CLIMATE CHANGE, WATER AND FOOD SECURITY

TECHNICAL BACKGROUND DOCUMENT

FROM THE EXPERT CONSULTATION HELD ON

26 TO 28 FEBRUARY 2008

FAO, ROME

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Introduction

This Synthesis Paper is based on an Expert Meeting held in Rome 26–28 February 2008 as a preparation for the FAO High Level Conference (HLC) on World Food Security and the Challenges of Climate Change and Bioenergy in June 2008. This Synthesis Paper contains a necessarily rapid appraisal of the implications of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (AR4-IPCC) for agricultural water management and, based on that evidence, offers a more operationally focused diagnosis. It provides a summary analysis of a baseline, including projected trends without climate change and mitigation measures; the anticipated set of climate change impacts; a set of possible responses; main findings and recommendations; and a set of options for decision-makers.

Climate change and water management

Summary of baseline

The areas of irrigated and rainfed land are based on updated country surveys (FAO, 2007a; FAO, 2007b). However, the nature of the global production systems and their dependence on water is not always clearly understood or appreciated. While, there are global data sets detailing freshwater bodies, renewable water resources, land-cover and areas equipped for irrigation together with comprehensive global assessments of soils and climate suitability (agro-ecological zones), the relative contribution of irrigated and rainfed production is not known with any degree of certainty. Only broad estimates are available with indicative estimates available for 93 developing countries (FAO, 2003; 2007) on a 1997/99 baseline and projections to 2015 and 2030 (Table 1 presents a regional summary).

Of all the climatic factors, the daily and inter-annual variation in precipitation are most crucial for rainfed and runoff for irrigated production. In both rainfed and irrigated systems, the spatial and temporal variation of precipitation is key. The day-to-day variability of rainfall associated with weather is the major risk factor for most forms of agriculture. Soil moisture deficits, crop damage and crop disease are all driven by rainfall and associated humidity. The variability in rainfall intensity and duration makes the performance of agricultural systems in relation to long-term climate trends very difficult to anticipate. This is particularly the case for rainfed production. Either there is replenishment of soil moisture storage as a result of rainfall or there is not. Cultivation practices, including soil biomass enhancement as well as tree/forest cover, can enhance the infiltration of rainfall and delay the drainage of soil moisture in some soil types but, ultimately, soils drain to groundwater circulation or lose water through evaporation and evapotranspiration.

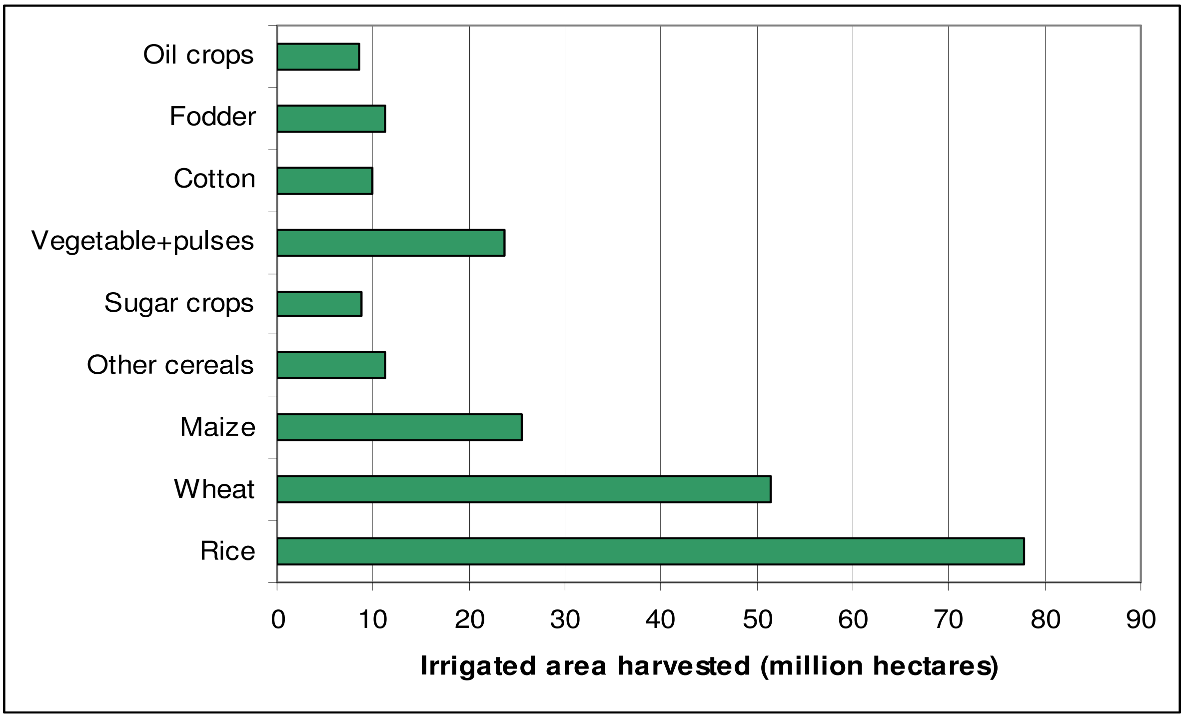
Table 1: Irrigated land, area and as percentage of arable land

World/Continent	Irrigated Land Area (1000 ha)			As % of arable land		
	1980	1990	2002	1980	1990	2002
WORLD	**210 222**	**244 988**	**276 719**	**15.7**	**17.6**	**19.7**
Developed countries	**58 926**	**66 286**	**68 060**	**9.1**	**10.2**	**11.1**
Industrialized countries	37 355	39 935	43 669	9.9	10.5	11.9
Transition economies	21 571	26 351	24 391	7.9	9.8	10.0
Developing countries	**151 296**	**178 702**	**208 659**	**21.9**	**24.1**	**26.3**
Latin America & the Caribbean	13 811	16 794	18 622	10.8	12.5	12.6
Near East & North Africa	17 982	24 864	28 642	21.8	28.8	32.3
Sub-Saharan Africa	3 980	4 885	5 225	3.2	3.7	3.6
East & Southeast Asia	59 722	65 624	74 748	37.0	33.9	35.1
South Asia	55 798	66 529	81 408	28.6	33.9	41.7
Oceania developing	3	6	14	0.7	1.2	2.4
Continental groupings						
Africa	9 491	11 235	13 400	6.0	6.7	7.0
Asia	132 377	155 009	193 869	31.3	33.8	37.9
Caribbean	1 074	1 269	1 308	22.0	23.3	26.5
Latin America	12 737	15 525	17 314	10.4	12.0	12.1
North America	21 178	21 618	23 285	9.1	9.3	10.5
Oceania	1 686	2 118	2 844	3.6	4.2	5.6
Europe	14 479	17 414	25 220	11.5	14.0	8.8

Source: FAO, 2004

Agricultural water management permits concentration of inputs and provides stability of supply for many key agricultural products. While only responsible for some 40 percent of agricultural production, this stability of supply buffers the volatility of rainfed production and is therefore a key supply factor in local, regional and global agriculture markets, including markets in animal products. In addition, basin-level water resource management determines the productivity of water-related ecosystems including local fish capture. Without some form of water control across the world's river basins, freshwater lakes and associated aquifers, local, regional and global food security would not be possible. In addition, since irrigated areas are limited to a few dominant food and cash crops, notably rice, wheat, maize, vegetables pulses and cotton (see Figure A), a key consideration for assessing the impact of climate change on agricultural production is an examination of how particular irrigated crops will perform across specific river basins under climate change scenarios.

Figure A: Distribution of crops under irrigation in the world (million ha)



Source: FAO estimates based on data and information for 230 million ha in 100 countries.

Figure B. FAO Global Map of Irrigated Areas V4

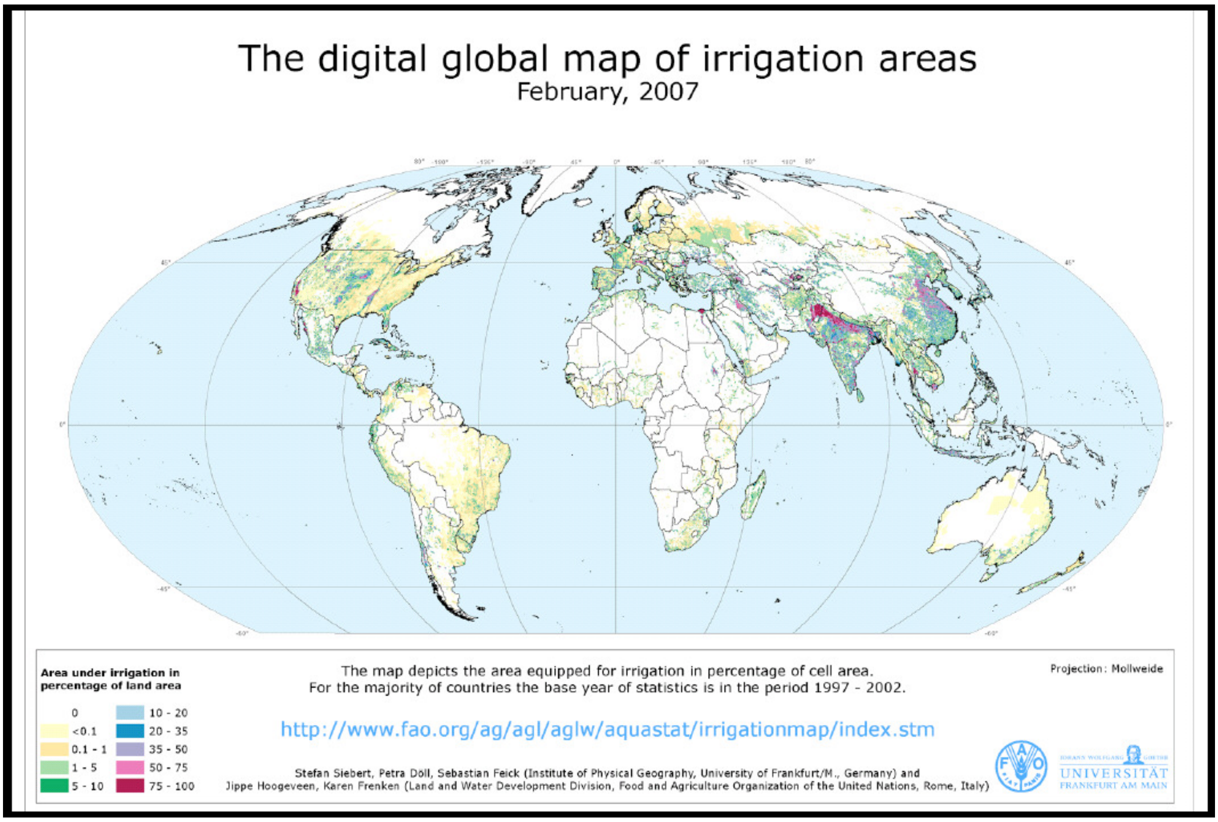


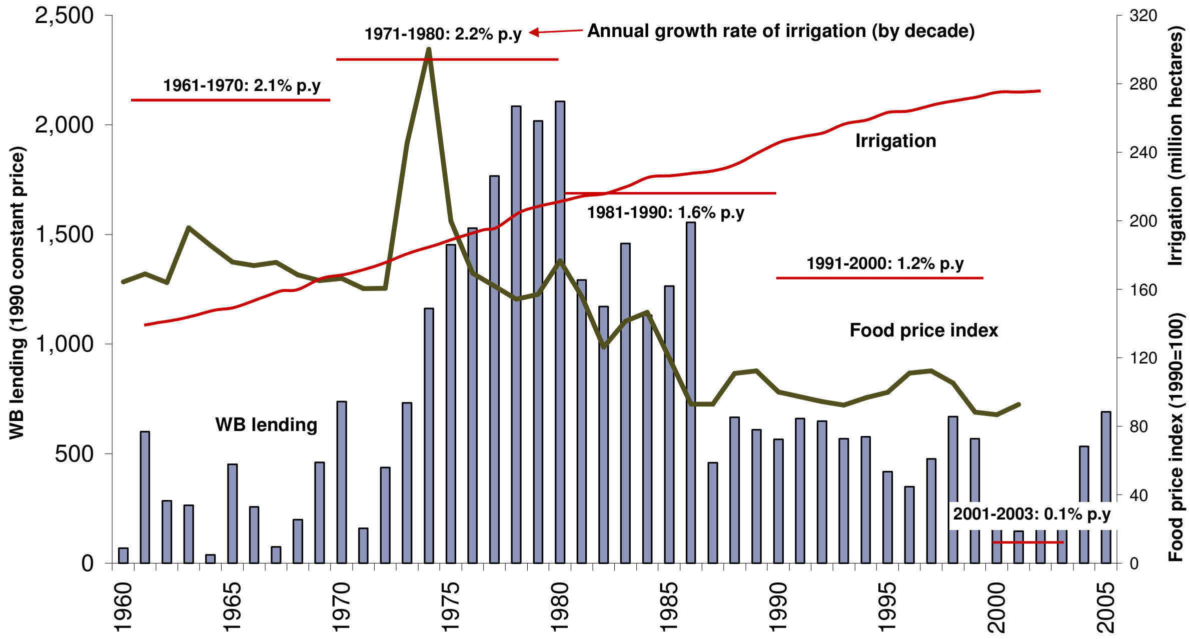
Figure B illustrates how irrigated agriculture is concentrated in the main alluvial fan/delta environments (Mekong, Yangtze, Yellow, Chao Prya, Godavari, Krishna, Indus, Narmarda, Brahmaputra/Ganges, Nile, Mississippi, Po). The altered hydraulic regimes, water quality changes and drainage impacts all effect the near-shore sea water quality and fisheries. The lateral inflow of pollutants and nutrients into the large marine ecosystems is significant. Stress reduction on these systems, through improved management of the environmental externalities produced by the concentration of irrigated areas (which are relevant to aquaculture, livestock, urban waste, etc.), is an environmental priority. Of particular importance is the groundwater depletion in key food-producing areas such as the Mediterranean, Middle East, Punjab and the North China Plain where it has proved impossible to relax pressure on aquifers from agricultural production. Much of the groundwater in these sedimentary basins and alluvial fills results from pre-historic pluvial periods. Progressively deeper groundwater sources are exploited and the prospects for replenishment are small, even if extraction were reduced.

The current styles of adaptation to water scarcity are differentiated. In marginal semi-arid zones with prolonged dry seasons, rainfed production may carry a high risk of crop failure. Some stability of production can be assured only where continuous access to annually recharged groundwater is available. Where this is not available, rural populations tend to be mobile, out-migrating during dry years and returning during wetter periods.

In the future, the demand for more reliable agricultural production systems at local and regional levels is expected to increase. In fact, trends toward more precision agriculture with more secure supply chains are already evident. Regional responses include domestic market protection as well as trade. Despite the long heritage of coping systems in many arid and semi-arid countries, institutional rigidity persists and some of the most productive areas of contiguous irrigation are at risk and hydro-environmental limits have been reached.

Finally, there has been a long-term decline in multi-lateral investment in agriculture. However, a continued rise in the expansion of irrigated agriculture appears to have happened in spite of World Bank lending into the irrigation and drainage sub-sector and a declining food price index (Figure D). Recent rises in food prices appear to be prompting a renewed interest in agricultural production and rural livelihoods (World Bank, 2007)

Figure C: World Bank lending (bars) for irrigation and drainage, area under irrigation and world food price index (of 1990 constant US$)



Source: World Bank, FAO.

Climate change impacts

There is consensus that socio-economic and environmental drivers will be dominant in shaping future water management policies. At the same time, climate change will superimpose itself by modifying and, in critical regions, by increasing future risk and vulnerability of crop production related to water supply and water availability. Two broad issues that need to be addressed for effective responses emerge:

- When and where will significant impacts to food production occur due to climate change; and
- What water management and production systems will face additional significant climate risk?

The recent IPCC Fourth Assessment Report indicates that climate change will have significant impact on crop production and water management systems in coming decades. In addition, there is the potential for earlier negative surprises linked to increased frequency of extreme events (Tubiello, *et al.,* 2007). The strong trends in climate change that are already evident, the likelihood of further changes and the increasing magnitude of potential climate impacts particularly in the mid-latitudes and tropical regions (but globally also) gives additional urgency to address agricultural adaptation more coherently (IPCC AR4, WGII Ch. 5).

With the accepted limitations of global agro-ecological modelling frameworks, projections for irrigated water withdrawals to 2080 indicate the pressure on renewable water resources and associated ecosystems that can be anticipated (Fischer, *et al.*, 2007; Doll, 2002). These modelled projections can be set beside the irrigation water demand results of the FAO Global Perspective Unit's expert analysis of the Near East Region, projected to 2050. Further regions will follow, but the Near East Region, comprising all the North African countries, is one of the zones for which there is good convergence of climate models and increased aridity is projected with high confidence.

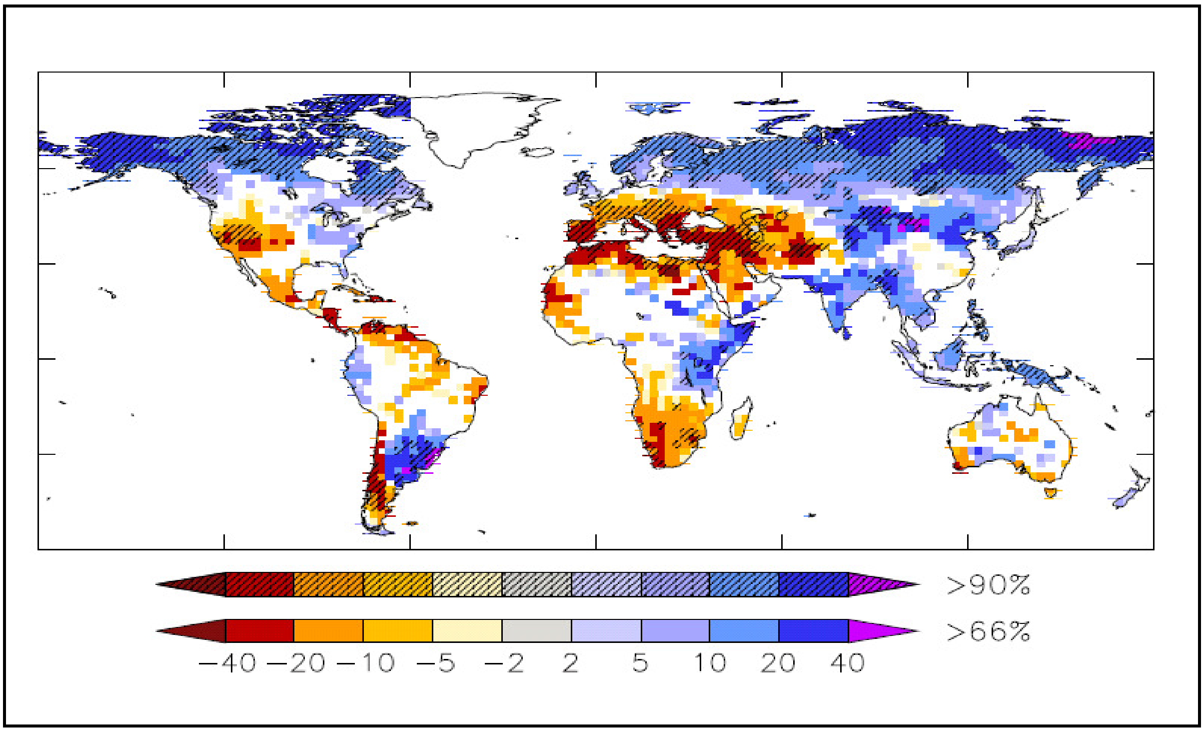
While the progression of temperature and crop evapotranspiration means may be incremental, the increased variability of rainfall events will increase the volatility of rainfed production at local and regional levels. Improvements in the performance of irrigated areas at smallholder and scheme level are expected under baseline conditions but some marginal schemes will risk being taken out of production if anticipated regional impacts take effect.

The spatial distribution of the annual hydrological cycles and the inter-annual trends (persistence) will result in basin-to-basin variation. Hence groundwater recharge, precipitation intensity-duration-frequency relationships, extreme hydrological events and salinity related to evaporation and water-logging are all expected to reach thresholds at which irrigated production is compromised.

Given the natural integration of variable rainfall patterns in river basin flow measurements, the projections for major basin responses available from Milly, *et al.* (2005) are helpful in identifying the river basin and agricultural systems likely to be at risk (Figure D). Runoff is important and particularly relevant for irrigated production, but it should be noted that g*lobal runoff maps are not precipitation maps.* The runoff maps integrate rainfall-runoff processes, soil moisture storage, evaporation, evapotranspiration and groundwater recharge – a complex set of processes.

Impacts on rainfed irrigation are related more directly to aridity than irrigated agriculture. Figure E presents multi-model mean changes in precipitation, soil moisture content, runoff and evaporation for the period 2080–2099 relative to 1980–1999. However, there is a technical disconnect between the Global Circulation Model (GCM) maps of runoff, and the actual simulations with crop models – including agro-ecological Zones (AEZs). The latter simulate their own soil hydrology and often result from a GCM and a crop model that are not comparable since there is no crop system in a GCM – only natural grasslands.

Figure D. Multimodel mean changes in annual runoff by 2060, in percent, indicating also degree of agreement between the 12 models used SRES Scenario A1B, i.e. very rapid economic growth, convergence among regions and technological change in energy systems.



Source: Milly, *et al.,* 2005

By 2060, the broad trends in precipitation and evapotranspiration are expected to result in reduced runoff across

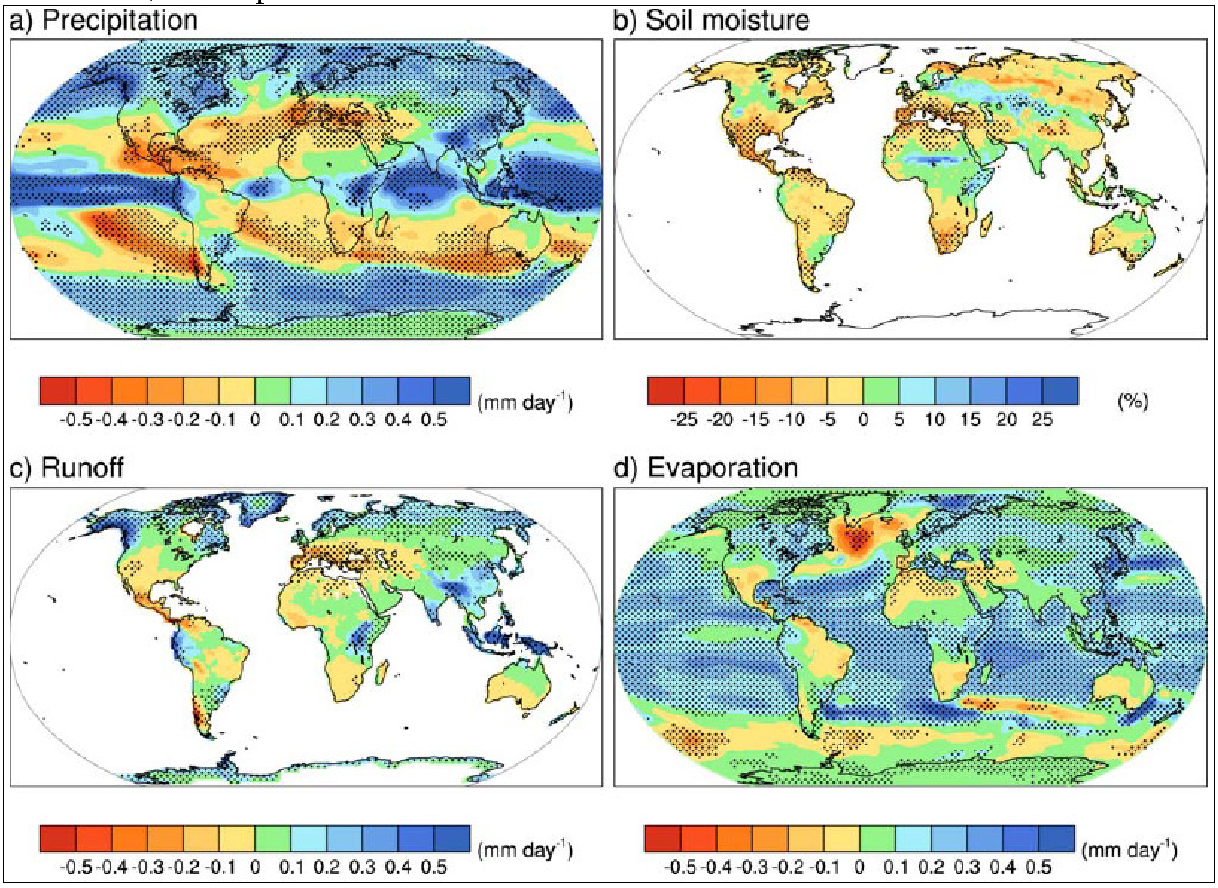
- Southwestern USA, the Mediterranean basin and the Near East
- Central America, northern Brazil and the western margin of the Sahara
- Western coastal margin of Chile, Southern Africa and Madagascar, south-western Australia

By 2060, this drying trend will be offset by patterns of increasing runoff across

- Canada/North America, northern Europe, Siberia Central Asia and northern China
- East Africa, southern Arabian peninsular, peninsular India, Myanmar to Papua New Guinea.

The large contiguous areas of irrigated land associated with river basin deltas are at risk from a combination of reduced inflows, salinity (Indus, Krishna, Godavari), annual flood cycles and sea-level rise (Ganges-Brahmaputra, Mekong, Yangtze) and are impacted by urban and industrial pollution. These stresses on some of the prime productive land will continue to reduce agricultural (including fisheries) output, biodiversity and the natural ability to recover.

Figure E: Multi-model mean changes in: a) precipitation (mm day–1), b) soil moisture content (%), c) runoff (mm day–1), and d) evaporation (mm day–1). Changes are annual means for the scenarios SRES A1B, for the period 2080–2099 relative to 1980–1999.



Source: IPCC, 2007

The key implications for global food production systems are manifold. First the runoff modelling confirms the conclusion by Shah, *et al*. (2008) that all SRES runs indicate a shift in potential for improved cereal production to developed countries. Second, many of the current centres of irrigated production in the western USA, the Mediterranean Basin and Near East, Southern Africa and Australia will experience additional stress. This may result in significant shifts of rural population.

In terms of hydrology and water resources, changes in pattern of rainfall in space and time (intensity-duration-frequency) will be the most important determinant of crop growth, crop damage and the status of aquatic environments. Hydrological processes can be expected to exhibit more variability, more extreme events and result in regional shifts in water balances (IPCC AR4).

The probable changes in precipitation and evaporation will translate directly to shifts in the existing pattern of soil moisture deficits, groundwater recharge and runoff. With respect to cropping calendars, the most immediate impacts will be felt by rainfed agriculture whose yield performance is expected to exhibit more volatility as a result of moisture stress in regions with declining rainfall. In areas experiencing increased rainfall and temperature, higher intensity rainfall may damage crops and erode soils (Rosenzweig, *et al*., 2002). Second order impacts on streamflow, groundwater, lake and dam storage levels and wetland contraction or expansion will translate into changed availability of water for irrigated production, aquaculture and *in situ* environmental services including capture fisheries and associated biodiversity.

Separating the impacts and responses to climate change from those related to other trends in agriculture and related economic sectors will not be straightforward, since autonomous adaptation will be driven by all of these factors at the same time. The challenge at hand is therefore to devise decision-support systems that include monitoring and forecasting and observations of ongoing socio-economic drivers. Such systems can indicate to decision makers the envelop of potential planned action, from timing of new infrastructure to governance and capacity building in the water management sector.

An impact typology is suggested in Table 3 as a means to tease out the major water management systems at risk and identify targets for phased intervention in order to reduce threats to global food security. It is important to stress here that many existing water problems have other causes (land-use changes, clear cutting, uni-sectoral water management) and that not all of these problems can be attributed to climate change.

Table 3 Typology of climate change impacts and response options for agricultural water management identified by the Expert Meeting

System	Current status	Climate change drivers	Vulnerability	Adaptability	Response options
1 Snow Melt Systems					
Indus System	Highly developed, water scarcity emerging.Sediment and salinity constraints	20 year increasing flows followed by substantial reductions in surface water and groundwater recharge. Changed seasonality of runoff and peak flows. More rainfall in place of snow. Increased peak flows and flooding. Increased salinity. Declining productivity in places	Very high (run of river): medium high (dams)	Limited room for manoeuvre (all infrastructure already built)	<u>Water supply management:</u> Increased water storage and Drainage; Improved reservoir operation; Change in crop and land use; Improved soil management; <u>Water demand management</u> including groundwater management and salinity control
Ganges Brahamaputra	High potential for groundwater, established water quality problems. Low productivity		High (falling groundwater tables)	Medium (still possibilities for groundwater development)	
North Western China	Extreme water scarcity and high productivity		High (global implications, high food demand with great influence on prices)	Medium (adaptability is increasing due to increasing wealth)	
Red and Mekong	High productivity, high flood risk, water quality		Medium	Medium	
Colorado	Water scarcity, salinity		Low	Medium: excessive pressure on resources	
2 Deltas					
Ganges Brahmaputra	Densely populated. Shallow groundwater, extensively used. Flood adaptation possible; low productivity	Rising sea level. Storm surges, and infrastructure damage. Higher frequency of cyclones (E/SE Asia); Saline intrusion in groundwater and rivers; Increased flood frequency. Potential increase in groundwater recharge.	Very high (flood, cyclones)	Poor except salinity	Minimise infrastructure development; Conjunctive use of surface water and groundwater; Manage coastal areas.
Nile river	Delta highly dependent on runoff and Aswan Storage – possibly to upstream development		High (population pressure)	Medium	
Yellow river	Severe water scarcity		High	Low	
Red River	Currently adapted but expensive pumped irrigation and drainage		Medium	High except salinity	
Mekong	Adapted groundwater use in delta - sensitive to upstream development		High	Medium	
3 Semi-arid / arid tropics: limited snow melt / limited gw					
Monsoonal: Indian sub continent	Low productivity. Overdeveloped basin (surface water and groundwater)	Increased rainfall. Increased rainfall variability. Increase drought and flooding. Higher temperature.	High	Low (surface irrigation); Medium (groundwater irrigation)	Storage dilemma; Increase groundwater recharge and use; higher value agriculture (Australia)
Non monsoonal: sub-Saharan Africa	Poor soils; Flashy systems; over-allocation of water and population pressure in places. Widespread food insecurity	Increased rainfall variability. Increase frequency of droughts and flooding. Lower rainfall, higher temperature. Decreasing runoff	Very high. Declining yields in rainfed systems. Increased volatility of production.	Low	
Non monsoonal: Southern and Western Australia	Flashy systems; overallocation of water; competition from other sectors		High	Low	
4 Humid Tropics					
Rice: Southeastern Asia	Surface irrigation. High productivity but stagnating	Increased rainfall. Marginally increased temperatures. Increased rainfall variability and occurrence of droughts and floods	High	Medium	Increased storage for second and third season; Drought and flood insurances; crop diversification
Rice: Southern China	Conjunctive use of surface water and groundwater. Low output compared to northern China		High	Medium	
Rice: Northern Australia	fragile ecology		Low	High	
Non-rice - surface irrigation			low	Medium	
Non-rice - groundwater irrigation			Medium	Medium	
5 Temperate (supplementary irrigation)					
Northern Europe	High value agriculture and pasture	Increased rainfall; Longer growing seasons; Increased productivity	Surface irrigation: medium; groundwater irrigation: low	Surface irrigation: low; groundwater irrigation: high	Potential for new development. Storage development; Drainage
Northern America	Cereal cropping; groundwater irrigation		Medium	Medium	Increased productivity and outputs; Limited optyions for storage
6 Mediterranean					
Southern Europe	Italy, Spain,Greece	Significantly lower rainfall and higher temperatures, increased water stress, decreased runoff	Medium	Low	Localised irrigation, transfer to other sectors
Northern Africa	Morocco,Tunisia: High water scarcity		High	Low	Localised irrigation, supplementary irrigation
West asia	Fertile crescent	Loss of groundwater reserves	Low	Low	
7 Small islands					
Small islands	Fragile ecosystems; groundwater depletion	Sea water rise; saltwater intrusion;increased frequency of cyclones and hurricanes	High	Variable	Groundwater depletion control; Water demand management

Relation to Food Security

Global food production and global food security are not directly linked. Although there are 830 million people worldwide who are undernourished, there is enough food produced to supply the calorie needs of a growing global population. In this respect, food security concerns are mostly related to local, not global, production, as well as to a number of critical factors not linked to climate change.

However, there is recent evidence that the global food production system is at an unprecedented level of risk from supply shocks, particularly with respect to cereals. This trend could be amplified by climate change, as trade is expected to increase as a result of shift in production patterns. Failures in rainfed production are not necessarily immediately buffered by irrigated production of food staples.

The impact of these anticipated hydrological changes on food production will be felt primarily in terms of supply stability. Although food availability, access and utilization are less directly linked to water, income from irrigated cash crops related to water availability and safe utilization is intimately related to household hygiene and food preparation – which depend upon water supply.

The consequences of degraded natural resource systems that once managed to produce large volumes of food staples are now clearly evident in areas such as the Indus and Murray-Darling basins. Local and global food security is compromised as local supply shocks transmit through into commodity chains. Against a background of degraded agricultural land, diminishing water resources and progressively thinner carry-over stocks of key food staples, the ability to improve agricultural production has become a key concern.

The rural populations most at risk from anticipated climate change impacts are those subsisting in semi-arid and arid zones who have few options for adapting to yet more water scarcity other than migration. Seasonal out-migration is already a consistent feature of many rural communities of sub-Saharan Africa and South Asia where food security is no longer dependent upon locally grown produce. Schmidhuber and Tubiello (2007) conclude that climate change will accentuate the existing focus of food insecurity on sub-Saharan Africa and, to a lesser extent, on South Asia, while "increasing dependency of developing countries on imports."

In addition, recent studies indicate that mitigation of climate change can help reduce negative climate impacts on food security but, due to lags in the climate system, the effects of such actions will be felt only after 2050 (Tubiello and Fischer, 2007). It also should be stressed that amplified climatic variability and further ENSO fluctuations will generate extreme events that impact food production well before 2050. This means adaptation strategies, regardless of future emission pathways, will be needed in coming decades to reduce the anticipated impacts of climate change.

Possible technical and policy responses; National, Regional and International

Contiguous irrigated and rainfed food production systems are set in large river basins. They comprise several climatic regimes – the Nile is a case in point – and often cover several countries. While projections for specific river basins or agro-ecological zones are uncertain, it is clear that adaptation will need to focus on increased resilience/robustness of management systems. There is already vast expertise in the area of agronomy and water management that can be tapped into to develop response strategies.

For agro-climatic predictions, projections of the ratio of precipitation to potential evapotranspiration are a lot more robust than projections for precipitation alone, (at least from a GCM perspective). This is simply because a warmer climate increases transpirational demand, over and above projected precipitation. In addition, with the current level of uncertainty with climate modelling on precipitation projections over land areas, the application of downscaled projections may simply create more hydrological noise (Conway, 2005).

Under the expected conditions of higher evaporative losses, understanding the nature of rainfall events plus the scope for water management to buffer/store rainfall will be key. Runoff can be controlled to a degree, while rainfall and evapotranspiration cannot. Hence with respect to the bulk requirements for food production, there are three main questions to ask at national and regional level.

- First, how will climate change influence natural processes? Will more intense periods/clusters of rainfall events result in locally higher runoff volumes and shorter duration groundwater recharge events?
- Second, what are macromanagement options? Specifically, what can be done with the management of existing surface and groundwater storages to optimize allocations and economic benefits? Will there be a need for more near real-time management of surface storage – particularly releases for downstream agriculture which also recharge alluvial fills – and will this require more storage? Will there be an incentive to bank groundwater through managed aquifer recharge and avoid evaporative losses? How should depletion of non-renewable groundwater be allocated/managed?
- Third, how significant will demand management (notably irrigation efficiencies) be in reducing stress? Will it be minor (marginal) in comparison to the management of supply?

Responses to climate change over and above the baseline trajectory would be best addressed at river-basin level where operational allocations are effected. It is only at this level that food production requirements can be reconciled with other competitors for bulk water. Indeed, a clear rationale can be made by pulling back from entirely local allocation decisions to target the degraded and vulnerable systems where competing uses of surface and groundwater resources are linked to mitigation of land-based pollution, rehabilitation of degraded habitats and conservation of linked freshwater and coastal resources and processes.

It is also at this level that land-use changes need to be negotiated in order to make discernible adjustments to overall water balances. In addition, all these land-based inputs to the freshwater lake and river basin and aquifers systems have a direct bearing on fisheries in terms of nutrients, pollutants and habitats. Hence, a more systemic perspective on systems at risk would allow better targeting of resources and result in a higher order leveraging of water resource (basin and catchments as well as coastal and marine management initiatives) to produce sustained benefits. This underlines the fact that climate change will affect the system as whole and no particular impact will occur in isolation. Therefore multidisciplinary, integrated watershed management is a promising approach to conserving water, land and biodiversity, enhancing local livelihoods and improving food security under global change.

Prospects for Adaptation

The history of water management in agriculture is one of constant adaptation to climatic and hydrological variability. Indeed, it is expected that a large component of climate change in the coming decades will be related to increased frequency of extreme events and will increase within and across season variability. A wealth of well-tested experience, information and technology is already available to water managers to begin implementing viable adaptation strategies in agriculture. Given that towards the end of the twenty-first century, the world will have a population of 9 billion human beings with non-negotiable calorie demands, key questions need consideration.

- What is the 'climatic coping' range of currently available water management techniques?
- Given the anticipated climate projections, what room for manoeuvre exists, in terms increased efficiency, enhanced design of current systems and development of new solutions?
- Are current and future adaptive responses sufficient to meet the demands for increased regional and global food supply while maintaining beneficial environmental services?
- Are there synergies between adaptation in water management systems and mitigation measures and, given the delay between such measures their effect, are they relevant?

Rainfed systems will continue to offer the greatest scope of adaptation in terms of area, number of farmers and overall contribution to global food production, particularly since average cereal (excluding rice) yields are low in developing countries. However, there is a significant difference in adaptation potential between the large-scale mechanized production of rainfed cereals from North America, Europe, Brazil and Australia and the small-scale systems that characterize cereal production in many developing countries. The combined effects of climate change and low adaptation capacity will increase vulnerability and local food insecurity in poor developing countries that depend on rainfed production. It is in these regions that specific efforts, such as adaptation techniques and capacity building, are most needed.

The large contiguous irrigated systems associated with the major river basins that depend on some form of water control can be adjusted immediately to increase yield performance. Performance gains in these systems will have the most impact on global food supply. At the same time, the large irrigated deltas in Asia are particularly at risk from upstream modifications. The projected changes in global runoff in irrigation areas will indicate where water scarcity can be expected and where increased precipitation will present expanded opportunities while taking into account concerns about flood damage and waterlogging. Due to the variable nature of precipitation across basins, net impact on agricultural production may only become apparent at regional and global scale once national production statistics are compiled, aggregated and analysed. Real-time monitoring of weather, water resources and farming systems responses need to be undertaken to understand the effects of future climate dynamics.

Many potential adaptation options available for marginal change of existing agricultural systems are variations of existing climate risk management (Howden, *et al.*, 2007), For some cropping systems, implementation of these options is likely to have substantial benefits under moderate climate change. However, there are limits to their effectiveness under more severe climate change. Hence, more systemic changes in resource allocation need to be considered, such as diversification of production systems and human activities in rural areas. Increased adaptation to severe climatic strain will need to be integrated with other risk factors such as climate variability and market risk and with other policy domains. Effective adaptation will need a comprehensive and dynamic policy approach covering a range of levels and issues, from farmer understanding of change in risk profiles to establishment of efficient markets that positively facilitate response strategies. A crucial component of this approach is an adaptation assessment framework that is relevant, robust and easily operated by the various agricultural decision-makers. To be effective, science also has to adapt, by continuously identifying research needs, shifting its focus toward integrated analysis that may be "fuzzy" in some respects, but not narrowly focussed on specific system components.

Forests can play a major role in adaptation strategies by regulating water flows, maximizing water yield and ensuring water quality in watersheds. However, climate change will also alter forests' role and these changes need to be better understood.

On the basis of IPCC projections, many drought-prone and marginal areas are expected to become drier, requiring additional irrigation while the water supply itself will become less reliable. Australia is contemplating significant reductions in cropped areas. Semi-arid and arid countries in a similar position will likely have to do the same.

From a global overview of climate change projections and current irrigated areas, it can be concluded that in most developing country situations, except the humid tropics, both rainfed and irrigated areas that receive sufficient water will be reduced unless there are opportunities for additional adaptation.

Prospects for mitigation

Mitigation measures for agricultural water management are not necessarily straightforward. First, it is not sure if sufficient mitigation measures will be implemented. Second, even if they are, there will a time lag between the implementation and effect in which time climate variability and extreme events will still have to be coped with.

The IPCC Technical Paper on Water (Chapter 6) evaluates mitigation prospects of the different sectors to which water-related mitigation strategies in agriculture are related. Some of these strategies may be synergistic with adaptation. For instance, water management of paddy rice can have positive implications for both adaptation and mitigation, reducing emissions of methane as well as improving water-use efficiency. Equally, practices that can increase soil organic matter content and improve water retention characteristics provide both adaptation (increased resilience to extreme events) as well as mitigation (carbon-sequestration in soils).

At the same time, several water-related adaptation strategies, in particular those related to increased irrigation needs, may be counter to mitigation needs, in particular increased pumping of groundwater using fossil fuel systems. Use of gravity or renewable energy sources for irrigation management may improve the scope for mitigation. Mitigation may also run counter to adaptation. For instance, large areas with monocultures of bio-energy crops may severely affect water (and land) resources needed for local food production.

With regard to forests, their role in mitigation could be important. Forests respond slowly to changing climate and can sustain land and water quality and regulate flows. However, there has been some controversy over the hydrological consequences in terms of afforestation. It has been projected that more than 50 percent of the suitable area for CDM plantations at global scale would reduce runoff by about 60 percent, meaning that there are significant implications of CDM-related plantations (affecting less than 1 percent of global carbon credits) and a strong need to factor this into land-use change and catchment management in developing countries.

The options for direct mitigation through irrigation are those of agriculture as a whole. Although there may be greater potential in certain specific contexts, such as intensive groundwater irrigation in the US. The possibilities are governed mostly by the increased intensity of irrigation, which allows for greater potential for carbon sequestration in tropical conditions and greater productivity, offset by more intensive use of inputs and energy which generate additional GHG emissions.

Methane production from rice paddies is another concern, as well as methane emissions from large multi-purpose dams.

Main findings and short - and medium-term recommendations

Water management in agriculture is a story of intensifying competition. Growing cities and industrialization demand relatively low volumes of high quality water but are able to add much more economic value per cubic metre of withdrawn water. Today, agricultural uses more than 70 percent of all water withdrawals, but must to adapt to a future in which water will be reallocated to other users. In addition, hydro-environmental limits are being reached through continued withdrawals from watercourses, lakes and aquifers in key grain producing areas such as the Mediterranean basin, the Punjab, peninsular India and the North China Plain. Non-renewable groundwater in these regions is depleted as a result of agricultural withdrawals. In addition, the return flows of degraded water from agriculture is leading to salinization, eutrophication and the accumulation of pollutants.

The effects of additional climate drivers that will be superimposed upon natural resource systems and their management cannot be predicted with high certainty. There are clear differences in the statistical variability of climate and hydrology among continents (Peel, *et al.*, 2001) that are not, as yet, well modelled by GCMs. Although there is only limited literature available on the prospective impacts of climate change on water balance and implications for irrigation, the impacts of these drivers are likely to include the following:

- reduction in crop yield and agricultural productivity where temperature constrains crop development (changes in diurnal fluctuation are as important as overall trends);
- reduced availability of water in regions affected by reduction in total precipitation (including Southern Africa and the Mediterranean Region);
- exacerbation of climate variability in places where it is already highest (Peel, *et al.*, 2004 and 2004b);
- reduced storage of precipitation as snow and earlier melting of winter snow, leading to shifts in peak runoff away from the summer season when demand is high (Barnett, *et al.*, 2005);
- inundation and increased damage in low-lying coastal areas affected by sea-level rise, with storm surges and increased saline intrusion into vulnerable freshwater aquifers;
- increased overall evaporative demand from crops as a result of higher temperatures;
- further depletion of non-renewable groundwater resources.

These climate-driven pressures are on top of other existing drivers adversely affecting water availability for agriculture and it is expected that climate change will intensify competition. Reconciling this competition will be the main water management challenge and agriculture will have to address the challenge much more progressively. Allocations to cities, industry, rural water supply and sanitation are unlikely to be materially affected by climate change but, collectively, they will reduce the quantity of water that can be allocated to agricultural use and hydro-environmental services.

Short term – until 2030: existing agricultural water management systems at national and basin level need to be analysed with respect to AR4. Specifically this will entail:

- monitoring the relative contribution of rainfed and irrigated production to global food balances to determine the long-term sensitivity of food production systems to climate change;

- elaborating vulnerability mapping such as the joint FAO/IIASA initiative that includes the Food Insecurity, Poverty and Environmental Global GIS database;
- determining the operational room to manoeuvre across river basin systems on the basis of updated assessments of the partition between surface and groundwater sources of supply, with the aim to improve the data for carrying out meaningful sensitivity analyses;
- building in as much operational flexibility as possible into local/irrigation-scheme-level water management strategies in anticipation of both increased demand and the need to adjust operational supply.

FAO can expect requests from member countries to improve the understanding of climate change impacts and adaptation strategies. In response, FAO with key partner organizations, could play a key role in promoting, assisting and backstopping a broad programme of regional and national analysis to identify hot-spots and priority areas for coordinated national and regional response.

Medium term – until 2050: investment plans and operational adjustments will need to be prepared to address national and sub-regional and regional issues. These plans and adjustments will comprise:

- large surface irrigation systems fed by glaciers and snow melt (most notably northern India and China);
- groundwater systems in arid and semi-arid areas, where rainfall will decrease and become more variable;
- upstream watersheds, where a combination of irrigated agriculture, rainfed agriculture, pasture and forestry is practised;
- large deltas, which may be partly submerged by sea-level rise, increasingly prone to flood and storm and cyclone damage or experience saline incursions and intrusion through surface and groundwater respectively;
- seasonal storage systems in the monsoon regions, where the proportion of storage yield will decline but peak flood flows are likely to increase;
- supplemental irrigation areas, where the consequences of irregular rainfall are mitigated by short-term interventions to capture and store more soil moisture or runoff.

FAO support to adaptive strategies

Upon request, FAO could assist member countries in understanding the implications of climate change on water resources and agriculture and in developing better regional and local projections of impacts in order to develop planned adaptive strategies, improve water governance and build specific capacity in water management. Additionally, FAO could engage in a number of high impact and strategically chosen pilot projects to improve institutional capacity for climate change adaptation. These would have to be well resourced, long term and have high level buy-in from the partner country.

Given the instrumental value of water to all economic sectors, agriculture cannot act alone. National water management actions will need to be focused at national level but supported by regional and international initiatives. Specific recommendations are given in the document "Options for Decision Makers."

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