Appendix 2.1. A review of effect of climate change on Renewable Natural Resource Sectors and their interactions with the fisheries sector

Contents

2 Executive Summary

This review is the main output of project logframe activity 1.1 “Review effects of climate change on other [DFID] natural resource sectors”. It aims to frame the impacts of climate change on fisheries within the wider context of other renewable natural resource sectors, particularly agriculture and forestry, and thereby highlight any important interactions that might exist.

Impacts in Africa and Asia form the focus of the review reflecting the importance of the fisheries sector to rural and coastal livelihoods and sensitivity to climate change in these continents.

Predicted exposure to climate change and seas level rise is first examined along with the anticipated changes to hydrological regimes and water resources. The impact of this predicted exposure and consequent changes in water resource availability and quality on fisheries and dependent livelihoods is then examined alongside other important renewable natural resource sectors, mainly agriculture and forestry, to identify important interactions among the sectors.

A great deal of uncertainty surrounds the predicted impacts largely because of the current inability of climate models to predict with sufficiently high spatial resolution, future rainfall patterns, but also because the net effects of potentially positive and negative impacts of climate change are difficult to determine. Uncertainty, surrounding the adaptive capacity of individuals, communities and nations further hinders sectoral impact and vulnerability assessment. The picture becomes further blurred when potential inter-sectoral interactions are also considered.

Declining lake levels are likely to diminish fish yields whilst warming may have a positive effect on the sector. Lakes sensitive to ENSO perturbations are likely to exhibit increasingly variable yields in the future. In Asian river basins where run-off and discharge rates are expected to increase the seasonal inundation of floodplain rivers, fish yields may increase as lateral migrants exploit larger areas of ephemeral spawning and feeding areas. The converse may be true in most African river basins where discharge rates are anticipated to decline.

Whilst the discharge rate and flooded area of many rivers in South and South-East Asia may increase, their dry seasons flows are often predicted to decline. This is true both for the Ganges and Mekong River Systems. Model predictions indicate that fish yields may be depressed by the diminished water availability during this period offsetting any potential benefits predicted by increased flood season water availability.

Whilst climate change may provide development opportunities for aquaculture if traditional wild fisheries are less stable, and may favour production, aquaculture may be constrained by water availability and exposed to greater disease risk.

In Africa, 60 to 70% of the population is dependent on the agricultural sector for employment, and the sector contributes more than thirty percent to GDP. Agriculture is similarly fundamental throughout most of Asia. In India, for example, 68% of the country’s one billion inhabitants are directly or indirectly involved in the agricultural sector.

A whole vector of factors affecting the agricultural sector make climate change impacts difficult to predict with any certainty. In the tropics, most crops are at or near theoretical temperature optimums, and any additional warming would be deleterious to yields. In temperate regions, however, crop yields would generally benefit at least some of the time from climate change. In other words, generally positive changes are expected at mid- and high latitudes, but these would be overshadowed by reductions in yields at low latitudes including many regions in Africa and Asia where farmers and consumers are less able to adapt.

Many studies, however, fail to account for potential changes in water availability for irrigation. Therefore, in regions where there is a likelihood of decreased rainfall, agriculture could be substantially affected regardless of latitude. Water availability (or runoff) is a critical factor in determining the impact of climate change in many places, particularly in Africa. The current inability to predict regional and sub-regional changes in precipitation is therefore a significant obstacle to reaching firm conclusions about related impacts on agriculture.

Not only shifts in climatic conditions, but increasing climate variability associated with global warning could also negatively impact on agricultural production. A net reduction in food supplies is predicted if warming of more than 2.5°C occurs, forcing price rises and straining food security. The economic impacts may also be acute, particularly if cheaper agricultural imports become available from countries positively affected by climate. Climate change will exacerbate the incidence of rural poverty, especially in developing countries where the agricultural sector is an important source of livelihood for a majority. Impacts on livestock performance variables such as somatic growth, milk and wool production, reproduction, health, and general well-being may further exacerbate the situation.

Approximately 60% of the world's total forest area is located in developing countries in tropical regions. As well as protecting biodiversity, forests and woodlands provide many important goods including timber, fuel, fiber and construction materials. Forests and woodlands also provide important non-wood forest products (NWFP) including edible mushrooms, nuts, fruits, palm hearts, herbs, spices, gums, game and fodder which make important contributions to household income and food security.

The effects of climate change on forested area and forest productivity, which can be both positive and negative, vary regionally. In regions where increased drought frequency is forecast, productivity would be lowered as a result of lowered photosynthetic rates and increased risk of fires.

Drought frequency in SE is anticipated to increase in response to more frequent ENSO events increasing the risk of natural fires. Fire frequency is also expected to increase in other regions where precipitation is reduced. The distributional range of some tree species is also expected to change in response to changes in seasonality, the length of the growing season, and diurnal temperature patterns induced by climate. In lowland humid tropics, temperatures already are close to optimum ranges for year-round growth. Further increases may depress growth and overall productivity. Elevated CO_2 concentrations can potentially increase production by as much as 25%, but plants may soon become acclimatized to increased CO_2 levels.

Damage caused by insects may change in response to climate change, particularly by those whose temporal and spatial distributions strongly depend on climatic factors. Changes in drought conditions appear to play an important role in insect outbreaks. Furthermore, extreme weather events such as hurricanes, tornadoes, heavy rainfall, and flooding can lead to extensive mortality and ecosystem change.

In Africa, geographical shifts in the ranges of individual species and changes in productivity are anticipated in response to forecasted changes in the spatial and temporal patterns of temperature and precipitation. Dry woodlands and savannas in semi-arid and sub-humid areas will be increasingly subjected to drying in the next century, as well conversion to agriculture. Climate change is very likely to alter the frequency, intensity, seasonality, and extent of vegetation fires that are critical to the maintenance of areas such as the Serengeti grasslands of east Africa, the miombo woodlands of southern Africa, and the fynbos of the Cape.

Climate change is also anticipated to have a profound effect on the future distribution, productivity, and health of forests throughout Asia. Because warming is expected to be particularly large at high latitudes, climate change could have substantial impact on boreal forests.

In the coastal zone, the fisheries sector will suffer from increased frequency of storm and severe weather events coupled with rising sea levels causing damage to fishing vessels, gear, increase the number of non- fishing days, and hinder access to markets, ultimately leading to lower earnings for fishers and supply of fish for consumption.

Reef-based fisheries are particularly at risk from the effects of climate change. Rising sea temperatures and elevated levels of atmospheric carbon dioxide are likely to increase coral mortality rates through 'bleaching', and reduce reef growth rates due to changing ocean chemistry and higher frequency of severe storms. Changes in the quality of water discharged from river basins into the coastal zone, including sediment loads and levels of pollutants could exacerbate these impacts.

In some regions, upwelling of cold bio-limiting nutrient-rich waters that support some of the most productive fisheries will be affected by climate change. Critical habitats such as mangroves and seagrass beds that support coastal fisheries are threatened by seas level rise and changes in salinity.

Forecasted increases in water and air temperatures could potentially lengthen the growing season for cultured fish and shellfish, thereby benefiting the mariculture sector. However, increased water temperatures and other associated physical changes, such as shifts in dissolved oxygen levels, have the potential to increase the intensity and frequency of disease outbreaks, offsetting any benefits. Any increases in the intensity and frequency of extreme climatic events such as storms, floods, and droughts will also negatively impact aquaculture production and may result in significant infrastructure damage.

Extreme weather events in the coastal zone will increasingly affect both agriculture and livestock. Sea level rise will also result in the physical loss and degradation of agricultural land. Loss and salinisation of land resulting from sea level rise is likely to have a major impact on yield from, and livelihoods dependent upon, the agricultural sector in coastal regions. In Egypt, for example, it has been estimated that 12-15% of the agricultural land in the Nile Delta could be lost. Sea level rise will also accelerate the intrusion of saline water in surface water resources and underlying coastal aquifers. Loss of land area will be significant in low-lying regions of coastal Asia, particularly in Bangladesh and Vietnam.

Mangrove forests comprising salt-adapted evergreen trees are an important natural resource in the coastal zone providing timber, food fuel and medicine. Depletion of mangrove forests by anthropogenic pressures has become a serious problem in south-east Asia, particularly in Thailand, the Philippines and Indonesia.

As well as being both ecologically and economically important within the coastal zone, mangroves trap sediment, creating natural barriers to sea level rise and salt intrusion into coastal soils and estuaries. The destruction of mangrove forests thereby reduces coastal zone (and lower lying river basin) resilience to future seas-level rise, wave erosion and flooding, which, may, in turn affect soil and (fresh) water quality.

Changes in salinity and sediment loads are anticipated to affect the growth and distribution of mangroves and submergence due to seas level rise is likely to cause dieback and erosion of their seaward margins. The survival of salt marshes and mangrove forests will depend largely on whether the rate of sedimentation is greater than or less than the rate of local sea-level rise.

Although adaptive strategies pursued by particular sectors have the potential to negate a significant amount of the vulnerability associated with climate change, they can augment impacts suffered by other sectors.

The adaptive responses of the agriculture sector to climate change appear to have the greatest potential to indirectly impact on fisheries. For example, changing patterns of precipitation and increasing frequency of extreme flooding events in lake and river basins may prompt adaptive strategies by the agriculture sector that focus upon the construction of more flood control, drainage and irrigation schemes. These structures are likely, however, to further exacerbate the direct adverse impacts of climate change on fisheries.

Crop diversification or replacement in favour of HYV that sometimes require more irrigation and flood control compared to traditional varieties could exacerbate these impacts. These extra needs, which are likely to be withdrawn from rivers other surface water bodies or aquifers, will affect hydrological and ecological regimes. The “direct” effect of climate change on hydrological regimes and ecosystems may therefore be enhanced.

Increasing intensity of fertilizer and pesticide application to mitigate the impacts of climate change on agriculture could adversely affect the quality water in rivers, lakes and coastal zones and thereby impact upon their fisheries. Changing the location of watering points for livestock may place further strain on dry season fish habitats.

Upstream changes in sedimentation and organic loadings are also anticipated to induce large scale changes in mangrove forests in coastal zones which provide critical habitat for many coastal fish species and an important source of seed, particularly shrimp, for the mariculture sector.

Changes to water quality in the coastal zone arising from upstream flood control measures and changing agricultural practice could further impact upon mariculture systems.

Potential declines in mangrove forest habitat resulting from sea level rise and changes in sediment and pollutant loading from river and lake basins could also impact on fisheries by reducing or degrading critical coastal habitat. Faced with declining yields, income and food security, fishers may seek alternative livelihoods placing pressures on other sectors or resources. For example, in West Africa, when coastal fisheries resources are scarce, fisheries adopt alternative livelihood strategies including hunting for bush meat.

3 Purpose, Scope and Approach of the Review

3.1 Purpose

This review represents the main output of logframe activity 1.1 “Review effects of climate change on other [DFID] natural resource sectors”. The review aims to frame the impacts of climate change on fisheries within the wider context of other renewable natural resource sectors, particularly agriculture and forestry, and thereby highlight any important interactions that might exist. It is hoped that this material will help to contribute to DFID’s “…cross programme synthesis of material on climate change”, and help develop communications products that will assist target stakeholders develop more integrated, and thereby effective, adaptive policies to help mitigate the impacts of climate change on the poor inhabiting land water interfaces.

3.2 Scope and Approach

Project R4778J mapped the vulnerability of fisherfolk to climate change on a global scale using the conceptual model of vulnerability described by McCarthy *et al.* (2001). In this framework, vulnerability is some function of *exposure* to climate change, the *sensitivity* of the system or livelihoods to this exposure, and the *adaptive capacity* of the system or livelihoods to accommodate or adapt to the exposure. Predicted ambient temperature change to 2050 was used as an indicator of exposure to climate change, sensitivity was quantified using indices of the economic importance of, and livelihood dependence on, fisheries, whilst adaptive capacity was described using indicators of human and economic development.

The mapping exercise revealed that fisheries within African countries, particularly those located in semi-arid regions with significant coastal or inland fisheries resources, were most vulnerable to climate change. However, Allison *et al.* (2005) emphasized that these countries were identified as being most vulnerable largely because of their particularly low adaptive capacity. “Given the fishery focus, it would have been justifiable to weight the analysis in favour of sensitivity, but more work is needed to establish appropriate weighting”.

The most sensitive countries in the developing world were found in Africa and Asia and Latin America (largely confined to Peru). This is exemplified by DFID (2004b) who report that 90% of the 200 million people at risk of annual flooding in the future will be within Africa and Asia.

Since the vast majority of the world’s poorest fisherfolk are found most notably in Pakistan, India, Bangladesh, Cambodia, Vietnam, Indonesia, and China; and in Sub-Sarahan Africa; countries in Asia (south and south-east) and Africa are the focus of this review. These regions also correspond largely to DFID’s geographic targets under their Natural Resources Systems Programme (NRSP), including the Land-Water Interface (LWI), as well as the Fisheries Management Science Programme (FMSP). Africa is expected to be the most vulnerable continent, suffering dramatic losses in agricultural productivity and increases in hunger as a result (McGuigan *et al.* 2002).

However, it must be borne in mind that a great deal of uncertainty exists surrounding *regional* climate especially with regard to rainfall which is fundamental to any analysis of future climate and its implications (Conway in press).

The review draws heavily from McCarthy *et al.* (2001): *Climate Change 2001: Impacts, Adaption and Vulnerability* – regarded as the most comprehensive and up to date scientific assessment of the consequences of, and adaptation responses to, climate change. This is supplemented by Allison *et al.* (2005) and additional relevant material.

The review begins by briefly summarizing the predicted exposure to climate change and seas level rise, focusing upon Africa and Tropical Asia. Hydrology and water resources are fundamental to renewable natural resource systems and inextricably linked with climate. The predicted changes to hydrology and water resources, in response to this exposure, are therefore also examined. The impact of this predicted exposure and consequent changes in water resource availability and quality on fisheries and dependent livelihoods is then examined alongside other important renewable natural resource sectors, mainly agriculture and forestry, to identify important interactions among the sectors.

4 Predicted Exposure to Climate Change and Sea Level Rise

4.1 Global

It is generally accepted that during the next century, the world is expected to warm by between 1.4 and 5.8°C. It is likely that most land areas will experience higher maximum and minimum temperatures and thereby more hot and fewer cold days. Regional changes in precipitation can be predicted with less certainty, although more intense precipitation events are likely over many areas as the ability of the atmosphere to retain more moisture increases. An increased risk of more intense tropical cyclones and destructive storms is also predicted (Table 1).

Table 1. Summary of predicted changes in the world's climate (Source: Allison *et al.* (2005).

Changes in phenomenon	**Confidence in projected changes**
Higher maximum temperatures and more hot days over nearly all land areas	Very likely
Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely
Reduced diurnal temperature range over most land areas	Very likely
Increase of heat index over land areas	Very likely, over most areas
More intense precipitation events	Very likely, over many areas
Increased summer continental drying and associated risk of drought	Likely, over most mid-latitude continental interiors
Increase in tropical cyclone peak wind intensities	Likely, over some areas
Increase in tropical cyclone mean and peak precipitation intensities	Likely, over some areas

Regional predictions are complicated by the complexity of the hydrological cycle. For example, a change in precipitation may affect surface wetness, reflectivity, and vegetation, which in turn may affect evapo-transpiration and cloud formation, which in turn affects precipitation. Ongoing human activities such as deforestation, urbanization, and the over-use of water supplies further complicates predictions (UNEP 2002).

4.2 Africa

Predicted annual warming across Africa ranges from 0.2°C to 0.5°C per decade with the greatest warming predicted over the interior of semi-arid margins of the Sahara and central southern Africa.

Future changes in mean seasonal rainfall in Africa are less well predicted due to high natural variability and large number of interacting factors driving precipitation patterns. Model predictions vary, but there is a general consensus for wetting in East Africa, drying in southeast Africa, and a poorly specified outcome for the Sahel (McCarthy *et al.* 2001). However, the Sahel has already experienced, on average, a 25% decrease in rainfall over the past 30 years, characterised by a decrease in the number of rainfall events (DFID 2004c). Sub-Saharan Africa is expected to experience drier and hotter conditions (UNEP 2002). Overall, climate variability and the frequency and intensity of severe weather events are also likely to increase (DFID 2004c).

Conway (in press) reports that in the Nile basin, there is high confidence that temperatures will rise, leading to greater losses to evaporation. However, there is much less certainty about future rainfall because of the low convergence in climate model rainfall projections in the key headwater regions of the Nile.

4.3 Asia

Depending upon the climate model employed, temperatures in south Asia are predicted to increase by 1.8-2.2°C in the summer, and by 2.1-3.2°C during the winter. In south-east Asia, the respective rises are 1.6-2°C and 1.7-2.3°C.

Annual mean precipitation over Asia is expected to increase by 5-9% by 2050. In south Asia, summer precipitation is expected to increase by as much as 6.6%, but winter rainfall is predicted to decline by between approximately 2-15%. In south-east Asia, on the other had, rainfall is expected to increase during both the summer and winter months by between approximately 2.5 and 3.5%. Inter-annual variability in precipitation is also predicted to increase in Asia, as is the intensity of extreme rainfall events (due to the warmer atmosphere), increasing the possibility of more frequent flash floods in parts of India, Nepal, and Bangladesh. Models with a spatial higher resolution predict increases in precipitation in flood-prone Bangladesh of approximately 20% (McCarthy *et al.* 2001).

Tropical cyclone intensity may increase due to disruption of the ENSO and increasing sea surface temperatures. A 1°C increase in sea surface temperatures in the Bay of Bengal could increase tropical cyclone intensity by 10% (DFID 2004c).

5 Climate Change Effects on Hydrology and Water Resources

5.1 Coastal Zones

5.1.1 Sea Level Rises

Coastal Zones throughout the world are expected to experience significant changes in sea level in response to thermal expansion of oceans and seas and melting land ice. Global mean rises of between 0.08 and 0.25 m are expected by 2050 and 0.38cm by 2080 (McCarthy *et al.* 2001). Regional patterns of seas level rise are more difficult to predict, but sea levels have been predicted to rise by 0.11 to 0.77m by 2100 in Asia (DFID 2004d).

5.1.2 Changes to Sea Surface Temperature

Climate models predict that seas surface temperature (SST) will continue to rise by between 1°C and 2°C during this century even under moderate global climate change scenarios (McCarthy *et al.* 2001).

5.1.3 Coastal Upwelling

Upwelling of nutrient rich cold waters in coastal zones is responsible for supporting some of the most productive fisheries (see later). These upwellings, caused by ocean circulation and wind shear, are sensitive to ocean-atmosphere perturbations such as the El-Nino-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). However, the effect of climate change on these perturbations is very uncertain.

In Southern Africa, it is believed that a major reorganization of the circulation of the southern oceans, which is a possibility at high rates of warming, could have significant impacts on coastal upwelling (McCarthy *et al.* 2001).

5.2 Rivers

5.2.1 Discharge (flow) Rates

Climate change is likely to affect river flows not only through a change in the magnitude of rainfall but also through possible changes in the onset (timing) or duration of rainy seasons.

Predicted effects of climate change to patterns of run-off and therefore river flow are broadly similar to those predicted for change in annual precipitation. Increased flows are expected in high latitudes and many equatorial regions but decreases are also expected in mid-latitudes and some subtropical regions (Figure 1).

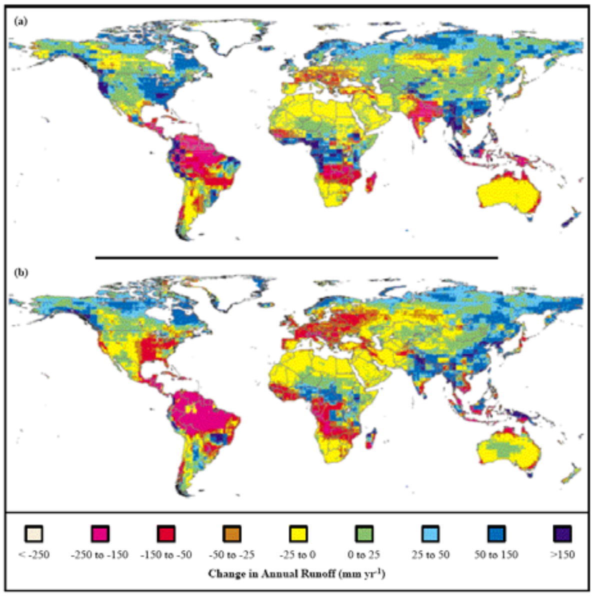

Figure 1 Change in average annual runoff by 2050 under HadCM2 ensemble mean (a) and HadCM3 (b). Source: McCarthy *et al.* (2001).

Because of higher rates of evaporation caused by higher air temperatures, some areas that see an increase in precipitation will experience a reduction in runoff. Seasonal changes in flow may be more significant. In river basins, changes in flow can have a significant effect on the extent of annual floodplain inundation. The periodic inundation of the floodplain or aquatic-terrestrial transition zone (ATTZ) is largely responsible for maintaining the productivity of large river systems (Junk *et al.* 1989).

Results of model predicts in McCarthy *et al.* (2001) suggest that with the exception of the Nile and the Niger, the major African river basins are likely to experience reductions in run-off of up to 40% (Table 2).

Table 2 Estimates of ranges of percentage changes in precipitation, potential evaporation, and runoff in African river basins Source: McCarthy *et al.* (2001)

Basin	Change in Precipitation (%)	Change in Potential Evaporation (%)	Change in Runoff (%)
Nile	10	10	0
Niger	10	10	10
Volta	0	4 to -5	0 to -15
Schebeli	-5 to 18	10 to 15	-10 to 40
Zaire	10	10 to 18	10 to 15
Ogooue	-2 to 20	10	-20 to 25
Rufiji	-10 to 10	20	-10 to 10
Zambezi	-10 to -20	10 to 25	-26 to -40
Ruvuma	-10 to 5	25	-30 to -40
Limpopo	-5 to -15	5 to 20	-25 to -35
Orange	-5 to 5	4 to 10	-10 to 10

In south Asia, changes in precipitation in the Ganges Basin resulting from global warming have been predicted to increase average flood season discharge rates for the Ganges, Brahmaputra, and Meghna rivers by as much as 15, 6, and 19%, respectively (Mirza *et al.*.1998). Glacial melt is also expected to increase which would lead initially to increased summer flows in some river systems followed by a reduction in flow as the glaciers disappear affecting countries including Bangladesh, north India and Pakistan (McCarthy *et al.* 2001). However, Arnell (1999) reports that declines in basin runoff would be expected in the Indus Basin, Pakistan, and Brahmaputra Basin.

Depending upon the choice of Global Circulation Model (GCM) model employed, Mirza *et al.* (2003) predict that mean annual discharge rates in the Ganges and Megna Rivers of the Ganges Basin could increase by as much as 60% assuming a 6°C rise in global mean temperature. Increases in mean discharge rates in the Brahamaputra river are predicted to be in the order of 20%. Consequently rates of sedimentation are also expected to increase (World Bank 2003).

Mirza *et al.* (2003) also predict than in response to these changes in discharge rates, mean flooded area will increase from 3.77 to between 4.65 and 5.24 million ha depending upon rises in global mean temperature, equivalent to increases of between approximately 20-40%. Under a 6°C rise in global mean temperature scenario, the duration of floodplain inundation is also predicted to increase.

Low flows and increased evapotranspiration during the dry season caused by reduced precipitation and elevated temperature will put increasing pressure on water availability during this period. Climate induced moisture stress in the upstream river basin area might lead to even lesser availability of water during this period (World Bank 2003).

Saline water intrusion is also predicted to increase further upstream as a result of a number of factors including higher seas levels and diminished river discharge rates during the dry season.

Drainage congestion is forecasted to be a major problem in some basins. The combined effect of higher seas levels and river beds, and reduced sedimentation in flood protected areas will impede drainage, increasing the depth, duration and extent of floodplain inundation.

No significant changes are projected in annual mean surface runoff in south-east Asia. Nijssen *et al.* (2001) examined the hydrological sensitivity of a number of large rivers to climate change including the Mekong in SE Asia. Using four different climate models, they found that flow rates were likely to increase marginally in the Mekong River during the flood season, but decline during the dry season.

5.2.2 Frequency of extreme flooding events

Forecasting the impacts of climate change of the frequency of extreme flood events is made difficult by the inability of global climate models to simulate, with accuracy, short-duration, high-intensity, localized heavy rainfall, and the fact that a change in mean monthly rainfall may not be representative of a change in short-duration rainfall (McCarthy *et al.* 2001).

In Africa, extreme flooding events such as those experienced in Mozambique during 2000 may have been caused by La Niña climate perturbation. Modeling exercises indicate that climate change may increase the frequency of ENSO warm phases and therefore the frequency of extreme flood events by increasing the warm pool in the tropical western Pacific or by reducing the efficiency of heat loss (McCarthy *et al.* 2001).

In Asia, it is generally accepted that the intensity of extreme rainfall events will increase, thereby increasing the possibility of more frequent flash floods particularly in parts of India, Nepal, and Bangladesh.

In Bangladesh, increased frequency and intensity of extreme events including flooding, droughts cyclones, and storm surges is forecast. A one-in-twenty-year extreme flooding event is likely to become one-in-five-year event (Huq *et al.* 1999).

5.2.3 Changes to low flow conditions

A global analysis by Arnell (1999b) indicates that patterns of change to river low flows are likely to respond in a similar manner to average annual runoff (Figure1) but that the percentage changes tend to be larger. Flows during particularly dry years are expected to decline by as much as 10% over 13-19% of the global area.

Changes in flow will also contribute to changes in water quality (see below) by affecting both concentrations and total loads of chemicals.

Droughts are predicted to become more common in Africa and temperate arid and semi-arid regions of Asia, including the south, in response to elevated temperatures, and reduced precipitation and streamflow. Droughts in Africa during the 1990's affected livelihoods and economies and heightened renewed interest in the impacts of climatic hazards The drought in Zimbabwe during the early 1990's is estimated to have been cost 9% of the countries GDP (Desanker & Magadza 2001).

Over large parts of Asia, water security is also likely to worsen with implications for irrigated agriculture, human water consumption and hydroelectricity generation.

Even without climate change, India's per capita renewable freshwater supply is predicted to fall by 40% based on projections of population growth, water demand and run-off within the major river basins. Climate change could significantly exacerbate the situation by decreasing rainfall supplies to major river basins (DFID 2004d).

5.3 Lakes

5.3.1 Lake Levels (and surface area)

Changes in air temperature and precipitation will affect rates evaporation, lake levels and entire lake ecosystems. Under some climatic conditions, lakes may disappear entirely.

Endorheic lakes (closed lakes with no outflow) are very dependent on the balance of inflows and evaporation and are very sensitive to change in either, and therefore small endorheic lakes are most vulnerable to a change in climate. Even relatively small changes in inputs can produce large fluctuations in water level (and salinity). Lake Chad, and some of the largest east African lakes including Lakes Tanganyika and Malawi can be regarded as effectively endorheic. Exorheic lakes (drained by outflowing rivers) also may be sensitive to changes in the amount of inflow and the volume of evaporation. Evidence from Lake Victoria, for example, indicates that lake levels may increase for several years following a short-duration increase in precipitation and inflows.

5.4 Water Quality (lakes, rivers and coastal zones)

5.4.1 Changes in temperature

River and lake water temperatures are predicted to increase by a slightly lesser amount than air temperature, with the smallest increases in catchments with large contributions from groundwater. Increases in both temperature and reductions in flow could exacerbate these problems (McCarthy *et al.* 2001).

5.4.2 Changes in chemical composition and dissolved oxygen concentrations

Biological and chemical processes in river and lake water are dependent on water temperature. Higher temperatures alone would lead to changes in the concentrations of chemicals. Dissolved oxygen concentrations are lower in warmer water, and higher temperatures also would encourage the growth of algal blooms, which consume oxygen on decomposition (McCarthy *et al.* 2001).

5.4.3 Changes to bio-limiting nutrient concentrations

Warmer, drier conditions are predicted to promote mineralization of organic nitrogen and thus increase the potential supply to the river or groundwater. Nitrate loading may also increase in response to more intensive storms following prolonged dry periods (McCarthy *et al.* 2001).

Nutrient loadings to receiving coastal zones would vary primarily with changes to streamflow volume. Increased frequency of heavy rainfall could further exacerbate the problem increasing pollutant loads flushed into rivers. In lakes elevated temperatures and changes in wind stress could bring about changes in thermal stratification, and thereby the vertical mixing of bio-limiting nutrients and oxygen (McCarthy *et al.* 2001).

5.4.4 Changes in sediment loads and salinity

River-borne sediments form and sustain important deltas in the coastal zones of Asia, some with an area of more than 10,000 km^2. Low-lying deltas are especially vulnerable to sea-level rise and increasing shoreline wave action. A decrease in river water discharge, as projected under some climate change scenarios, could lead to hindrance of delta progradation and increase the risk of irreversible change for estuarine ecosystems. Tidal rivers and estuaries will also become more prone to saltwater intrusion as a result of projected sea-level rise (McCarthy *et al.* 2001).

Droughts could increase water transparency and therefore the UV-B can penetrate deeper and cause more damage to coral reefs (see later). Wetter climates or climates with more extreme rainfall events would increase export of nutrients and sediment to lakes and streams whilst dryer climates would reduce export to lakes and streams, increasing water transparency and thereby increasing the depth to which harmful UV-B radiation can penetrate. Extreme rainfall events could potentially export nutrients and sediment if they occurred at during unplanted seasons (Gitay *et al.* 2001).

5.5 Groundwater resources

Groundwater is the major source of water across much of the world, particularly in rural areas in arid and semi-arid regions. The potential effects of climate change on these resources are, however, poorly understood (McCarthy *et al.* 2001).

Unconfined aquifers, which are recharged by rainfall, rivers and lakes directly, are likely to be most impacted by climate change. Recharge rates depend upon the permeability of overlying rocks and soils. Small changes in rainfall and stream flow can have a disproportionate effect on the recharge of aquifers. For example, a study in Central Tanzania showed that a 15% reduction in rainfall, with no change in temperature, resulted in a 40–50% reduction in recharge. Prolonged droughts are therefore likely to have a significant impact on groundwater resources (McCarthy *et al.* 2001).

Aquifers along floodplains, common in semi-arid and arid environments, are recharged by seasonal streamflows. Changes in recharge will therefore be largely determined by changes in the duration of flow of these streams or rivers. Coastal aquifers are at risk of saline intrusion in response to sea-level rise. Shallow coastal aquifers and groundwater in low-lying islands are at greatest risk (McCarthy *et al.* 2001).

Seawater intrusion into freshwater aquifers due to sea level rise has been reported for the coast of Thailand, the Chinese Yangtze Delta, and the Vietnamese Mekong Delta, amongst other environments. In Africa, groundwater resources are likely to be impacted by prolonged droughts and changes in land use (McCarthy *et al.* 2001).

Surface water and groundwater resources in Asian countries play vital roles in forestry, agriculture, fisheries, livestock production, and industrial activity. The water and agriculture sectors are likely to be most sensitive to climate change-induced impacts in Asia (McCarthy *et al.* 2001).

5.6 Water Stress

All the changes and variability in precipitation, run-off, river flow, changes in ground water resources described above are likely to combine to create greater ***water stress.***

6 Climate Change Impacts in Lake and River Basins

This section examines the potential impacts to, and responses of, important sectors utilizing natural renewable resources in lake and river basins (LRB). It begins by describing the importance of each sector in an attempt to set the vulnerability context. This review is repeated for the coastal zone (CZ) in Section 6. Intra and inter-sectoral, and physical interactions in response to climate change, both within and between LRB and the CZ are considered in Section 7.

6.1 Flooding threats to lives and infrastructure

Flooding events are predicted to become more frequent in river and lake basins in response to climate change. In East Africa, flooding, flooding caused by ENSO events in the recent past resulted in significant damage to property, crops and infrastructure, human suffering, loss of life, and triggered major emergency relief efforts. Floods in Mozambique during 2000 displaced more than 2 million people at a cost of US$167 million (Desanker & Magadza 2001).

6.2 Impacts on Fisheries and Aquaculture

Capture, culture, and recreational fisheries are reported to land about 23 million tones per year, but the actual numbers probably are twice that. Fish species in freshwater total about 11,800, but 100 fish species are reported in world catches—primarily cyprinids, cichlids, snakeheads, catfish, and barbs. Asia and China report the largest catches; Africa is second (Gitay *et al.* 2001)

Due to differences in their capacity to absorb changes in temperature and precipitation, small rivers and lakes will be more sensitive to climate change than large rivers and lakes. Climate change is expected to impact on fisheries through its influence on abundance, distribution, and species composition. Heavily exploited populations will also have less capacity to absorb climate change.

6.2.1 Lake Fisheries

Changes in lake levels, elevated water temperature and diminished water quality in response to climate change are likely to adversely impact on lake fisheries and dependent livelihoods.

6.2.1.1 Lake Levels

Lake levels may change, drying or excessively inundating critical or important feeding habitat leading to reduced recruitment, abundance and ultimately exploitable biomass. Such responses are well illustrated in Figure 2 which shows how catches from Lake Chilwa, Malawi, have responded to changes in lake level.

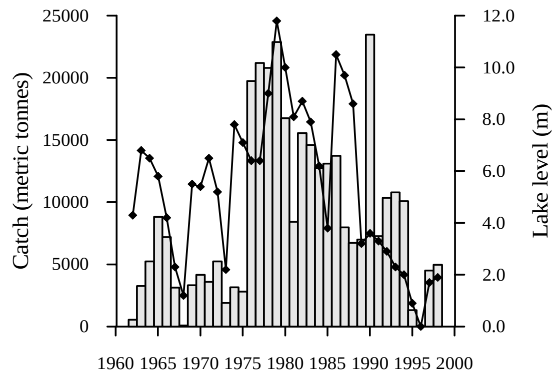

Figure 2 Catch fluctuations (shaded bars) and lake level variations in the shallow Lake Chilwa, Malawi, 1962-1998. Source: Allison *et al.* (2005)

Generally speaking, a linear relationship exists between log transformed fish catch (production) and log transformed lake area (Figure 3). Declines in lake level will reduce lake area and therefore yield and *vice versa*. On Lake Kariba, Magadza (1996) found that drought years were accompanied by decreased fisheries catch. Precipitation and run-off were found to be positively correlated with fish yields (Gitay *et al.* 2001).

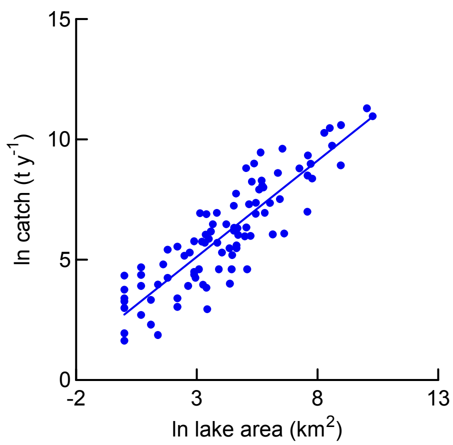

Figure 3 Relationship between lake area and annual fish yields. Note log scaling. Source: Halls *et al.* (in press).

However, lake warming, whilst likely to be associated with lower lake levels, may have a positive effect on fisheries (see below).

6.2.1.2 Temperature

Warming of lake environments and increased frequency of large scale climatic perturbations also has the potential to affect recruitment, both positively and negatively, to fish stocks. Changes in lake temperatures and increased levels of atmospheric carbon dioxide might increase metabolic demands and energetic costs, potentially reducing somatic growth, maturation and fecundity, and shell dissolution in calcifying (shell-building) species. Changes in lake temperature could also lead to changes in species distribution and thereby ecosystem functioning, impacting on potential yields, fishing costs and earnings, food security, GDP, and export earnings (Allison *et al.* 2005).

Empirical relations (Regier *et al.*., 1990; Lin and Regier, 1995) suggest that annual primary production by phytoplankton, zooplankton biomass, and fishery yields all increase with temperature (Gitay *et al.* 2005). However, in Lake Tanganyika, increased surface water temperature and reduced wind stress associated with ENSO perturbations have been found to be negatively correlated with indices of fish abundance (see Allison *et al.* 2005 for details). Increased thermal stratification is likely to reduce physical mixing and thereby reduce biolomiting nutrient concentrations in the photic zones available for fish production.

6.2.1.3 Water quality

Changes in lake salinity could increase metabolic stress, thereby reducing fisheries productivity. Increases in lake water transparency will increase the expose of fish to damaging UV-B radiation.

6.2.2 Floodplain River Fisheries

The biology and ecology of fish in large rivers are strongly linked to the hydrological regime in the main channel and the regular flooding of their adjacent floodplains (Welcomme 1985; Junk *et al.*. 1989). Fish have evolved physiological adaptations, life history strategies and spawning and feeding behaviour to cope with fluctuating flow conditions in rivers (Welcomme & Halls, 2004). Consequently, the absolute and relative abundance and biomass of species of fish inhabiting large rivers are predicted to change in response to both natural intra-annual variations in flooding regimes as well as long-term climatic shifts.

The impact of climate change on river fisheries and fisher livelihoods is likely to vary among river basins according to regional differences in the forecasted effects of climate on the hydrological regimes of rivers and their floodplains. Regional or river basin forecasts of regime changes are, however, lacking. Our ability to predict impact is further hampered by our largely incomplete knowledge and understanding of the way fish populations (and fishers) respond to changes to river hydrology.

In river basins where run-off and discharge rates are expected to increase the seasonal inundation of the floodplains of rivers such as those in the Ganges basin in South Asia, fish yields may increase as larger areas of ephemeral spawning and feeding areas are exploited by lateral migrant species (Figure 4). For example, in Bangladesh the 20-40% increase in flooded area predicted by Mirza *et al.* (2003) would raise total annual yields by between approximately 60,000 and 130,000 t based upon the model depicted in Figure 4.

Extended periods of floodplain inundation predicted for some river basins (see Section 5.2) may also favour fish growth, survival and reproduction (see Halls and Welcomme 2004).

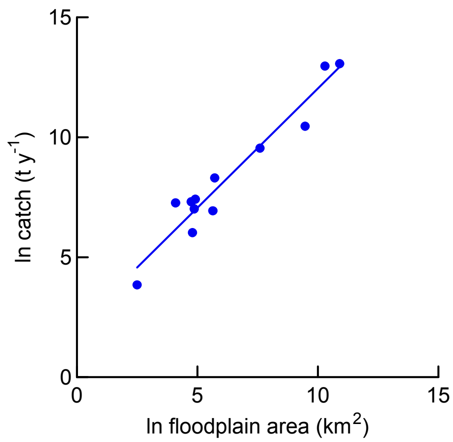

Figure 4. The relationship between catch and river floodplain area. Note logarithmic scaling. Source: Halls *et al.* (in press)

The converse may be true in most African river basins where discharge rates are anticipated to decline (see above). Diminished flows may not inundate floodplains (flood failure) resulting in the loss of whole year classes of fish (Gaygalas & Blatneve, 1971; Fuentes, 1998). Diminished flows may reduce flushing rates resulting in the accumulation or low dilution of toxic wastes leading to eutrophication and elevated fish mortalities or sedimentation of spawning grounds.

Whilst the discharge rates and flooded area of many rivers in South and South-East Asia may increase, their dry seasons flows are often predicted to decline (see above). This is true both for the Ganges and Mekong River Systems.

The dry season is a period of great stress to the majority of river fish species. At this time most species are confined to the main channels of the river although some specialists can survive in permanent floodplain waterbodies. Model predictions described by Halls *et al.* (2001) suggest that the exploitable biomass of floodplain-resident *blackfish* species (*sensu* Regier *et al.* 1989), is more sensitive to dry than flood season conditions when the area of water remaining on the floodplain may be less than 5% of that during the flood season. Extremely low flows can also lead to deoxygenation of the water leading in extreme cases to elevated mortality rates, particularly among whitefish species.

Potential increases arising from more extensive flooding in some river basins may, therefore, be offset by declines in potential production arising from lower water volumes during the dry season. Adaptive agricultural strategies are likely to further exacerbate these dry season impacts (see below).

Furthermore, elevated flood season discharge rates may actually impact negatively on *whitefish* populations. These species often migrate upstream to breed in the channel and whose fry drift downstream to be eventually washed onto floodplain nursery habitat. Elevated discharge rates are likely to reduce recruitment in these species as fish larvae, fry and juveniles are swept past suitable floodplain nursery habitat.

Increased down-cutting (erosion) of the river bed may also diminish recruitment in populations of fish that spawn on the beds of rivers. Significant temporal changes in river discharge rates may also disruption spawning in some species leading to changes in community structure favouring species with more flexible spawning behaviour. More catastrophic and unpredictable climatic events may also disrupt fishing operations, effectively reducing fishing effort and potential yield.

Jallow *et al.* (1999) predicted that elevated water temperatures within the Gambia River increase yields from the river by 13–21%. However, some components of the fishery such as catfish and herring would be negatively impacted by warming of more than 3-4°C. Shrimp yield is estimated to increase by about 38–54%.

Increases in rainfall intensity can lead to higher rates of soil erosion, leaching of agricultural chemicals, and runoff that carries livestock waste and nutrients into water bodies potentially causing eutrophication and oxygen depletion (World Bank 2003).

6.2.3 Aquaculture

Climate changes may provide development opportunities for aquaculture if traditional wild fisheries are less stable and markets favor the stability of the aquaculture product (Gitay el al 2001). This may be feasible because the aquaculture industry is mobile and large quantities of fish can be produced in small areas and that in many cases these sites can be moved to more favorable locations. Elevated temperatures may increase growth rates, but more food will be required and there is an increase risk of disease (see Section 7.2.5). Changes in groundwater may therefore be especially significant for aquaculture. Any increases in the intensity and frequency of extreme climatic events such as storms, floods, and droughts will negatively impact aquaculture production and may result in significant infrastructure damage.

6.3 Impacts on Agriculture

The vulnerability of the agricultural sector to climate change depends upon a host of environmental and management factors including soil content, type of crop grown, extent of knowledge and awareness of expected changes in climate and the ability of key stakeholders to undertake the necessary remedial steps to address climate concerns (World Bank 2003). Climate change is predicted to affect agriculture through:

- Changes in atmospheric concentrations of CO_2
- Changes in temperature and precipitation,
- Changes in soil moisture and soil fertility,
- Changes in the length of growing season and
- An increased probability of extreme climatic events

A great deal of uncertainty surrounds the impacts of elevated CO_2, high temperature, and precipitation and subsequent effects on crop yields including the potential indirect effects. For example, whilst increases in minimum day time temperatures and CO_2 concentrations are predicted to enhance photosynthesis, crop growth, and yield in some species (although at a possible loss of nutritional quality), increases in higher night time temperatures could extend the over-wintering range for some insect pests and broaden the range of other temperature-sensitive pathogens (McCarthy *et al.* 2001; World Bank 2003).

A review of studies predicting the impacts of climate change on crop yields by Arnell and Liu (2001) indicated that in the tropics, most crops are at or near theoretical temperature optimums, and any additional warming would be deleterious to yields. Plant metabolism begins to break down in some crops exposed to temperatures above 40°C (World Bank 2003). In temperate regions, however, crop yields would generally benefit at least some of the time from climate change. In other words, generally positive changes are expected at mid- and high latitudes, but these would be overshadowed by reductions in yields at low latitudes including many regions in Africa and Asia where farmers and consumers are less able to adapt (Table 3). A net reduction in food supplies is predicted if warming of more than 2.5°C occurs, forcing price rises and straining food security (UNEP 2002). Many of these studies however, fail to account for potential changes in water availability for irrigation where required i.e. irrigation adaptation is assumed possible (McGuigan *et al.*, 2002). Therefore, in regions where there is a likelihood of decreased rainfall, agriculture could be substantially affected regardless of latitude. In other words, water availability (or runoff) is a critical factor in determining the impact of climate change in many places, particularly in Africa. The current inability to predict regional and sub-regional changes in precipitation is therefore a significant obstacle to reaching firm conclusions about related impacts on agriculture (World Bank 2003).

Not only shifts in climatic conditions, but increasing climate variability associated with global warning could also negatively impact on agricultural production. Intensified hydrological cycles will cause loss of soil moisture and increased soil erosion which could exacerbate desertification and salinisation of agricultural land (DFID 2004b). Soil moisture, critical to agricultural production, will tend to decline in some mid-latitude continental regions during the summer. Some regions that are already drought-prone may suffer longer and more severe dry spells. Arid and semi-arid regions will be particularly sensitive to reduced rainfall and to increased evaporation and plant transpiration (UNEP 2002; World Bank 2003).

The economic impacts may also be acute, particularly if cheaper agricultural imports become available from countries positively affected by climate change – an example of the concept of *double exposure* (McGuigan 2002; O'Brien *et al.*, 2004). Climate change will exacerbate the incidence of rural poverty, especially in developing countries where the agricultural sector is an important source of livelihood for a majority (World Bank 2003).

Table 3 Summary of studies of climate change impacts on crop yields without and (with adaption strategies) in Africa and Asia. Modified from Gitay *et al.* (2001).

Country	Climate Scenario	Wheat	Rice	Maize	Soyabean	Cash crops	Study
Egypt	GFDL and UKMO 2xCO2 equilibrium scenarios, GISS-A transient scenario at 2xCO2	-51 to --5% (-25 to -3%)	-27 to -5% (-13 to -3%)	-30 to -17% (-15 to -8%)	-21 to -1% (-10 to 0%)		Yates and Strzepek (1998)
Africa	GISS, GFDL, UKMO	(-20 to -15%)	(0%)	(-29 to -23%)	(-2 to +10%)	(-10 to -4%)	Winters *et al.* (1999)
The Gambia	CCC, GFDL, GISS			-26 to -15%			Smith *et al.* (1996)
Zimbabwe	CCC, GFDL, GISS			-14 to -12%			Smith *et al.* (1996)
Indonesia	GISS transient		-14 to -9%				Amien *et al.* (1996)
India	Synthetic (+1.5°C, +2 mm day-1 precipitation)		-15 to -3%				Saseendran *et al.* (2000)
India	Sensitivity analysis (+2,+4°C; ±20, ±40% precipitation)				-22 to +18%		Lal *et al.* (1999)
Philippines	CCC, GFDL, GISS, UKMO		-13 to +9%				Buan *et al.* (1996)
Bangladesh	CCC, GFDL	-61 to -20%	-17 to -10%				Karim *et al.* (1996)
China	GFDL, UKMO, MPI			-19 to +5%			Jinghua and Erda (1996)
Asia	GISS, GFDL, UKMO	(-54 to -8%),	(-12 to -3%)	(-34 to -20%)	(-9 to +10%)	(-13 to +2%)	Winters *et al.* (1999)
Asia	GFDL, GISS, UKMO (+4oC)		-31 to -7% (+14 to +27%)[1]				Matthews *et al.* (1997)

1- with change in variety.
GFDL – Geophysical Fluid Dynamics Laboratory ; UKMO – UK Meteorological Office; GISS –Goddard Institute for Space Studies ; CCC – Canadian Centre for Climate; MPI – Max Plank Institute.
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6.3.1 Africa

In Africa, 60 to 70% of the population is dependent on the agricultural sector for employment, and the sector contributes more than thirty percent to GDP. In the West African Sahel alone, more than 80% of the population is involved in agriculture and stock-farming in rural areas (World Bank 2003).

Climate change is predicted to impact on agricultural throughout Africa. Agricultural systems in semi-arid and arid regions in sub-Saharan Africa are most at risk from the effects of climate change (UNEP 2002). "Desertification (caused by both climate and anthropogenic factors) has already reduced the potential vegetative productivity of more than a quarter of Africa's land by 25% over the past 30 years" (DFID 2004c).

In Uganda a temperature increase of 2°C is predicted to dramatically reduce the total area available for growing *robusta* coffee, and restrict it to higher altitude areas (DFID 2004a). In Tanzania, maize production is predicted to decrease by 33% but to significantly increase (84%) in the central regions of Dodoma and Tabora (McGuigan 2002; OECD, 2003). Yields in the northeastern highlands are predicted to decrease by 22% and in the Lake Victoria region by 17%. These reductions are due mainly to increases in temperature that shorten the length of the growing season and to decreases in rainfall. The two cash crops (coffee and cotton), on the other hand, are projected to experience increases in yield (OECD, 2003).

Crop yields in many areas of southern Africa are predicted to benefit from increases in carbon dioxide (higher water use efficiency, higher rates of photosynthesis) which outweigh the adverse effects of lower rainfall and higher temperatures. The window for planting is also lengthened (World Bank 2003).

Because Kenya has a wide range of agro-ecological conditions, impacts of climate change would vary. Productivity could increase in central and western parts of the country, but could decline in semi-arid areas where already low yields decrease further as a result of insufficient rainfall. Therefore, whilst the overall impact on the sector may be positive, results will vary by region (World Bank 2003).

Even with irrigation adaptation, maize production in Zimbabwe has been predicted to decrease significantly, affecting national food production and land use. Changes in quantity and timing of rainfall in the Niger Basin has already impacted on millet production and threatens sustainable agriculture in the region as farmers increasingly utilize marginal lands that are more susceptible to rainfall variability and wind erosion (World Bank 2003).

6.3.2 Asia

Agricultural systems in semi-arid and arid regions in South, East and Southeast Asia are most at risk from the effects of climate change (UNEP 2002). For example, models of farm incomes in India suggest that a 2-3.5°C increase in temperature would result in a decline in farm net revenues by between 9% and 25%. With about 68% of India's population of one billion directly or indirectly involved in the agricultural sector, impacts would be widespread but particularly acute in Rajasthan, Gujarat, Punjab, Haryana, Madhya Pradesh, Maharashtra, and Uttar Pradesh (Figure 5).

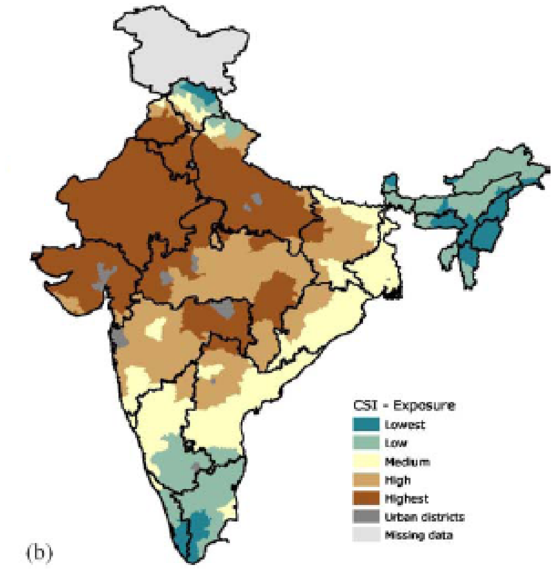

Figure 5. District-level mapping of climate sensitivity index (CSI) for the agricultural sector in India based on results from the HadRM2 model. The CSI is based upon measures of dryness and monsoon dependence. Source: O'Brien *et al.* (2004).

World Bank (2003) reports the results of several other studies for India including Seshu & Cady (1984) who estimate a decrease in rice yield of 0.71 ton per hectare with a one degree rise in minimum temperature (18°C to 19°C) and a 0.41 ton per hectare decrease with a temperature increase from 22°C to 23°C. Sinha & Swaminathan (1991) are reported to find that a 2°C increase in mean air temperature could decrease rice yield by about 0.75 ton per hectare in the high-yield areas and by about 0.06 ton per hectare in the low-yield coastal regions. Higher winter temperatures are estimated to account for a 10 percent reduction in wheat production in the high-yield states of Punjab, Haryana, and Uttar Pradesh. Rao and Sinha (1994) estimate that wheat yields could decrease by 28 to 68 percent. Other impact studies for India that take account of adaptive strategies suggest that a rise in temperature of 4°C could result in a reduction of grain yields of between 25 and 40%. In north India, rice production would increase in the absence of irrigation and nutrient limitations. Kumar and Parikh (1998) projected a 30 to 35 percent reduction in rice yields for India given a temperature increase of between 2-3.5°C.

In regions of Pakistan, rainfall during the wet season could increase by between 5% and 50% by 2070, with a doubling in the frequency of high intensity rainfall events. These climatic changes could significantly impact on cotton production, Pakistan's main cash crop, owing to flooding in its early stages of growth (DFID 2004a).

Changes in the hydrological conditions in the Ganges basin will have significant implications on rice agriculture and cropping patterns in Bangladesh (World Bank 2003). In the Philippines, more than 50% of the population are engaged in agriculture – a sector which accounts for more than 70% of the country's foreign export earnings. Rice is very vulnerable to tropical cyclones, flooding and drought-inducing delays in the onset of the rainy season (Kasperson & Kasperson 2001; World Bank 2003).

In Java, where more than half of Indonesia's rice is grown, ENSO events influence rice planting dates and resulting production. ENSO events are predicted to become more frequent with climate change (World Bank 2003).

Generally, rainfed agricultural systems are likely to be most affected by increased variability in the timing and intensity of the rains. Alarmingly, high yielding varieties (HYV) of crops which formed the basis for the 'green revolution' in Asia, may actually prove more susceptible to early flooding, salinisation and drought than hardier traditional varieties (O'Brien *et al.* 2004; DFID 2004d).

6.4 Impacts on Livestock

Livestock are impacted by climate directly and indirectly. The direct impacts include heat exchanges between the animal and its environment that are dependent upon air temperature, humidity, windspeed, and thermal radiation. Changes in heat exchanges influence animal performance variables such as somatic growth, milk and wool production, reproduction, health, and general well-being. Indirect impacts include climatic influences on quantity and quality of feedstuffs such as pastures, forages, and grain and the severity and distribution of livestock diseases and parasites (Arnell & Liu, 2001).

Grasslands support approximately 50% of the world's livestock. Changes in climatic conditions may reshape the spatial distribution of shrublands, forests, and other ecosystems. In tropical regions such changes in the evapo-transpiration cycle could strongly affect productivity and the mix of species (UNEP 2002).

Extreme weather events such as summer heat waves and winter storms can result in the death of vulnerable animals which can have substantial financial impacts on livestock producers. Adaptive strategies during heat waves include shades and/or sprinklers to reduce excessive heat loads (Arnell & Liu, 2001).

In Tanzania, 65% of the country is rangeland with a potential for a large impact on livestock through increased heat stress and an increase in animal vector borne diseases (McGuigan *et al.* 2002).

In the Greater Horn of Africa (GHA), the heavy rains associated with the 1997-98 El Niño lead to major outbreaks of Rift Valley Fever (RVF), a mosquito-borne virus affecting livestock and humans. Millions of livelihoods in some of the poorest countries, including Ethiopia and Somalia which depend on livestock were adversely impacted after fears of the spread of RVF lead livestock importing countries in the Middle East to ban the import of livestock from GHA countries for several years (Hansen *et al.* 2004).

6.5 Agriculture and Livestock Adaptive Strategies

Adaptive strategies have the potential to negate a significant amount of the vulnerability associated with climate change (World Bank 2003). Adaptation strategies to climate change include adjustments in planting dates, fertilization rates, irrigation applications, and cultivar traits (Arnell & Liu, 2001). For example, OECD (2003) conclude that in Tanzania, adaptive strategies for mitigating the impact of climate change on maize production might include increased irrigation, increased use of manure and fertilizer, and better use of management tools including climate information. Some studies find agronomic adaptation to be most effective in mid-latitude developed regions and least effective in low-latitude developing regions (McCarthy *et al.* 2001).

6.5.1 Diversification and changes to planting dates

Diversification towards drought or heat tolerant plant types, cultivars, hybrids, and animal breeds have been advocated as having the potential to increase productivity in the face of temperature and moisture stresses. In Zimbabwe, farmers have switched to more drought tolerant crops in areas where the frequent recurrence of droughts has made agriculture production difficult using the traditional crop varieties. The use of heat tolerant crops has also been identified as an important adaptive strategy in India (World Bank 2003).

Model simulations have shown that the use of new cultivars and changing planting dates can increase rice yields in southern China, and switching from rice to corn has the potential to reduce water demand (World Bank 2003). Adaptation to declining groundwater tables by substituting dry land for irrigated crops in regions of the U.S. Great Plains has been suggested to deal with increasing water stress (McCarthy *et al.* 2001).

6.5.2 Changes in agricultural practice

Changing the intensity of fertilizer and pesticide application and the timing of irrigation can help mitigate the impacts of climate change on farm production. Indeed, crop diversification or replacement may demand changes to inputs such as fertilizer and irrigation. Biomass production under elevated CO2 concentrations is unlikely to be sustained without fertilizer inputs. Adjusting the cropping sequence and the timing of sowing, planting, spraying, and harvesting, to take advantage of the changing duration of growing seasons and associated heat and moisture levels is regarded as another option Shifting production away from marginal areas has also been advocated to help reduce soil erosion and improve moisture and nutrient retention (World Bank 2003).

Adaptive strategies for livestock and rangeland management include shifts in biological diversity, species composition and/ or distribution; grazing management (timing, duration, and location); supplemental feeding and changing the location of watering points (World Bank 2003).

6.5.3 Increased irrigation and improved water-management

The World Bank (2003) predicts that improved water resource management "…will be vital to sustaining crop productivity levels in the face of both climate variability and longer-term change".

Many rain-fed systems, particularly those in arid and semiarid regions, where inadequate rainfall, high temperatures, and evapotranspiration rates limit crop growth, will rely increasingly upon the use of surface and ground water resources but must also compete with rising domestic and industrial demand, as well as the needs of other sectors such as fisheries (see later) necessitating improved management of water resources. "Improved water management is one of the most important long-term adaptation options that countries must pursue". Current irrigation efficiencies in many developing countries are very low. For example, in the Philippines in 1990 irrigation efficiency was only 18%, compared to the global average of 43%, requiring up to 5000 litres of water to produce just 1 kg of rice (Asian Development Bank, 1998).

Management strategies might include improving water distribution strategies; changing crop and irrigation schedules to use rainfall more effectively; water recycling and the use of groundwater. Irrigation availability and demand will be affected by both changes in temperature and precipitation. Reduction in precipitation will intensify aquifer exploitation for agriculture and place additional burdens on other surface and groundwater. An increase of potential evapotranspiration is likely to intensify drought stress, especially in the semiarid tropics and subtropics (World Bank 2003).

In some cases, a lack of water resulting from climate change might mean that increased irrigation demands cannot be met. Some workers have suggested that it may be necessary to shift irrigated agriculture to regions where climate change will decrease per hectare irrigation requirements (World Bank 2003).

6.5.4 Flood control measures and manipulation of hydrological cycle

Simple, but extensive flood control schemes, polders and impoundments have been constructed in river basins, most notably in Bangladesh to protect agricultural land and domestic areas against the effects of extreme flooding. In some parts of the country, elaborate flood control, drainage and irrigation schemes have also been built, with pumping stations capable of controlling water levels at optimum heights for agricultural production, over much of the year (Halls *et al.* 1998). Billions have already been spent on these structures and with the prospect of more extreme flooding and the need for increased irrigation and water management in the future as a consequence of climate change, structures of this types may become more widespread in river basins. While such flood control schemes give significant benefits to the agricultural sector and protect human lives and livelihoods, they may also adversely impact on fisheries production (see later).

6.5.5 Improved forecasting

The ability to anticipate climate fluctuations provides opportunity for adaptive management, both to prepare for expected adverse conditions, and to increase production and income during favorable conditions. Advances in environmental monitoring and prediction have the potential to improve the lead-time, accuracy and geographic specificity of early warning systems. For example, the international research institution (IRI) and others have developed methods that increase lead-time and accuracy of geo-referenced crop yield and forage forecasts by incorporating seasonal climate forecasts. Farmers can adapt their crop management and livelihood strategies accordingly, which might include changes to the selection of crops and cultivars; allocation of land and household labor; and soil, water, crop, livestock and forage management. Managers of irrigation systems may be able to use climate-based streamflow forecasts to improve water allocation to ensure irrigation water availability, or to warn farmers earlier when water is expected to be unavailable. (Hansen *et al.* 2004). Farmers in Uganda could also benefit from improved forecasting of ENSO events, allowing them to select alternative crops and planting dates in response to predicted rainfall patterns (World Bank 2003).

6.6 Impacts on Forest and Woodland Resources

6.6.1 Potential Impacts

Nearly a third of the world's total land area (excluding Greenland and Antarctica) is forested. Approximately 60% is located in developing countries in tropical regions of which about 2% comprise plantation forests (Arnell & Liu 2001). Frontier forests in Asia provide habitat for more than 50% of the world's terrestrial plant and animal species (Lal *et al.* 2001).

Forests and woodlands provide many important goods including timber and fuel, fiber, and construction material. Forests and woodlands also provide important non-wood forest products (NWFP) including edible mushrooms, nuts, fruits, palm hearts, herbs, spices, gums, aromatic plants, game, fodder, rattan, medicinal and cosmetic products, resins. These make important contributions to household income, food security, national economies, and environmental objectives of conservation of biodiversity. Forests also play a key role in the functioning of the biosphere, through carbon and water cycles thereby indirectly affecting the provision of many other goods and services (Arnell & Liu 2001). Forests also directly affect climate on the local, regional, and continental scales by influencing ground temperature, evapo-transpiration, surface roughness, reflectivity, cloud formation, and precipitation (UNEP 2002).

Timber contributes 4% to GDP in developing countries on average, but 6% in Africa. Approximately 60% of timber comes from developed countries. Developing countries are also the major source (90%) of fuel wood production for more than 2 billion people. It has been estimated that about 80% of the population of the developing world depends on NWFP to meet some of their health and nutritional needs. Several million households worldwide depend heavily on these products for subsistence consumption and income (Arnell & Liu 2001).

Changes in climatic conditions affect all indicators of forest productivity, and therefore their ability to supply goods and services. However, effects on forested area and forest productivity, which can be both positive and negative, vary regionally.

Increased drought frequency would reduce productivity as a result of lowered photosynthetic rates and increased risk of fires (Arnell & Liu 2001).

Natural fires ignited by lightening are common in mixed savanna-woodlands associated with dry tropical zones of Africa, South America, Australia. Natural fires are also common in large areas of tropical humid forests and contribute to the natural seasonal cycle of growth, decay, and combustion. In tropical humid areas including Indonesia, major fires have been particularly severe during ENSO events which can cause drought. These climatic perturbations may increase in frequency with global warming (Arnell & Liu 2001).

Fire frequency is expected to increase with human-induced climate change, especially where precipitation remains the same or is reduced. Changes in precipitation may also have pronounced effects on regeneration success for some species following disturbance, such as harvest or fire. Changes in seasonality, the length of the growing season, and diurnal temperature patterns induced by climate change all have the capacity to also influence the distributional range of some tree species (Arnell & Liu 2001).

In lowland humid tropics, temperatures already are close to optimum ranges for year-round growth. Whilst the affect of increased temperature on tree growth as a result of climate change may only be marginal, research conducted in Costa Rica has shown that the annual growth of six major species of a lowland forest over a period of 13 years was strongly negatively correlated with annual mean minimum (night time) temperatures (see Arnell & Liu 2001 for details).

Under experimental conditions, elevated CO_2 concentrations have been shown to increase production by as much as 25% but plants may become acclimatised to increased CO_2 levels. Field experiments provide inconclusive evidence to predict overall changes in carbon storage in forests (Arnell & Liu 2001).

Damage caused by insects may change in response to climate change, particularly by those whose temporal and spatial distributions strongly depend on climatic factors. Changes in drought conditions appear to play an important role in insect outbreaks (Arnell & Liu 2001).

Extreme weather events such as hurricanes, tornadoes, heavy rainfall, and flooding can lead to extensive mortality and ecosystem change. There is some evidence of recent increases in damage from such extreme events (Arnell & Liu 2001).

6.6.2 Africa

Forests cover one-sixth of Africa's land area. The moist tropical forests of the Congo constitute the second most extensive rainforest in the world and a globally important reserve of carbon. Trees and shrubs comprise an important component of the more than 12 million km^2 of agricultural lands, pastures, shrublands, and savannas outside of closed canopy forest areas (Desanker & Magadaza, 2001).

African forests provide firewood, timber, traditional medicines, and staple and drought emergency foods. Firewood and charcoal provide approximately 70% of the energy used in Africa. Exports of timber, nuts, fruit, gum, and other forest products make a significant contribution to the economies of African countries.

Geographical shifts in the ranges of individual species and changes in productivity are anticipated in response to forecasted shifts in the spatial and temporal patterns of temperature and precipitation. Dry woodlands and savannas in semi-arid and sub-humid areas will be increasingly subjected to drying in the next century, as well conversion to agriculture.

Climate change is very likely to alter the frequency, intensity, seasonality, and extent of vegetation fires that are critical to the maintenance of areas such as the Serengeti grasslands of east Africa, the miombo woodlands of southern Africa, and the fynbos of the Cape.

Almost half of Tanzania is covered by forest providing an important source of fuel wood and other products for large numbers of Tanzanians. Many of Tanzania's 43 threatened mammal species, 33 threatened bird species, and prodigious biodiversity also depend on its forests. Under climate change scenarios, most of the forests across Tanzania are projected to shift towards drier regimes: from subtropical dry forest, subtropical wet forest, and subtropical thorn woodland to tropical very dry forest, tropical dry forest, and small areas of tropical moist forest respectively. Much of this projected change in distribution is attributed to an increase in ambient temperatures and a decline in precipitation in forested regions of the country (OECD 2003).

Some studies described by World Bank (2003) show an increase in the aridity of forests in Zimbabwe with a decline in production of woody biomass. An estimated 20% of the total land area is predicted to "…shift from subtropical thorn woodland and subtropical dry forest to tropical very dry forest.

6.6.3 Asia

Climate change will have a profound effect on the future distribution, productivity, and health of forests throughout Asia. Because warming is expected to be particularly large at high latitudes, climate change could have substantial impact on boreal forests (Arnell & Liu 2001).

6.6.4 Potential Adaptation

Adaptive response are likely to include salvaging dead and dying timber, replanting new species that are better suited to the new climate, planting genetically modified species, and intensifying or decreasing management. Arnell & Liu (2001) also report that agroforestry, small woodlot management, and windrows (or shelterbelts) could provide adaptation options for maintaining tree cover and fuelwood supplies in developing countries. Agroforestry projects may also require more intensive irrigation programmes.

7 Climate Change Impacts in Coastal Zones

7.1 Flood risk and damage to coastal environments and ecosystems

Climate change is likely to have a major impact on the physical environment and infrastructure in coastal zones as the result of increased frequency and intensity of severe storms and weather events, sea level rise and changes to river and estuary flows with impacts on health, safety, water supply, fisheries, agriculture, aquaculture, property, transportation links, and other infrastructure (McCarthy *et al.* 2001).

7.1.1 Increased risk of flooding and inundation

Sea level rise will increase the threat of inundation of low-lying deltas, atolls, and reef islands and will also increase the risk of recession of flat sandy beaches typical of south and south-east Asia due to increased shoreline wave action. In Africa, sea level rise could threaten low-lying areas of eastern and western Africa, and coastal fisheries in Mozambique, Tanzania and Angola (DFID 2004c). Sea level rise will also increase the risk of flooding both in coastal zones and within floodplain river basins due to drainage congestion.

Adger (1999) reports that 46 million are currently at risk from flooding due to storm surges in the world's coastal zones, and that climate change induced sea level rise, in the absence of adaptation could double this estimate.

In Africa, more than a quarter of the population live within 100km of the coast. Model predictions indicate that the number of people at risk from coastal flooding will increase from 1 million in 1990 to 70 million in 2080. In Tanzania alone, a sea level rise of 0.5m would inundate over 2,000 km2 of land, at a cost of over US$50 million (DFID 2004c).

7.1.2 Physical and ecosystem impact

River deltas are among the most valuable, heavily populated, and vulnerable coastal systems in the world. River-borne sediments form and sustain important deltas in the coastal zones of Asia, some with an area of more than 10,000 km^2. In recent years, increases in precipitation and river flow have been responsible for damage to more than 50,000 ha of coastal territories. Decreasing river discharge rates, as projected under some climate change scenarios, could lead to hindrance of delta propagation and wetland renewal and increase the risk of irreversible change for the ecosystem in estuarine-deltaic areas (McCarthy *et al.* 2001).

Human activities such as draining for agricultural development; levee building to prevent flooding; and channelization, damming, and diking of rivers to impede sediment transfers have made deltas more vulnerable to sea-level rise. Tidal rivers, estuaries and freshwater aquifers will also become more prone to saltwater intrusion as a result of projected sea-level rise and changes to river discharge rates.

“Rising sea levels are already contaminating underground fresh water supplies in Israel and Thailand, in small atolls scattered across the Pacific and Indian oceans and the Caribbean Sea, and in some of the world’s most productive deltas such as China’s Yangtze Delta and Vietnam’s Mekong Delta” (UNEP 2002).

7.2 Impacts on Fisheries and Aquaculture

7.2.1 Coastal Fisheries

About 80% of the global fish supply originates from the 19 km closest to the shore and more than 60% of the world's population occupy the 150 km closest to the coast (Pernetta, 1994). In Asia alone, shallow coastal waters are estimated to support the livelihoods to 1 billion people (Whittingham *et al.* 2003, as cited by Allison *et al.* 2005).

The increased frequency of storm and severe weather events coupled with rising sea levels is likely to cause greater damage to fishing vessels, gear, landing sites and infrastructure in the coastal zone, increase the number of non- fishing days, and hinder access to markets, ultimately leading to lower earnings and greater costs (reduced incomes) for fishers and supply of fish for consumption. Loss of beaches and critical habitat, such as mangroves (see below) may also occur which would further contribute to these impacts.

Warming of the marine environment and increased frequency of large scale climatic perturbations also has the potential to affect recruitment, both positively and negatively, to fish stocks. Changes in sea temperatures and increased levels of atmospheric carbon dioxide might increase metabolic demands and energetic costs, potentially reducing somatic growth, maturation and fecundity, and shell dissolution in calcifying (shell-building) species. Changes in sea temperature could also lead to changes in species distribution and thereby ecosystem functioning, impacting on potential yields, fishing costs and earnings, food security, GDP, and export earnings (Allison *et al.* 2005).

Fishers may seek alternative livelihoods placing greater pressures on other sectors or resources (see later).

7.2.2 Coral Reef-based Fisheries

Coral reefs from the basis of highly productive ecosystems, providing income and food and supporting the livelihoods of an estimated 30 million people in over 100 countries, mostly developing in East Africa, South and South-east Asia and the Western Caribbean (Allison *et al.* 2005). Small Island Developing States (SIDS) tend to be particularly dependent on reef resources for their livelihoods where for some coastal communities it is the only economic activity and the sole source of food. As well as the direct impact of climate change on the fishery resources upon which they depend, their capacity to adapt to climate change is further hampered by their increased vulnerability to inundation caused by sea level rise.

Reef-based fisheries are particularly at risk from the effects of climate change. Reef fish diversity and exploitable biomass is dependent upon the area of live corals and the architectural complexity of coral reefs. Rising sea temperatures and elevated levels of atmospheric carbon dioxide is likely to increase coral mortality rates through 'bleaching', and reduce reef growth rates due to changing ocean chemistry and higher frequency of severe storms (Allison *et al.* 2005). Changes in the quality of water discharged from river basins into the coastal zone, including sediment loads and levels of pollutants (see Section 5.4), could exacerbate these impacts. Changes in sediment loads also have the potential to affect light penetration in coastal waters.

Changes in salinity resulting from changes to river discharge rates together with elevated sea temperatures could also increase the mortality rates of reef fish and invertebrates.

Increased strength of monsoon winds might also bring about increased algae growth and near shore anoxic conditions that could affect fish migrations and therefore availability of fish for exploitation (Allison *et al.* 2005).

Coral reefs also play a crucial role in protecting the coastline from wave action and erosion, both processes are likely to increase in response to climate change.

7.2.3 Pelagic Fisheries

Upwelling of cold bio-limiting nutrient-rich waters supports some of the most productive fisheries in coastal zones. Examples include the Canary Current off the coast of Morocco, driven by the shearing effects of the northeast and southwest trade winds, and the Benguela upwelling off the southwest coast of Africa that supports a pelagic fishing industry targeting several migratory species including anchovy. These species are an important resource in their own right, but they also are a key element in the food chain of larger fish, seals, and birds (McCarthy *et al.* 2001).

Research has shown that upwelling, driven by the Canary Current, is significantly weakened by the NAO, impacting on the sardine stocks and fishery, similar to the El Niño effect on the fisheries of Peru. Whilst the effect of climate change on these climatic perturbations and wind shear is very uncertain, the potential consequences on fisheries and dependent livelihoods is significant.

7.2.4 Estuarine and Coastal Wetland Fisheries

Sea level rise and changes to river discharge rates and consequent changes to salinity have the potential to significantly modify coastal wetlands including mangroves and seagrass beds. Changes to the availability and salinity of these habitats, critical for many fish and invertebrate species, would impact detrimentally on associated fisheries and dependent livelihoods. Changes in the quality of water discharged from river basins into the coastal zone, including sediment loads and levels of pollutants (see Section 5.4), could exacerbate these impacts.

7.2.5 Coastal Aquaculture

Marine aquaculture (mariculture) production (like freshwater aquaculture) more than doubled in the period 1990 to 1997. Aquaculture production is expected to continue its upward trend in the foreseeable future.

Fishmeal and fish oils are often key diet components for aquaculture production and may constitute more than 50% of the feed. Climate change could have dramatic impacts on fish production, which would affect the supply of fishmeal and fish oils.

Forecasted increases in water and air temperatures could potentially lengthen the growing season for cultured fish and shellfish. These changes could have beneficial impacts with respect to growth rate and feed conversion efficiency. Elevated temperatures of coastal waters also could lead to increased production of aquaculture species by expanding their range. However, increased water temperatures and other associated physical changes, such as shifts in dissolved oxygen levels, have been linked to increases in the intensity and frequency of disease outbreaks and may result in more frequent algal blooms in coastal areas.

Any increases in the intensity and frequency of extreme climatic events such as storms, floods, and droughts will negatively impact aquaculture production and may result in significant infrastructure damage. Sea-level rise can be expected to have a negative effect on pond walls and defenses.

Asia dominates world aquaculture, producing four-fifths of all farmed fish, shrimp, and shellfish. Farming of fish, shrimp, shellfish, and seaweeds has become a vital source of food supply in Asia in recent decades.

Fish farming requires land and water; two resources that already are in short supply in many countries in Asia. Nearly half of the land now used for shrimp ponds in Thailand was formerly used for rice paddies; water diversion for shrimp ponds has lowered groundwater levels noticeably in coastal areas of Thailand.

Intensive production systems and large scale facilities used to raise high-value shrimp, has taken a heavy toll on coastal habitats, with mangrove swamps in south-east Asia being cleared at an alarming rate. Thailand lost more than 15% of its mangrove forests to shrimp ponds from 1987 to 1993. Destruction of mangroves has left these coastal areas exposed to erosion and flooding, altered natural drainage patterns, and increased salt intrusion. In the north east pacific, coastal aquaculture, especially marine shrimp farming, is carried out entirely in mangrove areas (UNEP, 2001).

7.3 Impact on Agriculture

7.3.1 Extreme weather events

Extreme weather events will increasingly affect both agriculture and livestock. The scale of potential impacts is borne out by the cyclone that hit Orissa State (India) in October 1999 which affected the livelihoods of nearly 13 million people and resulted in the loss of 1.6 million houses, nearly 2 million hectares of crops and 40,000 livestock (DFID 2004d).

7.3.2 Loss of and salinisation of coastal land

In addition to those already described for lake and river basins (see Section 6.3), major impacts on agriculture in the coastal zone will arise from the physical loss of and degradation of agricultural land. Loss and salinisation of land resulting from sea level rise (SLR) is likely to have a major impact on yield from, and livelihoods dependent upon, the agricultural sector in coastal regions. SLR and increased natural disasters will also destroy infrastructure vital for economic development like ports, quays and sewer systems, as well as shelter (McGuigan 2002).

7.3.2.1 Africa

In Africa, the west coast of Africa and Niger Delta region are particularly vulnerable to sea level rise. Sea level rise would also cause drainage congestion exacerbating flooding in major rivers including the Niger (Magadza, 2000).

In Egypt, it has been estimated that 12-15% of the agricultural land in the Nile Delta could be lost. Sea level rise will also accelerate the intrusion of saline water in surface water resources and underlying coastal aquifers. Temperature rises are also likely to reduce agricultural productivity throughout Egypt (Kaperson & Kasperson 2001).

7.3.2.2 Asia

Loss of land area and the size of exposed populations will be significant in low-lying regions of coastal Asia, particularly in Bangladesh and Vietnam (Table 4) which could be further exacerbated by continued population growth in low-lying agricultural and urban areas (Lal *et al.* 2001). McGuigan *et al.* (2002) report that a SLR of 30 cm could flood parts of the Yangzte Delta where 30 million people live and work in agriculture.

Table 4 Potential land loss and population exposed in Asian countries for selected magnitudes of sea-level rise and under no adaptation measures. Source: Lal *et al.* (2001)

Country	Sea-Level Rise (cm)	Potential Land Loss (km²)	(%)	Population Exposed (millions)	(%)
Bangladesh	45	15,668	10.9	5.5	5.0
	100	29,846	20.7	14.8	13.5
India	100	5,763	0.4	7.1	0.8
Indonesia	60	34,000	1.9	2.0	1.1
Japan	50	1,412	0.4	2.9	2.3
Malaysia	100	7,000	2.1	>0.05	>0.3
Pakistan	20	1,700	0.2	n.a.	n.a.
Vietnam	100	40,000	12.1	17.1	23.1

n.a. = not available.

7.4 Impact on Forestry and Timber Resources (Mangroves)

Mangrove forests comprising salt-adapted evergreen trees, are an important natural resource in the coastal zone providing timber, food fuel and medicine, and occupy about 180 000 km^2 of intertidal tropical and subtropical coastline, extending landward along tidal rivers (Alongi 2002).

Important mangrove forest resources occur within tropical and subtropical deltas, but they also occur in low- to mid-latitude lagoon and estuary margins. The Sundarbans in Bangladesh and adjacent areas in India are the largest mangrove forests in the world covering about 6,000 km^2. These forests provide important habitat for Bengal tigers, Indian otters, spotted deer, wild boars, estuarine crocodiles, and marine lizards and turtles (McCarthy *et al.* 2001).

Depletion of mangrove forests by anthropogenic pressures has become a serious problem in south-east Asia, particularly in Thailand, the Philippines and Indonesia. Pressures include urban development, aquaculture, mining and overexploitation for timber, fish, crustaceans and shellfish (Perez, 1999, Alongi 2002).

As well as being both ecologically and economically important within the coastal zone, mangroves trap sediment, creating natural barriers to sea level rise and salt intrusion into coastal soils and estuaries. The destruction of mangrove forests thereby reduces coastal zone (and lower lying river basin) resilience to future seas-level rise, wave erosion and flooding, which, may, in turn affect soil and (fresh) water quality.

7.4.1 Impacts of climate change

Mangrove forests are highly vulnerable to climate change-induced sea level rise because it will change the salinity distribution and hence productivity - mangrove growth is influenced by salinity (Perez *et al.* 1999).

The growth of mangroves is usually affected by the salinity of water. Mangroves, which are found mostly in estuaries, may not be able to survive the increased salinity when the sea level rises. Changes in sedimentation and organic loading are also expected to induce large-scale changes in species composition and zonation.

Whilst increased rates of sedimentation in the coastal zone are likely to benefit mangroves, allowing them to expanded seaward in suitable habitats, some workers suggest that in some settings, low sediment supply may not be able to keep up with future sea-level rise McClean *et al.* (2001). Submergence is likely to cause dieback and erosion of their seaward margins.

The survival of salt marshes and mangrove forests will depend in part on whether the rate of sedimentation is greater than or less than the rate of local sea-level rise (UNEP 2002).

8 Sector Interactions

As well as the direct effects of climate change on the natural resource sectors described above, the adaptive responses of different sector may augment these impacts indirectly. These potential interactions among sectors are examined here.

8.1 Agriculture and fisheries interactions

The adaptive responses of the agriculture sector to climate change have the greatest potential to indirectly impact on fisheries.

8.1.1 Flood control impacts on fisheries

Changing hydrological regimes including changes to patterns of precipitation and increasing frequency of extreme flooding events in lake and river basins may prompt adaptive strategies by the agriculture sector that focus upon the construction of more flood control, drainage and irrigation schemes (see Section 6.5.4). These structures are likely, however, to further exacerbate the direct adverse impacts of climate change on fisheries. For example, studies described by Halls *et al.* (1998;1999) suggest that fish production can be 50% lower inside flood control schemes compared to outside due largely to diminished recruitment of high value migratory whitefish species and the passive drift of larvae from rivers to modified floodplains.

River flows will become increasingly constrained to the main channel, increasing peak and mean discharge rates and the likelihood of catastrophic flooding events. Increased down-cutting (erosion) of the river bed will further diminish fish populations that spawn on the beds of rivers. Increased sediment loads may choke spawning substrates, affecting the reproductive success of lithophils and psammophils, bring about changes to the benthos favouring illiophages, and block migration routes of whitefish and greyfish, combining to reduce fish diversity and exploitable biomass.

Increased downstream transport of sediment may adversely impact on coral reef and other coastal fisheries by affecting light penetration and physiological processes. Increasing sediments loads in the coastal zone may, however, help to sustain river deltas and critical habitat for fisheries such as mangroves threatened by rising sea levels and increased storm erosion but changes in salinity distribution brought about by changes to river discharge rates may also be important.

In some cases, hydraulic engineering adaptations have the capacity to impede sediment transfers making deltas and critical habitat more vulnerable to sea-level rise. Examples of sediment starvation include the Rhone and Ebro deltas and polder projects in the Ganges-Brahmaputra (McCarthy *et al.* 2001).

8.1.2 Irrigation impacts on fisheries

In some basins and coastal zones, climate change may increase demands for irrigation. Crop diversification or replacement in favour of HYV that sometimes require more irrigation and flood control compared to traditional varieties could exacerbate these impacts (Section 6.5.1 and 8.1.1). These extra needs, which are likely to be withdrawn from rivers other surface water bodies or aquifers, will affect hydrological and ecological regimes. The “direct” effect of climate change on hydrological regimes and ecosystems may therefore be enhanced.

In river basins for example, irrigation systems often extract surface water from residual bodies remaining during the dry season after flood waters have receded. These residual water bodies provide critical dry season habitat for blackfish and greyfish species. Shanker *et al.* (2004) have shown that, beyond some threshold, floodplain fish production is highly sensitive to removals of water from these bodies (Figure 6) impacting upon fish catchability, natural mortality rates and recruitment.

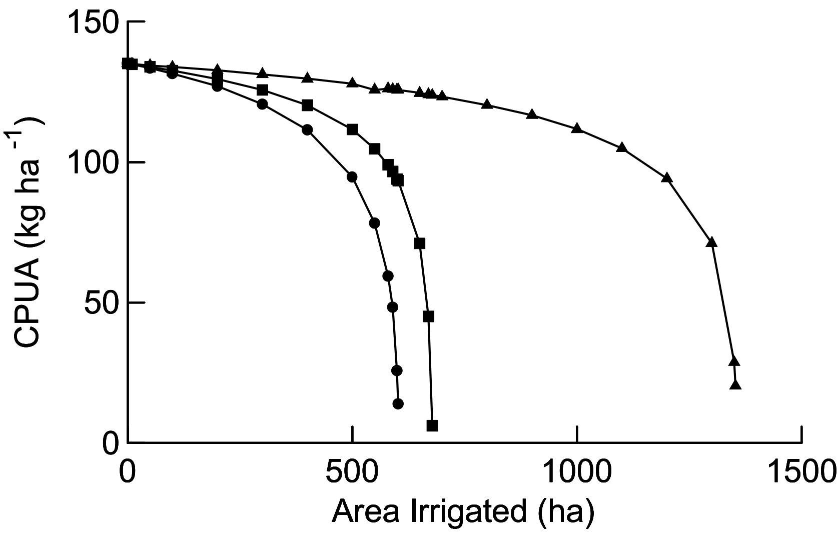

Figure 6 Predicted response of annual catch per unit area (CPUA) to changes in the area of land irrigated for dry season Boro rice cultivation for low (▲); intermediate (■); and high (●) irrigation schedules in part of the Pabna flood control and irrigation compartment, North-West Bangladesh. Source: Shankar *et al.* (2004).

Changes to siltation rates arising from the construction of more flood control schemes may further reduce the depth and surface area of dry season water bodies, transforming many from a perennial to a seasonal type. ISPAN (1992) report a 70% reduction in the water area of an important floodplain lake in North Central Bangladesh over a 15 year period as a result of siltation processes.

Higher forecasted temperatures will also decrease the solubility of oxygen in residual dry season waterbodies, potentially elevating rates of natural mortality. This problem will become more serious as the size of remaining water bodies diminishes in response to increased evapotranspiration rates and dry season irrigation.

8.1.3 Agricultural practice change impacts on fisheries

Increasing intensity of fertilizer and pesticide application to mitigate the impacts of climate change on agriculture could adversely affect the quality water in rivers, lakes and coastal zones and thereby impact upon their fisheries. Changing the location of watering points for livestock and adaptive strategies to deal with heat stress may place further strain on dry season fish habitats (Sections 5.4 and 5.5.2). Soil erosion from changing land use could also impact adversely on fisheries by increasing sediment loads in rivers and coastal zones. The loss of land in low-lying regions of coastal Asia (Section 7.3.2) might also place greater pressure on fisheries resources, as rural populations seek alternative livelihoods.

Upstream changes in sedimentation and organic loadings are also anticipated to induce large scale changes in mangrove forests in coastal zones which provide critical habitat for many coastal fish species and an important source of seed, particularly shrimp, for the mariculture sector (see below).

8.2 Other potential inter-sectoral interactions

8.2.1 Agriculture and Livestock

Livestock production and related food products would become costlier if agricultural disruption leads to higher prices grain and grain related feedstuffs. The vulnerability of communities dependent on pastoral livestock systems might also increase if the productivity and quality of the rangelands becomes degraded to climate change (UNEP 2002).

8.2.2 Agriculture and mariculture interactions

Changes to water quality in the coastal zone arising from upstream flood control measures and changing agricultural practice could impact upon mariculture systems. Sedimentation, eutrophication, increasing pesticide loadings and shifts in dissolved oxygen levels all have the capacity to impact coastal mariculture adversely.

8.2.3 Aquaculture and Fisheries Interactions

Increasing reliance on aquaculture to address diminishing supplies of fish and related products from the capture sector could exacerbate the irrigation impacts described above, particularly if the sectors share common water sources. Water diversion for shrimp ponds in Thailand for example, has already lowered groundwater levels noticeably in coastal areas (Section 7.2.5).

In the coastal zone, increasing reliance on mariculture to address wild fish supply deficits could further impact on the wild sector through further destruction of mangroves and other critical habitats, and increasing levels of farm pollutants.

8.2.4 Mangroves and fisheries

Potential declines in mangrove forest habitat resulting from sea level rise and changes in sediment and pollutant loading from river and lake basins arising from and forestry sector responses and agricultural adaptations could also impact on fisheries by reducing or degrading critical coastal habitat (Jallow *et al.* 1999).

8.2.5 Forestry and Fisheries Interactions

Geographical shifts in the ranges of individual species and changes in productivity may contribute to the changes in forestry practice, cover and land use in river and lake basins. These coupled with resulting changes to water run-off, river discharge rates and soil erosion could modify sediment and pollutant leadings in rivers and coastal zones impacting directly on fisheries or indirectly through its effect on critical habitat including mangrove.

8.2.6 Livelihood Adaptation

Faced with declining yields, income and food security, fishers may seek alternative livelihoods placing pressures on other sectors or resources. For example, in West Africa, when coastal fisheries resources are scarce fisheries adopt alternative livelihood strategies including hunting for bush meat.

Similarly, when Lake Chilwa water levels and fisheries productivity decline, fisherman reduce fishing effort, transfer there effort to nearby lakes, increase the cultivation of rice, cotton and vegetables, produce commercial handicrafts and hunt birds and rodents, or seek employment elsewhere (Allison *et al.* 2005). Conversely, when heavy rains impact on agricultural harvests, people have been observed to shift into fishing.

In the Argentine Pampas, the proportion of land allocated to crops has increased markedly at the expense of grazing land during historic humid periods, and vice versa during dry periods (McCarthy et al. 2001).

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