It is felt therefore that the production value of freshwater aquaculture as a percentage of GDP will play an important role in indicating the size and significance of the sector within a country not only to those directly involved in production, but also to those indirectly involved through the supply of goods and services. With these considerations in mind it was felt that the group's bias towards freshwater aquaculture production quantities as a percentage of total fisheries was too strong and it was decided to give weightings of 0.66 for production quantity and 0.33 for production value.

Table 2.7: Weighting of components by the focus group for the layer investigating sensitivity in terms of freshwater aquaculture.

Component	Decision maker A	Decision maker B	Decision maker C	Decision maker D	Decision maker E	Mean weighting using all 5 decision makers
Freshwater aquaculture production value as % of GDP	0.25	0.33	0.25	0.25	0.166	0.249
Freshwater aquaculture production quantities as % of total fisheries	0.75	0.66	0.75	0.75	0.833	0.749

Results

The layer indicating sensitivity in terms of freshwater aquaculture (layer 4) is shown in Fig 2.7. Asia scores highly with notable freshwater species including Cyprinids and tilapias, with higher value species such as freshwater prawns, snakehead and some catfish species being significant in some areas. Some eastern European countries also appear significant with carp species being of most importance.

Much freshwater aquaculture will consist of ponds where climate impacts are likely to take the form of water quality issues due to limited water availability and/or elevated temperatures as well as the impacts of extreme events such as floods and droughts. Freshwater species are often low value high volume species that in developing countries are likely to play a bigger role in food security compared with brackish or marine species.

It is worth noting that some species such as tilapias and salmonids are recorded as being cultured from brackish and marine as well as freshwater environments (Fishstat plus).

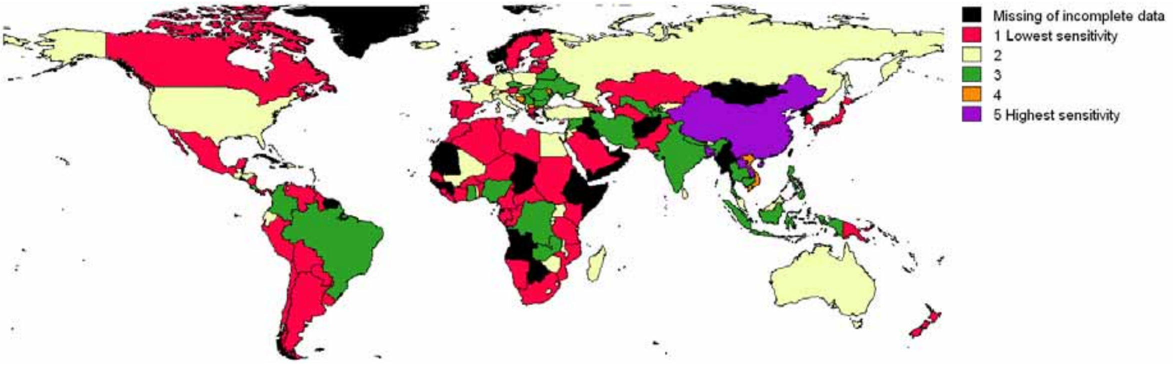


Fig 2.7: Sensitivity in relation to freshwater aquaculture (layer 4).

Layer 5: Sensitivity - brackish water aquaculture (Fig 2.8)

Constructed by MCE using layers:	Weighting
• Brackish water aquaculture production value as % of GDP	0.33
• Brackish water aquaculture production quantities as % of total fisheries	0.66

Layer purpose

Constructed as for freshwater but highlighting the importance of brackish water aquaculture.

Weighting of components

Table 2.8 shows the weightings assigned by the focus group. As in the case of the freshwater sensitivity layer (layer 4) there was a strong agreement as to the greatest significance of aquaculture production quantities as a percentage of total fisheries compared with production value as a percentage of GDP. It was decided to use the same weightings of 0.66 and 0.33 as used in the freshwater sensitivity layer (layer 4). It was felt similar arguments applied, and that these weightings corresponded very closely with mean values obtained from the focus group.

Table 2.8: Weighting of components by the focus group for the layer investigating sensitivity in terms of brackish water aquaculture.

Component	Decision maker A	Decision maker B	Decision maker C	Decision maker D	Decision maker E	Mean weighting using all 5 decision makers
Brackish water aquaculture production value as % of GDP	0.33	0.33	0.25	0.33	0.25	0.298
Brackish water aquaculture production quantities as % of total fisheries	0.66	0.66	0.75	0.66	0.75	0.696

Results

In the Asian countries shown to be significant with a score of 4 (Fig 2.8), shrimp species are of most importance with the same also being true for locations in Central and South America, and Australia. Egypt is the exception owing its high score for the brackish water culture of tilapia and mullet species.

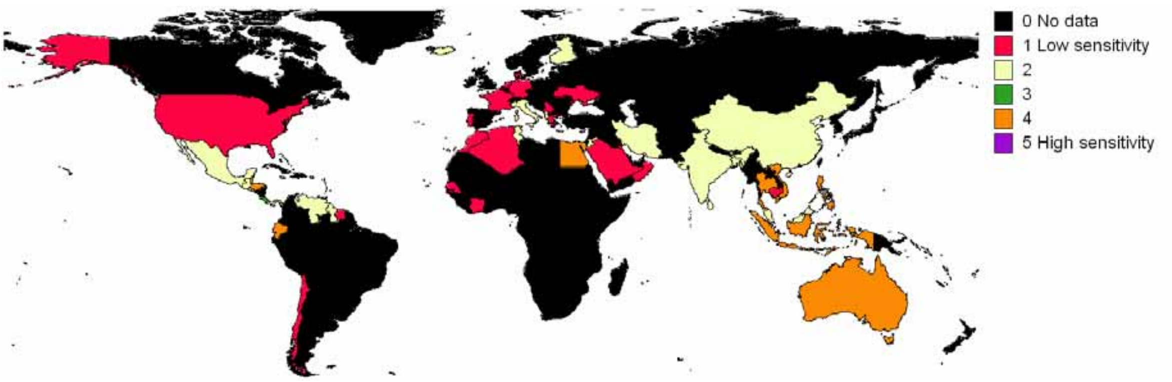


Fig 2.8: Sensitivity in relation to brackish water aquaculture (layer 5).

Brackish water culture is typically found in coastal areas and may be at risk of flooding during storm surges. Warming trends may be significant in reducing water quality in some areas, and loss of available land due to sea level rise may be an issue in the longer term. Shrimp species typically cultured are of high value and often exported meaning that climate related changes in relative costs of products between regions could be significant. Changes in the availability and costs of inputs, notably fishmeal, could also have an impact on the shrimp culture industry. In areas where seed for shrimp culture is of wild origin then changes to coastal ecosystems such as damage to mangrove areas associated with sea level rise could have an impact.

Layer 6: Sensitivity – mariculture (Fig 2.9)

Constructed by MCE using layers:	Weighting
• Marine aquaculture production value as % of GDP	0.33
• Marine aquaculture production quantities as % of total fisheries	0.66

Layer purpose

The same as in layers 4 and 5 but in this case indicating sensitivity in relation to mariculture.

Weighting of components

Table 2.9 shows the weightings given by the focus group for the layer representing sensitivity in relation to mariculture. The mean weightings obtained from the five group members are the same as the previous brackish water layer (layer 5). The same arguments along with the same weightings of 0.66 and 0.33 are applied here as in the last two layers (layer 4 and layer 5).

Table 2.9: Weighting of components by the focus group for the layer investigating sensitivity in terms of mariculture.

Component	Decision maker A	Decision maker B	Decision maker C	Decision maker D	Decision maker E	Mean weighting using all 5 decision makers
Mariculture production value as % of GDP	0.25	0.33	0.25	0.33	0.33	0.298
Mariculture production as % of total fisheries	0.75	0.66	0.75	0.66	0.66	0.696

Results

The countries scoring highest for sensitivity in relation to mariculture (figure 2.9) are China and South Korea where a significant proportion of production in terms of value comes from molluscs and seaweeds. Norway and Chile also feature highly with their large salmon industries although due to their adaptive capacities and levels of exposure in the current model they do not feature highly in terms of overall vulnerability. Nicaragua is indicated as important with shrimp accounting for the majority of the sectors production.

The limitations of the indicators used in this layer have already been mentioned in the case of layer 4 i.e. that they only represent a proportion of a larger figure without knowing the actual size of a countries aquaculture industry and more specifically the number of people involved. Unfortunately reliable data indicating numbers of aquaculturists is not currently widely available. It would seem likely that in the case of the current layer countries such as Vietnam and the Philippines may have been under represented as although they may have significant mariculture sectors these may only represent a moderate proportion of what are very large total fisheries industries.

Direct effects of climate change on marine culture are likely to be varied (see Table 1.7) and include damage to structures and loss of stock during extreme events such as storms as well as increase in disease or toxic algae blooms due to warming and changes in ocean current patterns. In the case of common mariculture fish species such as salmonids, groupers and milkfish, a significant amount of fishmeal and oil is currently needed in the diet. The influence of climate change on the availability and price of this input may prove to be a significant indirect impact (see indirect impacts).

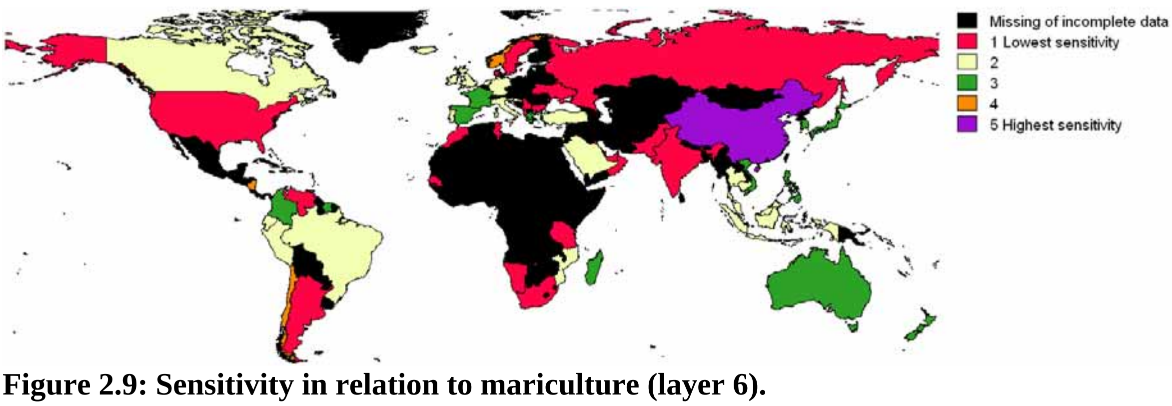


Figure 2.9: Sensitivity in relation to mariculture (layer 6).

Exposure sub-model

The layers used in the construction of the exposure sub model are shown in Table 2.10. This sub model deals with changes in climate trends, rather than extreme events which are covered in the subsequent section, and incorporates changes in mean precipitation and temperature along with population density. Unfortunately it was not possible to include the effects of sea level rise in the current study due to limitations in data availability and difficulties in determining significance to countries when modelling at low resolution and the global scale. The impacts of sea level rise will be best assessed during more local case studies making use of qualitative observations as well as by spatial modelling using data such as terrain elevation and land cover type to try to predict impacted areas.

Mean temperature trends are predicted with a reasonable level of confidence by GCMs (IPCC, 2001a), making them useful indicators of climate change. When considering effects on aquaculture, however, the impacts may be both positive and negative (see impacts on aquaculture production) with the type of species being cultured and the location also being important variables. For the purpose of the exposure sub model presented here greater temperature change is taken as a general proxy for climate change and the assumption is made that the level of temperature increase will indicate to some extent the general level of impact on the local ecosystem. While there may be perceived benefits to higher temperatures in some cases, there may also be as yet unknown negative consequences in some areas linked to high levels of warming.

Increases or decreases in precipitation may also be considered positive or negative depending on whether vulnerability concerns are over water stress and droughts, or flooding. Separate layers are created here placing greatest significance on increased or degreased mean precipitation in order to cover these possibilities.

Climate models and scenarios used to provide data

The spatial data used to investigate changes in temperature and precipitation was produced by the Canadian Centre for Climate Modelling and Analysis (CCCMA) using the second generation Coupled Global Climate Model (CGCM2). This model was chosen because data were available as means for 20 year climatologies which saves a large amount of time and work with data processing. The model also produces mean results that are in the mid range of those produced by a range of models. A mean value from the outputs of a number of climate models would help reduce the effect of inter-model variation but sufficient time and resources were not available during the current study to allow this.

Mean values from the period 2040 – 2060 were used under SRES scenario A2. Data for the period 2080 – 2100 and for SRES scenario B2 were also available (see box 2.3 for scenario definitions). While the amount of change seen is greater for 2080 – 2100 compared with 2040 – 2060, and for A2 compared with B2, the relative spatial distribution of change is very similar. The purpose of the vulnerability assessment model in its current form is to highlight relative levels of risk between areas and countries, and as reclassification of data was done to achieve this and is not related to specific thresholds. It was therefore considered that the use of a range of SRES scenarios at this stage would provide relatively little benefit and view of time and resource limitations it was decided to use a single Scenario and time period for the current model.

Box 2.3 Definition of SRES scenarios A2 and B2 as given by the IPCC (2001a).

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

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

Further studies focussed on quantifying water availability and temperature related aquaculture issues would be highly interesting. This type of modelling would probably be most useful at a local level and in relation to specific culture systems. In such cases the use of a range of emissions scenarios and time periods - maximum and minimum values as well as means - would be very useful in predicting a variety of potential consequences.

Table 2.10: Data layers used in the exposure sub models along with details of their construction and significance.

layer	Data sources, layer construction, reclassification and resolution	Description and significance
Change in annual mean temperature by 2050 under SRES A2	Data sources: Canadian Centre for Climate Modelling and Analysis (CCCMA). Construction: produced by overlaying a layer showing mean predicted temperature for years 2040 – 2060 under SRES A2 using CGCM2, with a layer showing mean predicted temperatures from a 200 year control run using late 20th	Layer showing predicted temperature change by the middle of the 21st century using a 96 x 48 cell global grid. The layer is classified to give higher significance to greater temperature increase in order to use temperature as a general proxy for climate change at a given location.

	century levels of greenhouse gases. Reclassification: (°C change in annual mean temperature) 1 = -2 to 0.5 °C, 2 = 0.5 to 1°C, 3 = 1 to 2 °C, 4 = 2 to 4 °C, 5 = >4 °C. Resolution: 3.75 degrees (96 x 48 grid).	
Percentage decrease in annual mean precipitation by 2050 under SRES A2	Data sources: Canadian Centre for Climate Modelling and Analysis (CCCMA). Coupled General Circulation Model vesion 2 (CGCM2). Construction: produced by overlaying a layer showing mean predicted precipitation values (mm/day) for years 2040 – 2060 under SRES A2 using CGCM2, with a layer showing mean predicted precipitation from a 200 year control run using late 20th century levels of greenhouse gases. Reclassification: (Percentage decrease in annual mean precipitation) 1 = 0%, 2 = 0 to 2%, 3 = 2 to 5%, 4 = 5 to 10%, 5 = >10%. Resolution: 3.75 degrees (96 x 48 grid).	Layer showing predicted precipitation change by the middle of the 21st century using a 96 x 48 cell global grid. This layer is classified to give greatest significance to reduced average precipitation levels. This can then be used to identify areas where reduction in water availability may be an issue. The layer does not indicate the existing availability of water as would be given by a water balance model, or say anything about an areas suitability for aquaculture in terms of water availability. Water availability for aquaculture is a complex issue that depends on many factors and many competing water users. The intension here is to highlight areas likely to experience greatest change and again use this to indicate the degree of climate change impacts. Areas known to have existing aquaculture that are predicted to experience a significant reduction in mean precipitation can then be highlighted for further investigation.
Percentage increase in annual mean precipitation by 2050 under SRES A2	Data sources: as above Construction: as above Reclassification: (Percentage increase in annual mean precipitation) 1 = 0%, 2 = 0 to 2%, 3 = 2 to 5%, 4 = 5 to 10%, 5 = >10%. Resolution: 3.75 degrees (96 x 48 grid).	This layer is the same as the layer above but the classification is reversed to place significance on areas with increased precipitation. This layer is intended to be used in conjunction with data on flood events to highlight inland areas at risk from flooding.
Population density for the year 2000	Data sources: Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT). 2005. Gridded Population of the World Version 3 (GPWv3): Population Density Grids.	Layer showing population density for the year 2000 (the most recent period for which data at this resolution is available) As well as indicating the number of people likely to be impacted, areas with higher population density are also likely

	Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University. Available at http://sedac.ciesin.columbia.edu/gpw. (01.12.2005). Reclassification: (number of people per km^2) 1 = <25, 2 = 25 – 100, 3 = 100 – 250, 4 = 250 – 500, 5 = >500. Resolution: 2.5 arc minutes.	to place increased stress on limited water supplies as well as producing more pollution. These factors when combined with changes in mean temperature and / or water availability may have a negative impact on aquaculture. While higher population densities may have certain benefits to aquaculture in terms of increased human and social capital they are considered here to be generally negative in terms of climate change impacts.

Outputs

Layer 7: Exposure SRES A2 (Fig 2.10)

Constructed by MCE using layers:	Weighting
• Percentage change in annual mean temperature by 2050 under SRES A2	0.3
• Percentage decrease in annual mean precipitation by 2050 under SRES A2	0.4
• Population density for the year 2000	0.3

Layer purpose

This layer is designed to give a general all-round indication of exposure without focusing on any particular variable. The component layers are classified so that increases in population density and temperature equate to a greater impact, while in the case of precipitation the reverse is true with greater impact coming from decreased precipitation levels.

Weighting of components

There appeared to be relatively little agreement between the focus group when it came to weightings for the general exposure layer (Table 2.11). Two members of the group gave equal weightings to all three components while two others gave relatively strong weighting to precipitation change, an average weighting to temperature change and a relatively weak weighting to population density. The final member of the group gave a strong weighting to population density, a moderate weighting to precipitation change and a relatively weak weighting to temperature change.

Precipitation change and the consequences in terms of water supply perhaps carry the greatest risks to aquaculture development and sustainability. However reduction in precipitation is largely a problem of freshwater aquaculture which although highly significant that the global level is not represented so strongly in all areas. The population density layer should probably not be underrepresented either as the number of people exposed has obvious significance. Population density could also be considered relevant to the sensitivity sub model when considering issues such as food security. However it was felt that overall the indicator was better suited to the exposure sub model as it was relevant to all exposure situations. It was also felt that it was best to include a single indicator only once in the model as a whole in order to save confusion.

There is agreement here with those members of the of focus group who assigned greater significance to precipitation change, but it is also felt that the weighting for precipitation should not be too strong to the extent of excluding the others components. A weight of 0.4 was given to the precipitation change, while temperature change and population density were both given equal weights of 0.3. These scores are similar to the mean weights obtained from the focus group although it should be remembered that the variance seen within the focus group was considerable.

Table 2.11: Weighting of components by the focus group for the layer investigating representing general exposure to climate change (layer 7).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker D		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Annual mean temperature change to 2050 SRES A2	0.333	1	0.33	1	0.1047	3	0.314	2	0.285	2	0.274
Annual mean precipitation change to 2050 SRES A2	0.333	1	0.33	1	0.258	2	0.558	1	0.571	1	0.410
Population density for the year 2000	0.333	1	0.33	1	0.637	1	0.122	3	0.143	3	0.313

Results

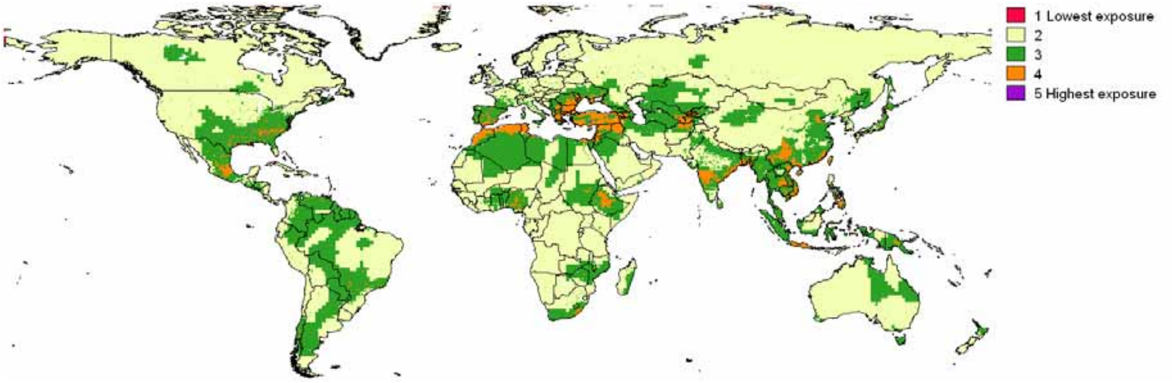


Fig 2.10: General exposure to climate change based on precipitation decrease, temperature increase and population density (layer 7).

Layer 8: Exposure – precipitation change SRES A2 (Fig 2.11)

Constructed by MCE using layers:	Weighting
• Percentage change in annual mean temperature by 2050 under SRES A2	0.2
• Percentage decrease in annual mean precipitation by 2050 under SRES A2	0.6
• Population density 2000	0.2

Layer purpose

This layer uses the same component as the previous exposure layer (layer 7) but places a greater emphasis on predicted precipitation change with the aim of indicating sites of potential water stress. In combination with the extreme events layer depicting areas of frequent drought, the layer depicting sensitivity in terms of freshwater aquaculture and the adaptive capacity layer, the current layer will form part of a vulnerability model focusing on the potential impact of drought on freshwater aquaculture.

Weighting of components

Layers 8, 9 and 10 are intended to focus on precipitation decrease, precipitation increase, temperature increase, and population density respectively. Due to the nature of these layers it is intended that they should have a strong bias towards the variable which they represent, and this largely determines the weightings of their relative components. The discussion group were not consulted with regard to any of the exposure layers other than layer 7 which aims to give an all-round indication of exposure without focusing on any one specific issue or variable.

Results

Substantial areas of high exposure are indicated in Africa, Asia, Europe and the Americas (Fig 2.11). Precipitation change in the current model is represented as a percentage change and is also based on annual mean precipitation values. Higher resolution, and typically more local, studies that can take into account seasonality, as well as the current climate, water balance, and the relationship between precipitation and surface water extent (de Wit & Stankiewicz, 2006), will be needed in many areas before informed decisions regarding aquaculture development can be made.

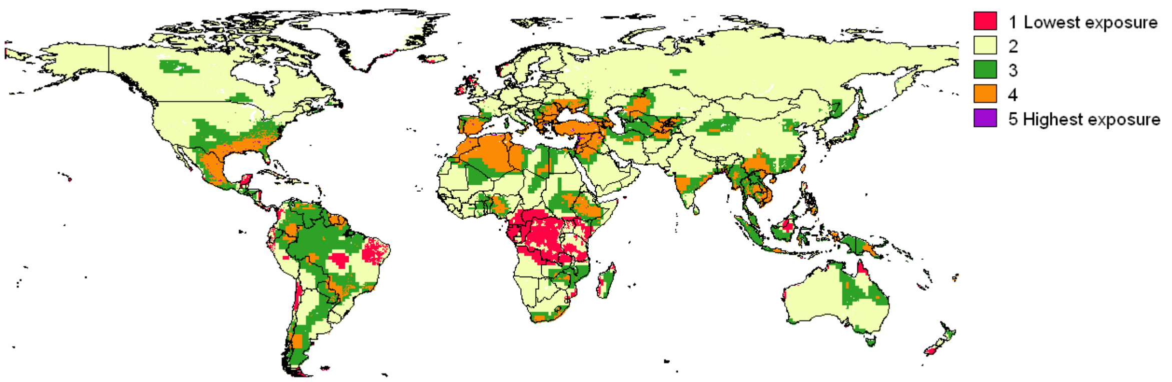


Fig 2.11: Exposure to climate change based with a strong emphasis on decreased precipitation (layer 8).

Layer 9: Exposure - precipitation change SRES A2 reversed (figure 2.12)

Constructed by MCE using layers:	Weighting
• Percentage change in annual mean temperature by 2050 under SRES A2	0.2
• Percentage increase in annual mean precipitation by 2050 under SRES A2	0.6
• Population density 2000	0.2

Layer purpose

In this layer the scoring for the precipitation component has been reversed so that areas with the greatest increase in precipitation are given the highest score. This layer is used as part of a vulnerability model investigating potential flood risk.

Weighting of components

As for layer 8.

Results

Areas of high exposure with the emphasis on increased precipitation are predicted in the northern India region (figure 2.12). It is worth remembering that increased precipitation over a given area may have impacts on other areas some distance away. In the current case a large part of the area indicted as having the highest exposure is situated over the catchment area of the Ganges. It is possible that increases in precipitation in this area may have severe down river flooding implications for Bangladesh (Mirsa, 2002; Mirsa *et al*., 2001 & 2003). The issue of cross border drainage and consequent flooding in Bangladesh are discussed in more detail in the Bangladesh case study (page 104).

While precipitation changes are represented here as annual averages, a lot of potential flood danger will come in the form of changes in seasonal variability, increases in the intensity of wet seasons, or via increases in the intensity and/or frequency of extreme events. Extreme flood events are addressed in the following section using historical flood data. Predicting variation in the timing and intensity of seasonal precipitation events contains a lot of uncertainty although it seems likely that the Asian monsoon will become more varied with greater intensities, and that in general areas with increased mean precipitation will see greater variation while those with a mean decrease may see less (IPCC, 2001a).

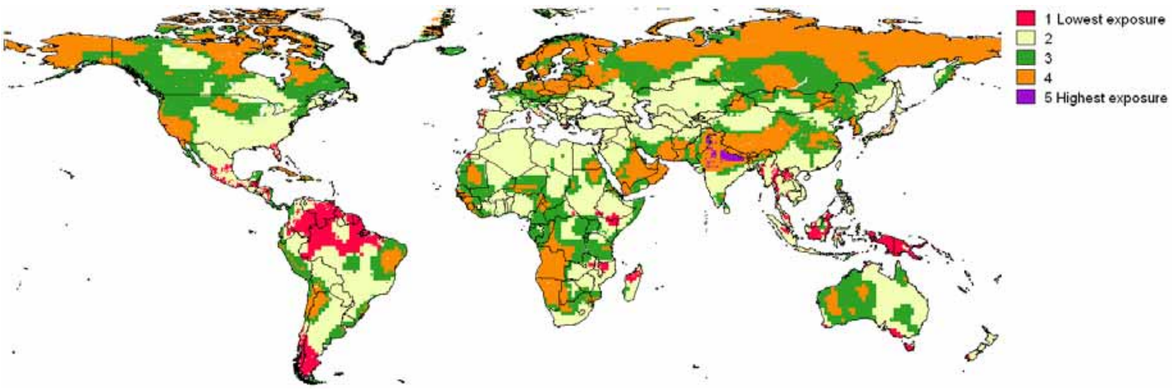


Fig 2.12: Exposure to climate change based with a strong emphasis on increased precipitation (layer 9).

Layer 10: Exposure – population density SRES A2 (Fig 2.13)

Constructed by MCE using layers:	Weighting
• Percentage change in annual mean temperature by 2050 under SRES A2	0.2
• Percentage decrease in annual mean precipitation by 2050 under SRES A2	0.2
• Population density 2000	0.6

Layer purpose

Constructed as for layers 8 and 9 but giving greatest significance to areas with high population densities. This layer is used as a part of the vulnerability assessment that focuses on issues of food security.

Weighting of components

See layer 8.

Results

As would be expected highly populated countries in Asia such as India, China and Bangladesh feature strongly (Fig 2.13).

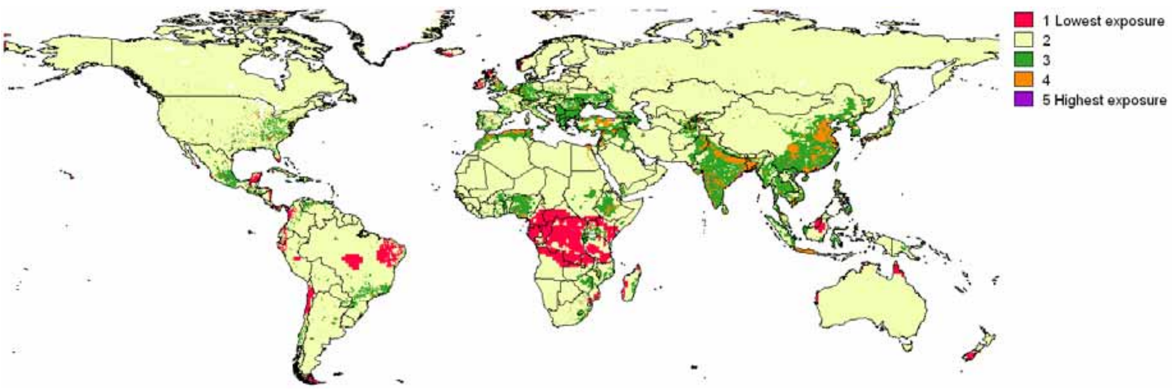


Fig 2.13: Exposure with the emphasis on densely populated areas (layer 10).

Temperature change

While temperature increase is a significant component of climate change, in the case aquaculture there will be both positive and negative impacts depending on species, location and culture methods. For this reason it was felt that a layer focusing specifically on temperature was not appropriate for inclusion within the vulnerability assessment model, and it was decided to only include temperature at a moderately low level in the general exposure layer (layer 7) as a proxy for climate change intensity.

Figure 2.11 shows predicted mean temperature increase in ˚C between the late twentieth century and 2050 and is included here as a reference to be used with the other data and information within this report when considering climate related aquaculture issues. While Fig 2.11 demonstrates how a sizeable proportion of global average temperature increase will be accounted for by high latitudes it is important to remember that the data shown is for annual mean increase which will be a component of mean minimum as well as mean maximum temperatures and that these may not increase equally. There may also be changes in the average temperature range at the diurnal, seasonal, or inter-annual time scales, as well as changes in the amount of variation seen in temperature patterns, and the number of very hot or cold days.

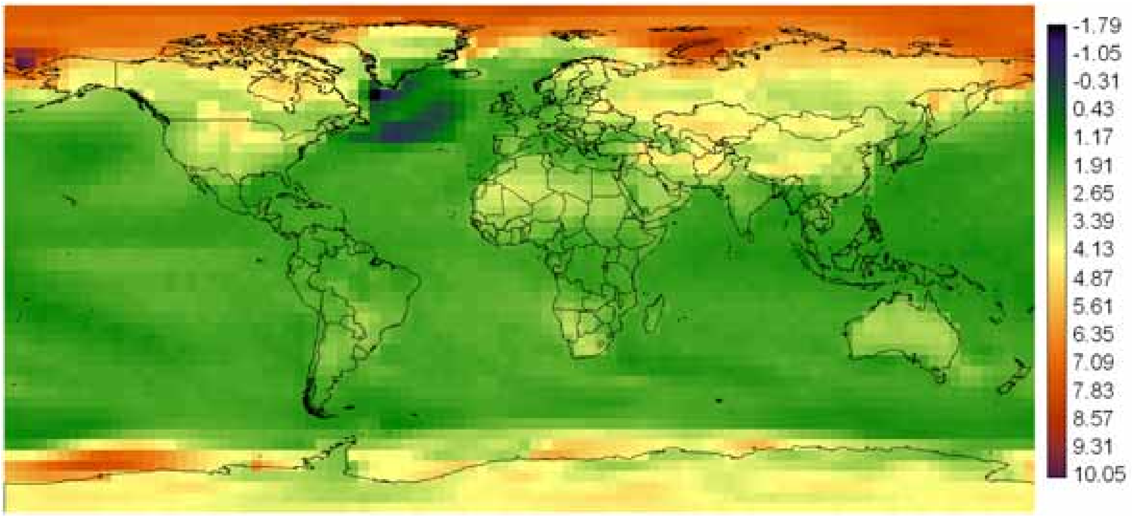


Figure 2.14: Predicted annual mean temperature change (°C) between late 20th century and 2050 using CGCM2 and SRES scenario A2.

Exposure to extreme climatic events sub-model

The extreme events sub-model also looks at exposure but in terms of climate shocks. Predicting the location, frequency and intensity of extreme climate events involves a lot of uncertainty. There is little agreement between models for many climate variables (see Climate prediction) although there is general speculation that the number and intensity of extreme events may increase and thus should be considered when assessing climate change vulnerability.

One method for assessing risk from extreme climatic events at a given location is to look at the prevalence of past events and assign risk values accordingly (e.g. Islam & Sado, 2000) making the assumption that a general increase in the amount or severity of extreme events will be most likely in areas where they are currently common. This approach is used in the current study with the types of events covered determined by the availability of useable spatial data. All extreme event data used was obtained from the Center for Hazards and Risk Research (CHRR) at Columbia University. Data for cyclones, floods and droughts were available; details are shown in Table 2.12.

Table 2.12: Data layers used in the exposure to extreme climatic events sub models along with details of their construction and significance.

Layer	Data sources, layer construction, reclassification and resolution	Description and significance
Cyclone risk	Data source: Center for Hazards and Risk Research (CHRR), Center for International Earth Science Information Network (CIESIN), International Bank for Reconstruction and Development/The World Bank, and United Nations Environment Programme Global and Regional Integrated Data Geneva (UNEP/GRID-Geneva). Data available from: http://www.ldeo.columbia.edu/chrr/research/hotspots/coredata.html Reclassification: Layers were obtained from CHRR classified on a scale of 1 – 10 with 10 representing the highest hazard. Layers were reclassified on a scale of 1 – 5 in order to be used with the other layers and sub models. Reclassification was as follows: 1 = 1 to 2, 2 = 3 to 4, 3 = 5 to 6, 4 = 7 to 8, 5 = 9 to 10. Resolution: 2.5 arc minutes.	Layer showing cyclone hazard based on past events between 1980 and 2000. Used to assess cyclone risk at a given location.
Drought risk	As above	Layer showing drought hazard based on past events between 1980 and 2000. Used for a spatial assessment of drought risk.
Flood risk	As above	Layer showing flood hazard based on past events between 1985 and 2003. Used for a spatial assessment of flood risk.

Outputs

Layer 11: Cyclone risk (Fig. 2.15)

A single component layer showing risk from cyclones based on historic data and classified on a scale of 1 to 5 with 5 representing the greatest risk.

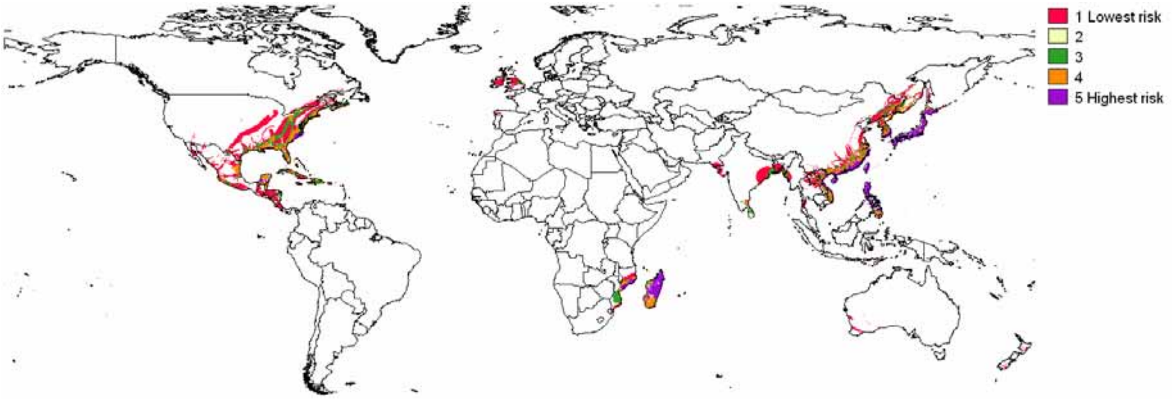


Fig: 27 Cyclone risk based on CHRR data.

Layer 12: Flood risk (Fig. 2.16)

Risk from floods based on historic data and classified on a scale of 1 to 5 with 5 representing the greatest risk.

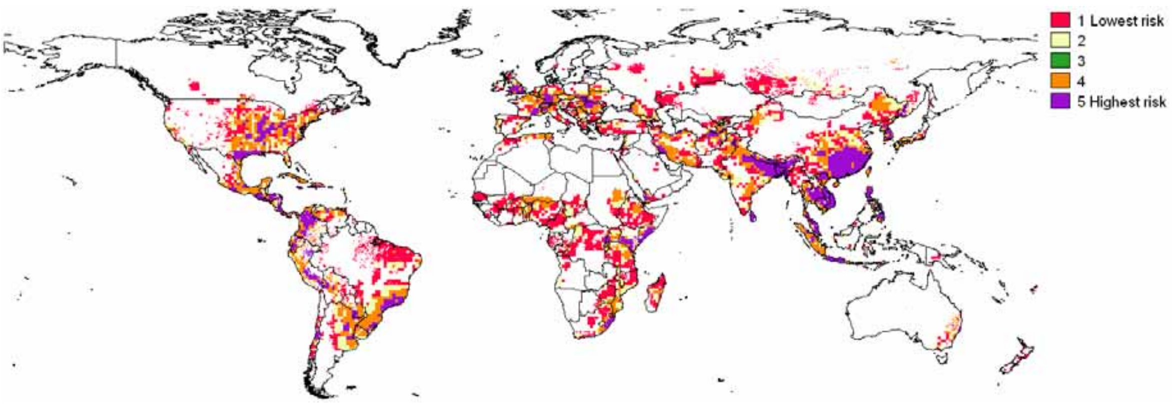


Fig 2.16: Flood risk based on CHRR data.

Layer 13: Drought risk (Fig. 2.17)

Risk from drought based on historic data and classified on a scale of 1 to 5 with 5 representing the greatest risk.

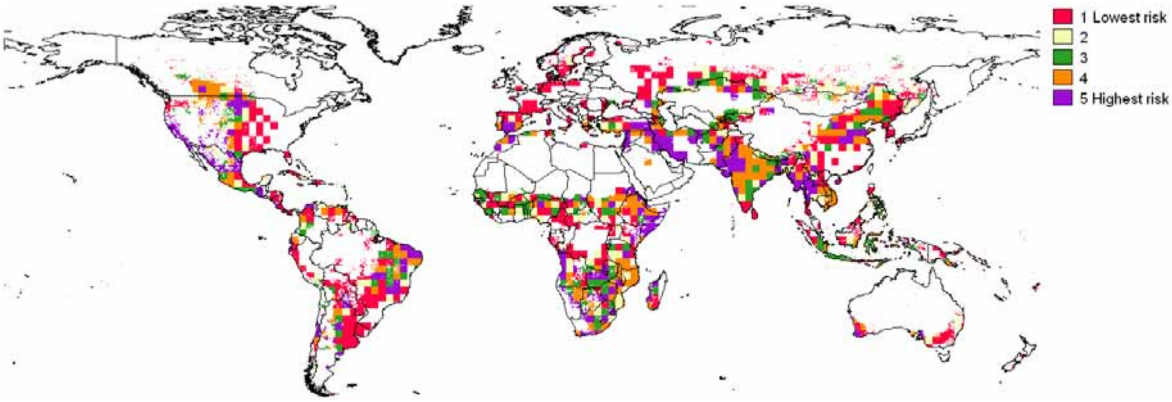


Fig. 2.17: Drought risk based on CHRR data.

Layer 14: Extreme events (Fig. 2.18)

Constructed by MCE using layers:	Weighting
• Cyclone risk	0.3
• Flood risk	0.3
• Drought risk	0.4

Layer purpose

This layer combines data for floods, cyclones and droughts shown in layers 11 to 13 into a single layer. This layer can then be used in combination with the other general layers for sensitivity and exposure (layers 1 and 7), as well as the adaptive capacity layer (layer 15) to give a broad, non issue specific indication of vulnerability.

Weighting of components

Only 4 members of the focus group successfully contributed weightings to the current layer (see Table 2.13 for details). There was considerable variation in values given and the order of importance in which group members ranked the 3 components. As an average the highest score was given to droughts. Drought has the potential to seriously affect aquaculture, for example Vietnam has recently experienced its worst drought in 28 years resulting in significant impacts on the shrimp industry via water availability and quality issues (NACA, 2005). Droughts will generally occur over a longer time period and impacts will typically be more gradual with increasing production cost and difficulties compared with potential sudden losses typically associated with floods and cyclones. This does not necessarily mean that drought is less significant with loss of production over a prolonged period having potentially serious financial and/or food security implications as well as social problems associated with competition for water resources. The focus group ranked floods as the next most significant extreme event. Areas such as Bangladesh, where aquaculture is common, are flooded regularly. Floods bring risks such as the potential loss of stock, introduction of predators and disease, and damage to facilities and infrastructure. While in some cases flooding impact may be easier to mitigate against compared with droughts through the building of flood defences, there is perhaps a greater possibility of less direct impact such as in the case of transportation networks supplying goods and services to the aquaculture industry, as well as for transporting stock to market. Cyclones were ranked less highly by the group as a whole due to 2 of the 4 members giving them low levels of significance while both rating drought as the most important. This was not the view held by the other group members with one rating cyclones as most significant along with floods. Here it is felt that while cyclones are typically localised and only affect a portion of the world's aquaculture producing areas, their impact can be severe in terms of sudden loss of stock, facilities and infrastructure. Brackish and marine aquaculture is at particular risk due to their coastal location with potential for loss of marine cages due to wave damage and inundation of brackish ponds by storm surge events. Both marine and brackish water aquaculture often concern high value species requiring considerable financial input in terms of food resources hence the economic impact of stock loss can be severe.

In conclusion, it is agreed that drought is perhaps the most significant variable although the distinction is not large. It is felt that while flood and cyclone impacts may be broad ranging and operate in different ways, neither one can be considered of greatest significance when modelling at the global scale and with the current data. As a result drought has been given marginally greater significance while cyclone and flood events are represented as equal.

Table 2.13: Weighting of components by the focus group for the layer indicating risk from a combination of flood, drought and cyclone events.

Component layers	Decision maker B		Decision maker C		Decision maker D		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Cyclone risk	0.400	1	0.136	3	0.077	2	0.250	2	0.216
Flood risk	0.200	2	0.238	2	0.461	1	0.500	1	0.350
Drought risk	0.400	1	0.625	1	0.461	1	0.250	2	0.434

Results

A number of large aquaculture producing countries such as Vietnam and Bangladesh are highlighted here as facing considerable risk from extreme climatic events based on the frequency of past events and the assumption that these may become more frequent and/or more intense.

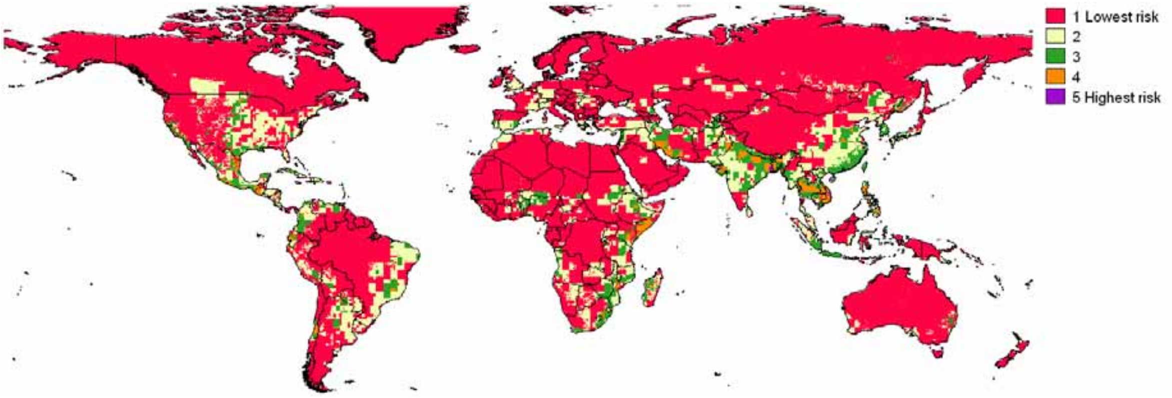


Fig 2.18: Risk of extreme events, combining data on floods, cyclones and droughts (layer 14).

Adaptive capacity sub-model

At the national level factors such as health, literacy and governance have been shown to relate strongly with adaptive capacity (Brooks *et al*., 2005). The selection of indicators in the current study was made with the aim of being broad ranging and relating to peoples access to a range of social, economic and human capitals while being limited by the availability of data at the global level. Table 2.14 lists the layers used in the adaptive capacity sub model and gives details of their construction and significance.

The current model uses per capita GDP as a measure of financial capital. What is not indicated in the current study is the distribution of wealth among the population. For country or region level studies then indicators such as the Gini coefficient or comparison of top *X* % with bottom *X* % would be useful. Poverty is often linked to particular areas or communities within a county making it hard for them to move or adapt to change. This could be a significant factor in relation to climate change and should be investigated at local level in regions that are considered vulnerable. Wealth distribution data has not been included in the current model due to limitations with available data. Specifically the number of countries covered was far less than the other indicators used in the adaptive capacity sub model, and due to varying methods of data collection values could not strictly be compared between countries (UNDP, 2005). If a similar method was used for studies at the national level or smaller then a far wider range of indicators are likely to be available and selections should be made carefully with consideration given to the particular vulnerabilities being assessed.

Table 2.14: Data layers used in the adaptive capacity sub model along with details of their construction and significance.

<table>
<tr><th>Layer</th><th>Data sources, layer construction, reclassification and resolution</th><th>Description and significance</th></tr>
<tr><td>Education index</td><td>

Source: United Nations Development Program (UNDP, 2005). Part of the human development data set. The data is indexed with potential values from 0 to 1. The education index is constructed from data on adult literacy rate and the proportion of the population enrolled in education (see technical notes from the 2005 UNDP human development report for details).

Reclassification: Reclassification was based on the UNDP categories which give scores relating to the index in question for high, medium or low levels of human development.

UNDP categories for the education index:
High human development = 0.96
Medium human development = 0.75
Low human development = 0.53

Maximum score in current UNDP data: 0.99
Minimum score in current UNDP data: 0.16

Classification on a scale of 1 to 5 with 1 representing highest adaptive capacity, and 5 the lowest, was achieved using the method described below. Resulting classifications are shown in table 2.14.2.

1. The high human development figure (0.96) was used as the lower threshold for class 1 and the low human development figure (0.53) as the upper threshold for class 5.
2. The medium human development figure (0.75) was set as the mid point of class 3.
3. The upper threshold for class 3 was then set one third of the way between the mid point and the high human development figure i.e. 0.75+(0.96-0.75)/3 and the lower threshold for class 3 was set a third of the way between the mid and low development figures i.e. 75-(75-53)/3. Numbers were rounded to 2 decimal places.

<table>
<tr><th rowspan="2">New classification</th><th colspan="2">Original education index scores</th></tr>
<tr><th>From</th><th>To</th></tr>
<tr><td>1</td><td>0.96</td><td>0.99</td></tr>
<tr><td>2</td><td>0.83</td><td>0.95</td></tr>
<tr><td>3</td><td>0.67</td><td>0.82</td></tr>
<tr><td>4</td><td>0.54</td><td>0.66</td></tr>
<tr><td>5</td><td>0.16</td><td>0.53</td></tr>
</table>

Table 2.14.1: Reclassification of UNDP education index scores.

Resolution: Whole country.

</td><td>It is assumed that the extent of education within a population will give some indication of human capital in terms of skills, and access to information and resources that may help people adapt to climate change through adaptation and diversification of livelihood options.</td></tr>
</table>

<table>
<tr>
<td>Per capita GDP (PPP) index</td>
<td>Source: United Nations Development Program (UNDP, 2005). Part of the human development data set. An index scaled from 0 – 1 calculated from; gross domestic product (GDP) at purchasing power parity (PPP) per capita. $40,000 and above represents a score of a of 1, $100 and below represents a sore of 0. The index scores are calculated between these two points using a logarithmic scale (see equation below and technical notes from the 2005 human development report for details).

$$\text{GDP index} = \frac{\log(\text{GDP per capita (PPP US\$)}) - \log(100)}{\log(40{,}000) - \log(100)}$$

Reclassification: The same methodology as applied to the education index layer was used for the GDP index based on the UNDP categories specified below. Resulting classifications are given in table 2.14.2.

UNDP categories for the per capita GDP (PPP) index:
High human development = 0.85
Medium human development = 0.70
Low human development = 0.58

Maximum score in current UNDP data: 1.00
Minimum score in current UNDP data: 0.28

Table 2.14.2: Reclassification of UNDP GDP index scores.
<table>
<tr><td rowspan="2">New classification</td><td colspan="2">Original GDP index scores</td></tr>
<tr><td>From</td><td>To</td></tr>
<tr><td>1</td><td>0.85</td><td>1</td></tr>
<tr><td>2</td><td>0.76</td><td>0.84</td></tr>
<tr><td>3</td><td>0.66</td><td>0.75</td></tr>
<tr><td>4</td><td>0.59</td><td>0.65</td></tr>
<tr><td>5</td><td>0.28</td><td>0.58</td></tr>
</table>
Resolution: Whole country.</td>
<td>An indicator of financial capital. The fact that purchasing power parity has been used is significant for the comparison between different countries.</td>
</tr>
<tr>
<td>Life expectancy index</td>
<td>Source: United Nations Development Program (UNDP, 2005). Part of the human development data set. An index scaled from 0 – 1 calculated with a life expectancy at birth of 25 years equating to a score of 0 and 85 years equalling 1 (see equation below and technical notes from the 2005 human development report for details).

$$\text{Life expectancy index} = \frac{\text{Life expectancy at birth (years)} - 25}{85 - 25}$$

Reclassification: The same methodology as applied to the education index layer was applied to the life expectancy</td>
<td>According to the World Health Organization, life expectancy provides a useful indicator of the overall health effects of environmental and other risk factors in a given population. Here the assumption is made that in countries where resources are limited to an extent that impacts significantly on life</td>
</tr>
</table>

<table>
<tr>
<td></td>
<td>index using the UNDP categories specified below. Resulting classifications are given in table 2.14.3.

UNDP categories for the life expectancy index:
High human development = 0.88
Medium human development = 0.70
Low human development = 0.35

Maximum score in current UNDP data: 0.95
Minimum score in current UNDP data: 0.12

Table 2.14.3: Reclassification of UNDP life expectancy index scores.
<table>
<tr><td rowspan="2">New classification</td><td colspan="2">Original life expectancy index scores</td></tr>
<tr><td>From</td><td>To</td></tr>
<tr><td>1</td><td>0.88</td><td>0.95</td></tr>
<tr><td>2</td><td>0.77</td><td>0.87</td></tr>
<tr><td>3</td><td>0.59</td><td>0.76</td></tr>
<tr><td>4</td><td>0.36</td><td>0.58</td></tr>
<tr><td>5</td><td>0.12</td><td>0.35</td></tr>
</table>
Resolution: Whole country.</td>
<td>expectancy, then the allocation of resources for climate change adaptation to a sector such as aquaculture could prove economically, politically and socially difficult.</td>
</tr>
<tr>
<td>Governance index</td>
<td>Source: Climate analysis Indicators Tool (CAIT, 2003) produced by the World Resources Institute (WRI). Originally created by the World Bank and based on 6 equally weighted factors; political stability, government effectiveness, regulatory quality, rule of law, voice and accountability, and corruption. For details see (Kaufmann et al., 2005).

Reclassification: The CAIT governance data is a mean of 6 indexes scaled from 0 to 100. No information is given relating the index score to real world values. Here the data is divided into 5 equal classes. Details are given in table 2.14.4.

Table 2.14.4: Reclassification of CAIT governance index scores.
<table>
<tr><td rowspan="2">New classification</td><td colspan="2">Original governance index scores</td></tr>
<tr><td>From</td><td>To</td></tr>
<tr><td>1</td><td>80</td><td>100</td></tr>
<tr><td>2</td><td>60</td><td>80</td></tr>
<tr><td>3</td><td>40</td><td>60</td></tr>
<tr><td>4</td><td>20</td><td>40</td></tr>
<tr><td>5</td><td>0</td><td>20</td></tr>
</table>
Resolution: Whole country.</td>
<td>Important in all aspects of peoples livelihoods, as well as issues relating to aquaculture. For example the aquaculture sector in well governed countries is more likely to benefit from factors such as being able attract investment, establish foreign trade, and receive support from NGOs and other interest groups.</td>
</tr>
</table>

Outputs

Layer 15: Adaptive capacity (Fig 2.19)

Constructed by MCE using layers: Weighting

- Education 0.236
- Governance 0.199
- Per capita GDP 0.456
- Life expectancy 0.108

Layer purpose

A single adaptive capacity layer is produced with the aim of using a range of social and economic indicators to highlight the ability of people in a given area to cope with the impacts described in other sections of the model.

Weighting of components

The opinions of the focus group were considered particularly useful in relation to the adaptive capacity sub model, where knowledge and experience of the indicator components used and there bearing on aquaculture issues will be very useful when setting weightings.

Table 2.15 shows the contribution of the focus group to assigning weights for the single adaptive capacity sub-model layer. There was a good level of agreement between group members (W = 0.579) with all but one member of the group describing per capita GDP (PPP) as most significant and life expectancy as least significant. The focus group's decisions are agreed with here and it is felt that financial capital is very important in relation to people's ability to adapt both through adaptation measures as well as to cope with losses. In view of the level of agreement seen within the group it was decided to leave the mean weights produced by the group unchanged.

Table 2.15: Weighting of components by the focus group for the adaptive capacity layer (layer 15).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker D		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Education	0.284	2	0.500	1	0.134	3	0.173	3	0.088	3	0.236
Governance	0.134	3	0.250	2	0.262	2	0.062	4	0.286	2	0.199
Per capita GDP	0.499	1	0.125	3	0.512	1	0.566	1	0.579	1	0.456
Life expectancy	0.083	4	0.125	3	0.087	4	0.200	4	0.047	4	0.108

W = 0.579

Results

Most countries in south and south east Asia score 4 or 5 indicating a low adaptive capacity, many of these countries can be considered significant in terms of their aquaculture production and hence the number of people who's livelihoods are linked to it. While not currently a significant aquaculture producer when considered as a whole, Africa can not be ignored due to the very low level of adaptive capacity indicated across many of its countries.

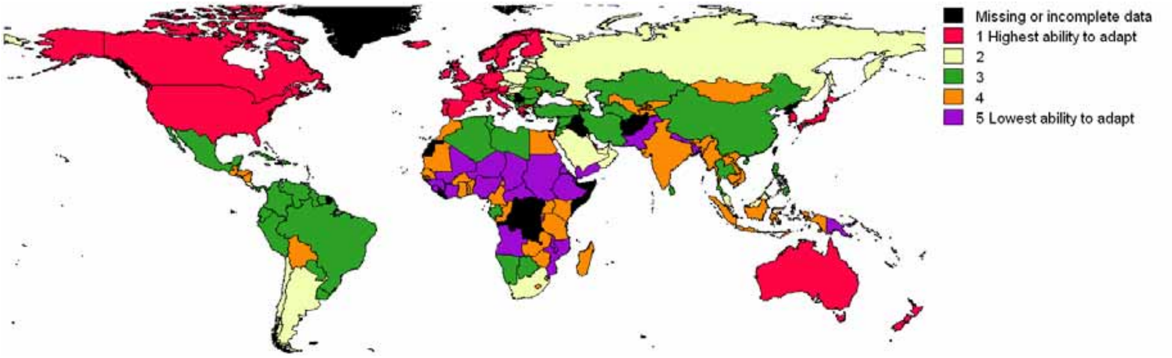


Figure 2.19: Adaptive capacity (layer 15).

Vulnerability

Here the outputs from sub models, as well as individual layers are brought together in a number of combinations with the aim of investigating a range issues relating to aquaculture and climate by using a range of layer combinations and weightings. The intention is not to produce a definitive model that ranks countries or areas in terms of vulnerability, but rather to provide some insight as to where and how vulnerability issues may occur. The results should then be used as a guide in conjunction with the rest of the data base, information presented in the report and other information's sources to make sensible informed decisions regarding vulnerability and as a basis for further investigation.

Outputs

Layer 16: Vulnerability (figure 2.20)

Constructed by MCE using layers:	Weighting
• Sensitivity	0.3
• Exposure	0.2
• Exposure to extreme events	0.2
• Adaptive capacity	0.3

Layer purpose

This layer aims to give an overall spatial representation of the vulnerability of aquaculture related livelihoods to the impacts of climate change. The intention is to create a very general layer that includes as many factors as possible. The following layers (17 to 23) are more specific focussing on certain issues, climate variables and culture environments.

Weighting of components

Table 2.16 shows the output of the focus group. Agreement between decision makers is generally poor ($W = 0.25$) although there appears to be a trend for low significance in the case of extreme events and high significance for adaptive capacity. It is agreed here that adaptive capacity is an important component but it is also felt that sensitivity i.e. the importance of aquaculture at a given location needs to be represented quite strongly. If the sensitivity layer is weighted too weakly then it will be possible to have area indicated as having quite high vulnerability in relation to aquaculture and climate change without actually having much, if any, aquaculture within the country concerned. The mean weighting obtained from the focus group for the extreme events layer may be a little weak compared with the exposure layer dealing with climate trends. While the extreme climate events may only affect certain regions many of these regions are home to significant aquaculture producing nations. It is also true that predictions concerning increase in the frequency and/or intensity of extreme events are currently inconclusive in many cased although there is a consensus that increases are likely and it is certainly worth giving careful consideration to this scenario. The impacts of extreme events can be severe and will typically be harder to adapt to when compared with climatic trends.

The intended purpose of this layer was a general representation which does not strongly emphasise or exclude particular issues, and with the above points in mind it was decided to weight the components more evenly than suggested by the focus group average while giving slightly greater significance to sensitivity and adaptive capacity.

Table 2.16: Weighting of components by the focus group for the general vulnerability layer (layer 16).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker D		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Sensitivity	0.3951	1	0.2857	1	0.2752	2	0.1019	4	0.1885	2	0.249
Exposure	0.1611	3	0.2857	1	0.4553	1	0.183	3	0.1047	3	0.238
Extreme events	0.0888	4	0.1429	2	0.0958	3	0.26	2	0.0617	4	0.130
Adaptive capacity	0.355	2	0.2857	1	0.1737	4	0.4551	1	0.645	1	0.383

$W = 0.25$

Results

As expected Asia features heavily with China, India, Bangladesh, Indonesia, The Philippines, Lao People's Democratic Republic, Thailand, Vietnam and Cambodia all having scores of 4 for at least part of their areas (figure 2.20).

In Africa Nigeria and Madagascar, Africa's second and third largest aquaculture producers, are indicated as vulnerable along with Mozambique while Egypt, the continent's largest producer, is indicated as less vulnerable. It is possible that the Nile delta area may be at risk in the longer term due to the effects of sea level rise (El-Raey, 1997). This is an example of how the lack of a sea level rise component may be a limitation in the current model.

In South and Central America Guatemala, Honduras and Nicaragua have areas with scores of 4, although the areas are small and are probably associated with urban areas having high population densities.

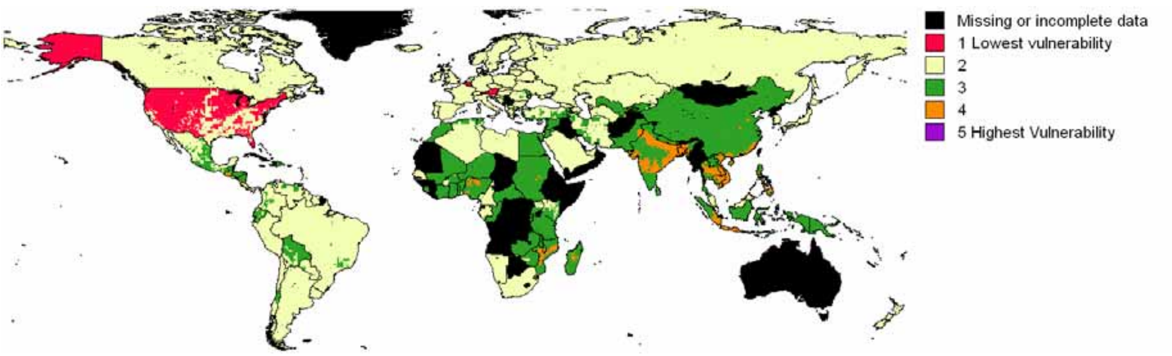


Fig 2.20: Vulnerability (layer 16).

Layer 17: Vulnerability - food security (Fig. 2.21)

Constructed by MCE using layers:	Weighting
• Sensitivity - food security	0.35
• Exposure - population	0.175
• Extreme events	0.175
• Adaptive capacity	0.3

Layer purpose

This layer aims to assess vulnerability where aquaculture is significant in terms of food security.

Weighting of components

Table 2.17 shows the decisions of the focus group where 4 individuals successfully completed the questionnaire in this instance. With 4 decision makers and 4 components a *W* value of 0.619 or greater is needed for the decision makers to be considered in agreement at a 95% confidence level (Siegel & Castellan, 1988). In the current case *W* = 0.44 suggesting a moderate level of disagreement within the focus group. There is agreement here with the trend shown by the focus group that the sensitivity component, which highlights areas of both malnutrition and significant aquaculture production, is very important along with adaptive capacity.

Some very low levels of significance were given for extreme events. It seems likely that the impact of climate extremes, and perhaps drought in particular, may have a significant impact on production and hence food security. For this reason and those outlined for the previous layer (layer 16) it is felt here that the focus group average weighting for extreme events may be too low.

Table 2.17: Weighting of components by the focus group for the assessment of vulnerability in relation to food security (layer 17).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Sensitivity - food security	0.5447	1	0.4	1	0.2799	2	0.2043	2	0.357
Exposure - population	0.1018	3	0.2	2	0.4647	1	0.1086	3	0.219
Extreme events	0.0853	4	0.2	2	0.1397	3	0.0634	4	0.122
Adaptive capacity	0.2682	2	0.2	2	0.1156	4	0.6237	1	0.302

W = 0.44

Results

Asia features highly as do parts of Africa notably Malawi, Mozambique and Nigeria. In many parts of Asia fish consumption is high and forms a very important part of the diet. In the case of Africa although fish consumption appears relatively low in many areas when considered as a percentage of total animal protein consumed then it is often shown to be very significant. This not only highlights the potential benefits of increased fish production but also the poor state of food security and nutrition in many African countries (FAO, 2006).

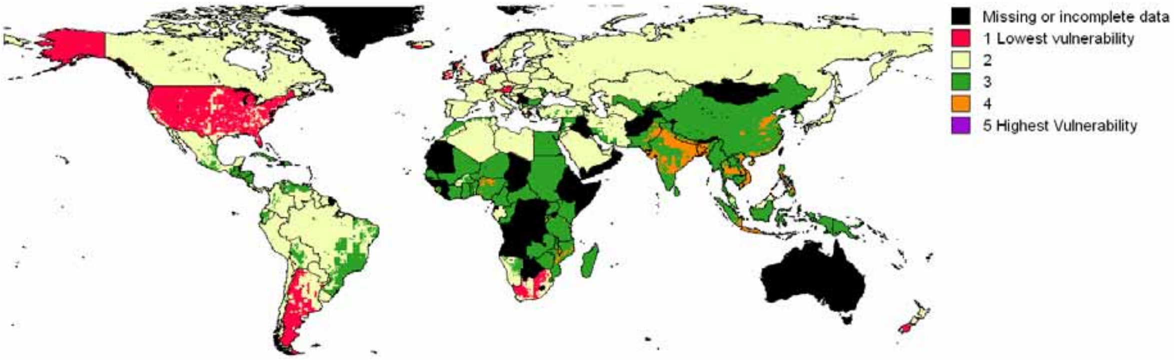


Fig 2.21: Vulnerability of aquaculture related food security to climate change impacts (layer 17).

Layer 18: Vulnerability - economic importance of aquaculture (Fig. 2.22)

Constructed by MCE using layers:	Weighting
• Aquaculture production as percentage of GDP	0.5
• Exposure	0.15
• Extreme events	0.15
• Adaptive capacity	0.2

Layer purpose

This layer places the emphasis on aquaculture as a percentage of GDP in order to indicate areas where aquaculture plays a significant role in the economy and that may be vulnerable in this respect. See layer 3 showing aquaculture production as a percentage of GDP for further details.

Weighting of components

As described above this layer is designed to show areas that are economically dependent on aquaculture and may be vulnerable as a result of this. With this in mind the weightings of the components of this layer are somewhat predetermined. The *W* value of 0.61 is borderline significant at the 95% confidence level (Siegel & Castellan, 1988) but is based on rankings and does not take account of the very different actual values given by group members in this case. Four members of the focus group completed the decision matrix for the current layer; two members gave greatest significance to aquaculture as a percentage of GDP as would be expected, the other two decision-makers gave a very high level of significance to adaptive capacity and relatively low levels of significance to aquaculture as a percentage of GDP (results from focus group are shown in Table 2.18). It would seem that in the later case the decision makers may have misinterpreted the intended purpose of the layers and were considering it in terms of areas where aquaculture may be very important economically to poorer individuals. Such situations would generally involve countries with low levels of development and typically poor adaptive capacity. It should be noted that while this was not the intended purpose of the current layer, the following layer (layer 19) is designed to have the emphasis placed on adaptive capacity and hence addresses these issues.

To fulfil the original purpose of the layer a high level of significance was given to the contribution of aquaculture to GDP. Other components were weighted fairly evenly so as not to be exclusive, but a slightly heavier weight was given to adaptive capacity as even those members of the group who interpreted the layer as intended gave relatively high levels of significance to this component.

Table 2.18: Weighting of components by the focus group for the layer showing vulnerability with the emphasis on areas where aquaculture is a significant contributor to a countries economy (layer 18).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Aquaculture production value as percentage of GDP	0.1075	3	0.4	1	0.4673	1	0.2043	2	0.295
Exposure - equal weight A2	0.1905	2	0.2	2	0.1601	3	0.1086	3	0.165
Extreme events - equal weight	0.0613	4	0.2	2	0.0954	4	0.0634	4	0.105
Adaptive capacity - equal weight	0.6407	1	0.2	2	0.2772	2	0.6237	1	0.435

$W = 0.61$

Results

Fig 2.22 suggests that aquaculture plays a significant role in the economy of many Asian countries such as China, Vietnam, Cambodia, Thailand, Indonesia and Bangladesh. With the exception of Madagascar and Egypt most African countries do not score highly, despite many having small GDPs, due to their relatively low level of aquaculture production. In South and Central America Chile with its large salmon industry, as well as Ecuador and parts of Central America with their shrimp industries are highlighted as having a strong economic dependence on aquaculture.

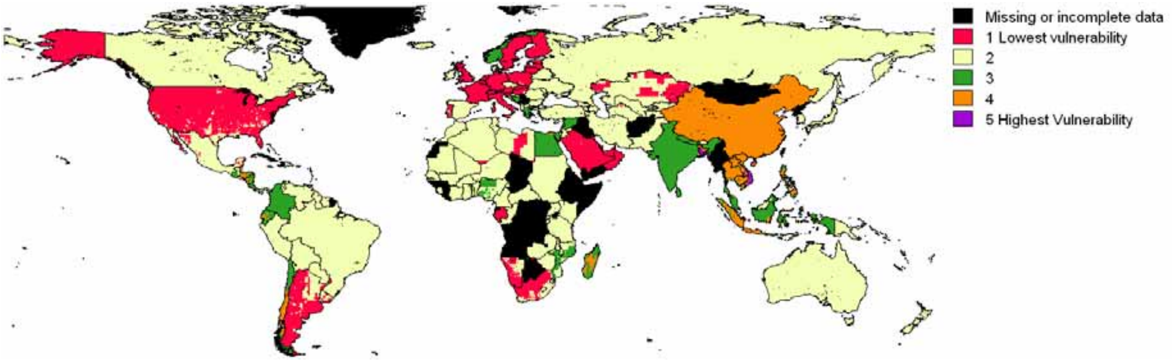


Figure 2.22: Vulnerability with main emphasis on areas where aquaculture makes a significant contribution to the economy (layer 18).

Layer 19: Vulnerability - adaptive capacity emphasis (Fig. 2.23)

Constructed by MCE using layers:	Weighting
• Sensitivity	0.25
• Exposure	0.15
• Extreme events	0.15
• Adaptive capacity	0.45

Layer purpose

Effects of climate change on aquaculture in the short to medium term may be very varied and often hard to anticipate making adaptive capacity of particular importance. Fig. 2.23 shows the result of a MCE with the greatest weight placed on adaptive capacity.

Weighting of components

Layer 19 is intended to have a bias towards areas of low adaptive capacity, this largely determines the weighting used and the opinion of the focus group was not sought. It was felt that while as much emphasis as possible should be placed on adaptive capacity as possible the other component layers still needed to be made relevant, with enough weighting placed on sensitivity so that the model only strongly indicates areas where aquaculture has some significance.

Results

Areas of Africa and Asia stand out while in Latin America Guatemala also scores 4 for part of its range. Africa as a continent has many countries indicated as having a low adaptive capacity (figure 2.19). The current analysis helps indicate areas of Africa where aquaculture is being promoted heavily and is beginning to develop, such as East Africa and Nigeria, and that may be vulnerable to future climate change.

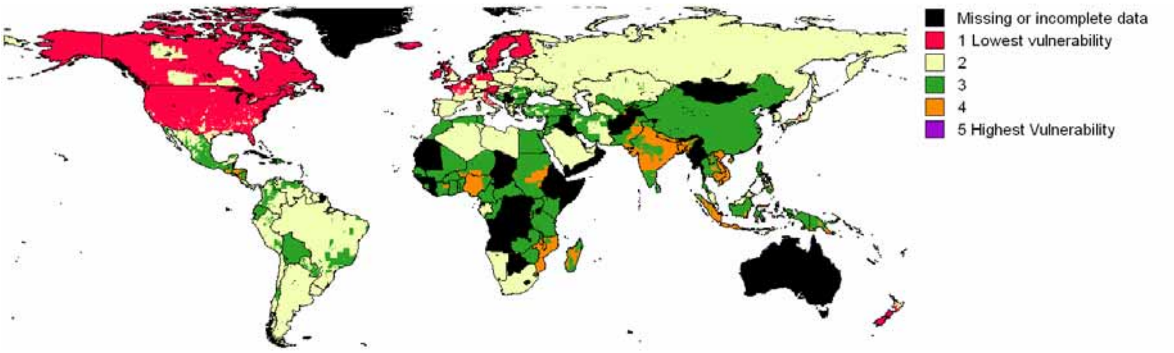


Fig. 2.23: Vulnerability assessment with main emphasis placed on adaptive capacity (layer 19).

Layer 20: Vulnerability of freshwater aquaculture to flooding (Fig. 2.24)

Constructed by MCE using layers:	Weighting
• Sensitivity - freshwater	0.25
• Exposure - precipitation change A2 reversed	0.25
• Flood risk	0.25
• Adaptive capacity - equal weight	0.25

Layer purpose

Flooding is a problem associated with inland areas which are typically dominated by freshwater aquaculture. This layer intends to highlight those areas where freshwater aquaculture is significant and floods are likely to occur.

Weighting of components

Five members of the focus group successfully completed the questionnaire for this layer (Table 2.19) although agreement between decision makers was very low ($W = 0.2$).

As in previous combinations the sensitivity layer is considered important in terms of indicating areas where aquaculture is relevant. Adaptive capacity has been indicated strongly be the focus group in all layer combinations and is considered important again here by both the focus group and the author. As a result of physical geography and climate patterns, floods are typically associated with certain areas, hence the flood risk layer based on the number of past flood events plays an important role in indicating likely flood distribution. By combining knowledge of flood prone areas with data on potential precipitation change, areas where flooding may become more severe can also be indicated. Bearing in mind the importance of each component layer outlined here as well as the lack of consensus within the focus group, it was decided to use equal weightings.

Table 2.19 Focus group decisions regarding weightings for the vulnerability model focusing on flood risk to freshwater aquaculture (layer 20).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker D		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Sensitivity - freshwater	0.3452	2	0.333	1	0.1545	3	0.0854	4	0.2938	2	0.242
Exposure - % precipitation change A2 reversed	0.185	3	0.1667	2	0.2449	2	0.2338	3	0.1564	3	0.197
Flood risk	0.0997	4	0.1667	2	0.508	1	0.2751	2	0.0877	4	0.227
Adaptive capacity - equal weight	0.3701	1	0.333	1	0.0926	4	0.4057	1	0.4621	1	0.333

$W = 0.2$

Results

A number of Asian countries including; Bangladesh, Cambodia, China, India, Indonesia and Vietnam all feature highly.

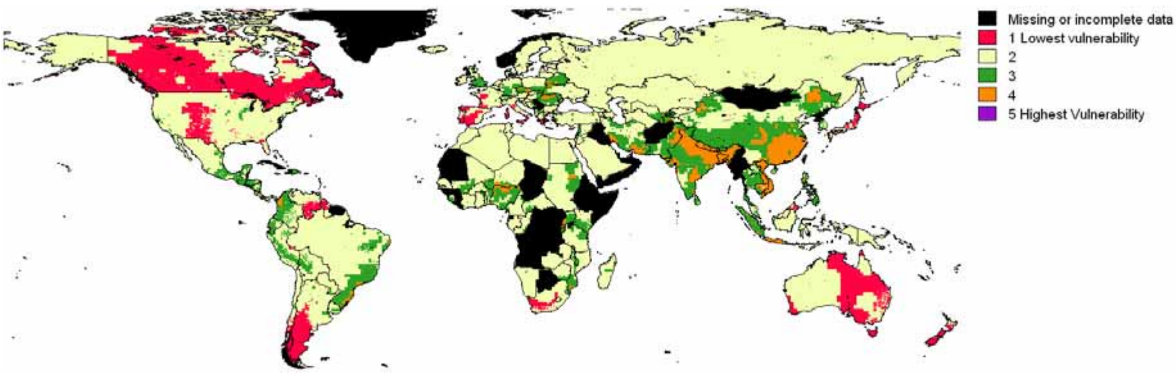


Figure 2.24: Vulnerability of freshwater aquaculture to flooding (layer 20).

Layer 21: Vulnerability of freshwater aquaculture to drought (Fig. 2.25)

Constructed by MCE using layers:	Weighting
• Sensitivity - freshwater culture	0.25
• Exposure - precipitation change SRES A2	0.25
• Drought risk	0.25
• Adaptive capacity - equal weight	0.25

Layer purpose

Drought is a problem that is likely to impact inland areas and freshwater aquaculture, although brackish water culture may also be affected with problems associated with maintaining suitable salinities and water quality. Here areas where freshwater aquaculture is important are investigated in relation to drought risk.

Weighting of components

The output from the focus group is shown in table 2.20. Agreement between focus group members is very low ($W = 0.04$) and again equal weighting is applied based on the same rationale applied to layer 20.

Table 2.20 Focus group decisions regarding weightings for the vulnerability model focusing on drought risk to freshwater aquaculture (layer 21).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Sensitivity - freshwater culture	0.2454	3	0.1667	2	0.1545	3	0.1428	1	0.268
Exposure - precipitation change SRES A2	0.176	4	0.333	1	0.2449	2	0.0863	3	0.224
Drought risk	0.281	2	0.333	1	0.508	1	0.2641	4	0.302
Adaptive capacity - equal weight	0.2976	1	0.1667	2	0.0926	4	0.5068	2	0.205

$W = 0.04$

Results

Many of the areas highlighted here as vulnerable to drought are highlighted in Fig. 2.24 suggesting they are also vulnerable to flood. For example Bangladesh is well known for large flood events, with about 30% by area being flooded annually, but it also scores highly in terms of drought impacts. Other areas of Asia such as India and Vietnam also feature highly in both layers highlighting the significance of climate seasonality and variability, both factors where confidence in predictions in relation to climate change are generally low (IPCC, 2001a).

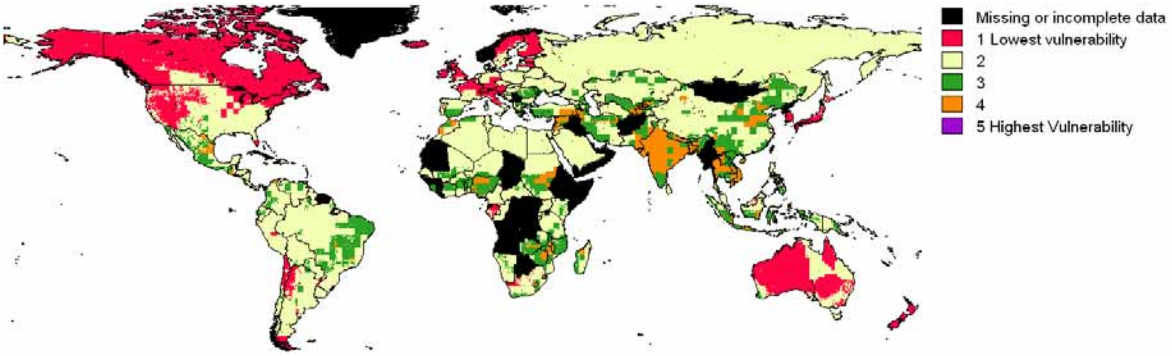


Fig. 2.25: Vulnerability of freshwater aquaculture to drought (layer 21).

Layer 22: Vulnerability of brackish water aquaculture to cyclone (Fig. 2.26)

Constructed by MCE using layers:	Weighting
• Sensitivity - brackish water culture	0.333
• Cyclone risk	0.333
• Adaptive capacity - equal weight	0.333

Layer purpose

An investigation of areas where brackish water aquaculture is significant and at risk of being impacted by cyclones.

Weighting of components

Table 2.21 shows the contribution of the focus group and again there was little consensus between group members. In this combination exposure to climate trends is not represented and the exposure component of the vulnerability assessment is based solely on risk of cyclone. Equal weightings are applied again here based on the arguments used for layer 20.

Table 2.21 Focus group decisions regarding weightings for the vulnerability model predicting areas of brackish water aquaculture at risk from cyclone impact (layer 22).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Sensitivity - brackish water culture	0.2857	2	0.4	1	0.297	2	0.5396	1	0.381
Cyclone risk	0.1429	3	0.2	2	0.5396	1	0.297	2	0.295
Adaptive capacity	0.5714	1	0.4	1	0.1634	3	0.1634	3	0.325

Results

Brackish water culture systems are often associated with coastal areas where wave and storm surge damage may be significant. Figure 35 indicates Vietnam, the Philippines, Bangladesh, India, and Belize as being particularly vulnerable. Other central American countries known to be at risk from tropical storms should also be considered as although not represented strongly in the current model using mostly national level data, brackish water culture may still be important at the local level. Caribbean countries are not represented here due to limited data availability but considering the frequency of storm damage in many areas further investigation is probably warranted. The southern USA is also frequently affected by storms and has some brackish water aquaculture but is not considered vulnerable in the current model. Again this is partly due to the limitations of national level data for what is a very large country, but is also a factor of the USA's very high adaptive capacity.

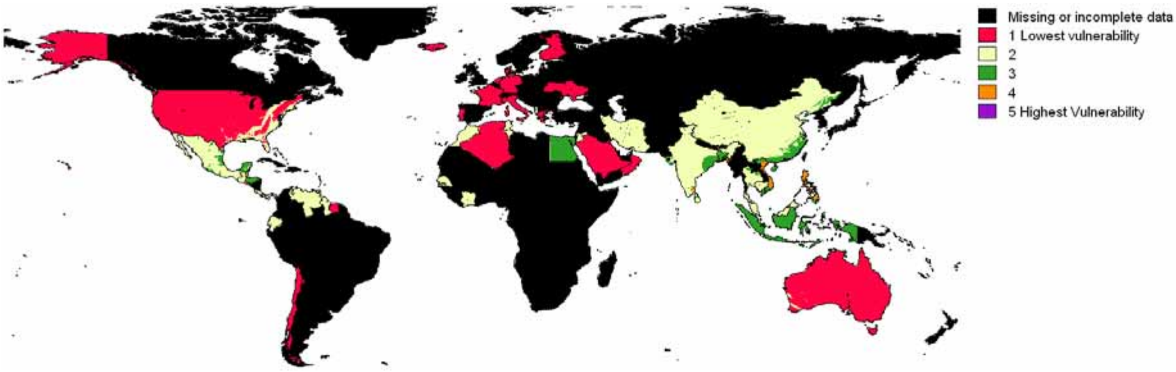


Figure 2.26: Vulnerability of brackish water aquaculture to cyclone impact (layer 22).

Layer 23: Vulnerability of mariculture to cyclone (figure 2.27)

Constructed by MCE using layers:	Weighting
• Sensitivity - mariculture	0.333
• Cyclone risk	0.333
• Adaptive capacity - equal weight	0.333

Layer purpose

Like layer 22 this layer aims to investigate potential cyclone impact but this time on mariculture.

Weighting of components

Weightings allocated by the focus group are shown in table 2.22 with little agreement between group members. Equal weightings were assigned as for layers 20 to 23.

Table 2.22 Focus group results for the vulnerability model predicting risk to mariculture from cyclons (layer 22).

Component layers	Decision maker A		Decision maker B		Decision maker C		Decision maker E		Mean weighting using all 5 decision makers
	Weighting	Rank	Weighting	Rank	Weighting	Rank	Weighting	Rank	
Sensitivity - mariculture	0.2857	2	0.333	1	0.297	2	0.2081	2	0.281
Cyclone risk	0.1429	3	0.333	1	0.5396	1	0.6608	1	0.419
Adaptive capacity - equal weight	0.5714	1	0.333	1	0.1634	3	0.1311	3	0.300

Results

Vietnam, The Philippines, South Korea, Mozambique, Madagascar, and Nicaragua are indicated as being most vulnerable to cyclone impact on mariculture (figure 2.27). As with brackish water production, species cultured are often of high value meaning the financial implications for lost stock as well as damaged facilities may be severe.

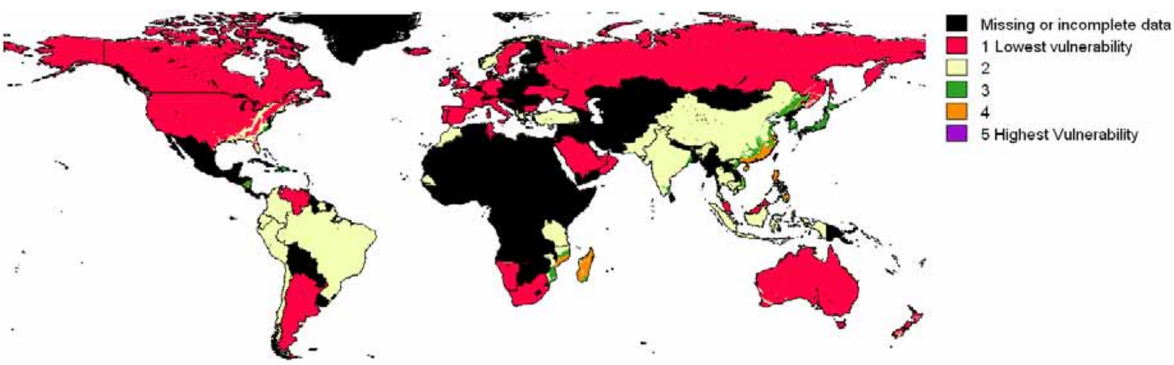


Figure: 2.27 Vulnerability of mariculture to cyclone.

Vulnerability assessment - summary

Table 2.23 summarises countries scoring 4 or more for at least part of their area in at least one of the vulnerability layers.

Asia featured highly in the vulnerability assessment with the large aquaculture producing countries such as; Bangladesh, Cambodia, China, India, The Philippines and Vietnam indicated as vulnerable under most of the layer combinations used.

Aquaculture production in Africa as a whole is low when compared to Asia. However many African countries are considered to have a very low adaptive capacity and are therefore considered vulnerable in some instances.

A number of Central and South American countries are considered vulnerable with Nicaragua and Guatemala being the areas of most concern.

The assessment of vulnerability in the current project represents a useful starting point both in terms of highlighting areas of vulnerability, and by providing the foundation for a database that can be improved and expanded, and hopefully be the basis for more detailed and accurate modelling. The database and vulnerability model in its current form should be viewed as an indicative tool to be used in conjunction with other available information and expert opinion in order to help make decisions relating to climate vulnerability.

Table 2.23 * = countries scoring 4 or more for at least part of their area.

Country	Vulnerability General	Vulnerability in terms of food security	Vulnerability based on economic importance	Vulnerability with emphasis on adaptive capacity	Vulnerability of freshwater aquaculture to inland flooding	Vulnerability of freshwater aquaculture to drought	Vulnerability of brackish water culture to cyclone	Vulnerability of mariculture to cyclone
Bangladesh	*	*	*	*	*	*	*	
Cambodia	*	*	*	*	*	*		
China	*	*	*		*	*		*
India	*	*	*	*	*	*	*	
Indonesia	*	*	*	*	*	*		
Iran					*	*		
Jordan						*		
Korea, rep. of	*	*	*	*		*		*
Kyrgyzstan						*		
Laos	*	*	*	*	*	*		
Nepal	*	*		*	*	*		
Pakistan	*	*		*	*	*		

Philippines	*	*	*	*	*		*	*
Syria						*		
Tajikistan					*	*		
Thailand	*	*		*		*		
Uzbekistan	*	*		*	*	*		
Vietnam	*	*	*	*	*	*	*	*
Papua New Guinea		*				*		
Burundi				*	*			
Egypt			*					
Ivory Coast				*				
Lesotho						*		
Madagascar	*		*			*		*
Malawi	*	*			*	*		
Mali				*	*			
Morocco						*		
Mozambique	*	*			*	*		*
Niger				*	*			
Nigeria	*	*		*	*	*		
Rwanda					*			
Sierra Leone		*		*				
Sudan	*			*	*	*		
Swaziland						*		
Tanzania					*			
Uganda					*			
Zambia						*		
Zimbabwe						*		
Belize			*				*	
Brazil					*	*		
Colombia					*	*		
Costa Rica			*		*			
Ecuador			*		*			
Guatemala	*	*		*	*	*		
Jamaica					*			
Mexico						*		
Nicaragua	*	*	*	*				*
Belarus					*			
Czech Republic					*			
Hungary					*			
Romania					*			
Turkey						*		
Ukraine					*			

3. Case study - Bangladesh

Introduction

Bangladesh is the developing world's most densely populated country with an average of 1061 people per km^2, it also suffers from considerable poverty with nearly half of the 138 million population being considered bellow the poverty line (World Bank, 2005). It is now well recognised that Bangladesh is one of the world's most vulnerable countries to climate change and sea level rise (Rahman & Alam, 2003; Ali 1999). Low natural resources and a high occurrence of natural disasters further add to the challenges faced by the country (Rahman & Alam, 2003). Despite its many problems Bangladesh has made great progress in recent years with reductions in malnutrition and infant mortality along with improved adult literacy and gender parity in terms of education (World Bank, 2005).

85% of the country's poor live in rural areas where the agriculture sector plays an important role in a large number of livelihoods (World Bank, 2005). The Bangladesh bureau of statistics estimates that 61.5% of the country's 58,066,000 employed people are connected to the agriculture industry (BBS, 2002) while the Inland Water Resources and Aquaculture Service (FIRI) suggest figures of 3,080,000 fish farmers, 1,280,000 inland fishermen and 450,000 fish and shrimp fry collectors (FIRI, 2005)

28 million people within Bangladesh are considered as ultra poor suffering chronic food insecurity and malnutrition, consuming on average 1800 Kcal per day, considerably below the recommended average of 2300 (WFP, 2004). As well as providing economic income, for a large number of people fish play a crucial nutritional role. For the period 2000 – 2001 fish provided a daily average of 7.2g of protein, 60.5% of all animal product protein consumed and 10.9% of the total average daily protein intake of 66.1g. This compares with 6.3g or 56.7% of animal protein and 11.1% of a total daily average of 56.9g in the 1996 – 1997 period (BBS, 2002).

Fig. 3.1 Satelite image of Bangladesh highlighting the large delta region of the GBM river system. Image details: Full colour MODIS image from October 23, 2001 (NASA, 2001).

Bangladesh is situated at the north of the bay of Bengal and south of the foot hills of the Himalayas. It is mostly a very flat and low lying deltaic country (Fig. 3.1) with a large proportion of its area comprising of the floodplain of three large and converging rivers; the Ganges, the Brahmaputra-Jamuna (the Jamuna is the down stream section of the Brahmaputra) and the Meghna (GBM river system). Approximately 92.5% of the combined catchment area for the GBM river system lies outside of Bangladesh, and with heavy monsoon rainfall occurring over most catchments, Bangladesh is forced to drain a large amount of cross-border runoff as well as its own (Mirza, 2001). The coastal area can be separated into three regions (Ali, 1999). The western region contains many channels and creeks and is known as the Ganges tidal plain. It is also home to the world's largest mangrove forest known as the Sundarbans. The central region contains the Meghna river estuary which carries the combined flow of the GBM rivers. It is the most geomorphologically active area with constant erosion and deposition of sediments. The eastern region is more hilly and can be considered more stable. Inland there are a large number of rivers, canals, lakes and estuaries, both annual and perennial, that cover an area of 4.56 million hectares (FIRI, 2005).

Current weather and climate

The climate of Bangladesh is characterised by fairly distinct seasons. There is a fairly cold winter running from November to March with low temperatures, especially in the North West of the country, and little rain. From March to May there is a transitional period known as the pre-monsoon, temperatures can be high at this time and short duration thunderstorms are common. The climate reaches its most severe in May with the potential for the highest temperatures, frequent strong winds, and the occurrence of cyclonic storms originating from the Bay of Bengal.

The monsoon season extends from June to September and is a result of warm winds from the southwest. During this period Bangladesh receives about 75% of its annual rainfall (Salam, 2000), while temperatures and humidity are typically high. Rain is normally steady at moderate rates with depressions typically lasting for a number of days.

From October to November there is a second transitional period known as the post monsoon when the majority of cyclonic storms occur. More than 75% of cyclones that strike the coast of Bangladesh occur during this time with most being in November (Salam, 2000).

Examples of average temperature, precipitation and humidity are given for Dhaka in Table 3.1.

Table 3.1 Average climatic conditions for Dhaka, Bangladesh (source: BBC weather (no date))

Month	Average Sunlight (hours)	Temperature				Discomfort from heat and humidity	Relative humidity		Average Precipitation (mm)	Wet Days (+0.25 mm)
		Average		Record						
		Min	Max	Min	Max		am	pm		
Jan	9	12	25	7	31	Moderate	46	-	18	1
Feb	8	13	28	8	34	Moderate	37	-	31	1

March	7	16	33	13	39	Medium	38	-	58	3
April	6	23	35	18	42	High	42	-	103	6
May	5	25	34	19	42	High	59	-	194	11
June	3	26	32	22	36	High	72	-	321	16
July	2	26	31	24	34	High	72	-	437	12
Aug	2	26	31	23	36	High	74	-	305	16
Sept	3	26	31	23	35	High	71	-	254	12
Oct	6	24	31	17	34	High	65	-	169	7
Nov	8	18	29	12	31	Medium	53	-	28	1
Dec	9	13	26	7	29	Moderate	50	-	2	0

Flooding

On average 20.5% of Bangladesh is inundated by floods annually, while during extreme flood events inundation can be as high as 70% (Mirza, 2002). The people of Bangladesh are used to flooding and have adapted their livelihoods around the lower-level flooding patterns that occur in an average year. For example an area used to grow fish in the wet season might then be used to grow rice during drier parts of the year. It is in years when flooding is greater than average that significant impacts on peoples livelihoods, including aquaculture, are most likely to occur.

Flooding in Bangladesh can be characterised as one of four main types; Riverine floods, flash floods, rain floods and storm surge floods (also known as tidal flooding). These flood types are outlined in table 3.2 and the areas likely to be affected are shown in Fig. 3.2. The river flooding data in Fig. 3.2 is based on 1988, a year that saw particularly bad flooding. Figs.3.3 and 3.4 illustrate the extent of flooding for 1998 and 2004, also years where inundation was severe.

Table 3.2 Key features of the four main flood types experienced in Bangladesh.

Riverine floods	• Overflow of major rivers and tributaries • Caused by excessive rainfall over river catchments. • Water normally rises and falls slowly. e.g. over 10-20 days or more (Mirsa, 2002). • Simultaneous peaks within the converging major rivers can cause large floods. • Can cause a lot of damage.
Flash floods	• In eastern and northern rivers. • Result of heavy precipitation over hills in India that neighbour Bangladesh. • Water rises quickly and is fast flowing.

Rain floods	• Intense local rainfall. • Annual variability.
Storm-surge floods	• Affect coastal areas and are a function of: Land elevation, the friction factor of the land and surge height. Surges have been recorded up to 6m and theoretically modelled up to 7.6m in the case of the 1991 cyclone (Salam, 2000; Ali 1996,1999)

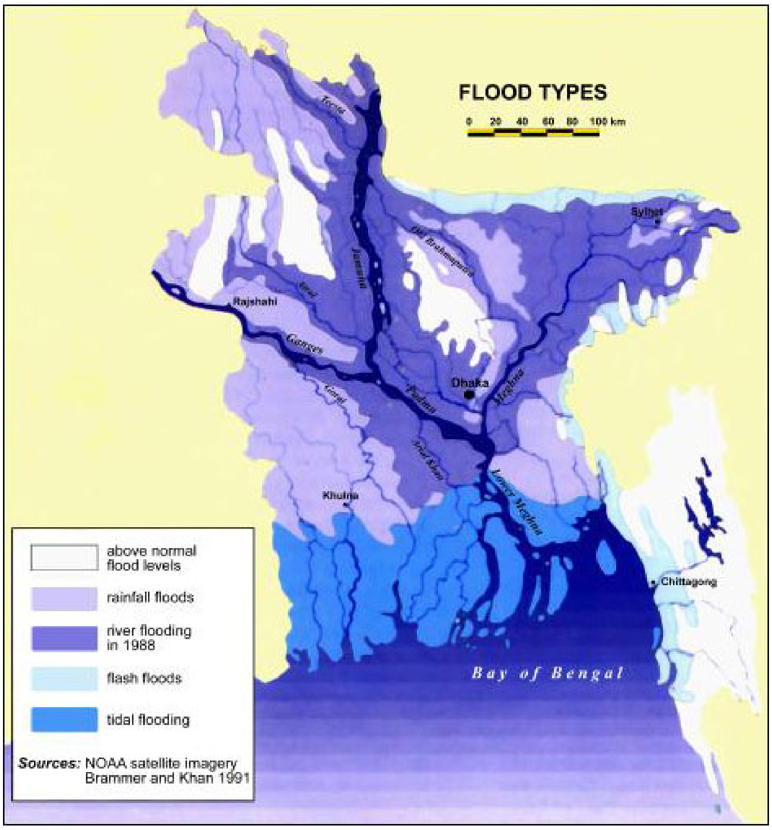


Figure 3.2 Predicted flood coverage (source: BDWD(a))

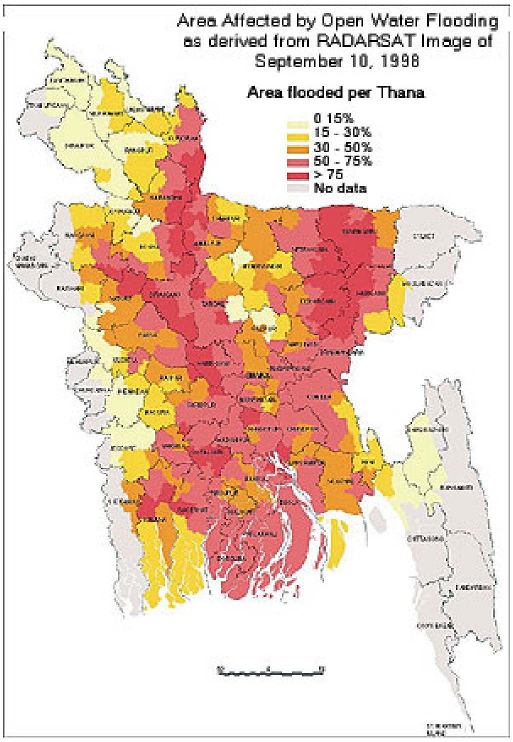


Figure 3.3 Areas affected by the 1998 flood. Derived from RADARSAT data for 10/09/1998 (source: BDWD(b))

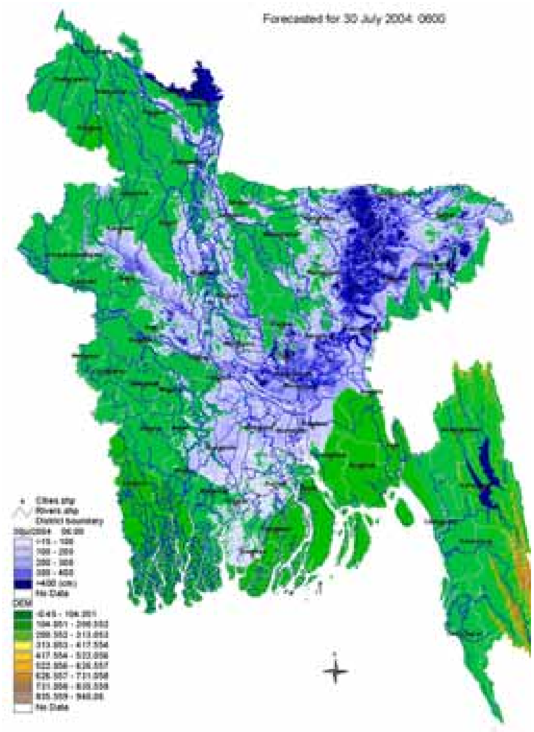


Figure 3.4 Forecasted inundation for 30/07/2004. (source: SDNP)

Fig. 3.5 shows the catchments for the Ganges, Brahmaputra and Meghna rivers. The Brahmaputra has increasing discharge from March due to melting snow in the Himalayas while discharge from the Ganges increases from the end of June as a result of the monsoon (Mirsa, 2002). The timings of peak discharge is crucial and while monsoon rains over the Brahmaputra and Ganges catchments are normally at different times this is not always the case. When synchronisation of river discharges does occur the result can be large-scale flooding as experienced in 1988 and 1998 (Mirsa, 2002; Mirsa *et al*., 2001 & 2003). In 1998 the peak discharges were only 2 days apart resulting in flood inundation of about 70% of the country (Mirsa, 2002).

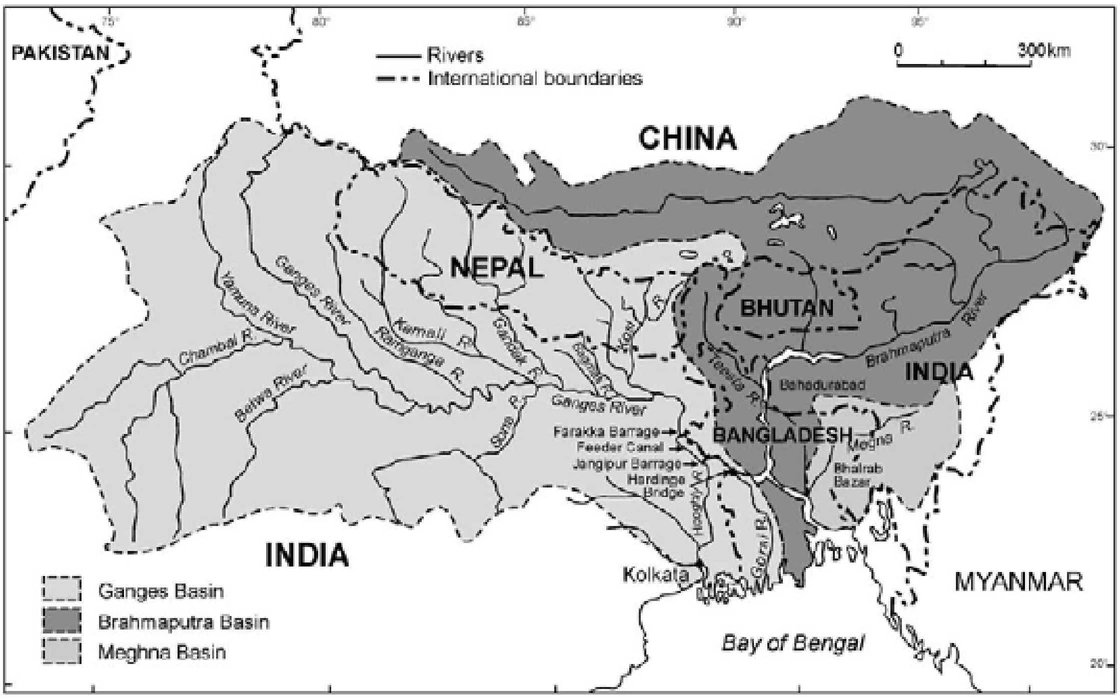
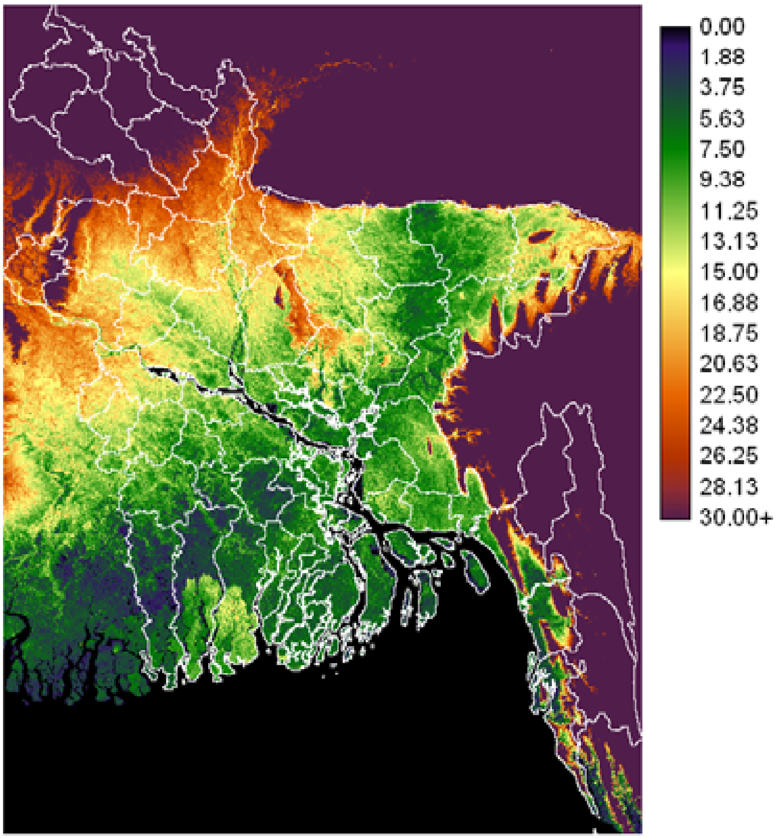


Figure 3.5 Drainage basins for the GMB river system (source: Mirza *et al*. 2001)

The length of time for which an area remains flooded can be significant with longer than average inundation periods often having adverse consequences for agriculture. Due to the low-lying and flat nature of Bangladesh with half of the country being below 12.5 m above sea level and 10% at barely more than a metre, floodwaters cannot drain quickly even after peak flow in the rivers has subsided (Ali, 1999; Mirza, 2001). The very flat and low lying nature of the country is illustrated in Figure 3.6, a graphical representation of a digital elevation model (DEM) derived from the Shuttle Radar Topography Mission (SRTM) data.



Data source: Consultative Group for International Agriculture Research - Consortium for Spatial Information (CGIAR-CSI).

Availability: Available online at: http://srtm.csi.cgiar.org/

Data type: Shuttle Radar Topography Mission (SRTM).

Resolution: 90m horizontal, 1m vertical.

Figure 3.6 Land elevation (metres).

Ali (1999) highlights the importance of the backwater effect in Bangladesh where elevated water levels in river estuaries reduce outflow from the rivers. This process is particularly relevant during the flood season where it can lead to increased accumulation of river derived flood water within the country. In Bangladesh these elevated water levels result from a number of dynamic processes within the Bay of Bengal with the main ones being the southwest monsoon winds, astronomical tides and storm surge events.

The coastal area of Bangladesh is hit by approximately 1% of the on average 80 tropical storms that form over the world's seas every year (Ali, 1999). While this figure may seem low it should be noted that 53% of deaths involving cyclones recorded to have more than 5000 casualties have occurred in Bangladesh (Ali, 1999). As well as socioeconomic factors meaning that people are unprepared and under resourced to cope with cyclones, the physical geography of the country has much to do with the scale of the impacts.

Storm surges, or tidal floods, are formed by a combination of the wind pushing sea water up against the land as well as raising of the water level due to the very low air pressures associated with cyclonic storms. Heights of up to 6m have been recorded while modelling studies have suggested a maximum of 7.6m for the wind speed and low pressure conditions encountered during the 1991 cyclone (Salam, 2000; Ali 1996, 1999). While cyclones also cause damage due to flooding from heavy rain and through direct damage from the wind itself, it is the storm surge inundation that is most destructive and accounts for 90% of the deaths caused by cyclones in Bangladesh (Salam, 2000).

The distance which surge water travels inland can be considered as a function of surge height, land elevation, and a land friction factor (Fig. 3.7). Due to the low elevation of coastal land in Bangladesh storm surges can travel considerable distances inland. Fig. 3.8 shows areas predicted to be at risk from inundation at two different water depths.

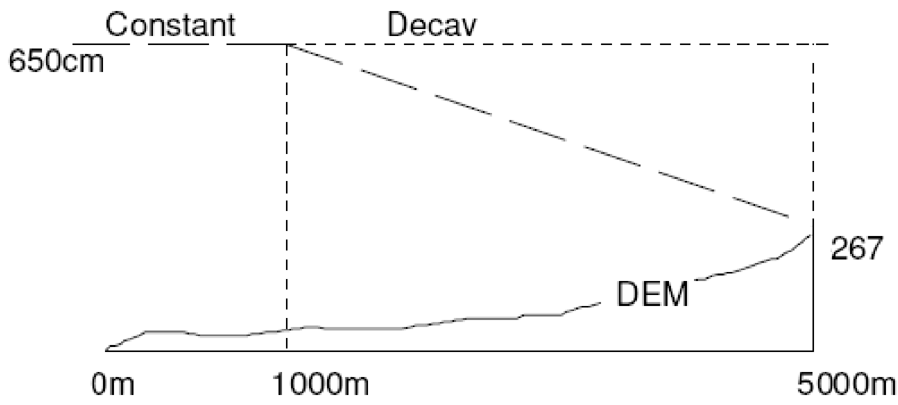


Fig. 3.7 Illustration of decay of inland surge (Source: Damen & Westen, 2002).

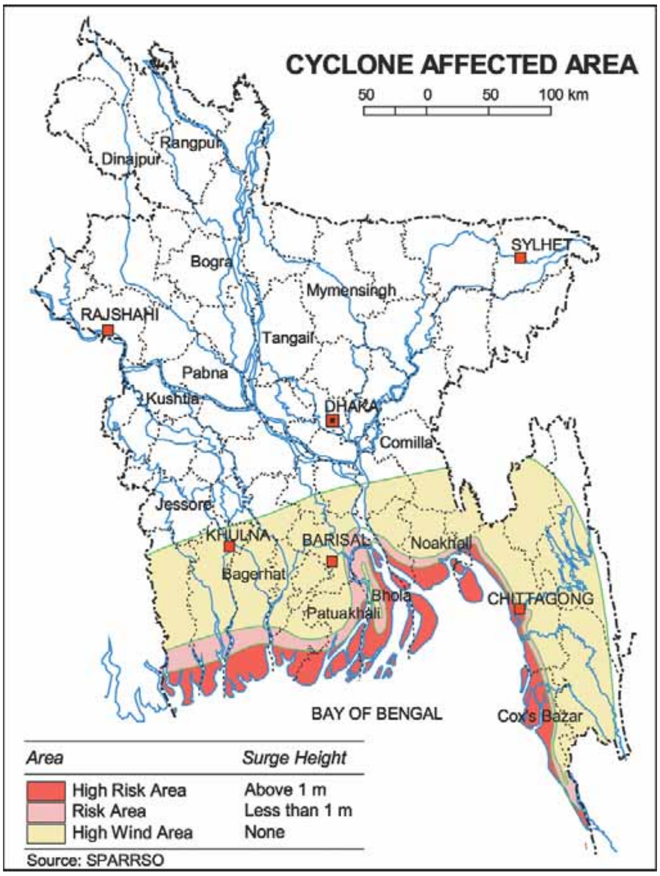


Fig. 3.8 Storm surge hazard map (source: Molnar, 2005)

Current State of Aquaculture in Bangladesh

Aquaculture as well as capture fisheries play a significant role in both food security and economic income, with Bangladesh estimated to be the worlds 7th largest aquaculture producer in 2003 with a total of 856,956 tons (FAO, 2005). Although considerable progress has been made in recent years malnutrition is common in Bangladesh, particularly among children where nearly a half of those under 6 are considered underweight or stunted (World Bank, 2002). Fig. 3.9 shows by area the percentage of the population receiving less than 1805 Kcal per person per day. Fish consumption for Bangladesh is estimated to average 14kg per person per year (FIRI, 2005). This figure could almost certainly be higher and an increase would help supply quality protein to people's diets.

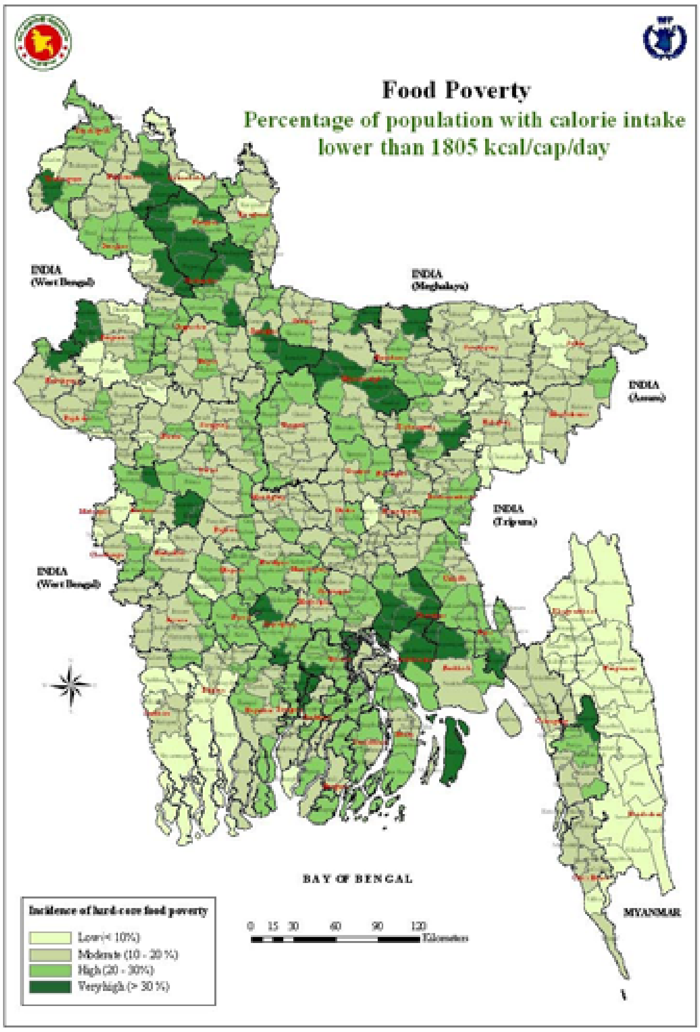


Fig. 3.9 Spatial representation of the percentage of the population receiving less than 1805 Kcal per capita per day (source: BBS/WFP, 2004).

Traditionally aquaculture in Bangladesh takes the form of freshwater fish species (predominantly carps) under extensive culture involving no inputs. During flood periods ponds are allowed to fill with water and the seed of a number of fish species. There is little control over the species entering the pond, predators are not removed and there are no inputs in the form of food or fertilizer (Salam, 2000). Yields from this type of culture are typically low although it is still practiced in some parts of the country (Salam, 2000).

Table 3.3 shows aquaculture production quantity data as available from Fishstat plus (FAO, 2005) for the years 1999 - 2003. While it is accepted that a greater range of species will be involved, and that underreporting of fisheries, both capture and culture, is likely, the figures do indicate a continued growth of aquaculture and an increasing share of total fisheries production.

Table 3.3 Aquaculture production in tons (data from: FAO, 2005)

Species	Culture environment	1999	2000	2001	2002	2003	Average APR
Silver carp	Freshwater culture	96653	120816	152086	170199	179964	**16.8**
Roho labeo	Freshwater culture	113971	120446	132974	144839	164841	**9.7**
Freshwater fishes nei	Freshwater culture	86779	105694	107841	122080	139359	**12.6**
catla	Freshwater culture	111169	104435	110578	127714	137015	**5.4**
Mrigal carp	Freshwater culture	71550	78804	89366	98192	105710	**10.2**
Penaeus shrimps nei	Brackishwater culture	57770	59143	55499	56020	56503	**-0.6**
Freshwater fishes nei	Brackishwater culture	26912	27801	28044	32026	34101	**6.1**
Grass carp(=White amur)	Freshwater culture	5128	10402	14195	14057	14669	**30.1**
Common carp	Freshwater culture	17876	24075	12586	11918	14594	**-4.9**
Giant river prawn	Freshwater culture	5394	5504	9471	9559	10200	**17.3**
Total		**593202**	**657120**	**712640**	**786604**	**856956**	**9.6**
Percentage of total fisheries production including capture		**38.2**	**39.6**	**40**	**41.6**	**42.9**	

Wild fish stocks both as a resource for the fisheries industry and as seed for aquaculture have declined in recent times. This decline would appear to be the result of a combination of factors including; flood control measures reducing the floodplain area available for spawning and impacts from industrial and agricultural pollution, for example increased pesticide use in relation to more intensive crop production (Barman, 2006, Alison *et al*., 2005).

Bangladesh is undergoing a gradual intensification of aquaculture, but while more sophisticated techniques are being employed, production per unit area is still below that of many Asian countries (Salam, 2000).

Carp species, both native and exotic, represent a large portion of total production, although tilapia, snakeheads, *Clarias* and *Pangasius* catfish, Anabantids, and other small indigenous species are also cultured. Most fish are produced in ponds which may operate continuously such as in the case of intensive systems or on a seasonal basis during the wetter part of the year with crop production during drier months. Large pens are also used which can be constructed on the ground during the dry season in areas that will be submerged during wetter months. Systems such as this are likely to be associated with fairly intensive culture and be in proximity to large towns and cities. In such cases fish can be harvested and taken to market by boat fairly quickly.

Fig. 3.10 shows aquaculture production quantities from ponds in relation to land area, at the district (zila) level, based on data collected by the Bangladesh Bureau of Statistics (BBS, 2002). The statistics are limited in that they do not indicate species and hence value of the fish produced. Variation in the degree of reporting error seen between districts as a result of different market, social and administrative should be considered before policy decisions are made.

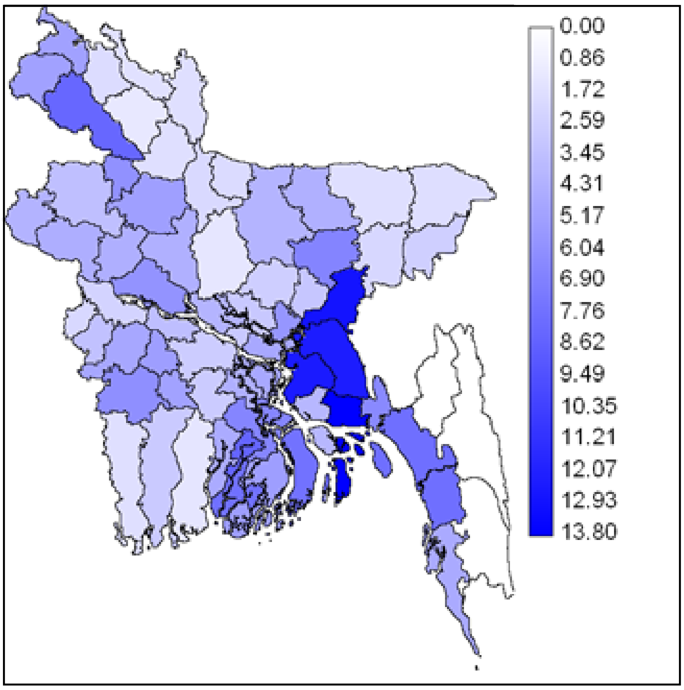


Fig. 3.10 Aquaculture production from ponds (tons per km^2 of land per year) for the period 2000 – 2001 shown at the district (zilla) level (BBS 2002).

Fig.3.11 shows shrimp and prawn production at the district (Zilla) level. While shrimp production figures were available for 22 districts in total, 3 districts (Bagerhat, Cox Bazar and Khulna) had substantially higher reported production compared with the other districts.

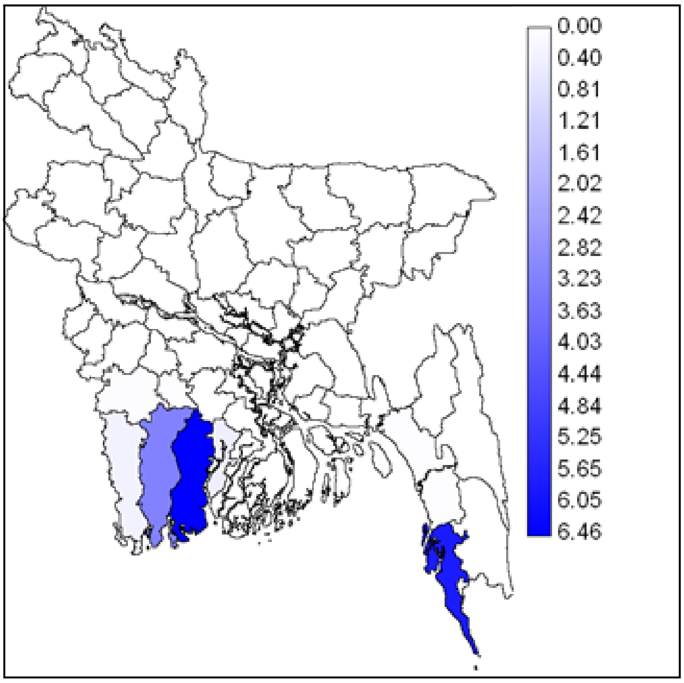


Fig. 3.11 Cultured Shrimp and prawn production (tons per km^2 of land per year) for the period 2000 -2001 shown at the district (zila) level (BBS, 2002).

Prawn culture in Bangladesh typically means production of the giant river prawn (*Macrobrachium rosenbergii*), known locally as *golda,* in freshwater, while the black tiger shrimp (*Penaeus monodon),* locally known as *bagda,* is the most commonly produced species in brackish water. Shrimp and prawn culture provides direct employment for an estimated minimum of 600,000 people with at least 3.5 million dependants as well as accounting for 70% of earnings from all agriculture exports (Fleming, 2004).

The production of Penaeid shrimp in Bangladesh increased rapidly during the 90s but appears to have levelled off and remained fairly constant since then. Brackish water shrimp production was estimated to occupy an area of 203,071 hectares in the period 2003 to 2004 (FIRI, 2005). Despite this considerable area under culture actual quantities of shrimp produced are fairly low with much production still being fairly extensive. Data from the Bangladesh bureau of statistics (BBS, 2002) suggest average shrimp production of 207kg per hectare per year or 321kg if fish produced along with the shrimp are also included. Barmen (2006) suggests that the figure may be nearer 500kg. While it is likely that there is an amount of under reporting meaning the statistics obtained by the BBS will be low, production of shrimp in Bangladesh can still definitely be seen as a fairly extensive practice and there is likely to be considerable capacity for increased production.

Future potential for aquaculture in Bangladesh

Table 3.4 summarises governmental plans for aquaculture in Bangladesh. Expansion is expected to come fairly equally from increased yields per unit area and from increasing the area under culture. Previous fisheries plans have overestimated output, but these plans are evaluated when forming a new one and the degree of inaccuracy has been reduced (Brugère & Ridler, 2004).

Table 3.4 Summary of fisheries development plans for Bangladesh (source: Brugère & Ridler, 2004)

Horizon	Two documents available: (2002) - 2007 (6th five-year plan) (2001) - 2020 (aquaculture development plan)
Projections (quantified)	6th five-year plan: *Freshwater aquaculture* output = 1 466 750 tonnes *Shrimp culture* output = 170 000 tonnes. Total output = 1 636 750 tonnes. (+ 16 percent *per annum* compared to 11 percent *per annum* during the previous plan). Aquaculture development plan: + 3.5 percent average *per annum* (from 296 000 tonnes produced in 2000 - 01 to 1 340 000 tonnes in 2019 - 20).
Species	Shrimps, carps, pangas, rajpunti, tilapia.
Methodology	Analysis of past plans and failure. Evaluation of development potential of various fisheries sub-sectors by documents authors.
Assumptions	Use of forecasted population and per capita fish consumption growth. No indication about price variations. (Expected total income from increased production calculated on the basis of average price of Tk80 per kg - fixed over plan duration).
Means of achievement	**Prices:** Not specified **Markets:** Shrimp for export markets. Inland aquaculture production for domestic markets. **Environment:** *Freshwater aquaculture:* Re-excavation, rehabilitation and restoration of all public water bodies for improvement and maintenance of healthy fish production. 39 percent increase in area combined with a 40 percent increase in yields. Optimal use of inland waters.*Shrimp culture*: Implementation of environmental management measures for the sustainable exploitation of coastal areas (coastal aquaculture). Integrated management to limit externalities from and to other users. Extend area under cultivation to 230 000 ha. **Regulations:** *Freshwater aquaculture*: leasing of government tanks, ponds etc. to targeted poor and unemployed youth. Provision of supervised credit. *Shrimp culture*: equal package of incentives as other export-oriented industries. Introduction of shrimp-crop insurance. Credit at low interest rates, tax free income and tax holidays, integrated land policy. **Development/Promotion:** Increased investments in research. Target farmers for credit provision and technical extension as NGOs tend to focus on the landless. *Freshwater aquaculture*: development of private-sector hatcheries and nurseries. Strengthening of extension and training programmes. Integration of aquaculture with household farming. Shrimp culture: Establishment of private hatcheries and distribution network, appropriate farm design and technology. Other quantitative technical requirements: 216 million fingerlings of 10 - 12 cm size. 450 million spawn (shrimp farming)

	3 million tonnes of fish feed (for both fish and shrimp production).
Constraints to overcome	Ensured supply of fish feed, selection of high-yielding broodstock, fish health management, multiple ownership of ponds and water bodies, complex credit norms, weak institutional capabilities in aquaculture development.

As the population of Bangladesh expands it will place an increased strain on the already limited food resources. Estimates for population growth produced by the United Nations population division are shown in table 3.5.

Table 3.5 Projected population figures for Bangladesh (UN Population Division, 2004)

Year	Medium variant	High variant	Low variant	Constant-fertility variant
2000	128 916	128 916	128 916	128 916
2005	141 822	141 822	141 822	141 822
2010	154 960	156 492	153 432	156 726
2015	168 158	172 346	163 980	173 352
2020	181 180	188 907	173 459	191 304
2025	193 752	205 409	182 201	210 471
2030	205 641	221 983	189 764	231 145
2035	216 664	238 756	195 734	253 642
2040	226 663	255 630	199 935	278 114
2045	235 472	272 293	202 368	304 621
2050	242 937	288 453	203 069	333 327

Currently Bangladesh is considered to be largely self-sufficient in terms of food production, the bulk of which consists of grains (USDS, 2005; Emmett, no date). Improved production methods, as well as seed variety and quality, have important roles in future food security both for aquaculture and agriculture in general. The majority of aquaculture products are currently destined for the domestic market although higher value products such as shrimp have an important role to play in export markets, which can in turn generate revenue used for imports of basic food materials (IPCC, 2001b).

After a hygiene related EU ban on importation of shrimp from Bangladesh in 1997 the Bangladesh shrimp industry has undergone considerable improvement. A large proportion of shrimp processing plants now meets the required standards and has certification for export to the EU (Cato & Subasinge, 2003). Currently shrimp and prawn are Bangladesh's second largest export after clothing, earning around 300 million US$ annually, with 40% of exports each going to the US and the EU and the remaining 20% to Japan (USINFO, 2005). The large areas of inter-tidal land found in Bangladesh make it especially suitable for shrimp production (Fleming, 2003) and growth in the industry is being encouraged through a number of aid programs and government initiatives. For example an investment program by the United States Agency for International Development (USAID) aims to increase export earnings 5 times by 2010 to 1.5 billion USD (USINFO, 2005). An industry on this scale would be highly significant to the economy and the livelihoods of a large number of people and given the typically coastal location of shrimp production potential climate impacts in the form storm surges and sea level rise will need consideration. Supply of freshwater may also be an issue for shrimp production with a recent example being the drought and consequent loss of production experienced in Vietnam (NACA, 2005).

Due to the fairly extensive nature of much aquaculture in Bangladesh there would appear to be opportunity for intensification and hence greater production from the limited land area available. This said, more intensive methods typically require higher levels of investment and as a result carry a greater degree of risk through loss or damage to stock. Due to the unpredictable nature of climate, and in particular flooding, in Bangladesh, and considering the lack of financial capital available to much of the population, reluctance to invest in more intensive methods is understandable.

There are a large number of NGOs operating within Bangladesh with the aim of promoting the fisheries sector. Development within the last two decades has been largely donor driven aquaculture receiving around 60% of total fisheries funding (de Graaf & Latif, 2002). Culture practices that aim to help people get more from their land have been promoted, with methods such as combining fish and rice production being successful in many areas. There are now more possibilities for small-scale landowners to become active in aquaculture in areas such as shrimp farming as organisations are keen to lend money for schemes in which they see as having a potential quick return on investment (Barman, 2006).

Commercial production of aquaculture seed is now fairly widespread reducing reliance on dwindling wild stocks, although concerns remain over seed quality in some instances (Barman *et al*., 2002). Increasing infrastructure sophistication will also aid in the continued growth and success of aquaculture. For example there are now a lot of shrimp hatcheries supplying post larvae which may sometimes be delivered by air reducing reliance on the road infrastructure which is more susceptible to flooding (Barman, 2006).

Riverine and coastal areas of Bangladesh known as ‘chars’ are home to many of the nations poor with over 80% living in extreme poverty (DFID, 2002). Capture fisheries are important to these communities but productivity has been declining. Currently aquaculture is relatively undeveloped on both islands and mainland chars of the upper Jamuna due to limited extension, credit and technical knowledge. Other significant factors include; poor water retention by soils, lack of natural water bodies, lack of seed and risk of flooding. However on some of the older more established chars the construction of aquaculture ponds may be possible providing potential income and food. Climate change impacts such as potential increases in riverine flood events, erosion, and the length or irregularity of the dry season and thus water supply for these relatively quick draining soils will be important factors when considering potential aquaculture development in these areas (de Graaf & Latif, 2002).

Potential future climate change in Bangladesh and its impacts on aquaculture

Sea level rise

Figure 1.12 shows potential inundation as a result of a 1.5 metre sea level rise. While these increases are greater than most predictions for this century, even a more moderate increase would have a significant impact through land loss alone in what is an already crowded country. (Ali, SPARSO – no data) predicts inundation of 2500 km^2 (2%), 8000 km^2 (5%) and 14000km^2 (10%) for 0.1, 0.3 and 1.0 metre rises respectively.

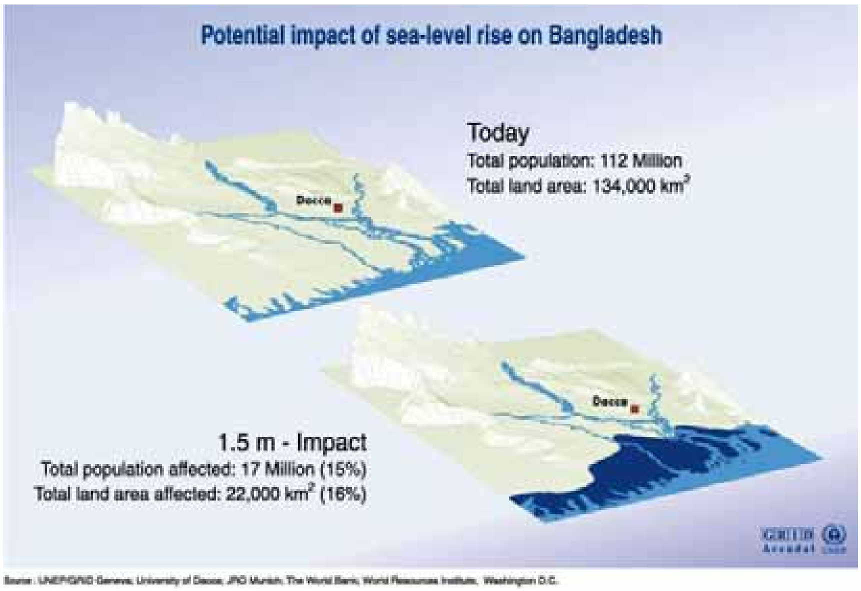


Figure 3.12 potential impact of sea level rise in Bangladesh (source: UNEP, Vital Climate Graphics)

The effective sea level rise (ESLR) experienced by Bangladesh - a result of land subsidence combined with actual sea level rise - is considerably greater than the actual sea level rise its self. A global study of effective sea level rise in delta areas (Ericson *et al*., 2006) indicates that the Bengal delta has one of the highest rates of subsidence under current conditions with an estimated ESLR of more than 10mm per year. Singh *et al.* (2000) showed tidal level increases of 4.0, 6.0 and 7.8mm per year at three points in Bangladesh (21º48'N, 89º28'E; 21º08'N, 91º06'E; 21º26'N, 91º59'E). Ericson *et al.* (2006) suggest that ground water extraction may be part of the cause in the Bengal delta and also highlight the possible consequences of increased storm surge damage in Bangladesh as a result of ESLR and climate change.

Sea level rise in combination with wave action and storm surges will result in coastal erosion. Coast Watch, a Dhaka based NGO claim that Bhola island, which is the country's largest and supports a population of 1.6 million, has lost half of its land mass over the last 40 years and may completely disappear within another 40 (COAST, 2005). The group also suggest that this erosion did not start to take place until the 1960's and is a result of increased estuary currents due to sea level rise. It seems likely that sediment delivery and deposition is also a significant factor and this may be affected by upstream activities and river discharge. While new land will be deposited in some areas there will be a significant period before this becomes useable (Krantz, 1999).

The average ratio of shoreline recession to sea level rise i.e. the distance the shoreline will recede for a given rise in sea level is given as 87:1 by Ali (1999) based on the mean of 7 sampling points with SLR scenarios of 0.3, 0.75 and 1m and using the equation developed by Bruun (1962). It is likely that this figure will vary considerably with location being lower in some areas and perhaps higher in others. Loss of features that protect the shoreline such as mangroves may occur under certain scenarios (see p. ***) exposing some areas to further erosion.

Increased salination of ground water and ponds has already been seen to occur in Bangladesh, most noticeably in the south west Sundarban area. Figs. 3.13 and 3.14 show soil salinity for the years 1973 and 1997 with a noticeable inland shift of increased salinity over the 24 year period. With the rate of sea level rise expect to accelerate over the coming decades further encroachment seems highly likely.

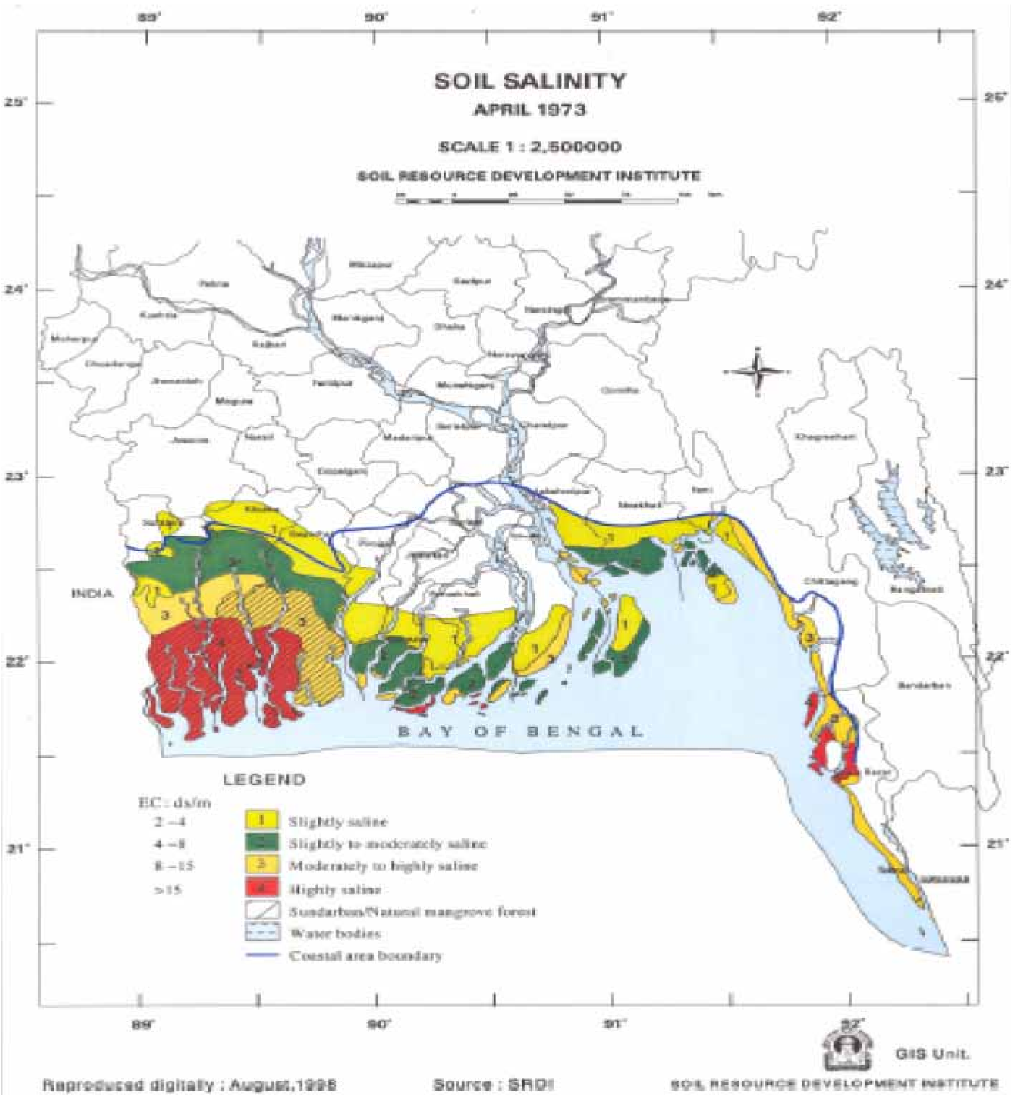


Figure 3.13 Soil salinity for the year 1973 (source: Sarwar, 2005)

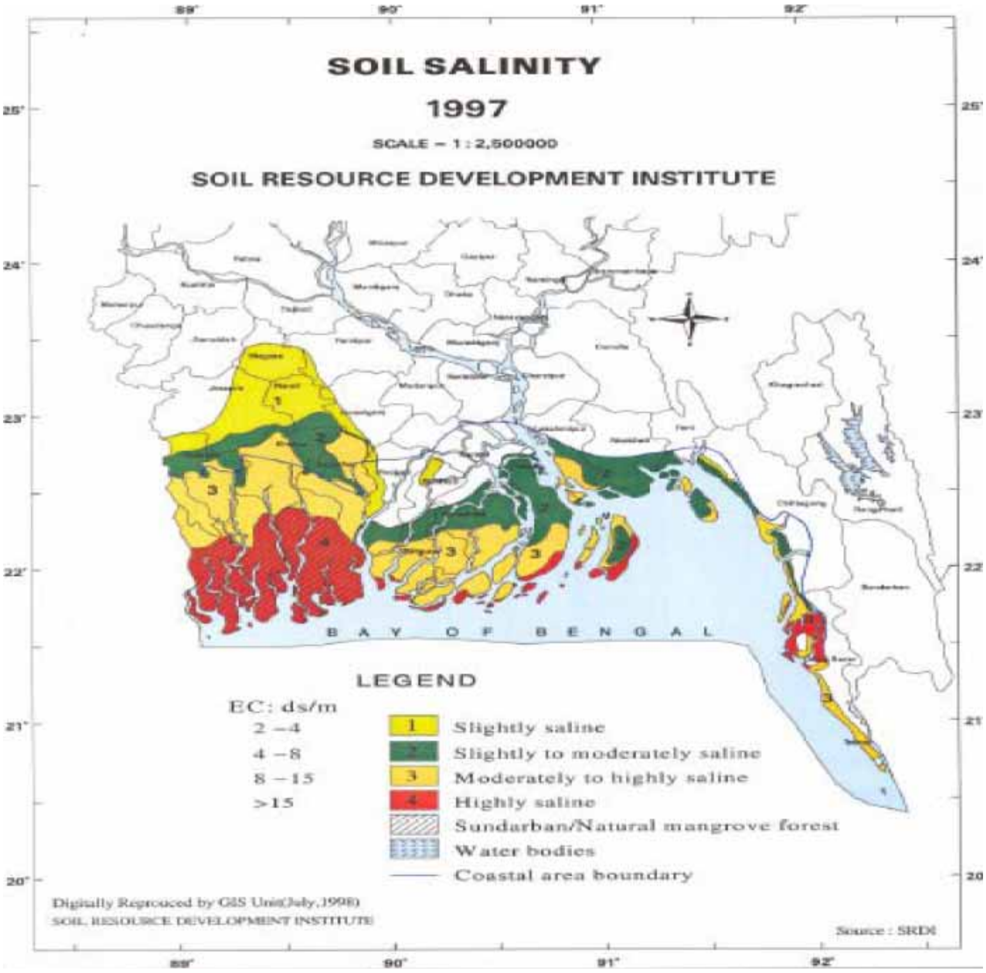


Figure 3.14 Soil salinity for the year 1997 (source: Sarwar, 2005)

Increased inland salination may have serious impacts on agriculture with a 0.5 million ton reduction in rice production predicted in association with a 0.3m sea level increase (World Bank, 2000). It is possible that aquaculture of brackish water species in affected areas may be able to provide some alternative sources of income and nutrition.

The culture of *Penaeus monodon* has expanded rapidly over the past two decades and it is likely that this growth has been helped to some extent by increasing salinities experienced in some areas (Sawar, 2005). However as new areas become available others may be lost through erosion or increasingly threatened by flood. Also while *Penaeus monodon* can survive a wide range of salinities, optimum growth and survival is achieved at salinities below 25‰ (Chanratchakool, 2003) so a general trend for increasing salinity may mean that some currently suitable areas will gradually become less so. Changes in freshwater runoff due to shifts in precipitation patterns may also play a part in changing the suitability of a given area, or the proportion of the year for which a given area can be used for shrimp production. With anticipated further expansion of the shrimp industry and the potential income it may generate, the potential impacts of sea level rise on this sector deserves serious attention.

Extreme events - cyclone and storm surge

There is likely to be a relationship between sea surface temperature and cyclone intensity (Ali, 1996,1999). Table 3.6 shows the estimated increase in surge height under different sea surface temperature increase scenarios (Ali, 1996). The base wind speed of 225km/h corresponds to the 1991 cyclone. It should be noted that the estimates given by Ali (1996) are based on work by Emanuel (1987) and have not been verified via quantitative experimentation and observation. This said, any increase in surge height will increase the distance that water travels inland and the consequent depth at a given point. Loss of natural coastal defences such as mangroves due to sea level rise, erosion and increased salination may also be a significant factor in the impacts of future storm surge events.

Table 3.6 Estimated increase in maximum surge height in relation to sea surface temperature increase (adapted from Ali, 1996).

	Current temp (27^{o}C)	2 ^{o}C increase	4 ^{o}C increase
Wind speed (km/h)	225	248	275
Maximum surge height (% change)	7.6m (0%)	9.2m (21%)	11.3m (49%)

Temperature change

Figures 3.15 to 3.18 show predicted mean temperature change (3 month averages) between the late 20th century and the period 2040 – 2060 for Bangladesh and the surrounding area. The images were produced using IDRISI (version 14) software and data from CCCMA. CGCM2 and SRES scenario A2, the same climate model and emission scenario as used for the exposure sub model within the global vulnerability assessment. Monthly mean temperature data was used to obtain averages for the three month periods. It should be remembered that the data used is for mean temperature and hence says little about the relative change in maximum or minimum temperatures.

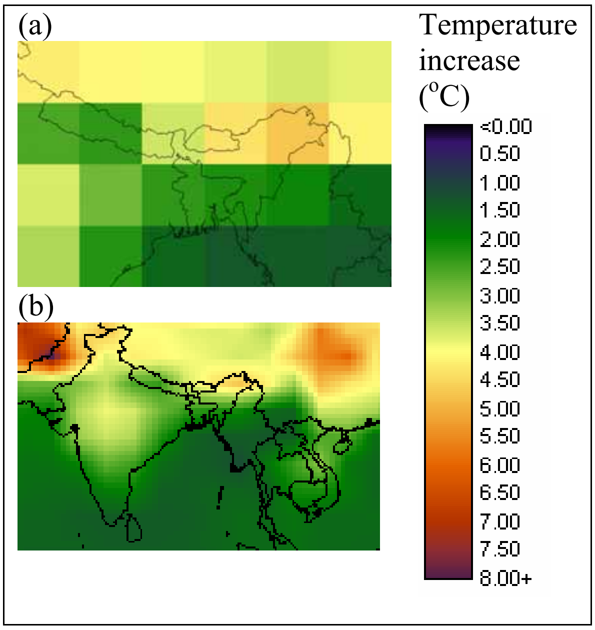


Figure 3.15 December, January, February

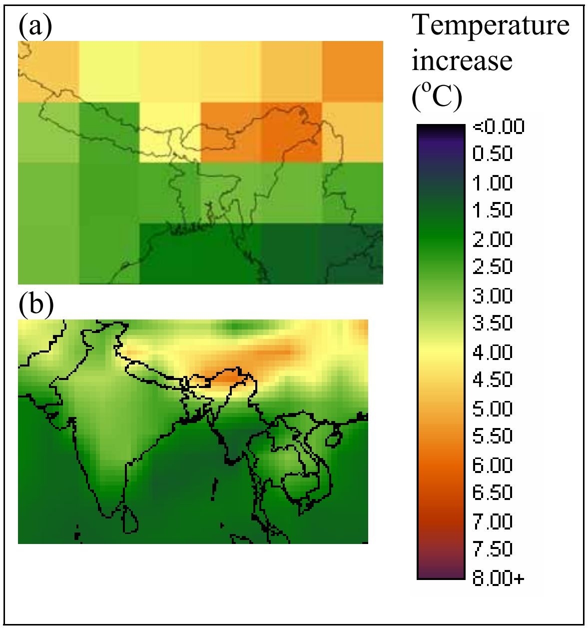


Figure 3.16 March, April, May

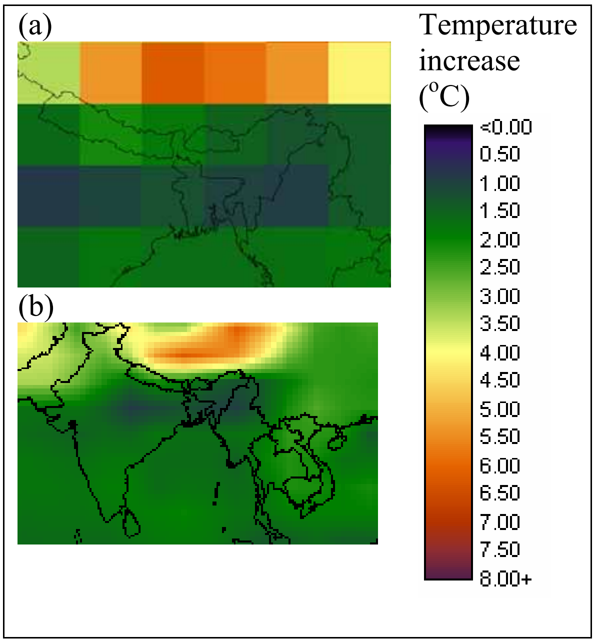


Figure 3.17 June, July, August

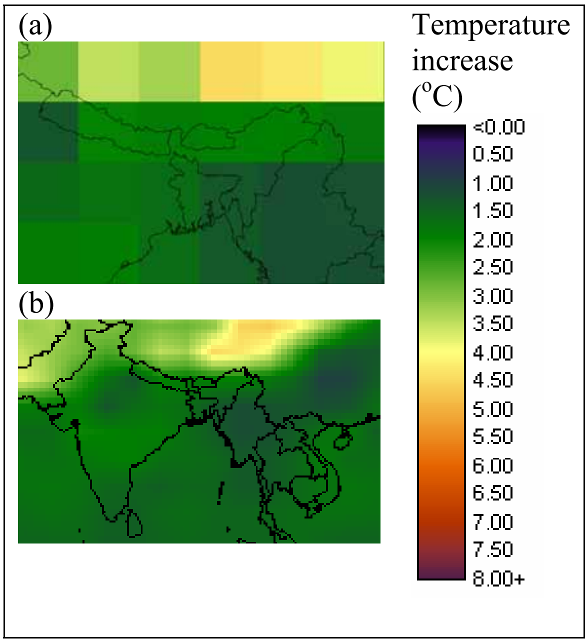


Figure 3.18 September, October, November

Figs. 3.15 to 3.18 Predicted increase in the mean temperature for three month periods between the late 20th century and the period 2040 – 2060 using data from CCCMA CGCM2 forced with SRES scenario A2. In each case image (a) shows actual data values for the Bangladesh area while (b) shows a larger area with the

resolution artificially increased and the image filtered to smooth the transition between cells.

For each three month period image (a) represents the actual data values for Bangladesh and its immediate surroundings. There are considerable differences between values in adjacent cells in all four images. This is a common feature in the output from GCMs, and while considerable variation between cells is definitely possible due to the large areas being represented, cases where individual cells contain very different, or extreme, values should be interpreted with caution. It should be remembered that these are theoretical models, with differences being seen between models as well as between different runs of the same model under varied forcing scenarios. All GCMs are based on a grid covering the surface of the globe with a number of vertical layers representing different atmospheric and ocean layers. The way in which climate model cells interact with each other will vary between models depending on how the model is conceptualised and the methodology used giving results that vary both spatially and in intensity. Where resources permit then a consensus of a number of climate models would be preferable with areas of agreement between a number of models being of particular interest.

Due to time and resource limitations only one GCM and emissions scenario were used in the current study. Considering this, and the other limitations discussed above, it is felt that the temperature data displayed in Figs. 3.15 to 3.18 should be viewed as indicative of general temperature trends such as seasonality and spatial variation, rather than an attempt to quantify temperature increases. With this indicative role in mind image (b) in Figs. 3.15 to 3.18 shows a larger area and has the resolution artificially increased 5 times followed by smoothing of cell values using the FILTER module in IDRISI (5 x 5 cell mean) in order to reduce the sudden transitions seen between cells in images (a).

Figures 3.15 and 3.16 suggest greater increases in temperature from December to May compared with June the August period. There is also a suggestion of slightly greater warming in northern areas of the country compared with the south.

A comparison of in inter-model variability by the IPCC for mean temperature change suggests agreement between models for the southern Asian area covering Bangladesh and its surrounding countries. Results indicate warming greater than the global average under SRES scenarios A2 and B2 for the winter period (December, January and February), and less than the global average for months June to August (IPCC, 2001a). A comparison of four GCMs (CCSR/NIES, CSIRO, ECHAM4 and HadCM2) by Lal and Harasawa (2001) also shows a similar pattern, with a greater temperature increase predicted during the winter for the South Asia region (5ºN - 30ºN, 65ºE – 100ºE).

An increase in average temperatures during the cooler months (December to February) may provide benefits for aquaculture in the form of improved growth performance, especially in the cooler northern areas of the country. April and May are very warm months in Bangladesh so the larger increase predicted over this period is less welcome. This is also the period before the start of the monsoon rains suggesting that water availability may be limited. For aquaculture, the potential for reduced water quality and/or availability resulting from a combination of limited precipitation and higher temperatures will need to be considered at this time.

Precipitation change

Analysis of historical data indicating peak discharge from the GMB river basins, as well as extent of flooding, shows no definite increases in flooding over the last few decades (Mirza *et al.*, 2001). The author advises caution in the interpretation of these results due to the range of time for which data was available at different stations (20 – 87years), but suggests that the increase in flood damage recorded over the analysis period may be at least partially accounted for by improved damage assessment methods as well as increased human settlement in vulnerable areas. The last point may prove to be highly significant in the case of Bangladesh where a rapidly growing population needs to be accommodated by an already crowded country. Reduction in total land area available due to sea level rise, or in useable land due to flooding, increased salination or lack of water as result of climate change may further exacerbate the situation.

An increase in inter annual variation for daily precipitation during the Asian summer monsoon is predicted by a number of GCM's along with an increase in the intensity of extreme rainfall events (Lal & Harasawa, 2001). Mirza (2002) suggests that potential changes in the precipitation regime over the Ganges, Brahmaputra and Meghna river basins could have four main consequences in terms of flooding in Bangladesh: (1) Changes in the seasonality of the monsoons may alter the timing of floods although not their duration i.e. they may start and end earlier or later. (2) Increases in the amount of monsoon rain received by the GMB river basins may increase the duration, depth, extent and frequency of flood events. (3) Timing of peak flow in the major rivers could change. Currently peak discharge for the Ganges occurs on average 45% of the time in August while the Brahmaputra peaks 35% of the time within the same month and as a result combined peak discharges and consequent flooding are therefore quite likely. One possible outcome of changing precipitation patterns may be a shift in peak discharge timings further increasing the likelihood large flood events. (4) Increases in depth, duration and magnitude of floods will cause changes in land-use patterns.

CCCMA data was used to investigate precipitation change over the GBM drainage basins. As in the case of temperature change SRES scenario A2 and CGCM2 were used. Mean monthly values were used to calculate mean precipitation for the periods November to January, and June to September, these periods were chosen to represent the drier winter season and the monsoon period respectively. Average values for the period 2040 to 2060 were compared with a late 20th century control run to obtain a predicted mean percentage precipitation change between the late 20th century and 2040 to 2060 for both the dry winter, and monsoon periods. The resulting precipitation change data is represented spatially at the same resolution as the source data on a global grid of 96 x 48 cells. The precipitation change data was then overlaid with spatial data (source: Graham *et al.*, 1999) representing the extent of; (1) the Ganges drainage basin, and (2) the combined drainage basins of the Brahmaputra and Meghna rivers. Resulting mean values for precipitation change over the two catchment areas are given in table 3.7 while Fig. 3.19 shows the extent of the catchment areas used.

Table 3.7 Predicted precipitation change over the Ganges, and the combined Brahmaputra and Meghna catchment areas.

Drainage basin (area km^2)	Mean annual precipitation (mm per day) and % change.			Mean precipitation (mm per day) for the monsoon season (June, July, August and September) and % change.			Mean precipitation (mm per day) for the dry season (November, December and January) and % change.		
	Control (late 20th century	2040 - 2060 SRES A2	% change	Control (late 20th century	2040 - 2060 SRES A2	% change	Control (late 20th century	2040 - 2060 SRES A2	% change
Brahmaputra and Meghna (696305 km^2)	6.1mm	6.7mm	8.9%	3.0mm	12.3mm	*303.9%	3.3mm	2.7mm	-18.0%
Ganges (944910 km^2)	3.6mm	4.0mm	9.8%	5.6mm	7.9mm	41.7%	3.7mm	2.0mm	-46.5%

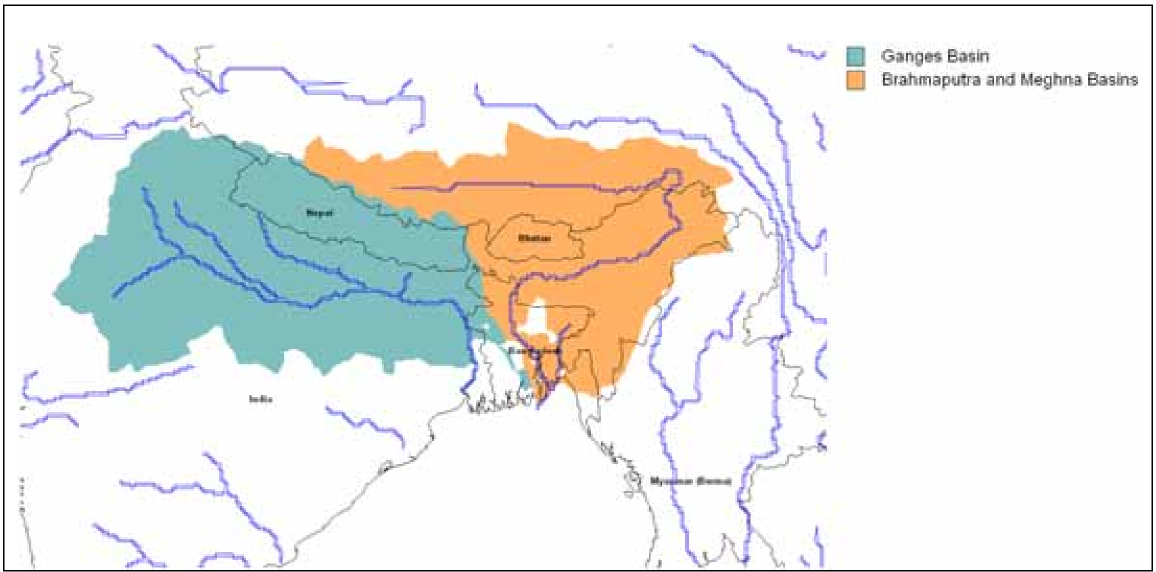


Figure 3.19 Coverage of the Ganges and Brahmaputra/Meghna drainage basins (spatial data source: Graham *et al.*, 1999).

The results shown in Table 3.7 predict some very large changes in precipitation, notably the 304% increase predicted for the Brahmaputra and Meghna catchment during the monsoon period. In view of other climate model data an increase to this extent is considered very unlikely. The limitations outlined for GCM data in the temperature section will also apply here. Due to the low resolution of the climate model data only a relatively small number of cells are covered by the catchment areas. As a result extreme values or errors in one or two cells will have a strong influence on the average value for the catchment. Again it is considered that a consensus from a number of models and emissions scenarios would help give a more informed picture in cases where data and resources permit.

As for temperature change in the previous section, the present results should be taken as indicative of possible trends rather than as an attempt to quantify changes. It is interesting that in the current case where a very large increase in precipitation is predicted over the Brahmaputra/Meghna catchment for the monsoon period, a decrease is seen for the winter period and a fairly moderate, and perhaps more realistic, increase is predicted over the same area when considering the mean value for the year as a whole. In the Ganges drainage the pattern for an average annual increase, an increase during the monsoon period, and a dryer winter is again followed but without the extreme values predicted for the Brahmaputra/Meghna basin. This pattern, and in particular the trend for greater annual average precipitation and greater precipitation during the summer monsoon period, has been supported by other climate models.

Lal and Harasawa (2001) using data from four GCMs for the 2050s and 2080s suggest a similar pattern of increased annual precipitation along with increased precipitation for June, July and August, and a decrease over the winter months (December to February).

Inter-model analysis by the IPCC (2001a) for the Southern Asia area shows agreement between models for a precipitation increase of 5 – 20% for the months June, July and August. For the months December, January and February results between models were considered inconsistent.

Mirza *et al*. (2003) using data from 4 GCMs (CSIRO9, UKTR, GFDL and LLNL) to investigate precipitation changes over the Ganges, Bhramaputra and Meghna basins, predicts an increase in both annual mean, as well as peak discharge for the three rivers in relation to 2, 4 and 6ºC temperature increase scenarios. Mirza *et al*. (2003) also uses the MIKE11-GIS hydrodynamic modelling tool to investigate potential increase in flooding associated with the predicted river discharges. Table 3.8 (adapted from Mirza *et al*., 2003) shows predictions of mean flooded area in relation to the three warming scenarios. Mirza concludes that potential increases in future discharge rates may increase the possibility of severe flooding in Bangladesh with north-eastern areas most affected by the Brahmaputra and Meghna systems while the Ganges is most likely to impact on central regions.

Table 3.8. Predicted area (million ha) flooded under 4 warming scenarios for 4 climate models (adapted from Mirza, 2003).

Climate model	Mean flooded area (million ha)			
	0˚C	2˚C	4˚C	6˚C
CSIRO9	3.77	4.65	4.68	4.71
UKTR	3.77	4.87	5.08	5.24
GFDL	3.77	4.84	5.02	5.17
LLNL	3.77	4.68	4.73	4.78

Potential increases in flood frequency, intensity and duration all certainly appear possible in light of the evidence presented above, and if such change occurs there are likely to be negative consequences for aquaculture in terms of loss of stock and damage to facilities. While less certain, the consequences of reduced precipitation during the dry season should also be considered. Reduced rainfall in combination with higher temperatures, potential evaporation, possible salination of ground water in coastal areas due to sea level rise, and the increased water demand of a growing population, industry and agriculture may seriously impact on the availability of water for aquaculture.

Changes in flow regime as a result of precipitation changes, as well as lower oxygen levels in flood plain waters due to higher temperatures, may impact on the recruitment of wild fish stocks. The mechanisms for, and consequences of, such impacts within Bangladesh are fully reviewed in Allison *et al* (2005). From an aquaculture standpoint the main consequences are a potential increase in demand for cultured fish products in combination with a decrease in the availability of wild seed. This will further increase the importance of quality seed production and distribution from hatcheries.

Summary - vulnerability of aquaculture in Bangladesh and potential adaptation

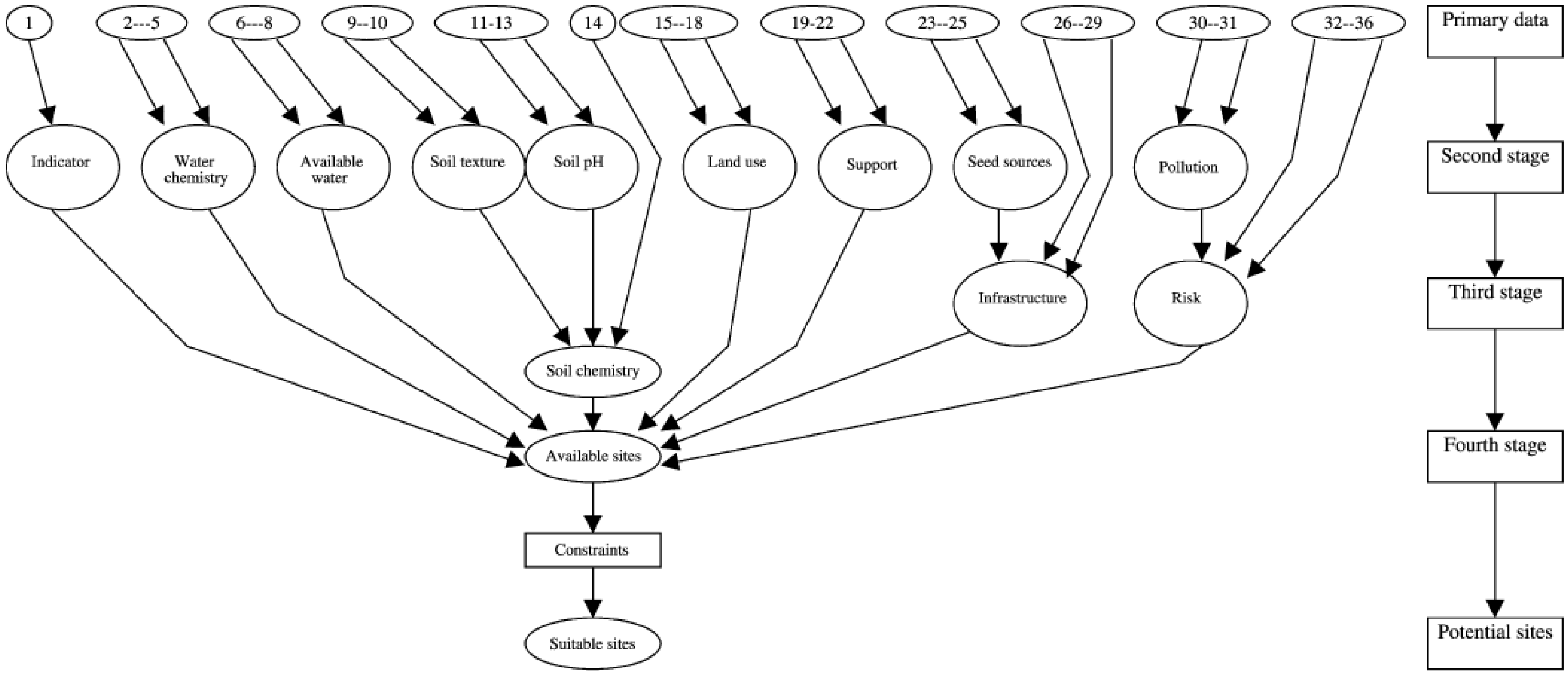
As with the global aquaculture vulnerability assessment (page 48), the concept of vulnerability as a function of sensitivity, exposure and adaptive capacity is used here to analyse the situation within Bangladesh.

Sensitivity

Data relating to aquaculture production such as that available from the BBS and displayed in Figs. 3.10 and 3.11 may provide a useful starting point when considering the current aquaculture trends and selecting areas for more localised study. Geographical indicators, such as land cover type, may also be of use when considering where aquaculture may be or may become and important activity. However care should be taken with currently available production data both in terms of potential inaccuracy of reporting and recording, and also in terms of the resolution available. Considering the widespread nature of aquaculture in Bangladesh it is certainly possible that communities where aquaculture is highly significant will be missed when considering data at the district (zila) or even sub district (upazila) level.

Establishing areas where future aquaculture expansion is either likely, or should be promoted will be of key importance. A number of useful studies have used GIS to model suitable areas for aquaculture within Bangladesh (Salam, 2000; Salam & Ross, 1999, 2000; Salam *et al*., 2003; 2005). Fig. 3.20 is taken from Salam *et al*. (2003) and shows the socioeconomic and environmental factors used in an assessment of suitable areas for brackish water shrimp and mud crab culture in the south west region of Bangladesh. Economic return and employment potential for shrimp and crab culture in relation to tilapia, prawn, carp and rice production from land identified as suitable within the study areas are also evaluated. The results suggested that shrimp, prawn and crab all had considerably greater potential than tilapia, carp or rice with prawn being moderately better than the others. The authors point out that products such as mud crab that have traditionally received little attention may have potential as a high value export in a global market that is likely to be less competitive than that of the well established shrimp industry.

Models such as the one described above have the potential to play an important role for future planning in relation to climate change. By manipulation of data such as salinity, temperature and risk from extreme events in line with future climate change predictions, it will be possible to assess the suitability of areas for aquaculture under a range of future climate scenarios. Key to the success of such projects will be the organisation and availability of a growing number of datasets. It is felt here that this is an area that deserves attention and could make a substantial difference to the feasibility, success and cost effectiveness of future work.



Primary data: 1= mangrove forest, 2= Temperature, 3= Dissolve oxygen, 4= pH, 5= Salinity, 6= rivers, 7= lakes, 8= under ground water, 9= sub soil texture, 10= surface soil texture, 11= surface soil pH, 12= sub soil pH, 13= field visit soil pH, 14= soil salinity, 15=agriculture land, 16= land under shrimp culture, 17= land under cities, 18= villages, 19= NGO offices, 20= Government offices, 21= Research station, 22= Universities, 23= seed from nature, 24= seed from hatcheries, 25= seed from local marker, 26= roads, 27= rivers, 28= markets, 29= processing plants, 30= pollution from industries, 31= pollution from urban development, 32= risk of drought, 33= risk of winter rain, 34= risk of disease, 35= risk of flood and cyclone and 36= elevation.

Figure 3.20. From Salam *et al*. (2003): Socioeconomic and environmental factors used for a GIS based site suitability study for brackish water shrimp and mud crab in the south west region of Bangladesh.

Exposure

As knowledge and understanding of climate change processes improves, emerging ideas and predictions should be constantly applied to Bangladesh. Based on current knowledge and focusing on the aquaculture sector it seems that precipitation changes and sea level rise are likely to be the trends of most concern in the medium to long term.

Cyclones and related storm surge events are a significant feature for coastal areas. While predictions of potential future increases in frequency and/or intensity cyclones contain a lot of uncertainty these scenarios should definitely be considered, as should the potential flood impacts of tropical storms over the Bay of Bengal when combined with factors such as sea level rise, increased river discharge, and backwater effect.

Prediction of future population and economic growth will also be vital when making informed policy decisions. A growing population will place an increasing strain on limited resources in what maybe in the face of sea level rise a potentially shrinking county. While flooding deservedly receives a lot of attention, the potential for water shortage should also be considered with increasing demand combined with the possibilities of reduced dry season precipitation, changes to dry season timing or duration, and the contamination of groundwater via sea level rise and salination.

Predicting potential levels of risk to the various types of flood event will be vital when making policy and development decisions for aquaculture as well as most other activities. The flood of 1988 was severe with a return period close to 100 years (Tingsanchali & Karim, 2005). This event has been used as a reference point in flood hazard prediction studies for the calibration of hydrodynamic models (Tingsanchali & Karim, 2005), and as source of multiple satellite images from different stages of inundation which are overlaid to reveal flooding patterns. Attempts have also been made to link these flood patterns to land cover characteristics and topographic variables in order to predict further areas of risk (Islam & Sado, 2000). (Mirza, 2002; 2003) linked GCM precipitation predictions to hydrodynamic models to predict the extent and depth of riverine flooding under future climate scenarios.

Continued monitoring of climate and environmental variables such as river flow, precipitation and salinity levels will help in the detection of trends and may help link such trends to any impacts been seen. Further work predicting the spatial extent of potential climate change impacts should be encouraged. Such work will not only be useful in indicating areas and people at risk but can also be linked in with site suitability studies to guide future development. A considerable amount of historic data in various forms, including satellite imagery which may help highlight patterns of land loss, erosion and flooding, already exists within governmental, non governmental and academic organisations within Bangladesh and elsewhere. Again it is felt here that an important goal should be to encourage the organisation of, and where possible, the easy availability of such data.

Adaptation

The poorest people typically find it hard to escape poverty due to a lack of financial capital that would otherwise allow the initiation of income generating activities. A number of NGOs have aimed to tackle this problem through the use of micro credit, with small scale aquaculture is seen as offering potential in such situations. Such schemes provide huge benefits but it is likely to be those with the lowest financial capital that will find it hardest to adapt to climate change. Therefore helping people make sensible and informed choices in relation to culture practices will be an important component of future aquaculture development work.

In the case of traditional extensive aquaculture flooding has supplied fish for ponds as well as letting others escape. Combined with minimal or no inputs, the impacts of flood events on such systems may not be too severe. These days aquaculture is typically more intensive with further intensification is being encouraged to help meet increasing demands for fish, and to provide income opportunities. As intensification increases, and where financial capital is limited, the potential loss of stock and/or damage to facilities due events such as flooding will be more serious. With poor people generally being unable to move and perhaps more likely to inhabit less favourable land, techniques for making the best of such areas need to be devised and promoted.

The concept of shocks (extreme events e.g. floods) and trends (gradual changes in climate and environmental factors e.g. temperature, water availability and salinity) is used here in considering adaptation to climate change in Bangladesh. In the case of extreme events such as floods adaptation strategies can take the form of trying to reduce losses, or accepting losses and trying to reduce the impact this causes to stakeholders. For example construction of higher embankments surrounding ponds may help reduce loss of stock during flooding but this option is likely to be too expensive for many people and is perhaps best suited to larger operations and higher value products. Alternatively the impact of losses could be reduced by minimising investment by harvesting fish at a smaller size and focusing on species that require short culture periods and minimal expense in terms of inputs.

Frequency and intensity of extreme events are also important considerations. For example in an area that is most likely to receive frequent but shallow floods then protection by embankments may be a good option. Alternatively a coastal area where the greatest risk may come from less frequent but much more intense storm surges, then the more economic strategy may well be to accept a certain degree of loss. For many poorer people there will be no choice but to accept occasional losses and the development and implementation of strategies to help people cope with these periods should be sought. Maximising production and profits during successful harvests will help offset losses. In this respect the availability of quality seed, information and support services, as well as the promotion of suitable species and culture practices in relation to the risks at a given area will all be important. This again highlights the relevance of site suitability and risk assessment work.

For adaptation to climate trends, and resulting gradual changes to the environment, the key focus will be on selecting suitable species and culture methods. A moderate increase in temperature will be tolerated by many of the species cultured in Bangladesh provided water availability and hence quality is reasonable. Many carp species are quite tolerant of warm water and low oxygen conditions (table 3.9), while others such as African catfish and the Anabantids may be more tolerant still.

Table 3.9 Lethal oxygen concentrations for some commonly cultured fish species (source: Varga & Chowdhury, 1992. Original data in: Doudoroff & Shumway, 1970)

Fish species	Lethal D.O. mg/l
Catla catla	0.7
Labeo rohita	0.7
Cirrhinus mrigala	0.7
Hypophthalmichthys molitrix	0.3–1.1
Ctenopharyngodon idella	0.2–0.6
Cyprinus carpio	0.2–0.8

Water availability during the dry season is likely to be an issue, especially if precipitation decreases and/or temperatures increase during this period. Poorer people are likely to have smaller ponds which will which will retain water for shorter periods. De Graaf and Latif (2002) suggest that small ponds (100 – 200m^2) that only contain water for up to four months can still be used for fish production providing appropriate species (the authors suggest African catfish) and management practices are used.

In summary the adaptation of aquaculture to climate change in Bangladesh will need to be varied depending on the stakeholders involved, their levels of capital (particularly financial), location, and the type and scale of aquaculture taking place. A flexible approach to policy making will be need, and diversification of species and culture practices should be promoted in what is likely to be a changing environment. Further research should be encouraged with the following areas seen here as especially significant:

- Awareness of latest climate predictions for the Bangladesh area, especially those involving precipitation regimes, sea level rise and if possible tropical storms.
- Organisation and availability of historic data and research.
- Analysis of site suitability for aquaculture based on:
    - Predicted changes in climate and consequent environmental factors: Water availability, Salinity and temperature.
    - Risk from extreme events notably riverine and storm surge floods.
    - Social and economic evaluations and predictions.
    - Resource availability e.g. Seed, inputs and support networks.
- Continued improvement and development of aquaculture practices for a broad range of species in order to maximise production where possible.
- Production and distribution of quality seed.
- Cost benefit analysis for a wide range of species and culture methods in relation to climatic and environmental variables.

4. Summary and conclusions

The aquaculture sector has expanded rapidly over recent decades representing an increasing percentage of total global fisheries. Many current capture fisheries are near or at their limit, while others have declined or may do so in the future due to fishing pressure and environmental impacts including those associated with climate change. It is predicted that aquaculture production and its share of the fisheries market will continue to expand and is set to play an increasingly important role in meeting global fish demands. The success of the sector therefore has important implications both in terms of food security, and as a source of income, for a growing number of people. Consequently any potential direct or indirect effects of climate change need to be taken seriously.

Asian countries dominate world aquaculture and look set to continue to do so. Hence it is in these countries, particularly those suffering from greater poverty, where the greatest number of aquaculture related livelihoods could potentially be affected. The Aquaculture sector is growing rapidly within Latin America making potential future impacts within this region significant. While aquaculture production in most African countries is currently quite low it is seen as an important potential aid to food security. As in other areas acknowledging the potentially changing climate and environment within Africa will be an important part of gaining the most benefit from the promotion of aquaculture.

The impacts of sea level rise on a low lying country with significant aquaculture in coastal areas is discussed in relation to Bangladesh, with many of the issues raised having relevance for other regions. The accuracy and resolution of land elevation data is very important for the modelling of inundation and land loss. In the case of the current Bangladesh case study the vertical resolution and accuracy of available remotely sensed elevation data was a limiting factor that precluded detailed inundation and land loss modelling.

The absence of a sea level rise component in the global vulnerability assessment is considered significant and this issue should be addressed where possible in future work. Estimates of predicted sea level rise at different locations under climate change scenarios were unavailable at the global scale. The availability and use of land elevation data of a resolution suitable for modelling sea level rise impacts is also a limiting factor. At present Shuttle Radar Topography Mission (SRTM) data with a horizontal resolution of 90m and a vertical resolution (not accuracy) of 1m is perhaps the best data that is freely available globally although the vertical resolution and accuracy in particular will limit modelling potential. Also with respect to current computing power, to work effectively with data of high resolution, such as SRTM, it will be necessary to work with smaller areas rather than at the global scale.

The database produced during the current project will be useful in identifying countries in which brackish and marine aquaculture, i.e. those likely to be associated with coastal areas, is significant. It is suggested that this information along with general knowledge of a countries aquaculture practices and physical geography be used to guide decisions regarding locations for further investigation of the impacts of sea level rise. Remotely sensed elevation data combined with data on aquaculture distribution may then be useful for highlighting vulnerable areas within countries. Where resources allow then more detailed modelling of impacts such as land loss and risk of inundation from storm surges may be possible. Such modelling processes will require data of high resolution and accuracy such as digital elevation models derived from detailed topographic maps. The production of such data sets is very resource intensive and the careful organisation, storage, and where possible free distribution and easy availability such data should be strongly encouraged.

With regard to climate data the low resolution of GCMs and the variation seen between models was noted in the current study. Some regional studies (e.g. de Wit & Stankiewicz, 2006) have attempted to overcome inter-model variation and improve accuracy of predictions by comparing data from a number of GCMs. Where resources permit, and depending on the objectives of the study, the use of a range of climate models should be considered for future work. Again it is felt that efficient organisation and availability of datasets created during such work will greatly increase scope and effectiveness of what can be achieved by subsequent projects with limited time and resources.

The distinctions between gradual climate trends and extreme events are helpful when analysing climate change vulnerability and considering adaptation. Predictions regarding the distribution, frequency and intensity of extreme events currently contain much uncertainty. It is suggested here that as more complex models are developed to assess future aquaculture potential that a range of extreme events scenarios should be considered allowing for increases in both frequency and severity.

A lot of the concepts of adaptation discussed within the summary of the Bangladesh section can be broadly applied across a range of locations. Local studies to establish areas of vulnerability and site suitability will be extremely important for informed policy making in relation to future aquaculture development and the concentration of resources in areas where livelihoods are likely to be most affected. The trade off between the costs of adapting to changing climate trends and protecting against extreme events through the movement or alteration of culture systems compared with accepting potentially increasing proportional production losses will need careful consideration. With much uncertainty remaining over climate change especially in regard to variation and extremes the continued improvement of aquaculture methods to maximise production and profit during successful growing seasons should be seen as an important part of climate change adaptation.

Financial capital is considered to be strongly linked to adaptive capacity, hence where possible the inclusion of future economic scenarios should also be considered when assessing potential vulnerability. The accuracy of economic predictions could have a large bearing on vulnerability in many cases and should be considered important in a similar way as those for climate variables and other factors.

Along with predicting vulnerable areas, the selection of suitable sites in relation to specific culture methods and species will be valuable in maximising profit and/or food production in the face of a changing climate. The use of Geographic Information Systems (GIS) has great potential not only for the organisation and display of spatial data but also as a powerful modelling tool capable of combining a range of demographic, economic, environmental and climatic data as well as considering factors such as infrastructure, services and inputs such feeds and fertilizers. The availability of water will be a particularly important component in some areas with aquaculture competing with other users associated with growing populations, industry and agriculture. As well as modelling future scenarios a properly established GIS can be easily updated making it useful for the monitoring of changing variables and hence changes in site suitability or areas of risk.

Finally it should be emphasised that the ways in which climate change may impact on aquaculture and aquaculture related livelihoods are extremely broad ranging and complex. While there are considerable bodies of work in the areas of both climate change, and aquaculture dependant livelihoods, there has been little specific focus on how climate change may affect aquaculture and more research is certainly needed. By giving an overview of potential impact mechanisms and through broadly indicating vulnerable areas at the global scale the current study provides a strong starting point and a useful guide for further investigations both at more local level and with a focus on more specific issues.

More focused case studies will be very important not only in guiding policy decisions for the areas concerned, but also for the increased understanding of the ways in which climate change impacts will take place along with possible adaptive measures to counter them. It may then be possible to apply the knowledge and working methods gained from one area to others with similar characteristics. With these points in mind the organisation, distribution and availability of data and literature will be very important in aiding the progress of future work and determining what can be achieved with the limited time and resources available.

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