CLIMATE CHANGE, WATER AND FOOD SECURITY: A Discussion Paper for an Expert Meeting 26-28 February 2008, Rome.

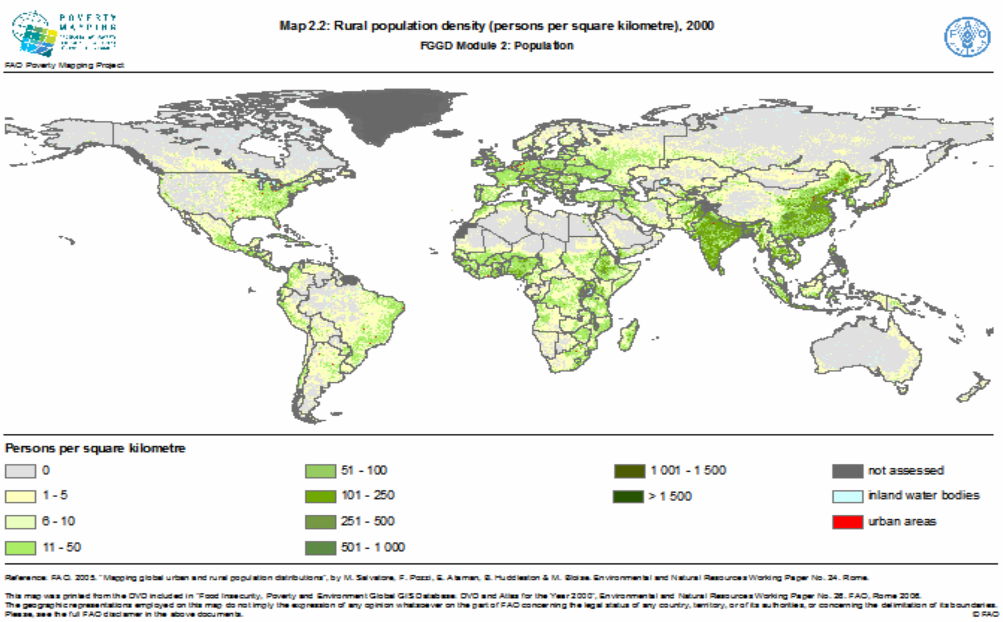
Zero Draft NRLW 12 February 2008

EXECUTIVE SUMMARY (OUTLINE ONLY: DRAFT VERSION FOR PRESENTATION/DISCUSSION AT EXPERT GROUP MEETING TO AS A ZERO DRAFT OF THE REQUIRED SYNTHESIS PAPER)

Introduction

The Current scene

Summary of baseline



Reference: FAO. 2005. "Mapping global urban and rural population distributions", by M. Salvatore, F. Pozzi, E. Ataman, B. Huddleston & M. Bloise. Environmental and Natural Resources Working Paper No. 24. Rome.

This map was printed from the DVD included in "Food Insecurity, Poverty and Environment Global GIS Database. DVD and Atlas for the Year 2000", Environmental and Natural Resources Working Paper No. 26. FAO, Rome 2006.
The geographic representations employed on this map do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal status of any country, territory, or of its authorities, or concerning the delimitation of its boundaries.
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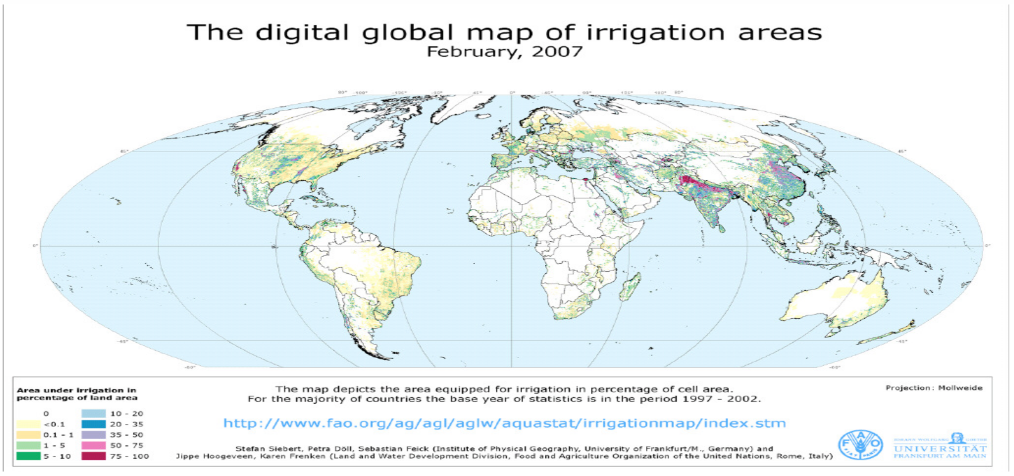
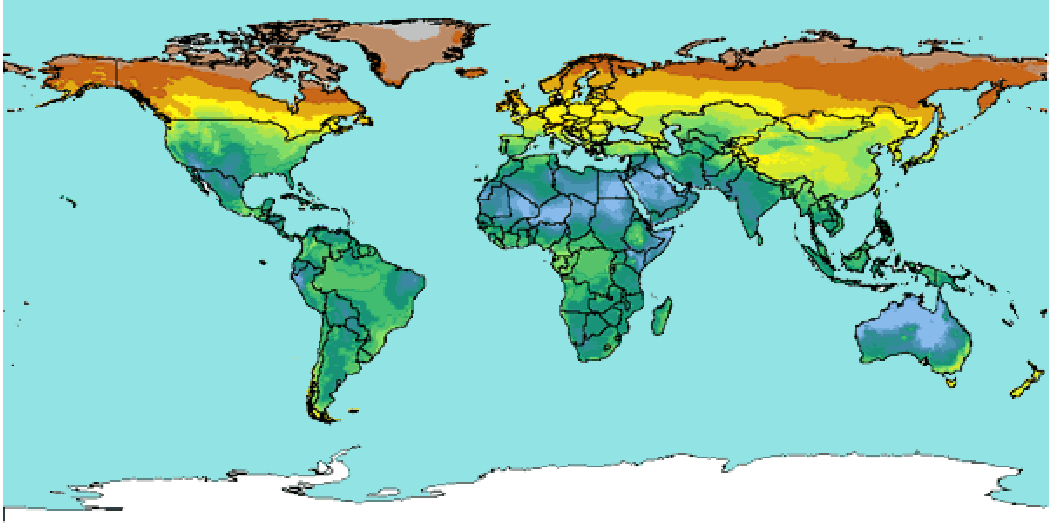


The map depicts the area equipped for irrigation in percentage of cell area.
For the majority of countries the base year of statistics is in the period 1997 - 2002.

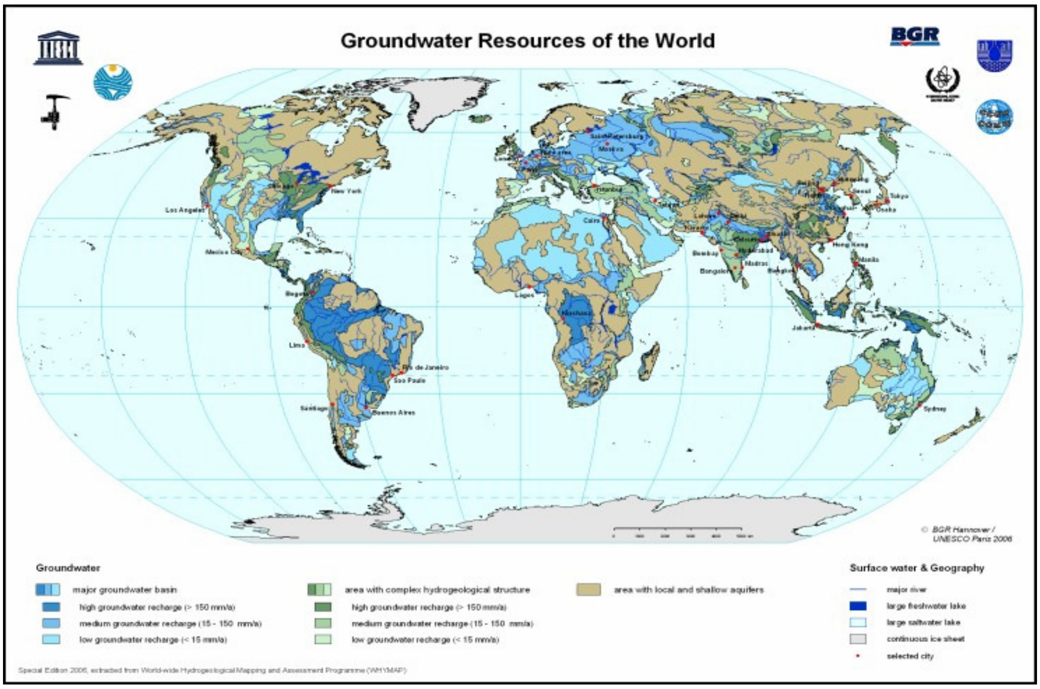
http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index.stm

Stefan Siebert, Petra Döll, Sebastian Feick (Institute of Physical Geography, University of Frankfurt/M., Germany) and Jippe Hoogeveen, Karen Frenken (Land and Water Development Division, Food and Agriculture Organization of the United Nations, Rome, Italy)

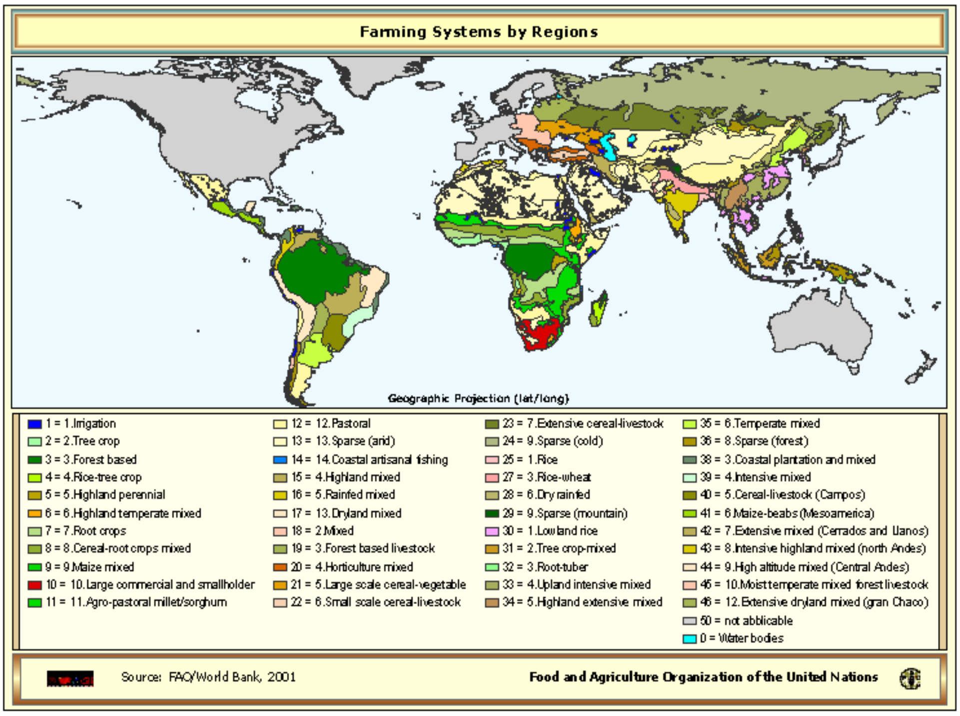
FAO Global Map of Irrigated Areas V4.
HTTP://WWW.FAO.ORG/NR/WATER/AQUASTAT/IRRIGATIONMAP/INDEX.STM



IIASA/FAO Global Agro-Ecological Zones
http://www.iiasa.ac.at/Research/LUC/GAEZ/index.htm

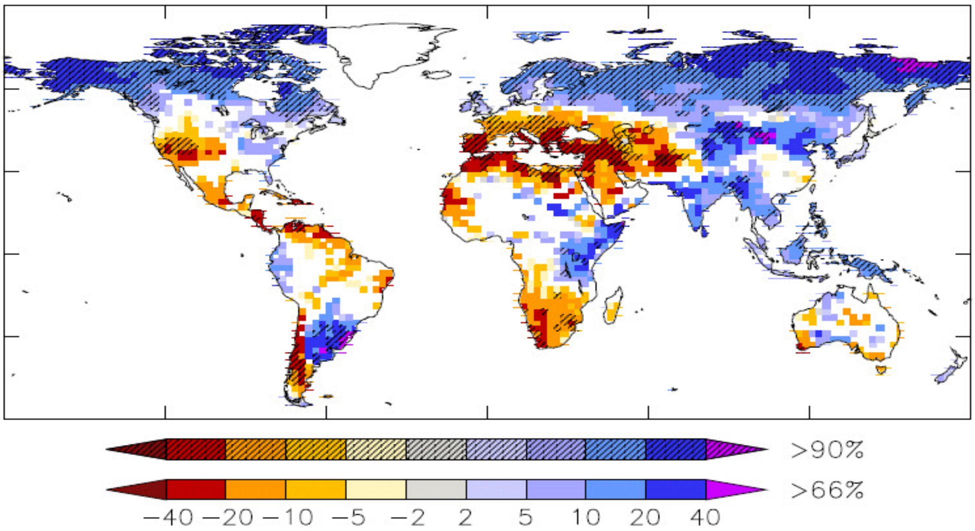


Groundwater Resources of the World Map
(http://www.whymap.org/cln_011/whymap/EN/Home/whymap__node.html?__nnn=true)



FAO/World Bank (2001) Farming Systems and Poverty – regional mapping. (to capture socio-economic factors within AEZs

Summary of Impacts



Multimodel mean changes in annual runoff by 2060, in percent, indicating also degree of agreement between the 12 models used Scenario A1B, i.e. very rapid economic growth, convergence among regions and technological change in energy systems. Illustration from Milly et al 2005.

Prospects for Adaptation

Prospects for mitigation

Recommendations

1 INTRODUCTION

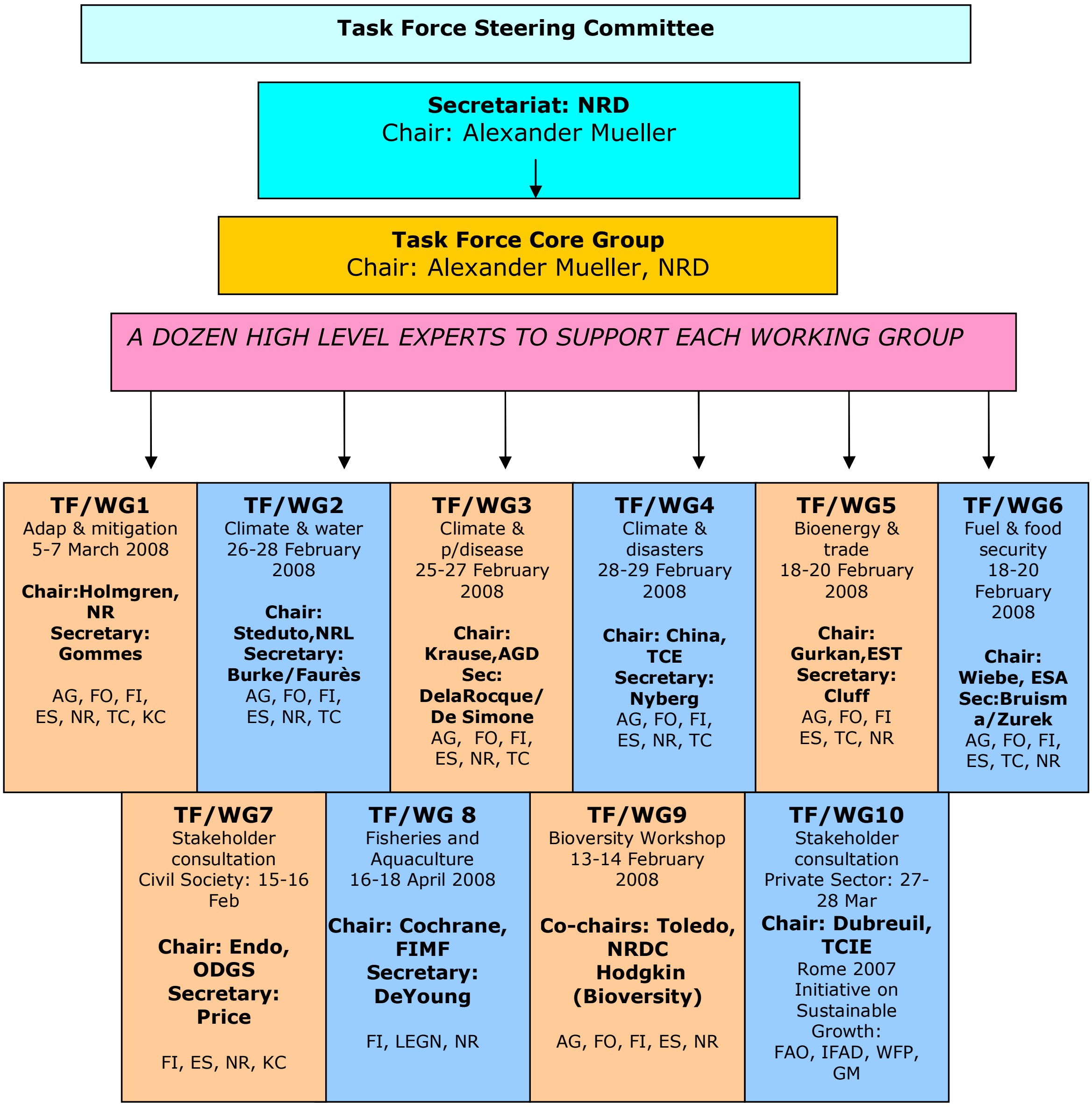
The purpose of this discussion paper is to prompt debate at an Expert Meeting on climate change, water and food security to be held in Rome form the 26-28 of February 2008. The outcomes of the meeting will then be taken forward to an FAO convened High Level Conference in June 2008. It is anticipated that the Expert Meeting will provide specific guidance on the drafting of a synthesis paper (5,000 words) and an 'options and considerations' note (1,600 words) to inform FAO member countries at the HLC. FAO members are keen to avail themselves of expert knowledge on the matter in order to either

- confirm the appropriateness of their current agriculture, food security and related policies, or
- to review and modify policies and strategies in the light of IPCC findings and subsequent analysis.

This paper is far from a through examination of the implications of climate change for agricultural water management. The IPCC 4th Assessment was only published in November 2007 and this is a necessarily rapid appraisal of the implications for water management in agriculture. It should also be noted that the IPCC plans to issue a Technical Paper on Climate Change and Water (TPW) in early 2008 after a round of government reviews. This discussion paper does not anticipate this IPCC TPW paper but rather attempts to tease out specific issues related to agricultural water management, that is agricultural systems that deliberately control and distribute surface and ground water to reduce moisture stress in crops.

The recent thirty-fourth session of the Food and Agriculture Organization of the United Nations Conference called for a series of expert meetings on climate change and bioenergy, to be held between January and March 2008 and two stakeholder consultations aimed at civil society organizations and the private sector, to be held in February and March 2008. The expert meetings and stakeholder consultations will be followed by a High-Level Conference on World Food Security and the Challenges of Climate Change and Bioenergy to take place 3 - 5 June 2008. The High-Level Conference will be informed by work undertaken and findings which emerge from the expert meetings and stakeholder consultations. The working groups are organized thus:

Ad Hoc **Task Force on**
World Food Security and Global Challenges



Task Force Steering Committee

Secretariat: NRD
Chair: Alexander Mueller

Task Force Core Group
Chair: Alexander Mueller, NRD

A DOZEN HIGH LEVEL EXPERTS TO SUPPORT EACH WORKING GROUP

TF/WG1
Adap & mitigation
5-7 March 2008
Chair:Holmgren, NR
Secretary: Gommes
AG, FO, FI, ES, NR, TC, KC

TF/WG2
Climate & water
26-28 February 2008
Chair: Steduto,NRL
Secretary: Burke/Faurès
AG, FO, FI, ES, NR, TC

TF/WG3
Climate & p/disease
25-27 February 2008
Chair: Krause,AGD
Sec: DelaRocque/ De Simone
AG, FO, FI, ES, NR, TC

TF/WG4
Climate & disasters
28-29 February 2008
Chair: China, TCE
Secretary: Nyberg
AG, FO, FI, ES, NR, TC

TF/WG5
Bioenergy & trade
18-20 February 2008
Chair: Gurkan,EST
Secretary: Cluff
AG, FO, FI ES, TC, NR

TF/WG6
Fuel & food security
18-20 February 2008
Chair: Wiebe, ESA
Sec:Bruisma/Zurek
AG, FO, FI, ES, TC, NR

TF/WG7
Stakeholder consultation
Civil Society: 15-16 Feb
Chair: Endo, ODGS
Secretary: Price
FI, ES, NR, KC

TF/WG 8
Fisheries and Aquaculture
16-18 April 2008
Chair: Cochrane, FIMF
Secretary: DeYoung
FI, LEGN, NR

TF/WG9
Bioversity Workshop
13-14 February 2008
Co-chairs: Toledo, NRDC
Hodgkin (Bioversity)
AG, FO, FI, ES, NR

TF/WG10
Stakeholder consultation
Private Sector: 27-28 Mar
Chair: Dubreuil, TCIE
Rome 2007 Initiative on Sustainable Growth:
FAO, IFAD, WFP, GM

Climate change is expected to alter hydrological regimes and the patterns of freshwater resources availability (IPCC, 2007). Agriculture yields 40% of the global food production under irrigation on 20% of the cultivated land, using about 70% of all water withdrawals. The other 60% of the global food production comes from the 80% of the cultivated land under rain-fed conditions. In a situation of water scarcity, agriculture, inland fisheries and aquaculture are expected to be significantly impacted. This Expert Meeting will review a draft issues paper on the climate change implications for agricultural water management that is where water is controlled and distributed. Where available, scenarios for water use in agriculture will be reviewed. If feasible, scenarios for other activities, such as inland fishery and aquaculture, will be reviewed as well. The issues paper will appraise adaptation options and implementation strategies that have significant potential to maintain or enhance water management and food security in a sustainable and economically viable way. It will propose strategic lines of action for FAO and its partners to address, and respond to, the uncertainties posed by a changing climate.

Climate change is expected to be a an additional driver of global agricultural transformation and associated rural development. It is acknowledged that the negative and positive impacts of climate change on global agricultural production will have implications for global food supply. In this discussion paper, it is the impacts of climate change on the supply of and demand for water resources in agriculture that is examined and particularly in relation to developing countries where impacts are expected to be felt most severely (Alexandratos, 2005). Related aspects in the field of trade, bio-energy, crop protection, fisheries are covered in the other working groups (See Box 1)

The two main drivers of food production are rising global population a change in dietary preference associated with increasing incomes, particularly in emerging economies. The dramatic increase in commodity prices seen in 2007 can also be accounted for by switches from food to bio-ethanol production (in the USA) and significant increases in meat consumption in countries such as China, which have combined to raise grain prices in real terms and end a declining trend in commodity prices that has not faltered since the late 1970s. Further stress on land and water is imposed by the rapid rates of industrialisation and urbanisation with its associated food, sanitation and water supply demands. In developing countries, negative impacts of agricultural water use have largely been ignored but are steadily emerging as an important factor, perhaps the key long-term factor, in determining the amount of water left available for agriculture. Even in a climate stressed world, there is little doubt that the emerging pressures to allocate and ensure high security water supplies for basic human needs and highly productive economic activity will take priority over agriculture.

It should be emphasised that from agricultural water management perspective the point of competition is access to raw water for reliable crop, livestock and freshwater fish production. Access to water services is a prime determinant of the stability of food supplies (Schmidhuber and Tubiello, 2007). However, reconciling that competition necessarily invokes interaction with competing economic sectors and preferences for environmental conservation. It also invokes a consideration of soil and land management practices that directly influence the natural hydrological cycle in which water control occurs. These economic, water resource and associated land management issues are of fundamental importance for the continued contribution of agricultural water management which withdraws some 70% of the globe’s renewable water resources, occupies 20% of cultivated land but produces 40% of total agricultural production. This production has come at an environmental cost that is often ignored, such as pesticide accumulation in aquifers or the loss of highly productive wetland biodiversity. But it is also the case that many irrigated areas are multifunctional and provide a range of rural services beyond basic food production. Hence the links between environmental services, livelihoods and food security that are found in agricultural systems that control water tend to be more intense than the more neutral impacts associated with extensive rainfed production. The control allows concentration of services, and the intensification of agricultural production but also the concentration of environmental impacts. Hence the links between food security, livelihoods and environmental sustainability are particularly acute when water control is applied.

The relative proportion of rainfed and irrigated production into local and global commodity markets and the structure of each sub-sector is not trivial. Certainly from the irrigated sub-sector, there are indications that supply will continue to be constrained, not just because of competition for water allocation into the sub-sector. The more critical issue has to do with the limits of their hydraulic, economic and environmental performance. Cropping intensities in many lowland deltas are in the order of 1.2 to 1.5 only. Assessments of large irrigation schemes reveal the dilapidated state of infrastructure and institutions suggesting that rapid, flexible response to food price signals may be choked by structural problems which are not easily overcome. Growth from new schemes is going to be slow anyway - the best sites have already been taken and, in the case of the Indus or Murray-Darling systems, will decline as salts continue to accumulate and productive land is lost. It is pertinent to ask under climate change projections, at what point of reduced flows and enhanced temperature and evaporative demand will the dominant sub-tropical irrigation systems flip from reliable centres of production to degraded saline sinks. Equally in systems subject to higher flows under precipitation projects – will water logging and impeded drainage compromise overall production.

Developing countries are the primary focus of this paper, for reasons that are consistent with the likely impacts of climate change on human development, and because of the mandate of the FAO. Nevertheless, where relevant information, context and observation from more developed countries is useful, it is included, beyond the more general global discussion. In particular, material from Australia is thought to be useful from the perspective of a country with large and export-oriented agriculture and irrigation sector, that already operates in perhaps the most variable climate in the world, and one that is now increasingly suggested to already be experiencing the impacts of climate change, over and above its natural variability and pre-disposition to extended drought.

2 SETTING THE SCENE

2.1 Linkages between water, food security and environment

A recent review of food security and climate change is given by Schimdhuber and Tubiello (2007) and underscores the FAO definition of food security, viz "situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 2002). The authors identify four key dimensions of food security: availability, stability, access, and utilization.

Water management plays a key role in maintaining stability of food production. It simply offsets the climatic risk that rainfed production would otherwise be exposed to but also makes possible the cultivation of a range of exotic crops that would not otherwise survive under rainfed conditions – notably horticultural products . However, it is clear that the allocation of increasing amounts of water to agriculture has had negative impacts on livelihoods that depend on downstream freshwater environmental services (Emerton and Bos, 2004; FAO, 2004a) The same is true of groundwater abstraction where environments and services dependant upon shallow groundwater circulation have been lost (Burke and Moench, 2000). Hence the economic argument for maintaining the integrity of hydro-environmental systems in order to produce higher net socio-economic benefits (Cai, Ringler and Rosegrant 2001, FAO, 2004a). It has generally been the case that water saved in a particular location as a result of improved irrigation facilities and services is simply used to expand irrigation at that location rather than being economically mobile and producing a set of higher value benefits downstream.

The implications are that adaptation strategies targeted at food security may actually include i) the re-allocation of water away from the agricultural sector in order to maintain or supplement environmental stream flows thereby supporting other forms of water dependent livelihood or economic activities (some of which could absorb excess farm labour); or ii) the capping of spatial expansion of irrigated areas where water savings are achieved to reduce overall demand. These are not academic considerations. Climatic variability in south eastern Australia has had even more profound impacts on water allocations and associated livelihoods in agriculture than even the most prudent farmers has anticipated (http://www.mdbc.gov.au/)

With respect to environmental functions and services associated with water, climate change will influence the productivity of aquatic ecosystems, and the services they provide in significant ways, both directly, for example in changes in rainfall patterns and rising sea levels, and indirectly, through shifts in demand and trade of commodities. The exact nature of these changes cannot be easily established and in any event there will likely be a wide margin of variability in predictions.

2.2 IPCC 4th Assessment and the Stern Review

2.2.1 The IPCC 4th Assessment

The outputs of the IPCC and its three working groups have been presented in 4^{th} Assessment Report (AR4) which now sets the scientific baseline. In general, this discussion paper will use the original AR4 material and text together with the results of the IPCC Special Report on Emission Scenarios (commonly referred to as SRES). Supplementary material dealing with hydrological and agricultural impacts will also be referred to where they derive from work carried out for the IPCC, largely as a result of the Third Assessment Report (TAR).

The heart of the IPCC analysis is centred around emissions scenarios as published in the IPCC Special Report on Emission Scenarios (commonly referred to as SRES) published in 2001. The IPCC (2001) SRES prepared 40 greenhouse gas (carbon dioxide, methane, nitrous oxide and sulphate) emissions scenarios for 2000-2100 that combine different combinations demographic, economic and technical factors that are likely to influence future emissions. These were then run through the suite of available Global Climate Models (GCMs) to generate a plausible range of outcomes in terms of likely maximum and minimum future temperatures, pressures and rainfall, for nominal years of 2030, 2070 and 2100. There are four "storylines", A1; A2; B1 and B2, each with approximately 10 variants. They are summarized in Box 2.

The models are calibrated against historical climate and the replication of observed trends, and have steadily improved in performance over the last 10 years, with the incorporation of atmosphere-ocean interactions (AOGCMs). Since the fourth report of the IPCC (AR4) in autumn 2007, there is a broader scientific consensus on the certainty of future projections, based on improved processes in modeling, a broader range of scenario assessment, and better scientific understanding of positive and negative feedbacks included in the models. Nevertheless there are still areas for further improvement related to 1) Scale and spatial representation (125-400km grid cells at present; 2) land-surface atmosphere interactions and their representation; 3) the trends and behaviour of aerosols in the atmosphere. These are partially included at the moment, but one conundrum is that global rates of actual evaporation have been declining, when current modeling suggest that they should be increasing (Barnett et al, 2005).

However, because uncertain climate projections are being used to predict impacts, and then to evolve mitigation and adaptation strategies, the chain of uncertainty lengthens. This is dealt with through the range of scenarios run through an ensemble of GCMs (some giving different outputs from others), coupled to estimates of uncertainty in the prediction of consequences. Therefore we see future projections of temperatures (Figure 2.1) varying from significant to slight increases. In the case of projected rainfall, we see higher occurrence of extreme events with global mean predictions varying from a light increase to a significant decrease, as explained in figure 2.2. The median scenarios are the ones with the highest probabilities of occurrence, based on current knowledge.

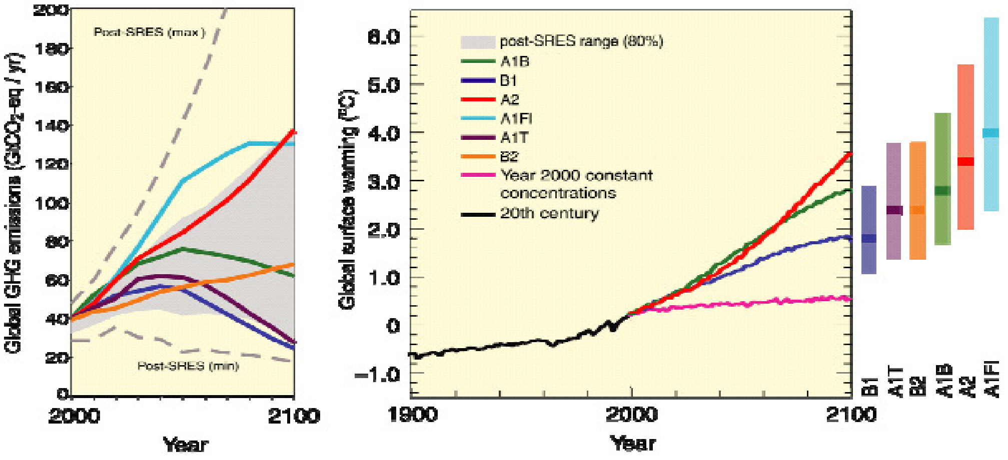


Figure 2.1 *An illustration of the range of scenario predictions of global warming under different scenarios, using a well calibrated set of different GCMs (IPCC 2007 (SPM Figure 5).*

Climate variability is thought likely to increase, but we cannot predict by how much and over what time period. The combined effect of a change in climate and an increase in variability results in more frequent and larger (negative) impacts than either one on its own, as illustrated for temperature in Figure 2.1.

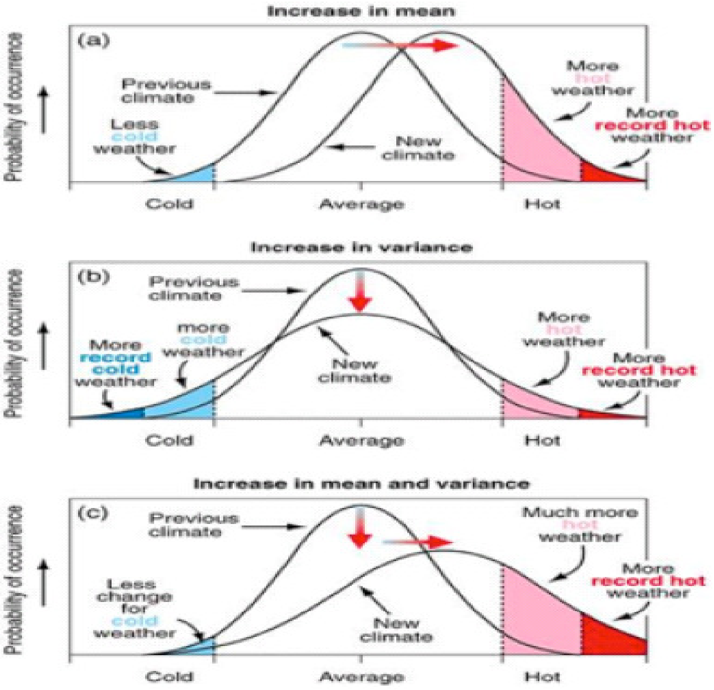


Figure 2.2 *An illustration of the effects of climate change (increase in mean) and an increase in variance and in combination. (IPCC 2001 a and b)*

All discussion of climate impacts should properly be tied to a specific scenario, time frame and location. The sensitivity analysis associated with uncertainty should also be stated to put observations in the correct context. It is quickly apparent that such qualified writing is not easy to read or to keep track of. As this document proceeds, we will ague for a progressively location specific analysis of spatially disaggregated projections and the evolution of appropriate adaptation strategies. A key factor in the improvement of climate model performance at global and regional scales, at least in terms of narrowing the range of projected outcomes, is the incorporation of land use feedbacks, which are responsible for modifying climate into weather. At the moment, these remain big questions and are the subject of considerable further research. Such enhancements are desirable to allow the development of more focused adaptation strategies, but for the time being, alternatives, such as scenarios with broader sensitivity analysis and probabilistic interpretation remain the most likely approach.

2.2.2 The downscaling problem

The problem of scale underwrites the interpretation of all projections in global climate change modelling. Although the highest resolution models have a grid size of 125 km^2, many are as course as 500km^2 per cell. Global climate models have become increasingly complex and integrate most of the process that drive climate, with perhaps the exception of land-surface-atmosphere interactions. Climate patterns are long term and relatively stable expressions of temperature, relative humidity, rainfall, circulation patterns and so on a global and regional scale. Weather is famously more variable and hard to predict. Weather is short term, highly variable over space and time and is affected by multiple interactions between topography, land use, and local scale atmospheric processes that all occur of ranges of scale that are smaller than one or a small cluster of GCM grid cells. Climate drives weather and some climatic processes, such as El Nino have a cyclic behaviour that can be used (through indicators such as El Nino Southern Oscillation Index (ENSO) and oceanic surface temperatures) to predict general weather patterns.

Regional scale climate models (RCMs) can be nested within GCMs, at scales ranging from 20-100km^2 per pixel, and, in theory, should do a better job of predicting climate variables. The simulations of RCMs are "driven" by climatic forcings derived from the GCMs under different scenarios of climate change. To date, it is fair to say that RCMs are less developed and less well calibrated than GCMs. Given the higher variability in weather patterns compared to climate as viewed at say monthly intervals, this is not surprising. RCMs and short-range weather models require considerably more computer processing power than even GCMs and incorporate more process detail. RCM temperature outputs largely agree with local observations and with GCM forcings (McKinnes et al, 2003), but can have quite divergent patterns and quantities of estimated rainfall.

RCMs will continue to be developed and refined, and increasingly deployed at local scale. However, they remain relatively coarse-scaled compared to real measurements on the ground. Some countries have relatively dense hydro-meteorological networks (OECD countries, FSU) whereas data may be very sparse, for example most of Sub-Saharan Africa and somewhere in between in places such as India and China. Remote sensing offers great opportunities to infill data at higher resolution than most RCMs – down to 1km^2 for actual evapotranspiration (using procedures such as SEBAL) and for net radiation and surface temperatures (Bastiaansen, 1998). The spatial distribution and amount of rainfall can increasingly be better estimated through correlation of satellite measurements with ground-station data (McVicar et al. 2002) using platforms such as TRMM, GMS and Meteosat at scales of a few square kilometres.

The problems of scaling are not unique to climate prediction, but are fundamental to the modelling and understanding of hydrological processes (Beven and Freer 2001). However, In terms of practical application, for determining inputs to agriculture/irrigation dependant systems it is evident that there may not be consistent GCM modelling at the scale of large basins such as the Nile (Conway, 2005) while at sub-basin level, detailed studies based on a lot of detailed hydrological knowledge such as that prepared by Serrat-Capdevil et al. (2007) lie below the cell resolution of 125km^2. Hewitson and Crane (2005) present a regional analysis at country level for South Africa.

Scaling problems related to agronomy are mostly concerned with the representation of the climatic and terrestrial factors that govern the processes simulated in crop models. Unlike hydrological modeling, they are not related to the scale of the processes themselves, but to the input data used to drive the models. Processes with crop models themselves are usually empirical to semi-empirical, and represented in terms of regression relationships between photosynthetic processes, radiation, water and nutrient status. There remains some uncertainty as to how well crop model processes calibrated to a current range of conditions represent what will happen in future climate projections.

2.2.3 The Agricultural Implications of the IPCC Working Group I Report (Physical Science Basis)

The Fourth Assessment report ("AR4") by the International Panel on Climate Change (IPCC, 2007) foresees a temperature rise in the range of 2 to 6 degrees Celsius by 2100. This compares with temperature increases in the Millennium Assessment scenarios are in the lower range of 1.5 to 2.0 degrees Celsius above pre-industrial in 2050, and 2.0 to 3.5 degrees Celsius in 2100 (Alcamo et al 2005). One of the main reasons for the higher temperature estimates by 2100 in AR4 is the better understanding of positive feedbacks that further increase carbon dioxide concentrations in the atmosphere, partly due to saturation of the absorptive capacity of the seas and terrestrial vegetation and soils. Other temperature reinforcing feedbacks result from the melting of polar and mountain ice caps at +4-5C (reduced albedo and reflection), thawing of permafrost with release of large volumes of methane, and higher atmospheric retention of CO2 in future at higher temperatures. It is also anticipated that there will also be considerable mobilisation of GHGs when temperature rise reaches around 5-6 C, with expected large releases of methane from Tundra and permafrost areas in the northern latitudes. These temperature and CO2 concentrations changes will have direct impacts on plant growth, in many instances positive. But this assumes there is sufficient soil moisture present to accompany the enhanced plant assimilation of carbon and consequent growth.

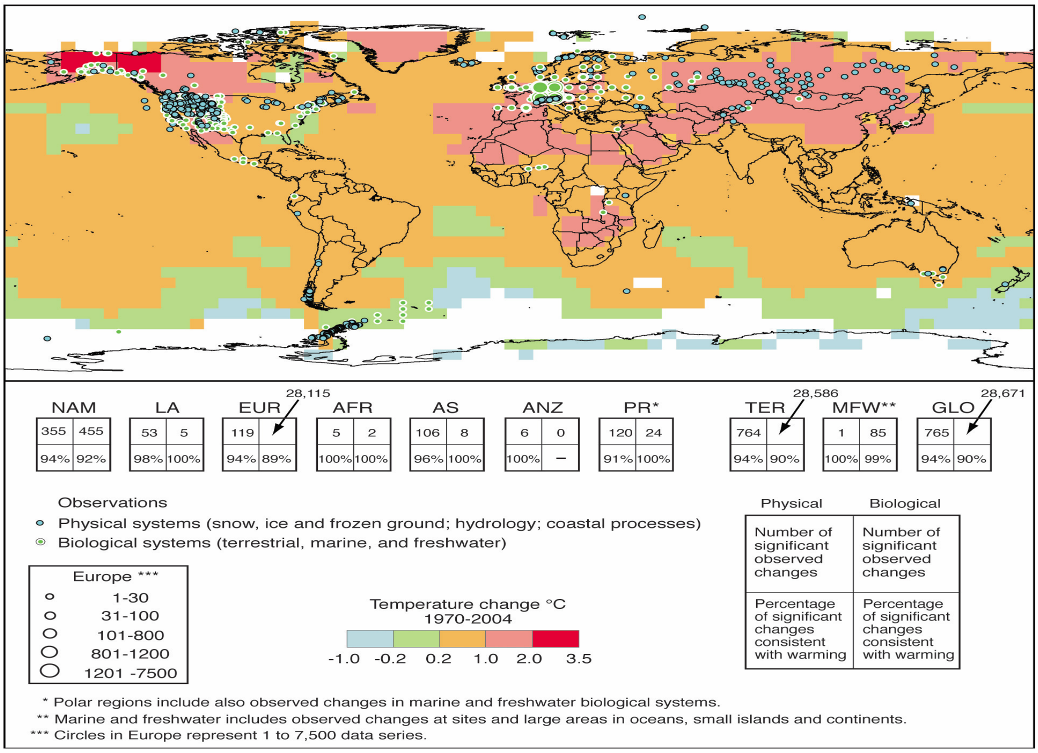


Figure 2.3 *Actual pattern of global temperature changes 1970-2004. Source: IPPC SPM II*

For the overall impact, the temperature changes have to be taken with the other key atmospheric variables, notably rainfall and evaporation since these three determine the basic agro-ecological zoning which set the spatial limits to plant growth. The global patterns of predicted changes in temperature, precipitation and air pressure rise are illustrated for 2080-2099 for "winter" and "summer" seasons are presented in Figure 3, derived from SRES A1B wich clearly illustrates the expected rise in temperatures; the increase of precipitation in the higher latitudes and humid equatorial tropics in contrast to the fall in precipitation in the semi-arid and arid areas falling in the inter-tropical convergence zones; and a notable increase in air pressures in the southern hemisphere. At this scale, there is clear correlation between the areas of lower expected rainfall (and higher temperature), and the areas currently featuring extensive irrigation – India, China, Western USA and Mexico, SE Asia, North Africa and Australia

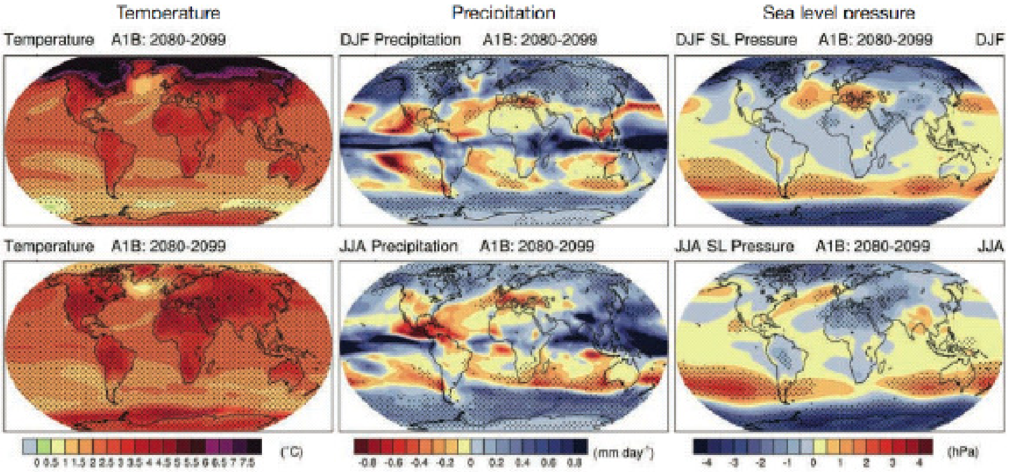


Figure 2.4 *Temperature, precipitation and sea level pressure change by quarter year (DJF and JJA), for SRES A1B, in 2080-2099 relative to 1980-1999 (source: Meehl et al, 2007)*

Sea level rise a result of thermal expansion and ice-melt to 2070 is of the order of 0.7-1.0 m, and will have significant impact on coastlines and deltas in particular. Irrigation is commonly found in major deltas in S, E and SE Asia, and their vulnerability in terms of displaced people as a result of current trends to 2050 is illustrated in Figure 4. Sea level rise due to climate change will further exacerbate this vulnerability. The impacts of sea level rise include greater and more frequent storm surge damage, and likely saline intrusion in estuaries and to coastal groundwater systems, with NE China being especially vulnerable due to the extent of depletion in existing coastal aquifers.

Figure 2.5. *Relative vulnerability of coastal deltas as indicated by estimates of the*

population potentially displaced by current sea-level trends to 2050 (extreme >1 million; high 1 million to 50,000; medium 50,000 to 5,000) (Source, SPM, 2007).

With the caveat that detailed patterns of runoff with vary considerably with improved resolution and scaling of rainfall patterns, the global implications for runoff are summarised in Figure 5 (AR4, 2007), with illustrative stress points noted on different continents.

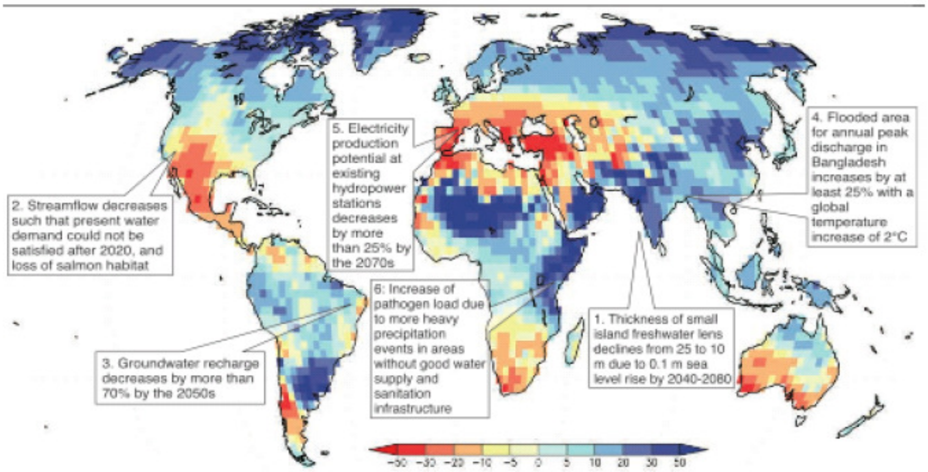


***Figure 2.6**. Illustrative map of future climate change impacts on freshwater which are a threat to the sustainable development of the affected regions. The background shows ensemble mean change of annual runoff, in percent, between the present (1981-2000) and 2081-2100 for the SRES A1B emissions scenario; blue denotes increased runoff, red denotes decreased runoff (Source, IPCC, SPM, 2007).*

Rising temperature, rising potential evapotranspiration rates and declining rainfalls conspire to increase the severity, frequency and duration of droughts. Large-scale land-use change is expected on all continents. AR4 estimates that some 75 million ha of land that is currently suitable for rainfed irrigation, with a growing window of less than 120 days, will be lost by 2080 in sub-Saharan Africa (REF). In rainfed systems, if potential evaporation rates increase, available root zone moisture content will be more rapidly depleted, requiring either shorter season crop varieties or acceptance of lower yields and more frequent crop failure.

Worldwide cereal yields are expected to decline by 5% for a 2°C rise in temperature and 10% for a rise of 4°C. Cereal yields decline above certain temperature thresholds, with grain number in wheat falling above 30°C and flowering declining in groundnut above 35°C. Yields are estimated to fall uniformly in the tropics due to temperature rise: higher productivity is expected in the higher latitudes with longer season growth, more optimal growing conditions, and likely the development of new lands. The mid latitudes will suffer from declining yields due to temperature and declining areas due to reduced water availability – for irrigation and rainfed farming in the Mediterranean, southern Europe, mid-west United States and the semi-arid to arid sub-tropics. These areas are close to the threshold temperatures for declining yield and so the yields of wheat and other staple crops in the Mediterranean, Western Asia and Africa are expected to fall by 25-35% with weak CO_2 fertilisation and by 15-20% with strong CO_2 effect. The estimated balance of changes in cereal production modelled by Parry et al (2005) for a temperature rise of 3°C and a doubling of atmospheric carbon dioxide concentration is shown in Figure 6.

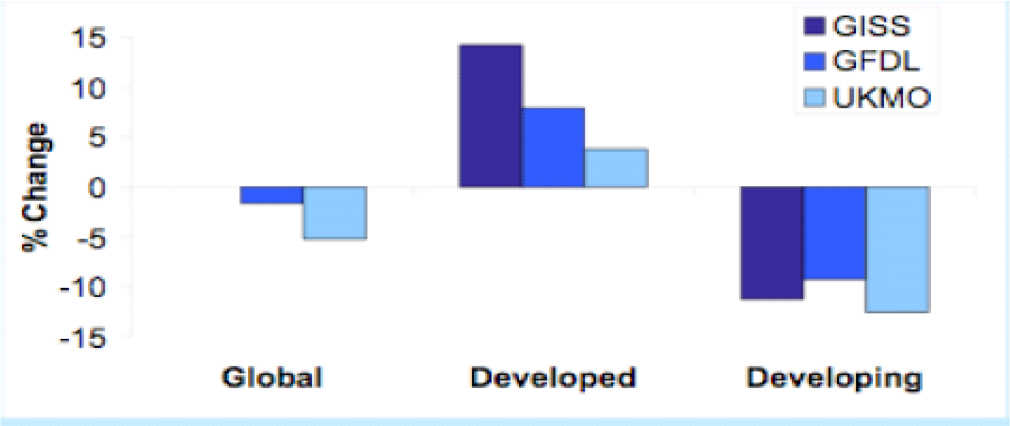


Figure 2.7 *Expected change in cereal production (compared to scenarios without climate change) after Parry (2005) in Stern (2006).*

2.2.4 The agricultural implications of the IPCC Working Group II report (Adaptation)

The anticipated impact of climate change in terms of crop production are summarized in the IPCC AR4 WG2 (Chapter 5.4) . These tend to focus mainly on agronomic impacts related to temperature gains and elevated CO_2. The combination of both are considered to the extent that CO_2 effects increase with temperature, but decrease once optimal temperatures are exceeded for a range of processes, especially plant water use. The CO_2 effect may be relatively greater (compared to that for irrigated crops) for crops under moisture stress. In general, plant response to elevated CO_2 alone, without climate change, is positive. The effects on plant growth and yield depend on photosynthetic pathway, species, growth stage and management regime, such as water and nitrogen (N) applications. On average across several species and under unstressed conditions, compared to current atmospheric CO_2 concentrations, crop yields increase at 550 ppm CO_2 in the range of 10-20% for C3 crops and 0-10% for C4 crops. However, the effects of elevated CO_2 measured in experimental settings and implemented in models may overestimate actual field- and farm- level responses, due to many limiting factors such as pests, weeds, competition for resources, soil, water and air quality, etc. In addition, Modelling studies suggest crop yield losses with minimal warming in the tropics and mid- to high-latitude crops benefit from a small amount of warming (about +2°C) but plant health declines with additional warming.

It is import to note that the IPCC anticipates that changes in temperature and precipitation will modify and limit the direct CO_2 effects on plants . For example e.g., high temperature during flowering may lower CO_2 effects by reducing grain number, size and quality. Increased temperatures may also reduce CO_2 effects indirectly, by increasing water demand. Importantly, climate impacts on crops may significantly depend on the precipitation scenario considered. Further, the Increased frequency of extreme events may lower crop yields beyond the impacts of mean climate change. The general conclusions that impacts of climate change on irrigation water requirements will be “large” and that ccountries with greater wealth and natural resource endowments adapt more efficiently than those with less are un-quantified. An elaboration on agricultural water demand can be expected in the Technical Paper on Climate Change and Water that the IPCC anticipates issuing in March 2008.

2.2.5 The agricultural implications of the IPCC Working Group III report (Mitigation)

The IPCC considers how agriculture can contribute to mitigation of global emissions of greenhouse gases, to help stabilise future carbon dioxide levels and restrain global warming. Agriculture contributes greenhouse gases and also cycles and stores carbon through the photosynthesis and biological accumulation of carbon in plant matter and soil organic matter. Agriculture contributes to greenhouse gas emissions through nitrogen fertiliser use, predominantly as nitrous oxide and through methane, from wet rice production and at a larger scale from enteric fermentation in ruminants (cows, sheep and goats). The IPCC (2007) estimates that there is good potential in agriculture, particularly in the tropics, to mitigated greenhouse gas emissions. Chapter 6 of this document is devoted to mitigation of greenhouse gas accumulation through agriculture.

2.2.6 The Stern Review

The Stern report (2006) has paid special attention to the economic impacts of climate change, and to the consequences for developing countries. Although the Stern report was published prior to AR4, it has used a good portion of the material and scenario assessment that contributed to AR4 and can be thought of as being consistent in terms of science base.

The main findings or the report have a considerable bearing on the vulnerable agricultural economies of the developing world. The report makes it very clear that LDCs are far more vulnerable than the industrialised economies, due to larger projected changes coupled to weaker economies. LDC's typically have a greater economic reliance on agriculture, a significantly larger number of citizens engaged in agriculture, the lack of broader economic strength and associated weakness in institutions and technology to allow more flexible adaptation.

Stern emphasises that the primary economic impacts will occur through the intensification of the hydrologic cycle, and that food production will be very sensitive to climate change. The report also points out the effects of carbon dioxide enrichment are crucial to future performance, and that these are now though to have less potential than before, and that temperature and loss of available soil moisture will outweigh the positive benefit. Increased temperature tends to decrease yield potential by accelerating growth rates and shortening the growing season, with a consequent reduction in assimilates in the plant. The Stern report observes that predictions based on average changes do not properly account for the impacts of extreme events, and it provides some useful examples, such as an expected doubling of losses due to water logging in US maize production by 2035, valued at around US$ 3 billion per annum.

From a water management perspective, there is one aspect of the Stern Review that . First is the assumption of about natural capital – that all natural capital is 'substitutable' in economic terms. This assumption has been questioned by Neumayer (2007) and others, arguing that while the Stern Review's assumption of low discount rates may appear reasonable, the 'strong' sustainability case can be make 'critical' water resources and associated aquatic environments (Dubourg, 1998) which and are there land and water resources that cannot be substituted in economic terms. Second, assuming that discounting is appropriate, the level of the discount rates is significant since discounted cash flow analysis is essential to the standard cost-benefit analysis (FAO, 2005) made for determining the economic viability of water control infrastructure

2.3 Agricultural systems dependant on water management:

The basis for identifying agricultural systems at global scale is established from a combination of soil properties and climate, as expressed in the IIASA/FAO Global Agro-Ecological Zones (FAO/IIASA,2000; IIASA/FAO, 2001). The socio-economic character of these zones are further developed as a set of regional farming systems (FAO/World Bank, 2001). These two sets of analysis give broad system boundaries amenable to global analysis for most agricultural systems – but not all. For instance, inland fisheries and aquaculture is not identified explicitly as a 'farming system'. In addition, the irrigation layers developed in later GAEZ products (IIASA/FAO, 2007a: 2007b)) are consistent with the known equipped areas established in the Global Map of Irrigation Areas (FAO, 2007c) where equipped areas occupy more than 50% of any 5 arc-minute cell (approx. 10 km^2 at the equator).

2.3.1 Rain-fed Agriculture and Related Land Management

The extensive nature of rainfed and pastoral agriculture and its dominance in terms of land use is significant in terms of overall hydrological response. Runoff, soil moisture retention and energy balances over rainfed land determine overall river basin balances and the nature of land-atmosphere coupling. However, the partition between rainfed and irrigated production is sharp, even in sub-humid climates where remote sensing may allow accurate discrimination between the two. As soon as water is actively applied to the root zone, the whole agricultural equation changes. This distinction is important because at national level in countries with a mix, the relative proportion of irrigated and rainfed production may change every season in a lagged response to the volatility from rainfed production.

In geographic extent, rainfed systems offer the most scope for adaptation through improvement of extensive and low intensity investments in *in situ* water and soil conservation and management, such as for example conservation agriculture. These may require some special tools and knowledge to be put into practice and taken to scale in low income communities with high labour inputs. Equally, conservation agriculture can also be applied at commercial level with a high degree of mechanisation (Brazil). However, rainfed production does remain inherently risky. While *in situ* soil and water conservation may extend soil moisture storage, if it does not rain, the investment in seasonal inputs is lost. Either there is replenishment of soil moisture stores as a result of rainfall or there is not. Cultivation practices, including conservation agriculture, can enhance the infiltration of rainfall and delay the drainage of soil moisture in some soil types. Equally, groundwater replenishment is also only negotiable at the margin where aquifer systems are open to recharge. *In situ* 'rainwater harvesting' can induce local replenishment of soil moisture where slopes and soil textures permit, but beyond in-field cultivation practices, the adoption of large scale storage structures such as tanks or hafirs and their associated water control generally permit the establishment of irrigated production.

While wheat, maize, sorghum and millet production is determined by the annual response from rainfed systems only, rice is more generally associated with water control. The global balance between rainfed and irrigated production is shifting all the time as a function of rainfall variability and the local structure of the irrigated subsector and its capacity to adapt to changes in market demands.

2.3.2 Irrigated Agriculture

When the volatility of rainfed production becomes intolerable, irrigation has been the local solution. Will we see shift in centres of intensive production toward the water rich areas? High intensity investment, reliable if water management is good, and has demonstrated moderate returns and solid growth.

Irrigation is likely to remain a keystone of food security policies. Moving away from a food production system that provides 40% of the world's food from just 18% of the cultivated area, and is an important production system in Pakistan, much of China and much of India is unlikely. Almost half of the total area under irrigation in the world is located in these three countries and irrigation covers 80, 35 and 34 percent of the cultivated area in Pakistan, China and India respectively (http://www.fao.org/nr/water/aquastat/main/index.stm). The distribution of land equipped for irrigated production is given in Figure 2.8

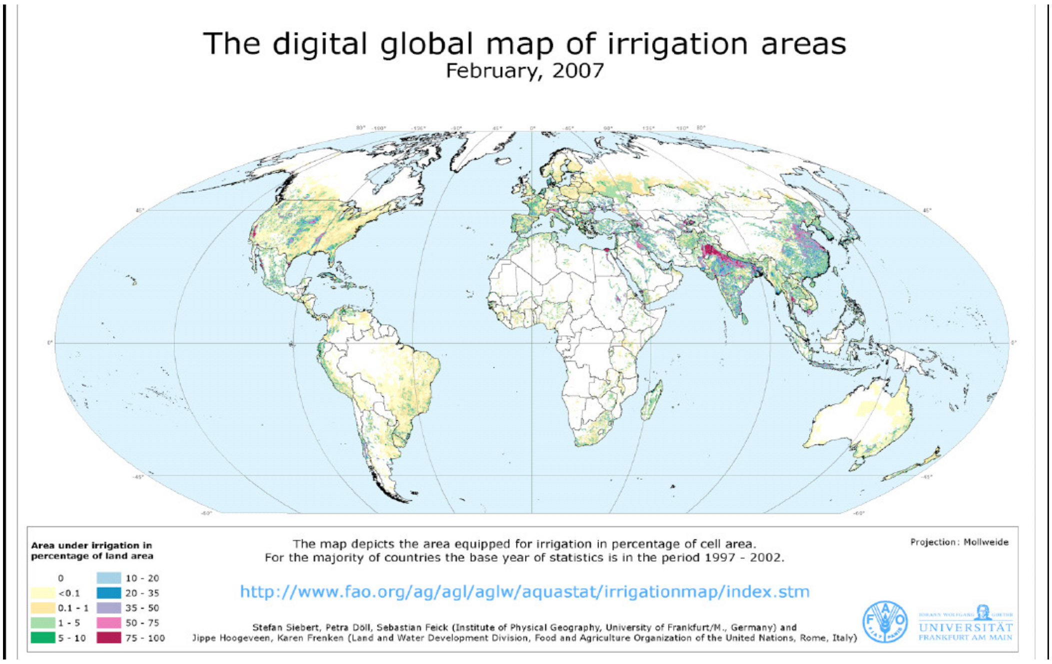


Figure 2.8 *FAO GMIA Version 4: HTTP://WWW.FAO.ORG/NR/WATER/AQUASTAT/IRRIGATIONMAP/INDEX.STM*

Both staples and high value crops are grown under irrigated conditions. It needs to be appreciated at the outset that as soon as irrigation is practiced, local energy and water balances are changed dramatically. Water control confers a very special micro-climate which can be sustained in sharp contrast to surrounding non-irrigated land. Irrespective of the performance of irrigation practice.

2.3.3 Inland fisheries and aquaculture

Fishing has historically been neglected in terms of the management of water resources, especially for agriculture, with losses of habitat in stream, and in floodplains and deltas due to upstream development for irrigation (CA, 2007). However, low contributions by inland fisheries to government income, under-reporting of catches and underestimation of participation in these fisheries result in a considerable monetary and social undervaluation of the sector in national economies in comparison with other sectors such as agriculture.

At the same time irrigation and associated water storages may provide new or alternative opportunities for both capture fisheries and agriculture. Irrigation supplies have long been used to manage water quality for high value prawn production in brackish, coastal conditions.

Therefore, it is useful to look briefly at the conclusions of the IPCC AR4 on fisheries. Fisheries will come under pressure from increased temperature stress and rising pH associated with global warming. The frequency of extreme droughts and floods will have a disproportionate effect on fish habitat and populations, and the incidence of diseases is expected to rise. This will result in species extinctions at the margins of their current habitats (for example salmon and sturgeon), and fish yields in places like Lake Tanganyika are expected to fall by around 30%. Effects anticipated in the Mekong include a significant change in the food chain, due to declining water quality, a changed pattern of vegetation and salt water intrusion in the lower delta.

In more broad terms, wetlands and their associated biodiversity are extremely valuable for sustaining rural livelihoods in many developing countries. Although farming tends to be the main occupation in these countries, the utilization of living aquatic resources is essential for adding proteins and minerals to a diet which is otherwise dominated by starches. In many developing countries, it is frequently the case that almost all households in rural areas around lakes, rivers and wetlands are involved in fishing on at least a seasonal basis. Although the products from inland fisheries mostly are for own consumption, or sold at the local or nearest urban market, significant numbers of people are employed in processing, distribution and marketing of the products. The end-result is an extremely high degree of participation in inland fisheries and a considerable degree of dependency on aquatic resources.

2.3.4 Livestock watering and fodder production

The global trend in animal protein consumption is accelerating as incomes grow. Pressure on rangeland and increasing demand for fodder will continue to intensify. It is the semi-arid rangelands that can be expected to see a cycle of natural resource degradation as increased aridity in key areas of southern Africa, Central Asia where rangeland quality, soil erosion and decreased recharge of local watering points and aquifers severely limit the extent of productive range. However, some upland areas exposed to higher monsoonal rainfall could see improvement if additional rainfall translates into longer growing seasons on upland ranges.

In other settings, such as the dairy industry in Gujarat, the production of fodder for zero grazing of milk cows involves a total dependence on groundwater pumping. Such ‘niche’ agricultural systems will be sensitive to reduced recharge.

2.3.5 Forested Land

Globally, land covered by forests accounts for almost 30 percent of the total area, going from over 90 percent in very humid countries to more or less 0 percent in very arid countries (FAOSTAT, 2008). The conservation and management of forest land does have significant impact on water demand through global evapotranspiration demand and consequently, flow regulation. The significance of forest management at basin level has been established (Calder, 2004, Hofer and Messerli, 2006). In terms of river basin water balances, afforestation in certain basins is now recognised as significant water user.

2.4 Economic competition for bulk water supplies

Inter-sectoral competition for water under conditions of scarcity is a daily reality. If climate change scenarios play out as anticipated by the IPCC 4th Assessment, the economic analysis of climate change impacts will hinge upon transparent methods water resource valuation to determine allocation. Even as trends in productive irrigation and supply into more sophisticated markets gather pace, will the agriculture sector as a whole remain a residual user – just getting what is left over? While there may be political pressure to subsidise the rural space, stabilize rural populations and deepen the rural economy, the dominance of urban demands in relation to rural development in many cities throughout the region are all too apparent.

In the absence of substantial claims for water from other sectors, and with little understanding about environmental impacts, irrigated agriculture has been able to capture large volumes of freshwater. Today, agriculture represents 69 percent of all water withdrawal in the world, and this percentage rises above 90 percent in some arid countries, in countries where irrigation is very important or in countries where other water withdrawal sectors such as municipalities or industries are less developed. As such, agriculture has acted as a residual user of freshwater. The situation is changing as population increases and more and more countries face water shortages. By 2030, over 60 percent of the population will live in urban areas, claiming an increasing share of water abstraction.

Appropriations of water from ecosystems have intensified with human population growth, the expansion of agriculture and increasing pressure to transfer water from rural to urban areas, to the point where agriculture is often seen as jeopardizing ecosystem sustainability. But it is equally important to underline the fact that such threatened ecosystems can no longer provide their water purifying and regulating services to sustain agricultural production and livelihoods. There is an urgent need, therefore, to reconcile water demands for maintaining ecosystem functions and for producing food. Finding this balance is particularly important in developing countries, where agriculture and the natural environment are often the principle potential "growth engines", and the key to alleviating poverty and reducing hunger.

Of all freshwater use sectors, agriculture in most cases shows the lowest return on water in economic terms. As the stress on water resources increases, competition grows between agriculture fighting to retain its water allocations and cities and industries needing to satisfy the needs of their rapidly growing populations. Water stress and the pressing need to renegotiate inter-sectoral allocations are usually factors that force changes in the way water is managed in agriculture. Declining water quality adds to the stress on supply. In developing countries, water diverted to cities is often released after use without adequate treatment. In arid areas, return flow from agriculture itself and multiple reuses of water lead to a rapid degradation in quality. It should therefore be clear that management of water in agriculture is multifunctional - it goes beyond commodity production and addresses a broad spectrum of social, economic and environmental services.

The scope and need exist therefore for rapid increase in water productivity in agriculture. Carefully designed water management strategies, associated with programs aiming at improving the efficiency and productivity of water use need to be put in place. Pressurized irrigation conveyance systems, associated with localized irrigation technologies and the promotion of high return agricultural produces should be part of such strategy. Systematic collection, treatment and re-use of urban wastewater for agricultural production, associated with the development of enhanced monitoring, health protection and education programs for wastewater reuse in agriculture offer new opportunities for irrigation in conditions of water scarcity.

In determining allocations, whether by market or administrative instruments, it is essential to understand the structure of the individual engagement with the water resource base (water use customs and statutes). The individual's interest in making sustained use of scarce water resources depends on the clarity and stability of this engagement. Valuation of water allows farmers and legislators alike to make informed choices in a future that is likely to experience more variability and more competition.

2.5 The issue of time and agricultural transition

Climate change concerns long term trends for which adaptation strategies are required. Weather, on the other hand is concerned with high frequency events, that if extreme enough, call for immediate risk management measures. As far as agricultural water management is concerned, these events comprise droughts and floods (which sometimes, as in the case of tropical storms/typhoons are associated with strong winds that also threaten growing crops). Where agricultural production depends on water management, many agricultural economies have learned both to manage the risks associated with extreme events, and/or to adapt their production systems to take advantage of them.

In recent decades, the advent of more sophisticated water development and management - access to deeper groundwater with mechanised boreholes for instance - has initiated and deepened a trend toward more precise water management and control, which in turn has tended to raise agricultural productivity overall. However, the time over which these adjustments are made is critical. Some areas have been transformed within a generation or less through the adoption of new technology. This rate of change begs many questions about the significance of the IPCC projections in relation to agriculture because by the time that the projections have been validated the pattern and style of agriculture may have changed anyway. Hence the adaptation in agricultural water management is of prime importance while mitigation measures are only likely to be introduced as an auxiliary, event driven measure tied to adaptive processes.

As Fischer et al (2007) conclude;

"In summary, our simulation results suggest the following. First, globally the impacts of climate change on increasing irrigation water requirements could be nearly as large as the changes projected from socio-economic development in this century. Second, the effects of mitigation on irrigation water requirements can be significant in the coming decades, with large overall water savings, both globally and regionally. Third, however, some regions may be negatively affected by mitigation actions (i.e., become worse-off than under non-mitigated climate change) in the early decades, depending on specific combinations of CO2 changes that affect crop water requirements and GCM-predicted precipitation and temperature changes."

What could be emphasized is that while there will be some agricultural systems that will be able to adapt in an incremental fashion, it could be that a higher frequency of large amplitude events will have more impact in driving adaptation.

In any event, the time horizon over which climate change impacts are modelled tend to be longer than current agricultural projections. For instance, the Fischer et al. study cited above performed simulations from 1990 to 2080. However FAO will only be updating the AT2015/2030 work to 2050 on the assumption that a firm baseline can be established at 2004. Therefore assessment of climate change impacts in relation to agricultural systems and agricultural practice is conditioned by trend analysis within agriculture. This is important in relation to investment decisions for large scale infrastructure in particular. While some large dams may be discounted over 50 years, very few programmatic investment decisions in agriculture look beyond 25 years.

3 THE BASELINE AND TRENDS IN AGRICULTURAL WATER MANAGEMENT

3.1 Global agricultural projections to 2030 and the associated demand for water

3.1.1 Global analysis

The 'baseline' is taken here to mean the state of management plus the currently planned activities in developing institutions and formulating investments i.e. things that countries would be doing irrespective of any consideration or 'internalization' of the IPCC 4th Assessment (AR4).

Current and projected trends in the demand for food and agricultural production as a whole are given for 93 developing countries in FAO's World Agriculture; towards 2015/2030 (FAO, 2003) on the basis of the UN Statistics Division medium population projection and the World Bank's income growth projections. The pattern of this demand is analysed at country level and summarised at regional level in the report to give a global picture based on the analysis of national supply-utilization accounts (SUAs).

From a 1998 baseline, when the total rainfed and irrigated areas were 549.812 million ha and 242.182 million ha respectively, by 2030 these are expected to become 698.743 million ha for rainfed, an expansion of some 27% and 322.670 million ha for irrigation, an expansion of 33%.

The demands for potable water and food are essentially non-negotiable. Minimum potable water and calorie requirements have to be met in order to avoid death and consumption beyond minimum requirements is generally not rationed. The demand for water allocations into agriculture are driven strictly by the preference to control water and irrigate. Rain-fed agriculture does not, by definition, generate demand over and above the evapotranspiration requirements of climax vegetation in a particular agro-ecological zone. Crop selection may influence marginal variation in evapotranspiration, but generally it is only significant land-use change such as afforestation or urbanization that will influence overall hydrological balances.

Climatic variability does affect the local demand for water to grow crops or the performance of cropping systems. For example, in the absence of assured surface water supplies, groundwater sources may be used to supplement irrigation requirements. But equally, high rainfall intensities and flooding frequently damage crops. To this extent periods of unforeseen drought or extreme rainfall events do affect the supply of produce into local agricultural markets. When aggregated, the net impact of such climatic variability has generally been accommodated by supply through drawdown of stocks and subsequent adjustment of production. The result has been a trend in falling commodity prices from the late 70's to the early 21st century. The recent recovery in global commodity prices initiated in 2002 as demand from developing countries, notably China, accelerated has also seen a reduction in carry-over stocks as just-in-time delivery became viable (FAO 2006 - SOCO). When taken with some water related supply shocks from major exporting countries (such as Australia in 2007), the condition of global commodity markets has now become much more sensitive (FAO, 2007 – Food Outlook). Hence if prices of agricultural staples such as rice, wheat maize and sugar remain high, which agricultural systems will exhibit elasticity of supply under conditions of more variable supply?

3.1.2 Regional analysis

The growth in arable land equipped for irrigation is projected to 2015 and 2030 (FAO, 2030) and summarised in Table 4.9 of the main AT2015/2030 report (Box 3.1)

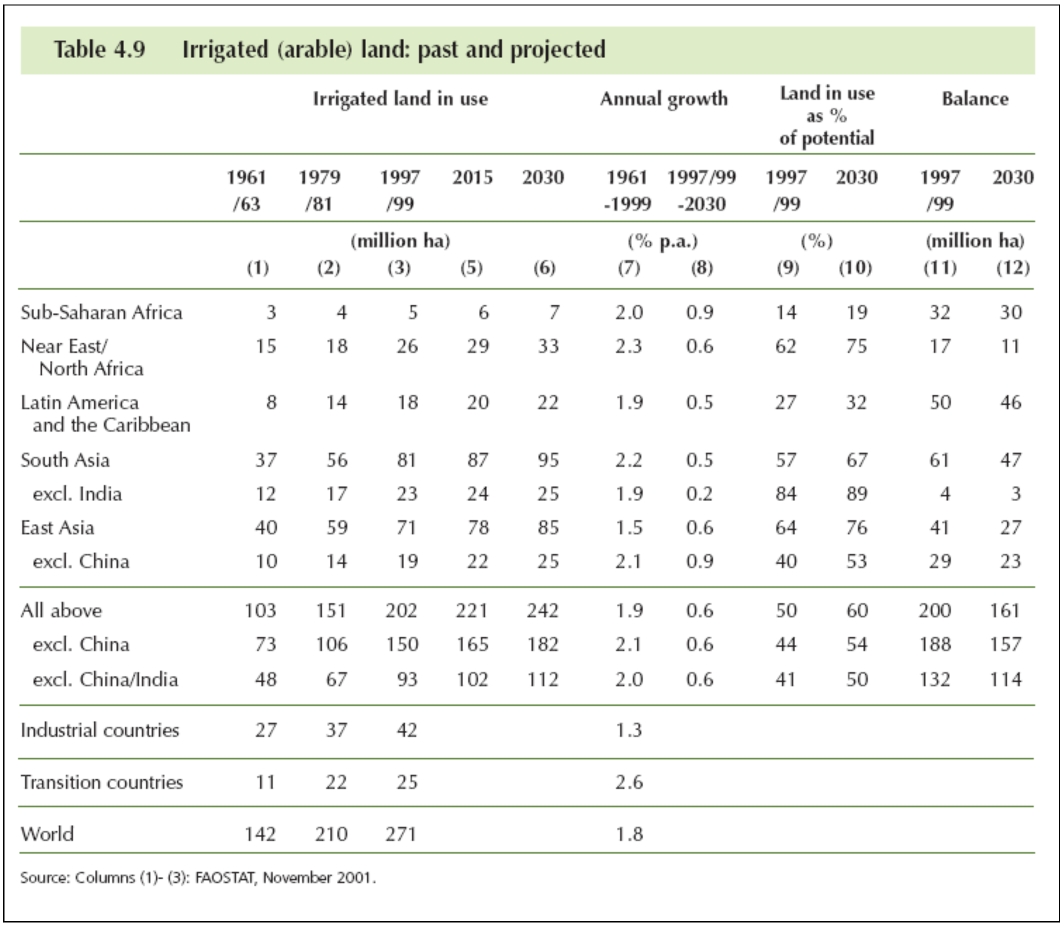


Table 4.9 Irrigated (arable) land: past and projected

	Irrigated land in use					Annual growth		Land in use as % of potential		Balance	
	1961 /63	1979 /81	1997 /99	2015	2030	1961 -1999	1997/99 -2030	1997 /99	2030	1997 /99	2030
	(million ha)					(% p.a.)		(%)		(million ha)	
	(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Sub-Saharan Africa	3	4	5	6	7	2.0	0.9	14	19	32	30
Near East/ North Africa	15	18	26	29	33	2.3	0.6	62	75	17	11
Latin America and the Caribbean	8	14	18	20	22	1.9	0.5	27	32	50	46
South Asia	37	56	81	87	95	2.2	0.5	57	67	61	47
excl. India	12	17	23	24	25	1.9	0.2	84	89	4	3
East Asia	40	59	71	78	85	1.5	0.6	64	76	41	27
excl. China	10	14	19	22	25	2.1	0.9	40	53	29	23
All above	103	151	202	221	242	1.9	0.6	50	60	200	161
excl. China	73	106	150	165	182	2.1	0.6	44	54	188	157
excl. China/India	48	67	93	102	112	2.0	0.6	41	50	132	114
Industrial countries	27	37	42			1.3					
Transition countries	11	22	25			2.6					
World	142	210	271			1.8					

Source: Columns (1)- (3): FAOSTAT, November 2001.

Box 3.1 Extract from AT2015/30

The current projected set of freshwater allocations to irrigated agriculture in the 93 developing countries are summarised Table 4.10 of AT2030 (Box 3.2)

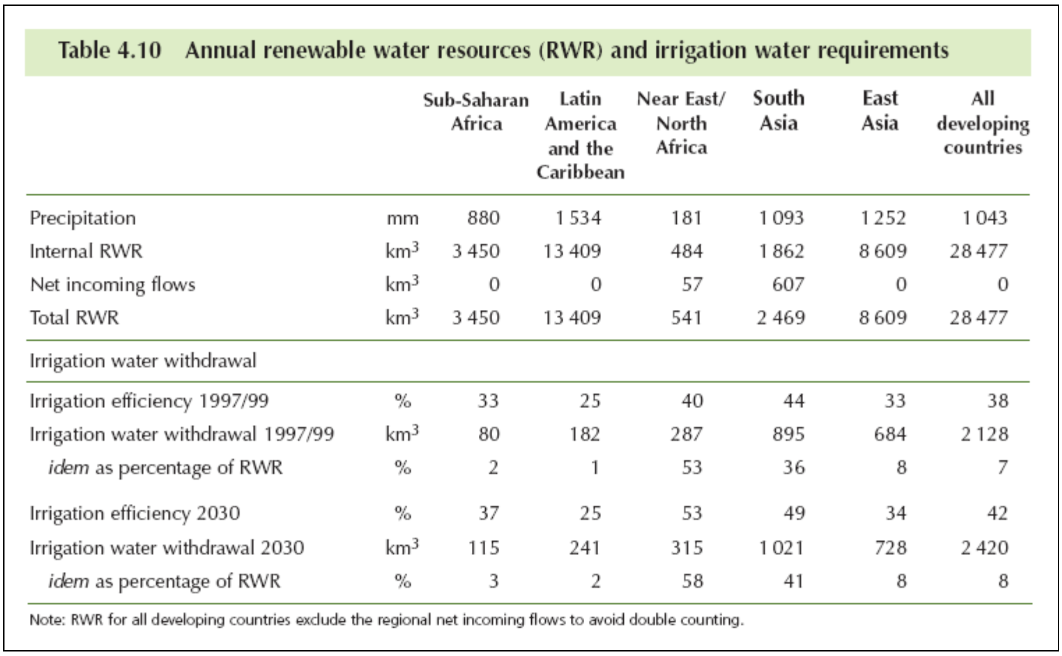


Table 4.10 Annual renewable water resources (RWR) and irrigation water requirements

		Sub-Saharan Africa	Latin America and the Caribbean	Near East/ North Africa	South Asia	East Asia	All developing countries
Precipitation	mm	880	1 534	181	1 093	1 252	1 043
Internal RWR	km³	3 450	13 409	484	1 862	8 609	28 477
Net incoming flows	km³	0	0	57	607	0	0
Total RWR	km³	3 450	13 409	541	2 469	8 609	28 477
Irrigation water withdrawal							
Irrigation efficiency 1997/99	%	33	25	40	44	33	38
Irrigation water withdrawal 1997/99	km³	80	182	287	895	684	2 128
idem as percentage of RWR	%	2	1	53	36	8	7
Irrigation efficiency 2030	%	37	25	53	49	34	42
Irrigation water withdrawal 2030	km³	115	241	315	1 021	728	2 420
idem as percentage of RWR	%	3	2	58	41	8	8

Note: RWR for all developing countries exclude the regional net incoming flows to avoid double counting.

Box 3.2 Extract from AT2015/30

As a general observation, any country withdrawing more that 40 % of its renewable water resources has agricultural growth impacted by physical scarcity of water. But the underlying assumptions in global projections of food production in this study and ohters (CA, 2007, Rosegrant et al, 2002; 2001) include the expectation of further gains in land and water productivity, in response to increasing scarcity and competition for water. The current rationale for this stems largely from the fact that land and water productivities are considerably lower than attainable levels (Type II yield gaps).

The overall impact of the agricultural demand for water has been immediately obvious. There has been widespread development of existing water resources in many basins, such as the Yellow River in China and the Peninsular Rivers in Southern India, mostly for irrigation and with an attendant economic and environmental impacts. The current debate the Murray Darling basin in Australia can be seen as an exemplary warning for many other stressed basins under which agriculture becomes progressively marginalised.

Less visible have been the impacts of agricultural practice on water quality degradation, particularly in shallow aquifers where accumulation of inorganic waste, such as nitrates, and pesticides will compromise future use.

More recent agricultural projections (to 2050) Thus the new Near East and North Africa forecasts for 2050 given in (FAO/NERC, 2008) are given in Tables 3.1 and 3.2 below

		Rainfed land			Irrigated land			Total land		
		Area	Yield	Prod.	Area	Yield	Prod.	Area	Yield	Prod.
		mln ha	mt / ha	mln mt	mln ha	mt / ha	mln mt	mln ha	mt / ha	mln mt
Cereals (incl. rice paddy)	2003/05	24.6	0.96	23.6	10.6	4.64	49.0	35.2	2.06	72.6
	2030	27.9	1.09	30.4	14.7	5.13	75.4	42.6	2.48	105.8
	2050	30.0	1.23	36.9	17.1	5.51	94.4	47.1	2.79	131.3
Oil crops	2003/05	5.0	0.66	3.3	1.0	2.01	2.0	6.0	0.89	5.3
	2030	7.9	0.81	6.4	1.7	2.75	4.7	9.7	1.16	11.2
	2050	9.5	0.98	9.3	2.1	3.08	6.5	11.6	1.36	15.8
Vegetables, citrus and fruits	2003/05	0.8	8.31	6.9	4.6	18.37	83.6	5.4	16.83	90.5
	2030	1.2	9.41	11.2	6.7	19.87	132.5	7.9	18.25	143.7
	2050	1.4	10.82	15.2	7.4	22.03	163.7	8.9	20.18	178.9
Pulses	2003/05	1.3	0.65	0.9	1.1	1.60	1.7	2.4	1.07	2.6
	2030	1.4	0.89	1.3	1.1	2.13	2.4	2.6	1.43	3.7
	2050	1.6	0.97	1.6	1.2	2.36	2.9	2.8	1.58	4.5
Total harvested land	2003/05	33.8			22.4			56.2		
	2030	40.6			30.3			70.8		
	2050	44.7			34.3			79.0		
Cropping intensity (%)	2003/05	65			99			75		
	2030	77			117			90		
	2050	84			120			96		
Arable land	2003/05	51.9			22.5			74.5		
	2030	52.6			25.8			78.7		
	2050	53.4			28.6			82.6		
Potential land		152			35			171**		
idem excl. Sudan		59			33			77**		
Arable land as % of potential	2003/05	34			64			43		
	2030	35			73			46		
	2050	35			81			48		

* including ‘old’ data and projections for Iraq.

** total potential land is not equal to the sum of rainfed and irrigable potential land since part of the latter is on rainfed land

Source: FAO: FAOSTAT; AT2050

Due to limitations of available or reliable data, this study covers only 14 countries of the Near East Region (plus Iraq, when data was available):

Table 3.1. Crop production and land use in the Near East Region*

		North East Africa	West Asia	North Africa	Arabian Peninsula	Total Region
		Water availability				
Precipitation	mm	308	225	102	78	177
Internal RWR	km3	37.8	176.2	48.1	6.5	268.5
Net incoming flows	km3	108.7	28.3	11	0	148
Total RWR	km3	146.5	204.5	59.1	6.5	416.5
		Irrigation water withdrawal				
2003/05						
Water requirement ratio	%	57	48	55	50	52
Irrigation water withdrawal	km3	98.4	126.2	22.2	21.7	268.5
idem as percent of RWR	%	67	62	38	334	64
2030						
Water requirement ratio	%	62	57	60	58	59
Irrigation water withdrawal	km3	125.1	160.1	29.1	21.5	338.6
idem as percent of RWR	%	85	78	49	331	81
2050						
Water requirement ratio	%	69	65	64	64	66
Irrigation water withdrawal	km3	130.2	164.7	30.1	21.7	346.2
idem as percent of RWR	%	89	81	51	334	83
2050 with climate change*						
Precipitation	mm	330	221	92	78	179
Total RWR	km3	147.5	195.7	47.5	6.6	397.3
Water requirement ratio	%	71	67	64	65	68
Irrigation water withdrawal	km3	137.5	174.1	33.8	22.6	365.8
idem as percent of RWR	%	93	89	71	343	92

*Under the assumptions of the International Panel for Climate Change (IPCC) Special Report on Emissions Scenarios, Scenario "SRES B2"

Note: The water requirement ratio is defined as the ratio between irrigation water requirements for optimal crop growth and water withdrawn for irrigation.

Sources: FAO: FAOSTAT; AT2050; for IPPC assumptions: IPCC (2000), "Special report on emissions scenarios – Summary for Policymakers", WMO and UNEP.

Countries:

North Africa: Algeria, Libya, Mauritania, Morocco, Tunisia;
West Asia: Iran, Iraq, Jordan, Lebanon, Syria;
North East Africa: Egypt, Somalia, Sudan;
Arabian Peninsula: Saudi Arabia, Yemen.

Table 3.2. Annual renewable water resources (RWR) and irrigation water requirements Updated estimates for Near East and North Africa. (FAO, 2007)

Elsewhere, however, the AT 2015/2030 projections may underestimate the shift to irrigation and subsequent expansion of areas equipped for irrigation. A systematic update of the 1997/99 baseline is long overdue.

3.2 The impacts of current management

The results of continued growth in water allocations to agriculture are evident across many river basins that are, or have been, key centres of agricultural production. Historic water allocations in the Murray Darling Basin cannot be honoured, making it impossible to reconcile supply and demand during the recent drought conditions. Similarly, the Aral Basin saw massively reduced inflows to the Aral Sea as a result of cotton irrigation upstream. Vietnam already has difficulty in meeting its Mekong Basin commitments due to the effective closure of the Srepok sub-basin (Riddell 2000), while elsewhere in the same country, over or inflexible allocation of water in the economically crucial Dong Nai is constraining economic growth and paradoxically increasing flood damage. In this examples, the water allocations have largely concerned cash crops, specifically cotton (in the Aral and Murray Darling Basins) and coffee or sugarcane in Vietnam.

But basins are also becoming stressed as a result of water allocation for subsistence agriculture or large scale cereal production. The Rufiji and Pangani Basins in Tanzania for instance are managed at their limit. Hydropower generation and pollution control are compromised and systemic integrity threatened. Were the Rufiji Delta to dry up, it is suggested that the marine fisheries between Mogadishu and Durban would fail because of breakdown of the vital relationship between river flooding and turbidity cycles and marine food chains/spawning processes that begin in delta regions. (Hirji and Patorni, 1994). Equally, the coastal (prawn) fisheries in Mozambique and Eastern South Africa have are already suffering because the small coastal basins are drying out, largely due to the withdrawals for cooling water and irrigated sugar cane (Maputo basin) and the impacts of rainfed sugar cane production in Natal Province.

This even without the prospect of climate change impacting water supply and evaporative demand, current agricultural water management is required to do much more than improve water use efficiencies. Workable water allocation mechanisms to reallocate saved or recycled water and allocation mechanisms that protect rights in use and are environmentally responsible are still required. Irrespective of progress toward Type II yield gap closure through in-field crop management, surveys of large irrigation systems indicate that overall hydraulic efficiencies are still low (FAO, 2007b)

3.3 Emerging trends in the agricultural water management

The key trends identified prior to the IPCC AR4 can be summarised;

1. Major emerging issue of water allocation – stressed basins and strong political imperatives to continue water development, even after full allocation – India, Northern China, Pakistan.

2. Highly productive delta systems under pressure from upstream flow variability, dense population pressure, sea level rise and saline intrusion.

3. Calls for productive environmental services (aquaculture, biodiversity) to be maintained.

4. Declining public investment in irrigation – major private investment in groundwater.

5. Transition from construction to management emphasis should be underway – but not really happening

6. Declining real commodity prices to 2007. Current reversal of trends

7. Declining rates of increase of staple crops in developing countries. Attainment of yield close to potential in OECD countries – with now widespread achievement – (I am not sure if this is correct, but I was told that more than 70% of European grain farmers now achieve around 10t/ha, compared 10% 20 years ago.)

8. Continuing poor technical performance of surface irrigation systems in Asia – with equity, water use efficiency, salinisation, and degradation of capital works being a major issue.

9. Minimal cost recovery in public systems and widespread maintenance of subsidies.

10. Resurfacing of interest in improving rainfed agriculture and in trying to establish better soil moisture conservation through a whole range of different techniques – predicated on 1) equity in poverty alleviation and 2) significant potential to increase production – but in practice constrained by capital availability, poor design and construction and continuing risk averse behaviour by farmers.

11. Irrigation still mainly supports the production of low value staples. There have been some remarkable diversifications – for example the rapid and massive expansion of horticulture in China since 1990 and the development of floriculture in east Africa. However the distributional impacts are limited

3.4 Agricultural water management in transition: analysis of economic drivers

The instrumental value of water in all productive economic sectors requires consideration of impacts and trade-offs beyond the agricultural sector and consequently this discussion paper does not limit itself to an analysis of agricultural production in isolation. Recent reports, such as FAO's Agriculture Towards 2015/2030 (FAO, 2003) and the update to 2050 (FAO, 2007) together with the Comprehensive Assessment of Water Management for Agriculture (CA, 2007) have concentrated on what have been perceived to be the main trends and drivers in agricultural water management, including trade projections, and broader pathways of economic development on the assumptions that the patterns of water supply will vary about the mean.

Within the limits of the physical environment, crop production patterns largely are determined by the economic demand for quantity and quality of agricultural produce broadly conditioned by agro-ecological zoning. Therefore, it is projected that in the short run (5 to 15 years) agricultural subsidies and trade policies likely will have a greater influence on crop production patterns than climate change. Irrigation is still used as a system of political patronage and may be politically important in maintaining rural employment and national food security (particularly with urbanizing populations) even if it is not performing in response to market signals, In the longer term, climate change and its large uncertainties pose potentially serious threats to agricultural water management, hitting hardest in poor, semi-arid areas that already suffer from water variability.

The Comprehensive Assessment (CA, 2007) contains a chapter on irrigation and investment in the sector (Faures et al, 2007). The following section provides a summary of the main points made in this chapter and two subsequent papers (Faures et al 2007; Turral et al 2007), and it is pertinent to comment that this material did not fully incorporate the additional stresses and challenge of climate change. The writings also propose a typology of irrigation and investment which is summarised in table 3. 3

Group	Scale and context	Economic status of agriculture % GDP		
		>40%	20-40%	<20%
1	Large-scale public irrigation systems in dry areas, growing mostly staple crops.			
2	Large-scale public paddy irrigation systems in humid areas.			
3	Small- to medium-scale community-managed (and -built) systems.			
4	Commercial privately managed systems, producing for local and export markets.			
5	Farm-scale individually managed systems, producing for local markets, often around cities.			

Table 3.3 Typology of irrigation contexts and conditions for investment .

This typology is bounded by what are considered to be the main drivers of irrigation development and investment –economic dependence on agriculture, management and sustainability and the major management considerations related to public and private ownership, water source and scale.

3.5 Anticipated trends in agricultural water management

1. The conditions that led to large public investment in irrigation in the second half of the 20th century have changed radically, and today’s circumstances demand substantial shifts in irrigation strategies. Irrigation has ensured an adequate global food supply and raised millions out of poverty, especially in Asia, thanks to massive investments. But a stable world food supply, declining population growth rates, continuing declines in the real price of food, and the rising importance of investment in other sectors diminish the need to maintain similar levels of irrigation investment today. The era of rapid expansion of public irrigation infrastructure is over.

2. For many developing countries investment in irrigation will continue to represent a substantial share of investment in agriculture, but the pattern of investment will change substantially from previous decades. New investment will focus much more on enhancing the productivity of existing systems through upgrading infrastructure and reforming management processes. Irrigation will need to adapt to serve an increasingly productive agriculture, and investments will be needed to adapt yesterday’s systems to tomorrow’s needs. Substantial productivity gains are possible across the spectrum of irrigated agriculture through modernization and better responses to market demand. These gains will be driven by the market and financial incentives that will lead to higher farm incomes.

3. Large surface irrigation systems will need to incorporate improvements in water control and delivery, automation and measurement, and training staff and water users to better respond to farmers’ needs. Conjunctive use of canal water and groundwater will remain an attractive option to enhance flexibility and reliability in water service provision. Under pressure from other sectors, irrigation will find it increasingly hard to secure public finance for irrigation and drainage infrastructure. This situation will increase the financial burden on local government and users. And it is likely to have profound outcomes on the irrigation sector. Cost-recovery mechanisms that guarantee the sustainability of systems

will become imperative. At the same time, private investment in irrigation will likely grow in response to new opportunities for agricultural production.

4. Irrigation and drainage will still expand on new land, but at a much slower pace. They should be more site-specific and much more closely linked with policies and plans in agriculture and other sectors. Irrigation will remain critical in supplying cheap, high quality food, and its share of world food production will rise to more than 45% by 2030, from 40% today. More farmers around the world will increasingly integrate into a global market, which will dictate their choices and behaviour. New market opportunities will emerge where suitable national policies, infrastructure, and institutions are in place. Countries will need to tailor irrigation investment more closely to the stage of national development, degree of integration into the world economy, availability of land and water resources, share of agriculture in the national economy, and comparative advantage in local, regional, and world markets.

5. In regions that rely heavily on agriculture, irrigation is likely to remain important in rural poverty reduction strategies. But irrigation’s contribution to poverty reduction remains contentious, with some experts arguing that there are more effective ways to address rural poverty. In these regions increasing productivity in agriculture is often the only way out of poverty, and new irrigation development can be a springboard for economic development. The type and scale of intervention will vary considerably from one region to another. In Sub-Saharan Africa investment in both rainfed and irrigated agriculture—combined with programmes to improve soil fertility, better access to inputs, information and markets, and strengthen local institutions—is the best option to enhance food security and reduce people’s vulnerability to external shocks and climate variability. Public investment in bulk infrastructure will be required to support private initiatives, especially those in small-scale irrigation.

6. The changing demand for agricultural products and the increasing understanding of possible impacts of climate change on agriculture and the water cycle will also influence future investment in irrigation and water control. Rapidly rising incomes and urbanization in many developing countries are shifting demand from staples to fruits or vegetables, which typically require irrigation technologies that improve reliability, raise yields, and improve product quality. But as the century unfolds, weather events will become more variable—extreme events will increase, rainfall distribution will change, and glaciers and mountain snow packs will shrink. Investment will be required to respond to these changes; especially where average precipitation declines and shrinking glacial and snow pack storage reduces summer streamflows. Adaptation strategies will generally require more storage capacity and new operating rules for reservoirs, posing onerous tradeoffs between allocations for environmental and agricultural water.

7. As competition for water from other sectors intensifies, irrigation will increasingly be under pressure to release water for higher value uses. Increased water scarcity will be an incentive for irrigation to perform better. The number of regions where water availability limits food production is on the rise, and inter-sectoral competition for water will increase almost universally with urbanization and economic development. Environmental water allocations will steadily increase and present a much greater challenge to irrigation than will cities and industries, because the volumes at stake are likely to be larger. Transfers of water from irrigation to higher value uses will occur and require oversight to ensure that they are transparent and equitable. Water measurement, assessment, and accounting will likely gain in importance, and water rights will need to be formalized, especially to protect the interests of marginal and traditional water users. The use of water pricing as an economic tool for demand management remains low and is

not a workable option in the prevailing economic conditions for most irrigation schemes.

8. Irrigation and drainage performance will increasingly be assessed against the full range of their benefits and costs, not only against commodity production. The overall performance of irrigation has been acceptable, as judged by the current stability in world food supply and continually declining real prices for food. But this global gain has come at considerable financial cost, and in many cases irrigation systems have failed to meet their performance targets. Some have failed completely. The success of irrigation has also often come at the environment's expense, degrading ecosystems and reducing water supplies to wetlands. It has also had mixed impacts on human health. Better nutrition and improved water availability for domestic needs have improved hygiene and reduced infections and diseases. But irrigation is also associated with higher incidence of malaria, schistosomiasis, and other waterborne diseases.

9. Decentralized and more transparent governance will be important in irrigation and drainage water management, and the role of governments will change. The recent trend to devolve the responsibility for irrigation management and the associated costs to local institutions, with more direct involvement of farmers, is likely to intensify. The many possible outcomes will range from full farmer ownership and operation, to contracted professional management, to joint management by government and farmers. As governments withdraw from direct managerial functions they will need to develop compensating regulatory capacities to oversee service provision and protect public interests. While control of system infrastructure will likely be devolved, bulk water supply infrastructure, because of its multiple functions and strategic value, will usually remain in the hands of the state."

4 SPECIFIC CLIMATE CHANGE IMPACTS RELATED TO AGRICULTURAL WATER MANAGEMENT

4.1 Introduction

Agricultural trend analyses prior to AR4 have arguably under-estimated the potential additional impacts of climate change in their projections (FAO, 2003). Equally, attempts to explain from the perspective of the SRES alone (Parry, Rozenzweig and Livermore, 2005; Fischer et al 2005) have had their own methodological limitations in dealing with complexity of farming systems. While the modelling in relation to irrigation water requirements is becoming more specific and robust, as Fischer et al. (2007) acknowledge, the body of work is still small when compared to that dedicated to analysis of global crop production.

It should also be made clear that the emission ' scenarios' used by the IPCC to drive crop modelling are very distinct from the non-replicable expert projections made for the FAO agricultural trends analysis (FAO, 2003; FAO, 2007).

However, as indicated in Chapter 3, patterns of production are currently confused by the actual impact of price signals on agricultural production (including biofuels) indicating the ability for rapid and sudden change in production patterns, and the knock-on effects on the whole sector. Obtaining an accurate partition between rainfed and irrigated production will remain a continual challenge.

At the outset, it should be emphasised that climate change impacts are additional ' stressors' or 'relaxors' to a set of economic factors driving agricultural demand for water. Hence the degree to which climate change will impact agricultural systems already subject to climate variability is a matter of second order differentiation. It could be that purely in terms of water availability and global food supply, further climatic stress on water short river basins will be offset by higher rainfall in temperate zones. Or, it could be that more frequent, higher intensity rainfall events over temperate cereal production regions result in widespread crop damage worsening the supply shock from water scarcity. Therefore a key question to ask at the beginning of any analysis is whether the IPCC 4th Assessment GCMs and RCMs of sufficient precision to consistently drive national supply and utilization accounts?

Rainfall projections from the IPCC models are the most critical and the current application of rainfall models in the IPCC ensemble runs is inherently limited to the extent that monthly rainfall amounts are uniformly distributed across the days of the month. This time averaging approach could therefore smooth rainfall input to such an extent that the terms in daily water balances at any particular point could misrepresent actual runoff events, replenishment of soil moisture and groundwater recharge – particularly in the more vulnerable 'flashy' hydrological systems.

While the IPCC AR4 view of climate change introduces a much broader range of uncertainty about the availability of water in the future (but with a clear alarm bells ringing for the already vulnerable semi-arid tropical zones), the aggregate balance of positive and negative impacts may cancel out in terms of global food supply if rainfed production from higher latitudes is boosted by higher rainfall.

In the end an analysis of agriculture water management sensitivity to climate change only makes sense within a systemic context – the river basin and related aquifers. For this reason, this section concentrates on the impacts across hydrological units which could eventually be categorised and a proposal is made for such a typology. Despite the fact that national policies and strategies to adapt to and mitigate the impacts climate change will be framed at national level, largely in response to macro-economic analysis, such a systemic approach will remain valid. Aggregate national production in semi-arid countries such as Morocco and Yemen, is a function of the hydraulic management of individual river basin and aquifer systems. Further, many of the larger basins and aquifers that are key to agricultural productivity such as the Aral Sea basin, Indus, Nile and Mekong are transboundary. It is the overall systemic costs and benefits resulting from changed hydrological regimes that have to be appraised.

4.2 Principal climate change drivers in agriculture

Five main climate change-related drivers will affect the agriculture sector in ways that will vary in intensity and importance across the regions. They are: temperature rise; precipitation patterns including rainfall and snow; the incidence of extreme events (floods and droughts); sea level rise; and the atmospheric carbon dioxide content. Impact pathways are summarised in Figure 4.1

There are clear differences in the statistical variability of climate and hydrology between continents (Peel et al., 2001), which are as yet not well modelled by GCMs. Although there is at yet only a 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 (Changes in diurnal fluctuation is as important as overall trends) constrains crop development;
- Reduced availability of water in regions affected by reduction in the total amount of precipitations (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 where 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;
- Generally increased evaporative demand from crops as a result of higher temperature.

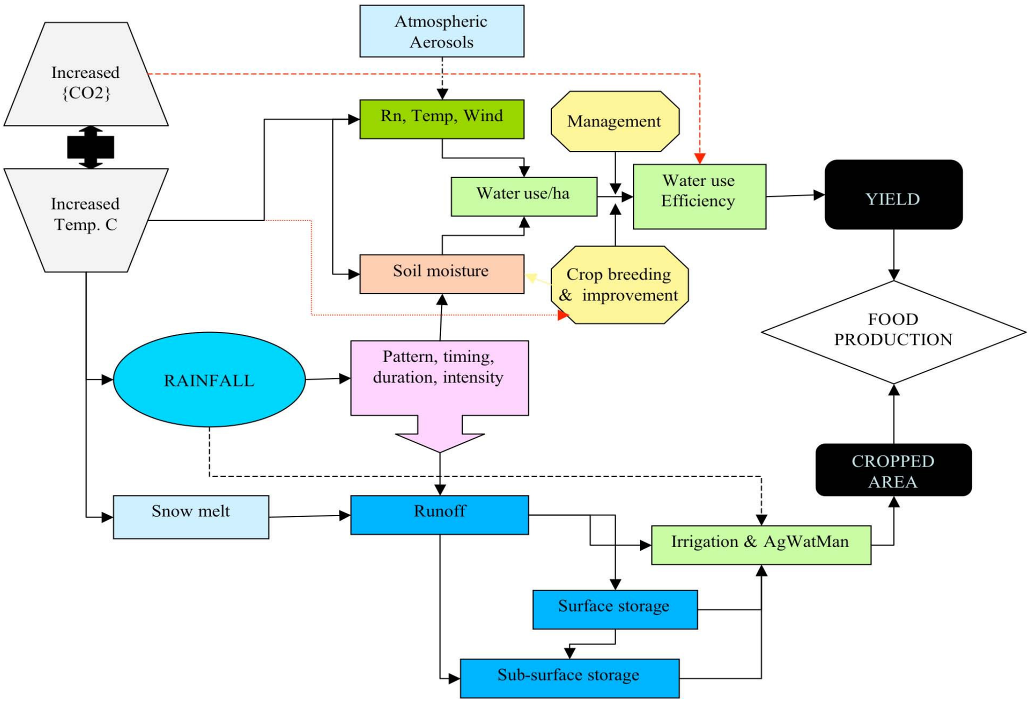


Figure 4.1 Impact Pathways

4.3 Overall impacts on crop production

In brief summary, at high latitudes crop yields are expected to rise with temperature increases of 1-3°C, but fall, due to declining crop health, once 3°C is exceeded. At lower latitudes, crop yields are expected to decline with temperature rises as little as 1-2°C. Overall, the benefits of carbon dioxide enrichment on photosynthesis are expected to be outweighed by increased temperature and lower rainfall. It is expected that agriculture (without any further adaptation), especially in the dry and wet tropics, will be more affected by an increased frequency of extreme events, rather than the mean change in climate. Additionally greater fire risk and incidence of pests and diseases are anticipated.

Average irrigation demand is expected to increase by between 5 and 20% by 2080. Increased temperature impacts crop production through increasing night-time respiration; increasing vapour pressure deficit, which enhances evapotranspiration rates; and increases direct thermal stress on water stressed plants. The local impacts of climate change on crop productivity are played out in the interaction between increased temperature, enhanced atmospheric CO_2 and the status of moisture and nutrient availability in the soil. The role of CO_2 fertilisation in raising yields is optimal when there is no water stress. Hence it is probable that once Type II yield gap closures have been achieved, the differential between rainfed and irrigated production may further increase.

The initial expectations of increased productivity from enhanced atmospheric CO_2 have been downgraded, because the very local scale (point and leaf scale in chambers) of field experiments tended to exaggerate field and larger scale responses. High temperature during flowering may lower positive effects of CO_2 by reducing grain number, size and quality. Increased temperatures may also reduce CO_2 effects indirectly, by increasing water demand (IPCC WG2, AR4, 2007). Larger scale experimentation continues, but most extrapolation has been undertaken using models that have been modified to include carbon dioxide concentration effects on photosynthetic efficiency. It is now thought that the best responses are obtained when other factor inputs (water, nitrogen etc.) are not limiting. C3 crops have been shown to be more responsive with increases in water use efficiency of up to 30% at $\{CO_2\}$ = 550ppm, compared to half that for C4 crops, which already have more efficient photosynthetic processes.

Climate impacts on crops may significantly depend on the precipitation scenario considered. Detailed crop modelling studies in Australia indicate that the likely reductions in water supply (lower rainfall and increased ET) will more than offset CO_2 enhancement to production resulting in an overall decline in productivity (CSIRO, 2007).

Expected yield trends for rice wheat and maize at low altitude, derived from modelling over a range of temperatures and carbon dioxide concentrations, are shown in figure 4.3 (IPCC, 2007). The orange markers indicate performance without adaptation and the green ones assume a variety of adaptations, including irrigation. The lighter coloured markers indicate RF crops with lower rainfall. The trends are predominantly downwards with outliers indicating more positive possible responses with adaptation. These are aggregated results, and more local variation is expected in specific conditions and locations.

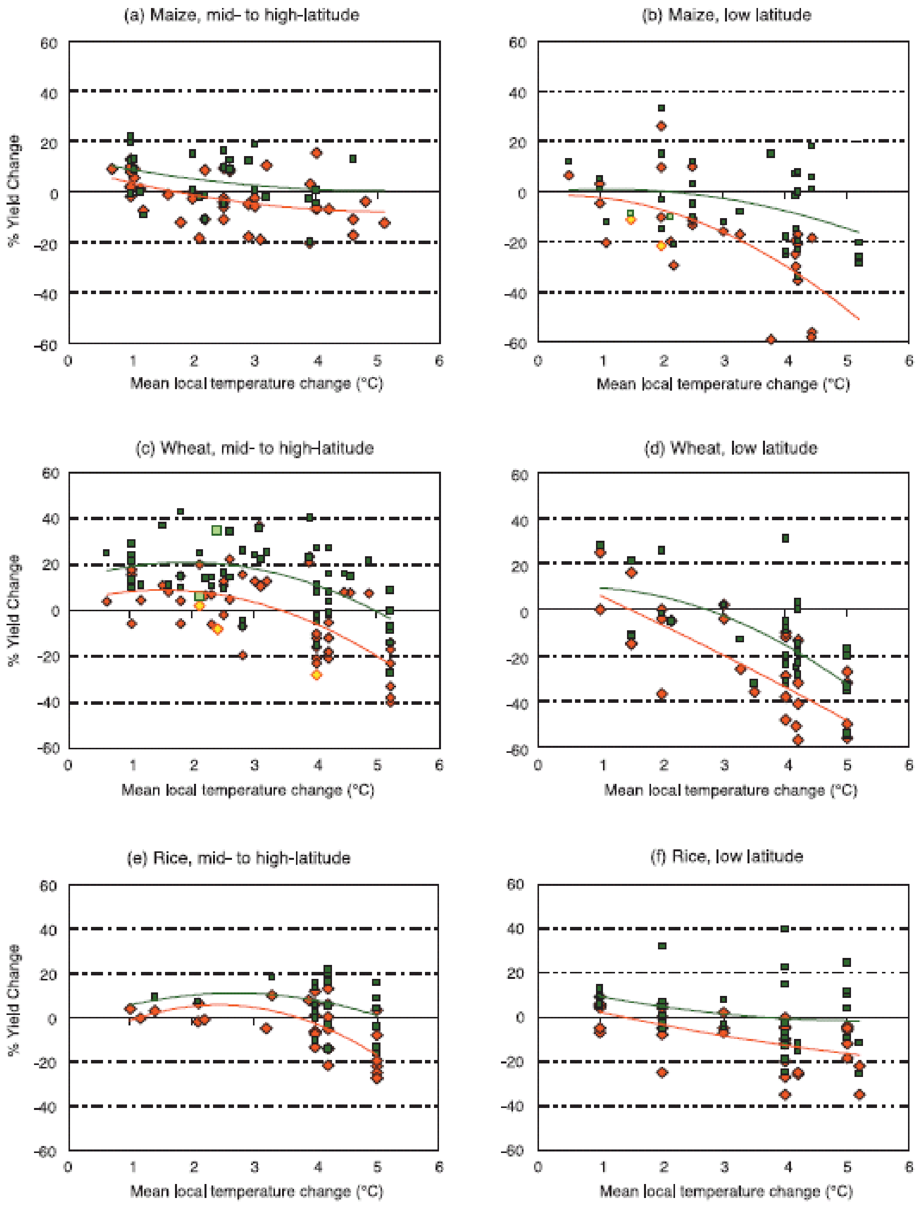


Figure 4.4 *Projected changes in yield for major cereal crops, at different levels of global warming (IPCC, AR4, WG2, 2007)*

Most recent detailed Australian analyses show that, despite adaptation, production and productivity will fall due mainly to reductions in water availability. This will be broadly true of other variable semi-arid and arid climates. Scientific commentary in Australia seems less concerned with temperature effects than the IPCC and Stern literature, possible because of the high ranges of temperatures already experienced in the main agricultural areas.

The consequences of rising temperatures have focused attention on loss of agricultural and natural habitat, and this is certainly echoed in the Australian horticultural industry, where temperature regimes are optimised to 1 degree. It also has great resonance to

Europeans and North Americans, because of the vernalisation requirement for wheat, but for C4 crops and pulses, legumes and tropical crops, temperature adaptability must be much greater than is being credited by the pundits. The key issue is more likely unnaturally hot dry years with longer high temperature spells. Understanding the probability and sequencing of these seems to be important, and is one reason that climate prediction/forecasting is seen to be a major tool in adaptation strategies.

The writings connected to the IPCC, Stern report and climate change literature are more pessimistic about the impacts of climate change on agricultural production, compared to recent analyses conducted by FAO and the Comprehensive Assessment of Water Management for Agriculture (IWMI 2007). These analyses have focused on the future food and water demands out to 2050, and have stated that, with conservative assumptions about improvements in both land and water productivity, most regions and countries will be able to meet these needs. These studies have factored in limited climate change impacts, but not the detail that is now available in AR4, which was published later. What may be happening is that the modelling exercises associated with climate change look at the reduction in potential productivity, whereas the development literature looks at possible improvements over current productivity, which are generally significantly below potential, or even achievable levels in most developing countries (China excepted). It is quite possible that both statements are true at the moment, but this discrepancy clearly needs to be better resolved.

4.4 Impacts on bulk water supply and demand – a global picture

4.4.1 Overall water supply impacts

Rainfall is the key climatic variable for agriculture but the prediction of rainfall by GCM simulation is not as good as that for temperature and pressure. GCM resolution is at a larger scale than at which weather processes are driven (REF). In AR4, there is some indication that the uncertainty associated with rainfall has been further increased by the incorporation of atmospheric-ocean interaction. Studies in many countries use Regional Climate Models at finer resolution, but nested within GCMs, to provide more detailed predictions of weather change, particularly in terms of the spatial and temporal variability of rainfall. It would be fair to say that the calibration of RCMs is still a challenge, and that additional methods of downscaling are required to assess water resources impacts.

The prediction of runoff is based on projected patterns of rainfall. Hydrologic models are parameterized against recent conditions, and these parameters are usually "re-used" to predict future flows (see figure 4.2 Chiew, 2003). Two systematic sources of uncertainty then arise: 1) due to the assumption of consistent rainfall variability on the input side and 2) the assumption of no change in hydrological model parameters. The former can be addressed by stochastic variation of the input rainfall series, as a form of sensitivity analysis.

Rising temperatures result in the melting and shrinkage of glacier and snow storage, which is particularly important in mountainous areas that are the source of surface flows and groundwater recharge that sustain irrigation, such as the sub-Himalaya. This is perhaps the most immediate cause of concern for the international irrigation community.

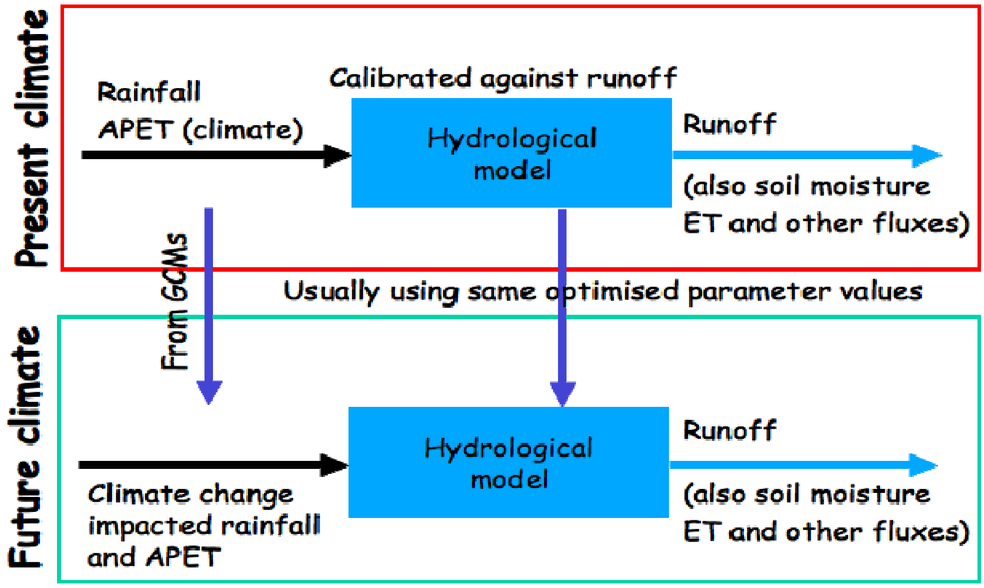


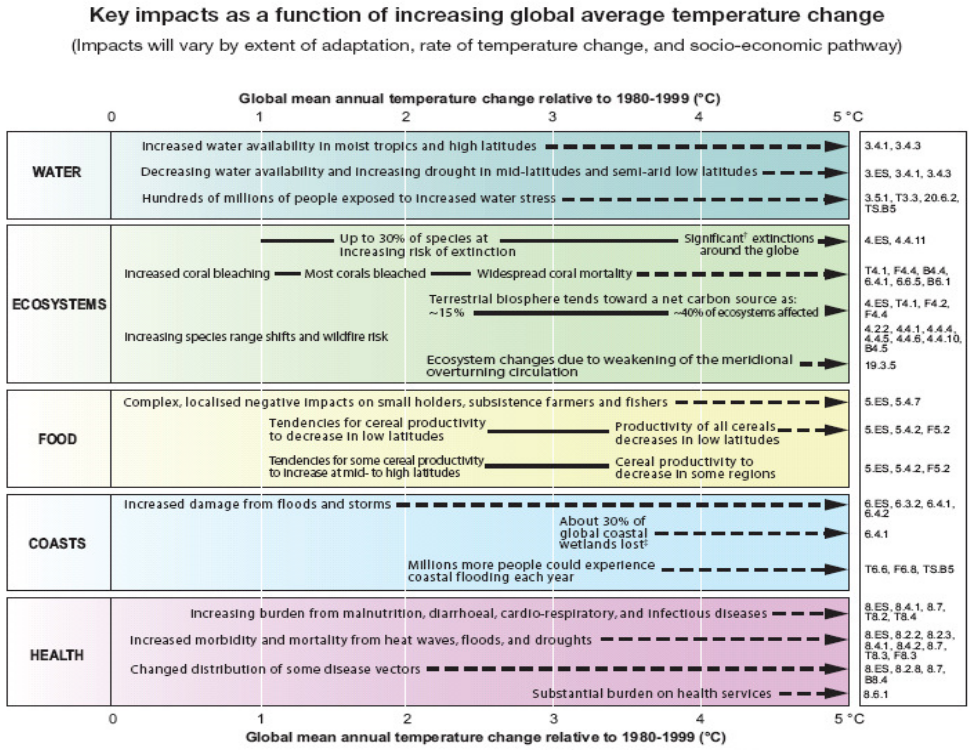
Figure 4.2 Prediction of runoff under climate change (Chiew, 2003)

4.4.2 Overall water demand impacts

Water use by plants is governed by the atmospheric demand (net solar radiation, temperature and wind) and soil moisture availability in the root zone. Water holding capacity of the atmosphere increases as the square of temperature, and therefore increased temperature drives potentially greater crop evapotranspiration. Where this is limited by soil water availability, water use will not increase, but where irrigation is provided, actual evapotranspiration should approach potential. The impact of climate change on radiation is so far modelled to be negligible, with little increase or decrease predicted. However, as mentioned, the impacts of aerosols due to increased atmospheric moisture content and other pollutants, such as black carbon, are not fully understood or modeled. Hence it is assumed that the balance of water use by natural vegetation, including forests and pastures, will determine runoff generation and soil moisture status across catchments.

A broad summary of climate impacts on 5 main sectors of interest is shown in figure 4.2, with the caveat that the numbers presented will vary according to scenario (rate of global warming, socio-economic pathway and extent of adaptation). Water, ecosystems and food are the key impacts to be considered with respect to agricultural water management

The areas most vulnerable to climate change are the ones that are already the most vulnerable to climate and climate variability. Figure 4.2 indicates that food production can be expected to fall in the mid-latitudes, whereas the mid term trend is for rising food production in northern hemisphere due to increased rainfall and increased temperatures.


Key impacts as a function of increasing global average temperature change

(Impacts will vary by extent of adaptation, rate of temperature change, and socio-economic pathway)

† Significant is defined here as more than 40%.
‡ Based on average rate of sea level rise of 4.2 mm/year from 2000 to 2080.

Figure SPM.2. *Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric carbon dioxide where relevant) associated with different amounts of increase in global average surface temperature in the 21st century [T20.8]. The black lines link impacts, dotted arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of the text indicates the approximate onset of a given impact. Quantitative entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of Special Report on Emissions Scenarios (SRES) scenarios A1FI, A2, B1 and B2 (see Endbox 3). Adaptation to climate change is not included in these estimations. All entries are from published studies recorded in the chapters of the Assessment. Sources are given in the right-hand column of the Table. Confidence levels for all statements are high.*

Figure 4.3 Broad summary of expected climate change impacts outlined in the Summary for Policy Makers (SPM) of AR4 (IPCC 2007). Data in the column on the right links specific paragraphs of the report.

While AR4 flags the fact that impacts on climate change of irrigation water requirements may be large, very little specific analysis has been carried out. A global assessment on the impact for irrigated areas has been modelled on the basis of TAR scenarios(Doll, 2002) It is suggested that in the light of AR4 and updated information on irrigated areas, such an approach would need to re-calibrated and consideration given to the rate of actual adaptation in irrigated systems.

The need for supplementary irrigation will increase in many locations and for instance, an emerging shortfall in the middle of the rainy season would not justify full-on irrigation; yet without some form of agricultural water management, which might simply require increasing organic content to the seriously overworked soils, but could justify supplementary irrigation (Riddell et. al, 2003) important subsistence crops will fail. Supplementary irrigation may also be required where cropping calendars have to change in order to avoid excessive temperatures to times of the year when precipitation is inadequate.

For similar reasons, in many locations changing cropping calendars have the potential to shift demand from times of the year when surface supply is adequate to seasons when it is not, in which case, given adequate quantities of renewable ground water, conjunctive use will be necessary.

So far, these changes in demand have concerned increases, either in terms of total abstractions, or in terms of specific increases at particular times of year necessitated by changing cropping calendars. But it is important to remember that demand will also change by reducing, ie where shifts to less thirsty farming systems are initiated, or by improving irrigation services, equipment and infrastructure, however there are significant governance, institutional and policy issues associated with the latter. These are reviewed later in the document.

Finally, demand will also reduce by shifting water outside of the agricultural sector completely. Examples of this would include the retirement of agricultural water rights in the Murray Darling Basin.

4.5 Regional impacts and the key water consuming crop sectors

The impacts of climate change on agricultural production and water resources remain highly uncertain, with potentially great spatial variation. Semi-arid and subtropical areas in the Mediterranean, the Near East, sub-Saharan Africa, Latin America will likely be affected most through higher temperatures, more rainfall variability, and greater frequency of extreme events (IPPC 2007, Kurukulasuriya et al 2006).

Predicted temperature increases might lead to reductions in crop yields, particularly in C4 crops. But these losses might be offset by increases in yields as atmospheric CO_2 acts as 'fertilizer'. The combined effect of temperature rise and CO_2 enhancement could be positive or negative, and impacts vary among crops (Parry et al 1999, Alcamo et al 2005). Farmers might be able to adapt to temperature increases by changing planting dates, using different varieties, or switching to different crops (Droogers and Aerts 2004, Droogers 2003). This might generate substantial transaction costs when institutional infrastructure is geared toward one primary traded crop, such as coffee in Uganda (Maslin 2004). The same applies to arguments for irrigation systems and management, including institutional adaptation geared towards service to a particular cropping system.

While future regional temperatures are uncertain, still more uncertain are future precipitation patterns within regions. Most climate models agree on a global average precipitation increase during the 21st century but they do not agree on the spatial patterns of changes in precipitation (Alcamo et al 2005), although some describe a trend of declining soil moisture (Dai et al. 2005).

Most climate change models indicate a strengthening of the summer monsoon. In Asia this might increase rainfall by 10% to 20%, but more importantly a dramatic increase in inter-annual variability (WWF 2005). For paddy farmers this might imply less water scarcity (and more erratic dry season flows) but more damage from flooding and greater fluctuations in crop production. Some arid areas become even drier, including the Middle East, parts of China, the Mediterranean Basin (Southern Europe and North Africa), north-eastern Brazil, and west of the Andes in Southern South America, West and Southern Africa. According to most climate models, the absolute amount of rainfall in Africa will decrease while variability will increase. In semi-arid areas where rainfall already is unreliable, this might have severe impacts on crop production (Kurukulasuriya et al 2006) and the economy (Brown and Lall 2006). Irrigation might help smooth out variability, but is only useful if the total amount of manageable precipitation remains sufficient to meet crop water demands.

Subsistence sectors are threatened (notably Africa, parts of Asia) by 2080 by which time some 75% of people could be at risk of hunger in Africa. Since Africa presents the greatest cause for concern, and because its limited economic development increases its vulnerability and limits adaptive capacity, it is useful to elaborate in slightly greater detail. In North Africa and along the Sahel margin, rainfalls and runoff are expected to decline, and with some dramatic changes in land use (increased desertification or encroachment) and reduced growth potential by 2050. Further South, in West Africa, agriculture GDP is expected to decline between 2 and 4 percent and coastal settlements which are now home to the majority of the population are expected to be affected by sea level rise and flooding. In East Africa, centred upon the Ethiopian highlands, rainfall is expected to increase, and runoff will do likewise, with risks of more extensive and severe flooding. However, it is possible that rainfed agriculture could become both more reliable and more productive at altitude. The risk of malaria and other water-related diseases is expected to increase.

In southern Africa, increased moisture stress is anticipated in the wake of lower rainfall, higher potential Et and higher temperatures. Crop yields in rainfed systems are expected to fall, and food security will decline. Vulnerability is high due to other factors such as poor governance and a high incidence of HIV/AIDS.

In Asia, water stress will increase, particularly in areas currently supplied with water from Himalayan snow and ice, which is expected to reduce to 1/5 of its current area by 2030. Irrigation demand is expected to increase by 10% for every degree rise in temperature in arid and semi-arid East Asia, and between 0.12 and 1.2 billion people are projected to be affected by water scarcity by 2050. Crop yields are predicted to rise by up to 20% in E and SE Asia, but expected to fall by 30% and become more variable in central and southern Asia. Moreover, many of those living in deltas are farmers, and IPCC estimates that a 1m rise in sea level will result for instance, in the loss of 100,000 ha of arable land in the Mekong basin due to inundation and salinisation, and that 50% of mangrove forests will disappear. Combined, it is expected that 3.5-5 million people will be affected.

The major issues identified for South America are a loss of crop and livestock productivity, accompanied by a loss of biodiversity in all major ecotomes – notably the Andes and the Amazon. Water stress will increase in the already dry areas (Savannah, southern latitudes, desert and desert fringe areas) that are dotted across the continent. In addition to human impacts, rising temperature and reduced rainfalls will see a natural conversion of jungle to savannah and valuable niches for coffee production will decline.

Temperature increases will not be limited to the lower latitudes, but instead will have global impact. In fact, it is predicted REF that temperature rise will be more pronounced at the higher latitudes. This means that crop production will be possible at higher latitudes than is currently the case, due to lengthening of possible growing seasons – although this opportunity could be somewhat compromised by decreasing vernalisation: especially – it is predicted – in parts of Canada and the former Soviet Union.

All this has several strategic implications for climate change adaptation that can be summarised as follows.

- Cereal production is expected to fall by between 9 and 11% in the developing country regions and Australia/New Zealand, but to increase by as much as 11% in the developed countries including the former Soviet Union, thereby contributing to the gap that already exists in agricultural production between the developed and the developing countries.
- However, the temperature increases that open up "new" growing seasons for cereals in the higher latitudes and the associated increases in evapotranspiration rates will mean that in many cases mean irrigation will be necessary.

- where irrigation is already commonplace, such as in Southern Europe, where not only is temperature expected to rise, but precipitation is also expected to reduce the productivity of irrigation water will have to increase, and this increases in turn the irrigation management challenge.

In the arid and semi-arid regions, usually associated with the mid-latitudes, real reductions in available water, even with improved storage along with increasing evapotranspiration rates will increase vulnerability, especially of the rural poor, and will necessitate significant rethinking of current food security assumptions, practices and investments. Policy makers will have to decide whether irrigation should be an economically efficient sub-sector based on comparative advantage, or a form of food security/poverty alleviation subsidy. Important questions should therefore establish whether or not there are options for continuing with "traditional crops", albeit with changed planting dates. This will depend on locally specific conditions including optimal temperature windows and patterns of rainfall relative to crop growth stages. It may in fact prove more effective to shift to new, higher value crops with better comparative advantage than the traditional crops and to irrigate them with more expensive groundwater where available, perhaps using mulches or economically useful cover crops to reduce overall evaporation/evapotranspiration rates, or even precision irrigation (see more on this below).

All this suggests a need to reassess local irrigation typologies with supplementary irrigation, of one sort or another, increasing in importance, possibly on the basis of a trade-off between expanded full irrigation on a limited area, or larger productive area based on a combination of revised cropping calendars (that reduce IWR) and supplementary irrigation. Other interventions will also have to be considered such as i) the breeding of drought tolerance, ideally without compromising yields; ii) improved weather prediction and early warning systems; and iii) improved drought preparedness.

Elsewhere, specifically in those tropical and sub-tropical regions where more rainfall and hence higher run-off is expected (South Eastern S America; East Africa and South East Asia) it will be possible to increase irrigated production; but increasing event variability may means that additional water storage facilities will be necessary. But given that food security is less likely to be an issue in these areas, increased water availability may justify and facilitate an expansion into cash cropping, perhaps of sugar or citrus.

Other parts of the tropics are, on the other hand, expected to become drier (eg Gulf of Guinea, Central America, North Eastern Brazil). Wetland rice is commonly grown in such locations. In fact, the AT 2015/2030 data suggests that the area planted to wetland rice is expected to expand in each of these regions. This suggests the need for radical changes towards alternative, water saving irrigation techniques such as alternative wetting and drying or SRI.

Small islands will face a direct combination of climatic and sea level rise impacts, which are likely to affect most of their populations. Although statistically small compared to the populations of Asia, there is good cause for concern. Agriculture is important on many tropical islands, and is sustained by rainfall and by freshwater, held either as groundwater or in sensitive lenses in Atolls. In either case, the freshwater is in a precarious dynamic balance with the sea. It has been estimated that fresh water lenses might decline by 295 in Atolls affected by seas level rise. Agricultural land will also be lost along the coastline, and economic costs without adaptation are predicted to reach 17-18% by 2050 for SRES scenarios B2 and A2. Agriculture, often already precarious, will be vulnerable.

Finally, for those countries or even regions spanning both areas that are expected to become drier and other that are expected to enjoy more rainfall, then it may be more advantageous simply to shift production from one area to another.

4.6 Impacts at river basin level: systemic considerations

4.6.1 Introduction

It is clear that changes in rainfall, hydrology, sea level, temperature and evaporation have local variations and detail that will be integrated at river-basin and catchment scales. Between the macro-economic assessment of impacts and the micro or farm unit level, it is the overall river basin responses that are of prime interest in determining bulk water allocations and management needs. Climate change impacts will become apparent as part of a systemic response to changed inputs, stores and outputs and no particular impact will occur in isolation. Hence it is important to identify the operational or systemic units across which impacts will become apparent and will need adaptive management.

A water resources management perspective is therefore an essential component of analysis, and in the long run it will be important to discern change over variability and this is most likely to be expressed river basin responses. However, there are many other factors contributing to basin level responses already, and these need to be well understood, attributed and quantified. Although this forms part of the everyday work of river basin agencies and hydrological services, logistical and capacity constraints tend to inhibit the collection of sufficiently detailed data to determine water resources, use and trends at basin level, particularly in those basins most likely to be impacted. It is very important therefore that these basic needs are addressed as early as possible to all the potentially serious consequence of climate change to be properly evaluated and understood. Figure 4.5 provides a quick summary of the needs and linkages that need to be consolidated.

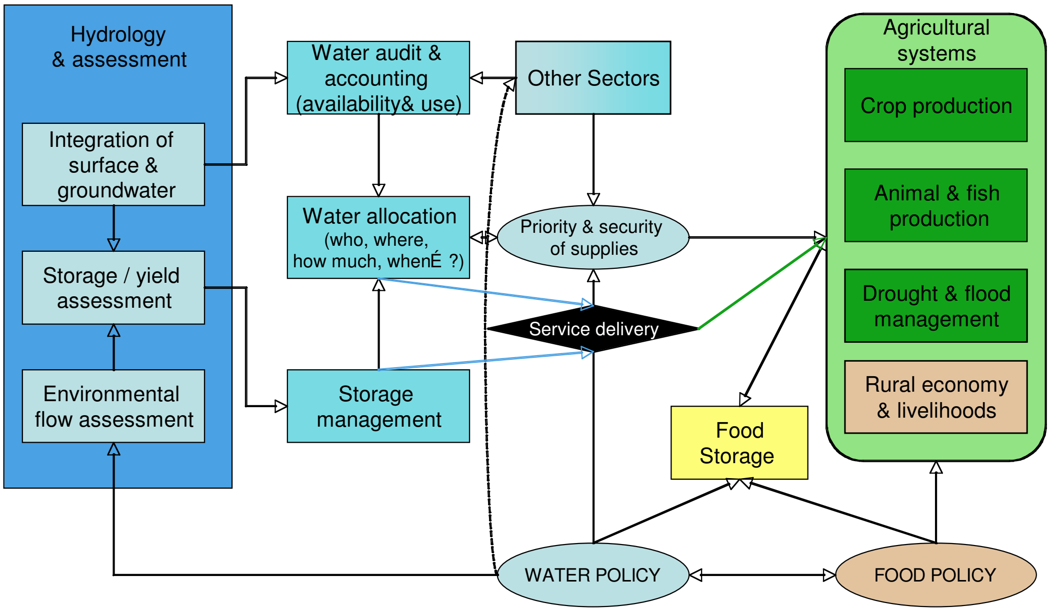


Figure 4.5 Elements of water and natural resources management that should be "business as usual" in order to 1) assess climate change impact on agriculture and 2) develop adaptive strategies.

It is important for managers and users to understand the likely changes over space and time at a level where the expected range of change and current levels of variability are better matched. Two tools that help considerably are spatial and temporal dis-aggregation through higher resolution models and through statistical downscaling, coupled to scenario analysis complemented by risk assessment.

There are a number of points arise from this diagram:

1. Water and food policy have implicit linkages at present, which need to be made more explicit in the context of competing demands for water and rising needs to maintain or restore environmental water allocation;
2. That there can be strategic alternatives between food storage and water storage, and that this will be one of the key links between agricultural and water resources policy in the future;
3. It is important to have a system of water accounting (and the supporting hydrology) to be able to monitor and predict change and additional stress. Water allocation systems in most developing countries are very ad hoc, and need attention to detail in each of the blue boxes;
4. Improving service delivery has been seen as increasingly important in all aspects of water management in both developed and developing countries for the last 15-20 years. With the additional stress of climate change, larger scale water resources management will be increasingly important in determining both macro and within system options to adapt agriculture and agricultural water management, and this will increasingly be mediated by better, and more specialist service delivery.
5. This points to the increasing importance of establishing effective institutional arrangements for water management, allocation and response. Such process take a long time to evolve, and cannot be created over night.

Because anticipated climate change impacts will be multivariate over space and time, it is argued that impact assessments can only be carried out across the operational elements of a multi-functional water resource system and its related aquatic environments. Food production arising from these systems are but one aspect of their processes and operational management. However, it should be clear that baseflow recession from snowmelt, dam operation, wetland conservation, irrigation abstraction, return flows, flood protection, conjunctive use and saline intrusion can and do appear in river basin management 'problematiques' under baseline conditions.

4.6.2 Basins impacted by snowmelt

The most immediate and large scale impacts on runoff are likely to be due to reductions in snow melt and retreat of glaciers (Barnett, 2005). Glacier retreat is already well documented (ibid). A period of low snowfall and rainfall in the Himalaya from 1999 to 2004 resulted in the lowest Indus flows on record with water allocations of around 40% of long-term mean in the Punjab in Pakistan. There is clear evidence of an average warming of 4 degrees (1980-2005) and loss of 7% of glacier area in the headwaters of the Yellow and Yangtze rivers in the Qing Hai Plateau in China (Institute of Tibetan Plateau Research, web reference, and personal communication, 2004) and low headwater flows have been attributed to the associated decline in glacier area (YRCC, personal communication, 2004). However, the science and understand behind these changes remains contradictory and is not yet well resolved. Forward predictions, as shown in Figure 4.6, should see a mid-term increase in annual average runoff (consistent with mass balance) and / or an increase in groundwater recharge (Rees 2005). However, it is not clearly documented (yet) and the fact of declining flows in major rivers is counter-intuitive. In Central Asia, there is emerging evidence in the Fergana system in the form of increased mud-flows from the TienShan mountains and new periods of late season melt and mud-flows (pers. comm. 2007 Raivodhkhoz, Osh: SDC IWRM Fergana Project).

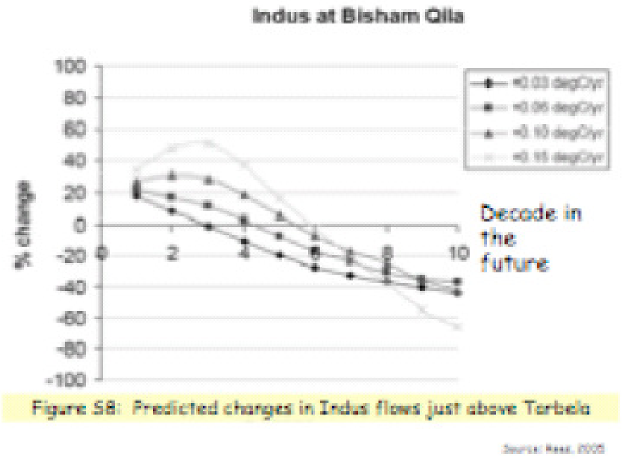


Figure 4.6 Predicted patterns of Indus flows with changes in snowmelt patterns and volume under climate change (Source, Pakistan Country Water Assistance Strategy, 2005, Rees 2005)

Given the importance of snowmelt to irrigation supplies throughout the sub-Himalaya, (India, Pakistan, Bangladesh, (Vietnam), China); and in other mountainous regions USA (Rocky Mountains), Andes, Central Asia (Tien Shan), further analysis and research is required. A key issue is to improve the monitoring of flows and their variability and the closure of the snowmelt water balances. Remote sensing (especially synthetic aperture radar) offers effective, frequent and relatively cheap means of monitoring glacier area and snow cover, but better temperature, precipitation and flow data will be needed to help understand the processes involved, especially in flow paths between glaciers and rivers and aquifers. The main puzzle for Chinese scientists investigating the Qing Hai source flows is the hydrological behaviour of the frozen ground in the plateau.

As far as snowmelt is concerned, changes in the amount of precipitation tend to affect the volume of run-off while temperature changes mostly the timing of the runoff Barnett *et-al* 2005. Increasing temperatures lead to earlier runoff in the spring or winter and reduced flows in summer and autumn. Furthermore, where temperatures rise such that the melt quantities exceed precipitation, the ice deposits will decline both spatially and in terms of their ability to supply downstream needs. This is already happening, with glacial retreat in evidence almost everywhere that they are encountered. And the knock-on effect is already apparent in large river systems and is expected to affect more, especially the large Asian drainage basins that depend on the Himalayan Ice, and in which much of the world's large scale irrigation is situated. The Yellow river basin for example is already highly stressed, and is experiencing declining flows in the source areas in the Qing Hai Plateau (Chinese Tibet). Runoff does indeed occur earlier in the season and peak earlier, requiring a gradual shift in the cropping season. In some places this may be beneficial, if supplies peak ahead of monsoon rains, supply may in fact be more consistent, although it will encourage use when crop water demands are highest, and possibly least efficiently used. In addition Barnett *ibid,* suggests that one sixth of the world's population lives in areas and one quarter of global GDP is generated in areas, including much of North America, that are or will be effected by declining snowmelt and changing hydrographs.

4.6.3 Basins impacted by aridity

Decreasing runoff will have a variety of effects in salinity: dilution flows will reduce, but so may mobilisation of salt from flows through saline zones. Groundwater recharge may decrease, with declining surface flows, which may lower saline water tables in arid situations such as Pakistan, northern India and Australia. However, this will be offset by more limited leaching, because of lower rainfall and possibly lower surface water availability. Reduced river outflows to the sea will encourage further saline intrusion and contamination of near coastal aquifers (as seen due to upstream abstractions in the Krishna Delta in India (Venot et al, 2007))

Conjunctive use of surface and groundwater will be particularly relevant on alluvial fans and coastal delta systems where groundwater is easily accessible. In the case of the coastal deltas however, over-abstraction of groundwater can result in saline intrusion, which would require leaching and hence additional water. But this may be a practical solution where sufficient water is available on a seasonal basis – another change in demand.

The risk of saline intrusion will also increase as run-off decreases, and evapotranspiration increases. Again, it may be possible to deal with this either by means of salt extracting trees and crops, or where there are marked flood seasons, by growing wetland rice as a means by which to keep the saline front at bay (as in the case of the coastal margins of the Nile Delta) or to leach out salt accumulated during dry season cropping.

As is now the case, detailed salt balance and dynamic modelling will be required to assess the actual impacts of salinity, which will also be governed by land use change, and patterns of water use and abstraction in the basin. To date, we are unaware of any detailed scenario assessment of the salinity impacts of climate change on agriculture and water systems.

Current variability in stream flows spans a greater range than the predicted future median change. At one level this implies that adaptation to new median conditions can be understood in terms of current responses to more extreme events (in terms of floods and droughts). However, even with no change in variability, the frequency of what are now extreme events will increase dramatically (AR4 – give example for Europe?) and the resilience of systems (economic, social and biological) is bound to be blunted. If the variability of future hydrology also becomes greater, resilience could be much further impaired in vulnerable eco-regions.

Both Sub-Saharan Africa and in Central and Southern Asia are expected to be impacted by declining runoff. In Africa, this will limit options for irrigation as a solution to declining rainfed areas. Africa, mostly, does not have the luxury of a "reliable and steady" Himalayan type of water source – which buffers against inter-annual variability in rainfall, which is one of the factors that has limited irrigation development to date. Even if monsoon rainfall increases in the Indian sub-continent, declining snowmelt will have major consequences on water supply for agriculture in the Indus and Ganges basins, largely because of the enormous number of people already dependent on irrigation, and more so the food surplus generated in Punjab and Haryana. Without additional storage to capture increased summer runoff, much water will flow unused to the ocean, leading to water scarcity in the drier months (Barnett et al., 2005, Wescoat and White 2003, Rees and Collins 2004, Dinar et al. 1998).

Changing rainfall patterns affect both the seasonal availability and the manageability of water and both. By 2070 there will be less water available in Central America, South Western South America, North East Brazil, the Eastern USA, West Africa, Southern Africa, South Europe and the Mediterranean Basin, the Middle East and Australia. Furthermore supplies everywhere will vary more greatly than at present. In fact, even in some of the areas where climate change is expected to result in greater run-off (much of the Amazon Basin, the Central and Eastern USA, Central and East Africa, South Asia, parts of Central Asia and of Australia etc Milly et-al 2005) the intensity of specific events as well as overall variability in the seasonal distribution of rainfall means that additional storage is necessary to smooth out supplies so as to match the seasonal crop water requirements. And where especially high intensity (extreme) events are likely, it may not be possible to capture adequate proportions of the peak flows with infrastructure that is affordable in social, economic or environmental terms hence the paradoxical situation that an increase in water supply results in reduced availability.

Where food security or other factors suggest that the problems of reduced supplies, unmanageable supplies or annual hydrographs that are changing with snowmelt change need to be fixed, several man made options are available. Two involve storage either above ground (surface storage) or in aquifers; a third: forestation. Changes in water use is also a possibility, but this is dealt with as a demand side issue in the next sub-section.

Several challenges are associated with surface storage, the most obvious being that many of the “easy” dam sites have already been taken. New sites will increasingly be expensive, involve difficult ground conditions and have steep stage-discharge characteristics and hence high evaporation and seepage losses. These problems can be avoided by building multiple small dams rather than single large dams. Studies have shown (REF) that these are usually cheaper in terms of cost per unit of water stored, while bringing the benefits of stored water closer to beneficiary communities while being less socially disruptive. However, greater run-off capture means reduced environmental stream flows while multiple, small water bodies can cause gene pool fragmentation of aquatic species.

Another challenge associated with surface storage concerns the need for increasingly sophisticated spillways, probably variable, in order to deal with increasingly intense storm events. However, modern technology such as remote sensing, gives greater flexibility to dam operators who would not have to try and keep the dam filled when the remote sensing system tells him or her i) how much water that is on the way; ii) how much can be relied on and iii) when it will arrive (REF Kafue). In fact imaginative, real-time technology influenced operating rules would also have flood attenuation benefits and facilitate closer convergence of hydropower and agricultural benefits.

Finally, where water rights are in operation, there are the possibility of water banks such as those being pioneered by sugar growers in Kwa Zulu Natal in the RSA. By this means, rights-in-use that are not required at a given point in time, can be kept until later (either in the season, or trans-seasonally). Such facilities are small, generally community driven and are ideal in polities where water management is decentralised.

Aquifers are potentially a water resources safety valve against scarcity but need to be properly managed for long term, high security and because in the future, groundwater will, arguably, be too valuable to use the cultivation of staple crops, the aquifers should also be managed so as to manage the risks of high input/high output farming. In this respect, well managed groundwater is especially useful as a risk management option when used conjunctively with groundwater, or for supplementary irrigation where the recurring costs of groundwater abstraction are economically more favourable than the total costs of a surface irrigation system that is only partially.

4.6.4 Basin re-cycling

Supply side problems can also be addressed by greater re-use of agricultural run-off, or by the use of urban wastewater. In the case of irrigation drainage even if in-field irrigation efficiencies are low, overall basin system efficiencies can be high. The Nile system is a case in point.

A useful example of this would be the informal water markets that operate along the Jatilahur river in Indonesia, where savings from group rights-in-use are left in the river for use downstream for high value potable water supplies, while facilitating an increase in capture fishery yield along the way. There is however, a risk of accumulating agrochemicals that must be managed. To scrub this would be excessively expensive, but artificial wetlands serve well to the sale end, but of course do so at the cost of evaporation losses. Urban wastewater, by definition also needs to be scrubbed before it can be used for irrigation. Usually, local standards specify the level of purification according to the type of crops to be irrigated. Thus water intended for tree crops, cut flower or fodder for instance, does not need to be purified to the same level as say, salad greens or root vegetables. The decision is usually made on economic grounds; but having said that, urban wastewater –including storm run-off – will have increasing relevance for peri-urban irrigation.

4.6.5 Basins impacted by land-use changes – afforestation and the sediment problem

Afforestation has the potential not only to attenuate flood peaks and maintain baseflows; but also sequestrates carbon while contributing to or maintaining biodiversity. However, mature tree stands do mobilise soil moisture from deeper soil horizons and the hydrological impact of afforestation can also include significant reductions of baseflow (Calder, 2004) even if in some cases the multiple benefits of afforestation (which also include the reduction of advective energy and hence of potential evapotranspiration in and around the forests) may be considered to outweigh the disadvantages. Reservoirs, which may be the direct beneficiaries of upstream de-forestation also lose water, either to seepage (which can often be recaptured as groundwater) or to evaporation. Reservoirs also contribute to GHG as result of the decomposition of inundated biomass, where forests mitigate the effects of GHG.

Linked to landscape stability and hydrological response is the issue of sediment yield. The effective life of many storage and distribution structures are severely compromised by accumulation of sediment. The Tarbela dam on the Indus is a case in point. Sediment loads in the Blue Nile are now impacting the operation of large irrigation schemes in Sudan

4.6.6 Basins with increasing runoff – the delta problem

Increased annual runoff is predicted in the higher latitudes, and will be accompanied by larger and more frequent flood flows in both areas of increasing and decreasing rainfall. Deltas, and alluvial plains have long been the sites of massive human drama – in the Yellow River, the Yangtze Delta and in Bangladesh, are prime examples. Millions have been killed or displaced, and flood defence has been the major priority in water management in China and northern Vietnam through millennia (Malano et al. 1999). Structural measures, such as dyking and dam construction have been widely used, sometimes at high human and financial cost, to protect agriculture and habitation. Since physical measures are still susceptible to events of lower probability than used in the design, the consequences of failure can be costly and extreme. The expected shifts in rainfall patterns will challenge these structural measures more than in recent times, and if accompanied by increased variability, the risk will be further exaggerated.

Non-structural measures, such as land zoning and insurance have been increasingly promoted in developed countries and also in Bangladesh. Under most flood management systems, there are reserved areas which are preferentially flooded should cities or other sites of high economic value be threatened: mostly this is agricultural land with relatively low population density, although populations tend to rise rapidly in flood plains protected by structural measures (Red River Delta, Yellow River, Yangtze Delta for example).

With increasing flood frequency and severity, these two broad trends will continue, especially in transition countries with rapidly developing high capital value infrastructure. However, at the same time, the need to protect agriculture from floods, especially less severe ones, will become increasingly important to maintaining levels of food production. This will have particular importance in irrigated systems within the humid tropics, and within deltas.

4.6.7 The susceptibility of wetlands and their products (fisheries) to climate change.

For people living in sensitive wetland areas, food security depends on the dynamic relationship between social and environmental variables beyond the control of the wetland dwellers. In other words, diversification and adaptation are essential for the viability of livelihood strategies in dynamic flood-based environments.

Inland fisheries are for instance notoriously vulnerable to environmental changes and show dramatic declines in both productivity and the underlying biodiversity as a response to habitat alterations and losses of ecosystem integrity caused by anthropogenic pressures, including climate change. However, the crucial role played by part-time activities such as inland fisheries that provide food and jobs during harsh times of unemployment or when crops fail have too often been neglected in upstream water management schemes. While irrigation and associated water storages may provide new opportunities for both capture fisheries and aquaculture. These alternatives are poor substitutes for the loss of environmental services resulting from the impacts of water management schemes on aquatic ecosystems and biodiversity.

The lifecycles of fishes and other aquatic organisms are closely adapted to the rhythmic rise and fall of the water level and changes to this pattern may disrupt many species. Dams on rivers and streams interrupt migration routes, and changes in flooding patterns may lead the fish to spawn at the wrong time of the year resulting in the loss of eggs and fry. Increasing flash floods may wash juvenile fish and eggs out of their normal habitats thereby increasing chances that they will die from starvation or predation. Prolonged periods of drought will reduce available habitat to the fish especially during the dry season.

Although rises in water temperatures may benefit the farming of tropical species under colder climates, capture fisheries activities will come under pressure from increased temperature stress and rising pH associated with global warming. This will result in species extinctions at the margins of their current habitats, and fish yields in places like Lake Tanganyika are expected to fall by around 30%. In the Mekong, where the most significant inland fisheries in the world takes place, significant changes in the food chain may result from declining water quality, changed vegetation patterns and salt water intrusion in the delta.

4.6.8 A basin example

To round out the discussion on macro-level considerations, let us consider the well-known Murray Darling Basin, in Australia, which has been over-allocated despite having one of the best water accounting systems in the world. It is predicted that climate change will have a big impact in semi-arid and arid Australia, through reduced rainfall and higher evapotranspiration rates, resulting in dramatic reductions in runoff by 2070 – 20% overall in the basin (CSIRO, 2007) and up to 40% in some sub-basins, such as those in NW Victoria (DNRE, 2007). In such circumstances, the additional impacts of climate change are sharpened and will press for even tougher decisions on water use and trade-offs between agricultural and environmental water allocation. A brief score card for MDB is presented in Box 4.1

Box 4.1 Assessment against framework criteria — Murray Darling Basin

Exposure: The Murray–Darling Basin (MDB) is likely to experience reduced annual average rainfall and increased temperatures leading to an overall drying trend. More frequent and severe drought is also possible.

Sensitivity: Sensitivity is high. Water is already over–allocated and climate change impacts will exacerbate the difficulties associated with managing demand and water quality. Agriculture, biodiversity, natural systems and the quality of water for towns and cites are likely to be significantly affected.

Adaptive capacity: Adaptive capacity of the agricultural systems is high, although this will take planning and some time to realise. There is considerable scope to adapt to reduce run–off through measures already under investigation such as changes to the allocation of water (including trading and price mechanisms) and water conservation measures.

Adverse implications: The MDB accounts for about 40% of Australia's agricultural production. Adelaide draws a significant proportion of its drinking water from the Murray. There are an estimated 30,000 wetlands in the MDB supporting important populations of migratory birds.

Potential to benefit: There are considerable potential benefits in taking climate change into account when planning for future management of resources, particularly water, in the Murray–Darling Basin.

4.7 Food security and environment linkages

Taken together, the anticipated impacts of climate change on water management will translate into broader food security equation (Schmidhuber and Tubiello, 2007). Underlying these macro considerations are a set of impacts and externalities which will not be equally distributed. In coming years the farms and regions most at risk are likely to be those:

- currently at the edge of their climate tolerance and where that tolerance will be further eroded;
- already stressed due to economic, social or biophysical condition (e.g. threatened by salinisation or labour availability);
- where large and long-lived investments are being made — such as in dedicated irrigation systems, slow growing vulnerable plantation species and processing facilities (ACG 2005).

Allocating water for productive use, including agriculture and hydropower will compromise the integrity of aquatic ecosystems and associated biodiversity which sometimes has profound economic implications. It is clear that where excessive abstractions impact natural flow regimes biodiversity, including economically important capture fisheries, will suffer. Less obvious and often ignored however (EPCO 2000) is the risk that stored water will be released and appear in dry season flows when local eco-systems have adapted to dry river beds and wetlands.

Similarly, with increasing attention being paid to the maintenance of environmental stream flows, or reserve flows as they are called in the new South African Water Law, the importance of flood peaks is ignored. Thus storage facilities that capture or over-attenuate flood peaks can seriously disrupt food chains, especially important marine food chains that depend on reliable annual flood peaks bringing fresh sediment into the brackish margins.

In addition, dams not only attenuate the flood peaks; but also capture crucial sediments thereby reducing the seasonal nutritional value of the overall river regime in sediment dependent aquatic/marine ecosystems.

Elsewhere, where other kinds of ecosystems depend on the sustainability of sediment free waters, including not just the upstream reaches of river systems, but also coastal reefs, sometimes called nowadays "the rainforests of the seas", poor land preparation practices in newly developed, or intensively irrigated areas increases turbidity to levels that are unsustainable with dreadful consequences for the complex and often economically significant ecosystems. This is already happening, for instance at Australia's Great Barrier Reef (WWF 2001).

All these risks can be expected to both expand and intensify as new irrigation and storage facilities are provided as climate change adaptation measures.

4.8 Climate change impact typology

Following on from the impact pathways outlined in Figure 4.x, a coarse typology of irrigation and agricultural water management situations has been prepared to further tease out where and in what way these different impact pathways will play out (Table 4.1). We propose a number of situations based largely on agro-ecological and climate impact factors. Thus the typology becomes rather different from the one proposed in the Comprehensive Assessment Irrigation Chapter (7), which emphasises scale and socio-technical considerations. Scale remains important, especially in terms of institutional arrangements but has been bypassed here as it can be dealt with at a second level of regional and local analysis.

Table 4.1 Typology of climate change impacts on agricultural water management

#	Situation	Examples	Current status	Impacts	Technology	Adaptability	Vulnerability	Options
1 **1`** **11**	**Snow Melt Systems**					f(dependent population, water scarcity)		
	Arid and semi arid plains; Link to deltas; Link to monsoon systems	Indus system	Highly developed, water scarcity emerging	20 year increasing flows followed by substantial reductions in sw and in gw recharge Changed seasonality of runoff and peak flows More rainfall in place of snow Increased peak flows (?) and flooding Increased salinity Declining productivity trend	Surface irrigation systems	Low	Very high (run of river): medium high (dams)	Increase productivity Better gw storage and management Increase productivity
		Ganges Brahmaputra	High potential for gw, established water quality problems Low productivity		Groundwater	Low	High	
		Northern China	Extreme water scarcity and high productivity		Conjunctive use	Low	High	
		Red and Mekong	High productivity, high flood risk, water quality					
		Colorado	Water scarcity, salinity					
2	**Deltas**							
	Note that deltas fall within other agro-ecologies.	Ganges Brahmaputra	Densely populated Shallow gw extensively used OK flood adaptation Low productivity	Rising sea level Storm surges, and infrastructure damage	Formal surface systems	Poor except salinity	Very high (flood, cyclones)	Minimise infrastructure development Conjunctive use

				Higher frequency of cyclones (E/SE Asia); Saline intrusion gw Saline intrusion surface water Increased flood frequency Potential increase in GW recharge				Manage coastal aquifers
		Nile	Delta highly dependent on runoff and Aswan Storage - possibly to upstream development				f(population)	
		Yellow river	Severe water scarcity					
		Red River	Currently adapted but expensive pumped irrigation and drainage		"Groundwater" systems	High except salinity		
		Mekong	Adapted groundwater use in delta - sensitive to upstream development					
3 **33**	**Semi-arid / arid: limited snow melt / limited gw**							
	a. Monsoonal	Indian sub continent	Low productivity	Increased rainfall Increased rainfall variability - increase drought and flooding Lower rainfall, higher temp. Falling runoff	Surface systems	Low	High	Storage dilemma Increase gw recharge and use Higher value ag (Australia)
			Over developed basins (sw and gw)		Groundwater systems	Medium	High	
					Conjunctive use	Medium	High	
	b. No monsoon	SSA, Southern and Western Australia				Medium	Very high in SSA	

					Flood water spreading	Low	High	Declining areas Breeding and increased yield. Commercial agriculture?
4	**Humid Tropics**							
	a. wet rice systems	SE Asia	higher productivity - stagnating?	Increased rainfall Marginally increased temperatures Decreased Rn? / decreased ET? Increased variability - more droughts, more floods	Surface irrigation	High	Medium	Increase storage for second and third season Drought and flood insurance Crop diversification
		Southern China	low output compared to north		Conjunctive use	High	Medium	
		Northern Australia	feasibility assessment now - fragile ecology		Groundwater	High	Low	
	b. non-rice systems				Surface irrigation	Medium	low	
					Groundwater	Medium	medium	
5 **5**	**Temperate supplemental**							
				Increased rainfall Longer growing seasons	Pressurised systems	High	Low	Potential for new developments Storage dvpt.
		Northern Europe	High value and pasture		Surface systems	Low	medium	

		Northern America	Cereal cropping gw	Increased productivity	Pressurised systems	High	Medium	Increase productivity & output Limited options for storage dvpt (gw and sw)
6 **65** **6**	**Supplemental systems**							
		Mediterranean	Italy, Spain, Greece	Significantly lower rainfall and higher temperatures	Flood water spreading	Low	High	Decline in areas Decline in productivity
		Northern Africa	Morocco, Tunisia	Increased water stress				
		Middle east	Fertile crescent	Loss of groundwater reserves.				

4.9 Summary: the combined impacts – positive and negative

The smoothing of short-term climate variability provided by irrigation is threatened by long-term shifts in climate resulting from human-induced global warming. One consequence of warming is an increase in variability of precipitation, which, together with the loss of mountain snow packs, decreases the security provided by irrigation (IPCC, 2001). Intensifying changes in long-term climate provide a dynamic backdrop to the forces driving reallocation of water to "higher value" uses. Climate change will increasingly be entwined with complex choices and trade-offs among irrigation, food security, and ecosystem health.

Although there is now considerable interest in raising the productivity of rainfed agriculture, and in shifting more public investment to that sub sector, it is the storage of water, either behind dams or underground, that enables cropping in droughts and in dry seasons. Although it is certainly possible to enhance rainfed production in "normal" seasons (Rockstrom et al. 2001), if there is no rain, then there is no agriculture, bringing us back to the importance of irrigation.

Climate change impacts will further increase risk in rainfed farming systems (MA 2005) and may exaggerate current risk hedging behaviour by small farmers. By contrast it has been assumed that because productivity is higher in irrigation, the potential marginal gains of further improving land and water productivity are more limited. However, yields and water productivity are well blow potential in many regions, notably the Indian sub-continent, and significant productivity increases can be expected in both yield and water use efficiency by better management of all farm inputs, and by optimal use of nitrogen fertilizer (Nangia, 2007). Irrigated agriculture, even with declining water availability, generally offers a more secure risk environment for more intensive management.

Projections developed in the Comprehensive Assessment (2007, Chapter 3) on the basis of IPFRI macro-economic modelling show that without substantial improvement in the productivity of rainfed agriculture, and despite a considerable expansion of cropped area, irrigated area would have to increase to close to 500 million ha globally to meet expected food demand, entailing a doubling of water use. It is unlikely that either adequate land or water are available to allow this, even without likely transfers of irrigation water to other uses. Thus, raising the productivity of irrigated agriculture (especially its water productivity) will be a key target of investment and management, and one that will, in public investment terms, be balanced with strategies to enhance the productivity of rainfed agriculture.

One critical impact on hydrology is temperature-related, as rising temperatures push mountain snowlines higher and cause more precipitation to fall as rain rather than snow at higher elevations. This effect is already shifting the peaks of runoff hydrographs in snow-fed rivers such as the Columbia in the Western United States to occur earlier in the year and reducing summertime flows, when demand for irrigation is the greatest. This loss of natural storage has powerful negative implications for the extensive irrigated areas which depend on snow and glacier-fed rivers for their water supply, such as the vast Indo-Gangetic Plain and large areas of North China. At the same time, evaporation losses from artificial reservoirs will increase, reducing their useful supply, while more intense rainfall events may increase reservoir sedimentation rates.

Irrigation plays a multi-faceted role in relation to climate change. On the one hand, it contributes to the problem though methane emitted during rice production, use of petroleum-based nitrogen fertilizers, and the use of fossil fuels in cultivation and in transporting inputs and outputs. On the other hand, by adopting improved cultural practices such a low-tillage agriculture, it can help remove carbon from the atmosphere and store it in the soil thus helping to mitigate the impacts of fossil fuel combustion elsewhere in the world economy. Irrigation also has the potential to buffer agriculture against increased variability in rainfall and higher crop water requirements, while itself being vulnerable to warming-induced changes in its water supply. The Himalayan drainage is a case in point, since a large share of the world's irrigation is practiced with water descending from its shrinking snowfields and glaciers. Increased artificial storage to compensate for the loss of this natural storage will be a huge and necessary investment requirement, whether above or below ground, would be hard to satisfy. Food storage strategies and crop insurance schemes are another possible response, but one which only buffers against variability in output and not against secular declines in production. Investments in wastewater treatment and reuse, and inter-regional water transfers will also be prominent. Whether greatest productivity is achieved through concentrated management or diffuse, low intensity investment, is a matter of debate.

5 PROSPECTS FOR ADAPTATION

5.1 Introduction

While this discussion paper has emphasized a systemic analysis of impacts linked to some form of hydrological integrity (river basin, aquifer), this next section reviews the possible adaptive responses is a more hierarchical fashion, starting at farm level and scaling up to national level policy considerations. This on the assumption that most adaptive strategies will be set at national level and scaled through regional economic initiatives.

As with agriculture more generally, agricultural water managemnet will adapt and respond to changing constraints and opportunities. Climate change impacts will come into play over the top of many other pressures, and the formulation of adaptive responses, and the ability to respond will be governed by a complex mix of factors. Adaptation strategies will be continuously changing and will create feedbacks amongst themselves but it is clearly important to understand such feedbacks early and to know if they are positive or negative.

The IPCC make a distinction between autonomous adaptations which respond to changing conditions but are not designed specifically for climate and planned adaptations which deliberately take climate change into account. In relation to water use, agricultural adaptation will comprise a mix.

Adaptations, such as biological and market adjustments, will be incremental, autonomous and "unnoticed". Adjusted cropping patterns, changing crop types and land use or even adjusting diets are all example of such autonomous changes. Many such adaptations can be quickly and easily implemented with good communications and social marketing campaigns, for instance.

Other changes, such as designing water control structures to cope with a higher frequency of extreme events will involve proactive planning on the basis of economic appraisal on the assumption investments now can lead to reduced uncertainty in the long-term and improved benefits in the short-term. However, such macro-planning requires broad inter-sectoral coordination, with implications for dams, levees, flood detention areas arising from increased frequency and severity of flood, which in turn impact human settlement including farming.

Given the trends in agricultural demand for water – as driven by population, income growth and changing diets, the key questions that comes back to agricultural water management is doing more with less. Competition for bulk water is already driving this autonomous adaptation but climate change is expected to sharpen the points of competition and give added impetus to water management adaptation to reduce demand and re-arrange supply or extend it through re-cycling and de-salination.

Adaptation is ultimately about maximising welfare over time. In the context of agriculture and climate change, taking advantage of the potential benefits of climate change can largely be handled by application of existing technologies from existing agro-climatic systems. Where the impacts are negative, they occur because the conditions have become worse than now, leading to the possibilities of using (sub-optimal) technologies and solutions from today's more marginal systems or better adaptation to those, and even more hostile or uncertain conditions.

Adaptation takes place on farm, the system/catchment and basin levels. The former is what farmers can and will do in response to how natural resource managers adapt the water supply regime at system scale, in the light of trade-offs and constraints at basin scale. Adaptations can be private or public, planned or autonomous. There is clearly a great deal of room for all, but private and autonomous adaptation will largely be in terms of what can or cannot be done in practice at the farm-gate. In the absence of planned and public strategies, farmers may find themselves in an age-old situation of some familiarity – fending for themselves. However, most richer country governments clearly take the view that co-ordinated and planned responses are required, even as they dodge the issues of responsibility and mitigation. Poorer countries are likely to do the same, but have much weaker economic foundations on which to do so.

In situations where climate change will have adverse impacts – principally in terms of reduced productive capacity due to declining water resources availability and poorer agro-climatic conditions for crop growth, the broad adaptive capacities and options can be summarised as follows (after UNEP, 2006):

1. Bear the loss – accept reductions in area or productivity.
2. Share the loss – distribute the impacts of reduced water resources to share reductions in area and productivity – a more managed approach involving a re-allocation of water use rights, for instance.
3. Modify the threat – at an individual level, expand farm size and benefit from economies of scale; improve water use efficiency through better technology and management, where real water savings can be made.
4. Prevent the effects – for example increase water and input use (perhaps the former is not a good example and is anyway a rare opportunity for many countries – though may work in cases where more favourable eco-regions emerge, as expected in northern China, possibly (and contentiously) in northern Australia, and in Northern America and Northern Europe.
5. Change use – crop change, land use change, change mix of rainfed and irrigated production on farm (if you have sufficient land to make a choice)
6. Change location – farming regions (see 4 above).
7. Research to find adaptations – improve crop productivity in higher temperatures and with greater moisture stress.
8. Educate for behavioural change

5.2 On-farm adaptation

Malcolm (2000) wryly observes that: '*a glance through history suggests that in the most important ways, the fundamental elements of managing a farm have altered little'*. Successful farm management in a commercial context will continue to depend on good decisions about the farm's enterprise mix, machinery replacement, land leasing or purchase, labour hiring, and off-farm investments. For subsistence farmers, the same is basically true, save perhaps the question of machinery, but in an increasingly large number of Asian countries, this is also a consideration (FAO, 2001). Much can be made of the differences between commercial and subsistence farming in terms of scale, technology and capital deployment, but the fundamental decision and management processes of how to produce more, and more reliably for the inputs made are remarkably similar.

Farm size and access to capital set the limits for the scope and extent of adaptation and change at farm level. Larger farms have more scope in changing and adapting enterprise mix (Nix, 197X): where conditions allow, the balance of irrigated and rainfed production can be changed on an annual basis, as in the irrigation areas of New South Wales in Australia. Larger farms can concentrate their water allocations on smaller areas, and (providing the supply is assured) move to higher value production, such as horticulture. Capital is still required to intensify, even at subsistence scale. Large farmers, such as commercial dryland farmers in South Africa, can afford capital equipment for timely operations, and can insure their crops against failure.

There is much discussion of extending crop insurance to developing country agriculture, but so far there is little progress in Africa and Asia, but emerging progress in South America (Cook, 2006). The total annual agricultural and forestry insurance premiums, worldwide, in 2001 amounted to some US$6.5 billion. Of this amount, 70 percent is accounted for by crop and forestry products. This sum must be compared with the estimated total farm gate value of agricultural production globally, which is US$1,400 billion. In this case the insurance premiums paid represent just 0.4 percent of this total. Geographically these insurance premiums are concentrated in developed farming and forestry regions, i.e. in North America (55 percent), Western Europe (29 percent), Australia and New Zealand (3 percent). Latin America and Asia account for 4 percent each, Central/Eastern Europe 3 percent and Africa just 2 percent (Roberts, 2005). Roberts (2005) identifies the challenge as smoothing the tensions between insurance being a business and run in the private sector, with agriculture and natural resources management being in the strategic national interest. Therefore insurance companies need to be sound and well backed, and international re-insurance is held to be an important stabilizer and back-up for emerging national companies as well as international insurers entering a more uncertain arena. It is suggested that there be a clear understanding of the national government’s role in promoting crop insurance, and if it is managed as another subsidy, considerably extra precautions are needed to ensure success.

Farm financing also is a major constraint on the adoption of better technologies and changes in practice. The first constraint is a lack of collateral for small subsistence farmers. Micro-credit schemes have variable success (REF, and where), and subsidies are often implicit, even in low cost technologies, such as “drip-kits” in Africa (Keller and Keller 2003, IDE, 2005). Where there is a consolidation of farming, if not in ownership, but in management, through renting, economies of scale may become more favourable. The declining real-prices of food products over the last 20 years has placed increasing pressure on “profit margins”, and it is not uncommon to find subsistence producers cross-subsidising their own food production from other sources in countries like Indonesia and Vietnam (ACIAR, 2005). It remains to be seen if the 2007 turnaround in crop and commodity prices will be sustained, and then to observe what impact it has on small farmer investment in technology, and ultimately the ability to adapt to the pressures of climate change.

Aerts and Droogers (2004) identify two main groups of adaptations at farm level: 1) improved farm management; and 2) crop production, to which could be added non-structural measures such as insurance, withdrawal (finding alternative income strategies and renting out land), diversification into specialist livestock production (as with pig production in China). Clearly different sub-sectors have different structural and capital bases, and differing constraints and abilities to adapt.

Irrigated horticulture (which is probably most of horticulture in developing countries…figures and REF) often services tight marketing niches. Reliability in water and input supply is paramount, and capital investment is much higher than for field crops. Within increasing involvement of supermarkets, and demand for year round supplies, lettuce varieties may be optimised to match 1°C changes in ambient temperature over each growing period (HRA, 2006). Vegetables, fruits and vines are all more sensitive to temperature change and water stress than staple commodities, but their better-endowed capital base gives them more options for adaptation in the medium and long term. Short-term climatic variation and uncertainty is dealt with through better technology and a high security in water supply. In many countries, high value horticulture

At the other end of the scale, small subsistence farmers growing low value staples (wheat, rice, sorghum, pulses) and have limited costs, but limited returns. Many true subsistence farmers may have no disposable surplus, but it is common for irrigators to have and sell excess production (REF). Larger scale cultivators of staple crops or small-scale producers of higher value field crops lie somewhere in between. Fodder producers for livestock cover the range from extremely vulnerable and poor, to highly profitable. For example peri-urban maize producers near Karachi, who grow 5 crops of fodder maize in year to sell to stall fed buffalo milk producers in the city.

Statistically, the largest proportion of irrigators produce staple crops of relatively low value, and the strategic interest of many governments in food security is based on the stable provision of coarse grains – rice, wheat and maize.

The options in improved water management include:

1. More efficient irrigation technologies that reduce un-productive evaporation losses.
    a. Sprinkler and drip methods of water application
    b. Direct seeding/dry seeding in rice (Bouman 2007)
    c. Soil moisture retention through conservation tillage (zero tillage, direct seeding etc, Ahmad (2006))
2. Deficit irrigation – to reduce actual evapotranspiration whilst maintaining (cereals) or even enhancing (fruits) yields (Jerie, 200X)
3. Reduction in local (on farm) storage losses due to evaporation
4. Better spatial uniformity of irrigation to minimise accessions to saline water table in areas where saline groundwater table is a problem (many surface irrigation areas in the arid and semi-arid tropics).
5. Reduction in evaporation losses from bare soils (organic and plastic mulching; dust mulching)
6. Dynamic and changing balance of irrigation and rainfed production from year to year.
7. Adoption of irrigation or water harvesting practices where conditions allow.
8. Improved management - intensification of use of other factor input such as fertilisers, pesticides, soil amendments, better timing of operations.
9. Improved drainage

It is very important to be clear that adoption of a “better” technology does not guarantee a saving of water. A wide range of international experience shows that management of water saving technologies is crucial to achieving their potential for success. A recent study of the adoption of micro-irrigation in Andra Pradesh revealed that water usage actually increased through larger unit delivery and an expansion of intensively irrigated area, driven by the profitability of the crops and technology, and limited costs and concerns for water conservation (Rao, 2006).

Adaptation strategies related to crop pattern, can be summarised as follows (adapted from Aerts and Droogers, 2004):

1. Change crop to one with greater resilience or value.
2. Change planting dates for a better match with season length and productivity in relation to temperature, water availability and rainfall.
3. Use better adapted varieties for the same season, or for a shifted season.
4. Increase on-farm diversity of cropping/enterprise mix, with or without livestock.
5. Change (increase) cropping intensity, where possible: this requires increased rainfall, or a reliable source of irrigation, or a sharing water over two crop seasons instead of one with sub-optimal or deficit irrigation in each one.

6. Expand area and irrigate sub-optimally – increase total production and returns to water with lower yield – but this is only possible if land surplus is available.

Howden *et al.* (2003) reviewed the adaptive capacity of the more commercial Australian agricultural sector to climate change and **found that most potential adaptation options for Australian agriculture were extensions or enhancements of existing activities for managing current climate variability**. In broad-acre farming a range of coping and adaptation options are either available or in need of development. An incomplete list, rather more nuanced than the options given above, is derived from Pittock (2003), Fuhrer (2003), Ash *et al.* (2000) and Howden *et al.*, and includes:

1. development of varietal portfolios suited to greater weather-year variation. In particular, developing varieties with greater drought tolerance, heat shock tolerance, resistance to flower abortion in hot/windy conditions, resistance to new or more virulent pests and diseases.
2. reduction of downside risk of crop production (e.g. staggered planting times, erosion control infrastructure, minimum soil disturbance crop establishment, crop residue retention, varietal portfolios)
3. further facilitation of crop operations (e.g. seeding, spraying, swathing and harvesting) by improvement in skill of weather forecasting
4. further facilitation of decisions about crop type, variety selection and crop input levels by improvement in skill of seasonal forecasting
5. greater opportunism in planting rules and planting decisions (e.g. time of sowing, seeding rates, row spacing, tactical applications of nitrogenous fertilizers)
6. improved pasture and crop management decision support systems based on satellite imagery technology and advisory services drawing on expert systems
7. further facilitation of decisions about stocking and de-stocking through improved climate prediction systems that more accurately forecast the extent and duration of drought
8. alteration of mating time or mating populations based on seasonal conditions and forecasts
9. development of water use efficiency strategies to manage potentially lower irrigation water availabilities
10. assessment of genetic variation across and within livestock breeds regarding their production response to extreme heat, so that more productive animal systems can be developed
11. development of low cost surface sealants on farm dam catchments to allow run-off from small rainfall events
12. development of low cost desalination plants to use saline groundwater to supply water to stock or irrigated crops
13. utilization of R&D findings on the effect of prolonged dry conditions and extreme heat on weed and pest ecology, especially weed seed survival
14. re-design of farm housing, building, machinery and outdoor clothing to accommodate extreme heat
15. development of profitable crops or tree species that include returns as renewable energy or carbon sinks

Examples of risk management measures would be the rice/maize systems in South Eastern Tanzania, where rice and maize are grown simultaneously in alternative rows on heavy, black cotton style soils. If one year it floods, then the rice survives, whereas under drier conditions it is the maize that is harvested. Similarly, around the shores of Lake Poyang in China, one encounters wheat and rice planted together, but this time on sandy soils. In both cases however, production is low – but at least risk is avoided.

5.3 Adaptation at irrigation system level

5.3.1 Introduction

Irrigation will remain very attractive as an adaptation to further water scarcity and variability, especially where seasonal and inter-annual storage (in reservoirs or groundwater) is involved. At the same time, irrigation itself becomes less of insurance as water availability decreases, unit demands increase, higher value uses draw water away from farmers to cities and industry and variability increases. As we learn better how to value and conserve aquatic ecosystems that support livelihoods and even agriculture as a system, the stress on irrigation will further increase. Other agricultural water management practices that are important are drainage, flood control, and water conservation agriculture in rainfed systems.

It is unfortunately true, that if irrigation is vulnerable to climate change, then all shorter-term strategies aimed at conserving and optimising the use of rainwater stored in the soil are more vulnerable. In areas where cropping is almost fully dependent on irrigation, such as Pakistan, that dependence will remain, and at the same time be exposed to greater demands and conflicting stresses.

Very broadly, there may be less irrigation than now, where less water is available and demands are higher (as in south eastern Australia) and there may be more irrigation where water supplies are sufficient but climatic variability has increased sufficiently to require it (northern Europe, for example). Alternatively, less water can be applied, usually with a consequent reduction in yield. Improved water use efficiency may offset this or even increase production whilst depleting less water, but this in turn depends on many factors from breeding through management and the use of other factor inputs of production. The balance of production of high and low value commodities may change, and the over-riding factor will be national government policy to food security and subsistence livelihoods at one end of the spectrum (say India) to economic efficiency at the other (for example Australia).

5.3.2 Supply Allocation

The options for adaptation by water managers include better and more sophisticated water allocation and its corollary, better service delivery (Aerts and Droogers, 2004). More sophisticated water allocation provides different users and uses with differentiated products, usually at differing prices. High security water supply for rural towns, permanent plantings (orchards) and high value vines and horticulture costs considerably more than general security allocation in Australia. Improved allocation requires improved information for water users to assess and make decisions – for example about how much area they will plant and to what crop. Allocations need to be set with regard to long-term hydrological variability, and an understanding of that on the frequency of low allocations and drought sequences. As more information becomes available about the trends in means and variability of rainfall, runoff and recharge, these allocation procedures can be updated or managed accordingly.

Allocation announcements, that are regularly updated are helpful, the more so if they are given in with different levels of probability so that farmers can make their own assessment of risk. Better allocation may use weather and climate forecasting tools, such as ENSO and stream persistence (Panta et al., 1998). Clearly this level of sophistication is better tailored to smaller numbers of larger farmers, and different approaches to improving allocation, mostly through better bulk allocation to groups of users, are more appropriate where there are large numbers of poor, small farmers. Allocations could be redefined across the spectrum of surface, groundwater and conjunctive use and almost uniformly need to be designed in such a way as to internalise natural hydrologic variability. Once this is in place, the mechanics of dealing with more variable water availability due to climate change impacts (and re-allocation to other uses) becomes more comfortable and familiar. Even sophisticated allocation systems can still witness zero allocations in protracted drought, but drought risk can be delayed and sometimes offset if users are allowed to manage their allocations across successive water years. This is necessary if they are to be able to adopt productivity strategies that spread water use across seasons and years. Of course, storage management and storage losses may have an impact on the benefits of such strategies.

5.3.3 System Performance

Enhancing the performance of irrigation systems through modernization of institutions and technology to be more responsive and flexible as supply allocations become more volatile will continue to be the main systemic means of adaptation (FAO, 2007b). Water efficiency and agricultural productivity gains can result if improved management can be effective across the whole scheme – including the scavenging of drainage and prevention of waterlogging and salinity build up.

Irrigation service providers are now under pressure to become reliable, transparent and equitable in their delivery to farmers while infrastructure and equipment improvements are sought to facilitate greater physical efficiency and flexibility at user/scheme level. For instance, where irrigation on demand is a possibility, experience tends to confirm that users abstract less than when supplies are available only on a rotation basis (Fontanelle 1999).

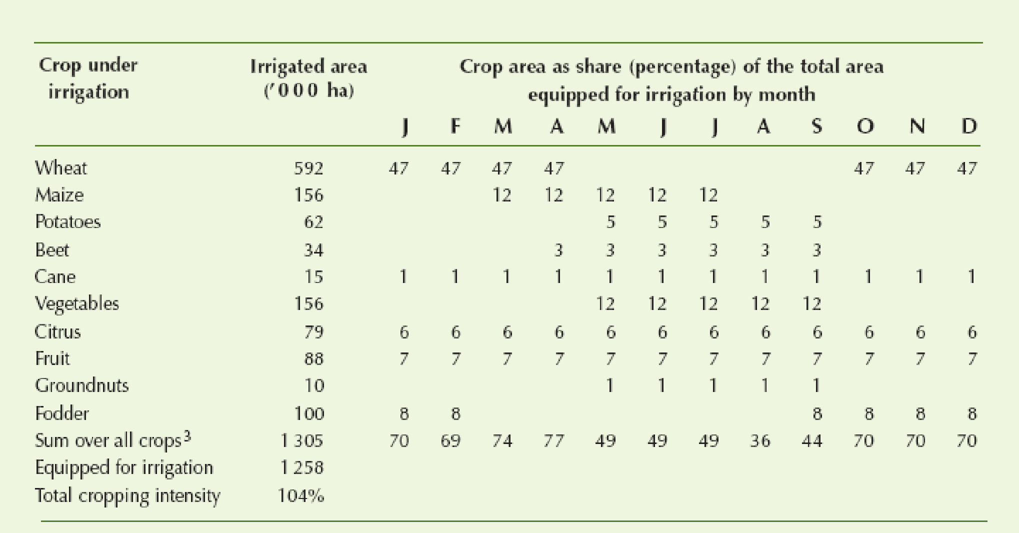
However, the nature of water use efficiency has an important element of scale. Increased physical efficiency at user/scheme level only translates into increased water productivity (or economic efficiency) if there are mechanisms to reallocate the saved water elsewhere in the water economy of the basin (this may or may not involve irrigation). In Egypt for instance, the physical efficiency of irrigation water use in-field is low at around 30%, while, as a result of downstream re-use, its economic efficiency, with respect to water quantity only, is around 230%. Progressive salinity build-up in the cycling of drainage water clearly limits this process. Therefore adaptation measures to cope with increased water scarcity do need to be accompanied by accompanying measures that reallocate the savings in way that maximizes overall system and basin benefits.

5.3.4 Cropping patterns and calendars

The scope for adjusting cropping calendars and crop types in line with reduced or more volatile water will still be constrained by market conditions which will determine whether the revised harvest or new product be sold at an acceptable price level at the time of harvest. This tends to be less of a consideration with high value horticultural production, for instance, but is an important consideration if lower value staples are irrigated since irrigated production can compete with rainfed production and undercut rainfed producer prices. Adjustment of cropping calendars is already noted through MODIS imagery analysis for the Nile basin (FAO, in press) which may be indicative of an adaptive shift.

An example of cropping calendar for irrigated production Morocco (Box 5.1) to illustrate what is possible in a country whose agriculture is operating beyond the limit of its renewable water resources. Despite a distinct climatic advantage in relation to European markets, cropping intensities on land equipped for irrigation are still only in the order of 100%. Given the AR4 projections for the Mediterranean basin, the room to adjust cropping patterns and calendars in such countries may be limited.

Box 5.1. Irrigated production cropping calendar for Morocco



Crop under irrigation	Irrigated area ('0 0 0 ha)	Crop area as share (percentage) of the total area equipped for irrigation by month											
		J	F	M	A	M	J	J	A	S	O	N	D
Wheat	592	47	47	47	47						47	47	47
Maize	156			12	12	12	12	12					
Potatoes	62					5	5	5	5	5			
Beet	34				3	3	3	3	3	3			
Cane	15	1	1	1	1	1	1	1	1	1	1	1	1
Vegetables	156					12	12	12	12	12			
Citrus	79	6	6	6	6	6	6	6	6	6	6	6	6
Fruit	88	7	7	7	7	7	7	7	7	7	7	7	7
Groundnuts	10					1	1	1	1	1			
Fodder	100	8	8							8	8	8	8
Sum over all crops[3]	1 305	70	69	74	77	49	49	49	36	44	70	70	70
Equipped for irrigation	1 258												
Total cropping intensity	104%												

Source FAO, 2003.

Conjunctive Use

Conjunctive use of surface and groundwater is widespread in large surface irrigation systems, throughout Pakistan, northern India and northern China. Increasingly, this is an autonomous and privately financed adaptation to poor service and restricted water availability in surface irrigation systems. There is considerable scope to improve the management of conjunctive use of ground and surface water, in maintaining effective recharge, managing salinity and improving the productivity of water use. Conjunctive use may offer a cost-effective adaptation to the storage problem associated with glacier melts systems – runoff patterns will change, median flows reduce and peak flows increase in the sub-Himalaya. Enhanced ability to store and manage these flows as groundwater is inherently attractive, subject to satisfying other competing and in-stream needs. There are significant policy and water management dimensions to moving from conjunctive use to management, and the state has a key role in assessment, promotion and facilitation of local institutions of management, sensitizing its irrigation bureaucracies and evolving locally based, economically effective compliance networks.

There is a useful potential trade-off between using groundwater to improve drought proofing, by selectively abstracting only in drought years, and above a well-defined level of impact. Although this makes great strategic sense, it is hard to implement and police. Many governments are under extreme pressure to provide short-term solutions, even at the cost of more severe long-term impacts.

The last observation related to groundwater is that, in general, we lack insight and knowledge about the extent of the resource, the modes and effectiveness of recharge, and the true extent and pattern of abstraction. Given that groundwater, and improved groundwater management will be key to successful and economically attractive adaptive strategies, a big effort is required to improve the science and socio-ecological base of groundwater use and potential.

The mitigation of salinity on farm will become a more challenging task in areas within lower and more variable rainfall. Mitigating soil salinity, whilst having lower water availability will often presage abandonment the farm, as has happened under structural adjustment programmes in north-western Victoria, Australia. Strategically, and if alternative lands are available, and compensation can me made to failing producers, it makes sense to re-allocate water to areas with less or no salinity problem. Maintaining irrigation supplies in saline areas inevitably results in lower water productivity than if the water was allocated elsewhere. One of the main reasons for further enabling the water market in Australia by severing water entitlement from land title was to enable sales of permanent water right to compensate farmers leaving saline and other unproductive areas (Turral at al, 2006). Water markets have evinced great international interest, but most developing countries do not have sufficient institutional and water accounting capacity in place to implement them equitably and effectively (ibid).

5.3.5 Irrigation policy measures

Water pricing continues to be advocated as a tool to limit demand, and shift production to higher values (Aerts and Droogers, 2004), at the time as other authors doubt the ability of water pricing to deliver this, suggesting that since water service charging strategies have yet to travel a long way to even cover operational costs of irrigation service (Molle and Berkoff, 2007) resource pricing remains an unattainable objective. Certainly many countries are loath to charge fully or even at all for irrigation service, whilst others have quite rigorous systems (emerging in volumetric pricing in China, and a long tradition in Vietnam). We see water markets continually promoted by the World Bank and other international agencies, with little acknowledgment of the institutional and information impediments outlined in section 3. However, an analysis by Beare and Heaney (2002) of the potential for increased water use efficiency and water markets to mitigate economic losses in the irrigation sector arising from climate change, finds in favour of markets. This is in a country with an established and active water market – Australia, but is again highly dependent on the assumptions made underneath the modeling.

A very likely autonomous response to climate change will be further, and extensive development of groundwater. In the policy dimension, this could be viewed as "mission impossible", and it will be important to avoid the current trap that many states in India have fallen into. Although the provision of subsidies to locate and drill wells have largely been restrained, it has, an continues to prove politically impossible to back away from the provision of partial and full electricity subsidies to irrigation pumpers. This is resulting in many negative impacts arising from falling water table and competitive deepening of wells, including failure of domestic water supplies and associated fluoride contamination. Initiatives in Andhra Pradesh (www.apfamgs.org) are attempting to reverse resource depletion and degradation through programmes of self-monitoring to improve the management of groundwater resources and reduce agricultural risk. At the same time the financial burden of free agricultural power supply is a heavy burden on state finances, with imminent financial collapse of state power authorities (Shah, 2007).

Although extremely challenging, establishing good groundwater governance is therefore a key part of the policy matrix of climate change adaptation. In developing countries with large numbers of small users (famously 20 million in India), the transaction costs of licensing, fee collection and auditing are very high. Rational energy pricing, even at flat tariffs, may not completely restrain groundwater abstraction to sustainable levels, but should go a long way to avoiding short term loss of the resource. This will prove to be an increasingly political problem as governments try to juggle rural livelihoods with sustainable development.

5.4 Adaptation at river basin level

Comment: It would be useful to relate this to the typology of irrigation contexts and climate change.

5.4.1 Coping with droughts

The regional response to drought within river basins has been continual pre-occupation in agricultural water resource management (FAO, 2004). No specific adaptation measures over and above the range offered in the example of the Limpopo can be anticipated.
TO BE COMPLETED

5.4.2 Coping with flooding; structural and non-structural interventions

Structural solutions to flooding either to shift the problem downstream or to attenuate its passage downstream. Land drainage for instance, while draining land that is immediately affected by flooding simply increases downstream flow, sometimes catastrophically as evidenced by recent events in the Danube and Rhine basins. Similarly, containing floods within the natural drainage system by means of levees does the same thing while in addition disrupting flood plain functions introducing the possible of significant, negative implications for biodiversity and capture fisheries (due to the gene pool deterioration that accrues to fragmentation of water bodies).

At some point therefore, if the flood is to be managed rather than moved it will have to attenuated, and this requires either a functioning flood plain or an adequately sized water body, natural or man-made, with suitable stage storage and outflow characteristics.

Non-structural measures include storage trading where dams are available and insurance or compensatory schemes.

Storage trading is one possibility. Where operating rules of say, hydropower dams can be "relaxed" either due to indemnification against production losses by those at risk downstream, or because remote sensing upstream obviates the need to keep the dams full then storage volume can be kept in reserve in order to attenuate flooding without recourse to new investments (notwithstanding that a remote sensing facility is of course an investment).

Examples of adaptation would include the Lower Nile Valley where communities learned to adapt to the Nile's annual flood, or Bangladesh, where the annual flood plays a vital role in the agricultural economy by i) by bringing fertilising silt; ii) replenishing the ground water supplies on which a significant amount of the irrigated agriculture is dependent; and iii) maintaining the connectivity of water bodies, thereby maintaining biodiversity in capture fisheries.

5.4.3 Groundwater and Managed Aquifer Recharge

Despite the growing reliance on groundwater resources for municipal and agricultural services (Burke and Moench, 2000), aquifer recharge is one of the least explored aspects of climate change impacts. – probably because it is anyway an uncertain process in many parts of the world and there is great uncertainty associated with rainfall patterns which is amplified through variability in runoff, and also other impacts on surface water use. Obvious climate related impacts, in general terms, are:

- If flooding increases (frequency and extent), aquifer recharge will increase, except in continental outcrop areas. A significant part of aquifer recharge happens during over-land flooding (Australia, Bangladesh…..)
- If drought frequency, duration and severity increase, the cycle time will lengthen, and abstraction will need to be better balanced, with less in sequences of wet years and more in dry ones. There is clearly greater potential for banking groundwater for use in extended droughts as a first line of reserve, although there are considerable challenges to the governance of such regimes, in terms of the transaction costs of monitoring and compliance, and in the communication and institutional arrangements required for implementation.
- If snow melt increases, aquifer recharge rates should increase but this is dependent on permafrost behaviour and recharge patterns, which remain largely in the realm of unknown science.

Localised alluvial aquifers that are annually replenished have good connection to surface flows and are dependent on stream flow (duration and stage) and surface water bodies for recharge. Groundwater in such systems serves to buffer annual and seasonal variations in rainfall and runoff, and will require increasingly careful management for sustainable use. The influence of land use on groundwater recharge is generally well documented in post-industrial economies where groundwater is an important component of potable supply. However, it will be important to understand the relative importance of base flow versus flood events in long term recharge of alluvial aquifers. The role of forests in raising base flow, even while reducing overall runoff, needs to be better understood.

The benefits of groundwater in allowing broad and even access (Shah 2006; 2007) will need to be tempered against 1) the difficulties and transaction costs of regulation and control over abstraction; 2) avoidance of pumping subsidies which promote over-abstraction; 3) water quality problems associated with groundwater use, including salinisation, fluoride mobilisation and elevated arsenic content; 4) the promotion of increased fossil fuel use in agriculture as a contributor to greenhouse gas emissions. There has been some recent research in technologies and strategies for groundwater recharge in Australia, US and Central Asia, but more will be required. A good understanding of surface and groundwater interactions is increasingly understood to be important. Whatever the balance of storage technologies and strategies is appropriate in precise contexts, groundwater management will assume increasing importance and complexity. It will require good information and data to allow proper accounting and abstraction strategies that are better tailored to meeting inter-annual variability in recharge and optimising use between average and dry years.

5.5 Adaptive capacity in agricultural water management – policies, institutions and the structure of the sub-sector

5.5.1 Mechanisms for allocation

Under conditions of scarcity and competition, the fundamental issue of water allocation – who gets what – can be expected to become much more prominent in public debate. Allocation systems have to smooth out short-term variability in supply and meet longer meet development objections. A challenge in water allocation and hydrology is to understand the nature and partitioning of return flows between uses or parts of a landscape (up-stream to downstream in a basin). It will for instance be necessary to separate regulatory from supply functions, and then to ensure that transparent, well-enforced regulations are in place. This in turn may require a reconciliation of economic efficiency and equity in relation to water. All this places new demands on the institutional landscape. In addition, there are infrastructural implications. In order to manage and allocate water as a scarce resource the ability to monitor flows and distribute them accurately and reliably will become increasingly important. This will require appropriate new infrastructure and the institutional capacity to operate it.

Reconciliation of growing demands with declared environmental preferences further complications the issue of allocation. What is very clear is that maintaining the highest possible levels of biodiversity is a sensible adaptation measure to climate change. With a wide biodiversity base, aquatic ecosystems stand the best chance of being able to adapt to the changes that are already happening. Climate change is also increasing awareness of the crucial role of the services that wetlands provide, for example in the sustained delivery of freshwater, nutrient recycling and the mitigation of extreme rainfall events (both droughts and floods), and the role of healthy coastal wetlands in mitigating the damage caused by extreme storms. Using nature's ability to cope with change is a sensible and cost effective response option to climate change and in this process considerable benefits will also accrue to biodiversity and the fisheries reliant upon it.

5.5.2 National food policy issues

In a scenario of a globally averaged increase in temperature, agriculture may progressively adapt to new conditions, resulting in incremental changes in cropping patterns. In more extreme or rapid scenarios, large areas of staple food production would be affected, and when combined with surges in demand from transition economies, buffer or carry-over stocks will be depleted and prices can be expected to rise.

Populous and poor countries have tended to place a high premium on self sufficiency in food, and are reluctant rely on trade. China, with the backing of enormous industrial wealth, has relaxed slightly in its attitude to importing food, but nevertheless continues to place a great emphasis on maintaining self-sufficiency (CAAS, 2007). The existence of significant food stocks does not necessarily ensure food security, as witnessed by a number of localised famines in India in 2003, at the same time that central food stocks were at an all time high around 60m tonnes, a proportion of which was rotting due to low turnover (REF). Nevertheless, there is clear possibility to substitute new water storage by inter-annual grain storage, providing the dynamics of surplus and deficit years can be determined, and the necessary distribution infrastructure put in place to provide food where it is most needed. Clearly it is possible to buffer inter-annual and seasonal variation in food supply through storage. This has been a central pillar of food policy in many countries (with dedicated and powerful agencies such as BULOG in Indonesia), but food stocks in both China and India have been run down in recent years (Von Braun, HTTP://WWW.IFPRI.ORG/PUBS/AGM07/JVBAGM2007.ASP).

Agriculture based livelihoods are likely to be most impacted by climate change, and Africa is likely to be the most adversely affected continent (Stern, 2006). The most vulnerable people are the poor, landless and marginal farmers in rural areas dependent on isolated rainfed agricultural systems in humid, semi-arid and arid regions; small changes in rainfall can result in locally significant changes in surface water and groundwater resource availability in the semi-arid and arid regions. Further compensatory irrigation development will be necessary in these regions, both in areas where it already exists and to supplement rainfed areas. Necessary changes to fixed capital associated with irrigation may represent one of the largest costs associated with climate change adaptation, and this will present considerable challenges to the poorest farmers (Quiggin and Horowitz 1999).

5.5.3 Institutions

Building resilience among affected populations can be achieved through a mix of rural development strategies in which all forms of agriculture and water management, not only irrigation, will contribute to food and livelihood security. Possible changes include crop diversification, less water intensive varieties or increasing irrigation water use efficiency. While some farming communities prove resistant to change, particularly if incentive arrangements such as credit facilities or hedging mechanisms are not aligned, the Comprehensive Assessment (CA, 2007) foresees a general "industrialisation" and high value orientation of irrigated production, with the caveat that the bulk of demand will remain as staples. This trend is emerging with aggregation of farmed holdings (not necessarily ownership) and a declining proportion of the population engaged in agriculture.

The ADAPT project (Aerts and Droogers, 2004) considered adaptive capacity at three levels :

- field and farm;
- water manager ; and
- policy maker.

This can be seen to match well with the impact pathways outlined in Figure 5.1.

At a national level, there are a number of options to adjust the focus and balance of agricultural water management. Investment and subsidies can follow shifts in agro-ecological zones, and can focus on areas that continue to have comparative advantage. This approach makes sense in terms of food security but is less likely to deal with problems of social and livelihood equity. Subject to water resources availability, and the economics of management, storage and construction, irrigation can be "re-located" to less impacted or more productive areas. Alternatively new irrigation systems can be constructed, or governments can create incentives for private development (mostly in groundwater).

Governments will also play a key role in policies and incentives that define the balance of irrigated and rainfed agriculture in different river basins. Different approaches will be required depending on preferences and careful scrutiny of rural benefits. The trade-offs in water scarce basins will be between the value of a reliable if also more variable irrigated production base, versus a larger area of rainfed production, which will be increasingly vulnerable to climatic extremes. Governments will also have to factor in GHG mitigation strategies through agriculture, both via the substitution of fossil fuels with bio-energy and the sequestration of carbon in vegetation and soils. Again, such considerations and complexity argue for more detailed and localised analysis of impacts and adaptive strategies.

National government will, as now, play a strong role in protecting agriculture from flooding and water logging as a matter of public interest. This will be both through structural measures, and increasingly through non-structural approaches. Approach to drainage that involve the generation of greenhouse gases, such as pumped drainage, will increasingly come under review, and more attention will be paid to the carbon accounting in the protection of agricultural crops from flood hazard.

Wastewater re-use from cities offers an increasingly reliable flow of water for agriculture, albeit with vary variable and often hazardous quality. Untreated wastewater is being widely used, often without government sanction and without appropriate public health safeguards (Scott et al. 2004). Although industrial use is rising dramatically, the total volume available is a fraction of agricultural water use (about 5-15 % of total abstractions, potentially rising to 30-35% in some parts of China and India) (Van Rooijen et al, 2005: 2008). Increasingly a large proportion of urban water use will be sourced from agriculture (Molle and Berkoff, 2006) and will contribute to a reshaping or location of parts of the irrigated landscape. Government will become more directly involved in managing and safeguarding this resource.

Finally, governments can and will underwrite the research into adaptation of crop patterns, and the adoption of on-farm technologies and management responses, and can also incentivise these through market levers or subsidy programmes.

5.6 Long term investment implications for agricultural water management

Estimates of sector investment needs have been given for both agriculture and water supply by the UNFCC (UNFCC, 2007). The water demand estimates are derived from Kirshen (2007). These estimates are based on partial baseline data and generalised modelling assumptions. The quantity of investment in well adapted agricultural water management is perhaps less important than the quality.

Adapting to climate can be seen as an opportunity to change particularly if taken combination with other socio-economic shocks, including managing transitions to higher value crops or even transitions out of agriculture. With respect to large scale investments in irrigation systems and associated flood protection structures, there is little point in capital expenditure that is compromised by climate change before the end of its economic life – this is an important conclusion of the Stern report, for instance, but it does involve a debate over the use of appropriate discount rates and the extent to which some natural resources can be considered as economic substitutes. (Neumayer, 2007). Overall, irrigation costs will increase – primarily through re-adjusted operation costs and subsequently capital costs. Even without investments in additional inter-annual storage, for instance, the operational costs of re-designing and re-scheduling irrigation on the basis of more extreme or more frequent hydrological events are not negligible.

These considerations notwithstanding, two positive outcomes can be anticipated. First that adaptation may involve regional concentration of irrigation where domestic resource cost ratios are low in a particular crop sector and natural resources less constrained (e.g. gravity schemes such as Office du Niger in Mali). Under suitable trade agreements, there may be good economic and resource management reasons for establishing regional production centres in food staples and thereby relieve pressure on domestic production where climate variability is expected to worsen. Second , the prospect of change may present an opportunity to re-tune investment styles. With more emphasis on early warning systems and demand management rather than direct structural investment, new economic opportunities.

It is not possible at this stage to determine the incremental costs of climate change adaptation in terms of water management alone. This can only be done on the basis of national economic analysis of the water economy. However it is possible to indicate what the scope of that investment could be – assuming a national consensus on the urgency of implementing an adaptation strategy has been reached.

An immediate adaptation that would have impact at scale is the adjustment operational rules for multi-purpose dams and large scale irrigation schemes. Such operational fine-tuning of existing assets can extend to the point of delivery and would eventually necessitate overhaul operational institutions and farmer awareness.

In the short term, the scaling of small-scale water control initiatives that exploit shallow groundwater circulation to take advantage of inter-annual storage will offer the most scope for autonomous adaptation.

In the short to medium term, the rehabilitation and modernization of existing irrigation schemes can be expected to come viable if demands upon supply and climate shock necessitate.

In the medium to long term the adjustment of storage and investment in new build water control can be appraised but with the acceptance that most of the economic sites have already been developed and that the marginal cost of increasing irrigated areas will be significantly higher, necessitate higher factors of safety or involve substantial energised pumping.

It should be stressed that in all cases, institutional capacities would need to be adjusted to suit and that environmental appraisal will also be called for to maintain biodiversity and protect existing uses.

Box 5.2: The case of Investment choices in Australia

The broad pattern for SE Australia been confirmed by more detailed regional climate modelling and the use of statistical downscaling with expected reductions of stream flow of -40% by 2070 in North Eastern Victoria (DSE, Victoria, 2007) and -20 to -30% in the Murrumbidgee and Macqarrie Vallies in New South Wales (CSIRO, 2007).

The biggest implication of reduced runoff is that expected water allocations for irrigation, and water availability for environmental flows will both decline, as is the case for the Murray-Darling Basin. An immediate consequence of reduced surface water availability is that the trade-off between environmental and agricultural water use will come into sharper focus.

There are a number of important aspects of the changes in runoff: where yields are expected to decline, we can cautiously assume a reduction in groundwater recharge, but this may not always be the case. Due to an expected increase in the frequency of larger rainfall events, there is likely to be an increase in peak runoff rate, and increases in probable maximum flood. This has implications for storage management in that the proportion of currently available storage that would be filled in the future may decrease, unless peak flows can be captured and stored. Where runoff declines and the proportion of large events increases, we can expect lower median annual storage volumes and supply security. At the same time, spillway sizes will have to be increased to pass larger probable maximum floods, especially if more dams are designed or modified to harvest peak flows and carry storage from year to year. Thus the costs of surface water storage can be expected to increase, especially in terms of unit costs of median annual volume stored. In Australia, there has been a revision of estimated Probable Maximum floods (Australian Rainfall and Runoff, 1999) and a revision of spillway capacity, overseen by ANCOLD (Australian National Committee on Large Dams) (CSIRO, 2007). If this logic is correct, then there will be considerable interest in enhancing groundwater recharge as an alternative and possibly cheaper means of storage

6 PROSPECTS FOR MITIGATION

6.1 The greenhouse gas emission context

This review of mitigation prospects takes a less hierarchical approach that that used for the adaptation above It focuses on specific aspects of agricultural water management that contribute to greenhouse gas emissions and offer prospects for mitigation. In addition to the impacts of cycles of wetting and drying, the concentration of inorganic and organic fertilizer on land with some form of water management means that the practice of irrigation has scope to mitigate GHG emissions. Global emissions by sector and greenhouse gas are summarized in Figure 18, which shows that agriculture is a significant contributor (13.5% of total), but only in terms of methane and nitrous oxide.

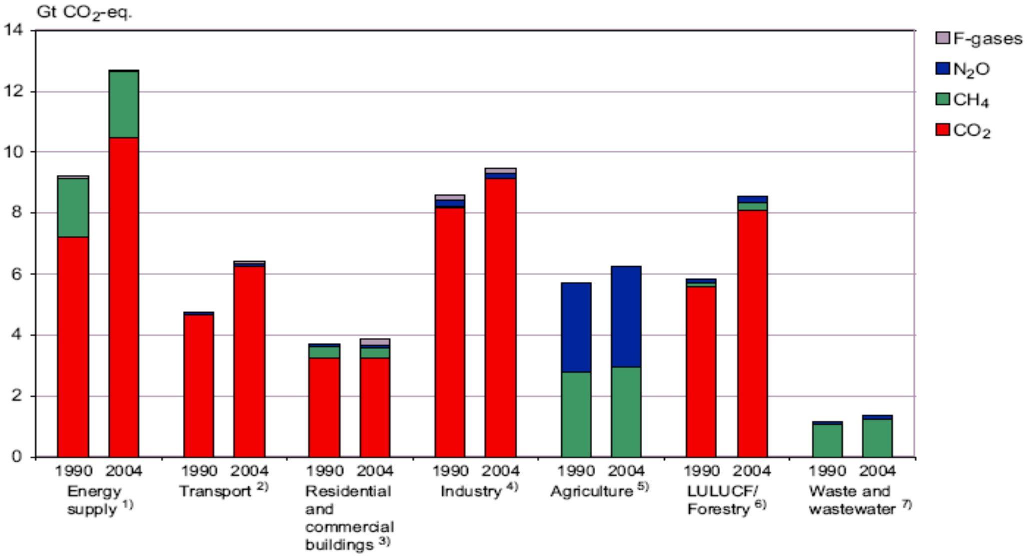


Figure 6.1 *Contributions to global greenhouse gas emissions (CO2 equivalent) by sector and gas in 2004 (Source FAO or IPCC).*

Globally, there has been an increase in GHG emissions of 70% from 1970 to 2004, with a reported increase in emissions of 27% in agriculture from 1970 to 1990 (REF). Figure 18 indicates that most of this increase is in the form of N_20, attributed to increased and inefficient use of artificial fertilizer.

The Stern report (2006) noted that the prospects for stabilizing greenhouse gas concentrations will be determined considerably by the price attached to carbon equivalent in the future. At three levels of prices, the potential for stabilizing carbon at between 445 and 710 ppm in 2030 are summarized in Figure 6.2.

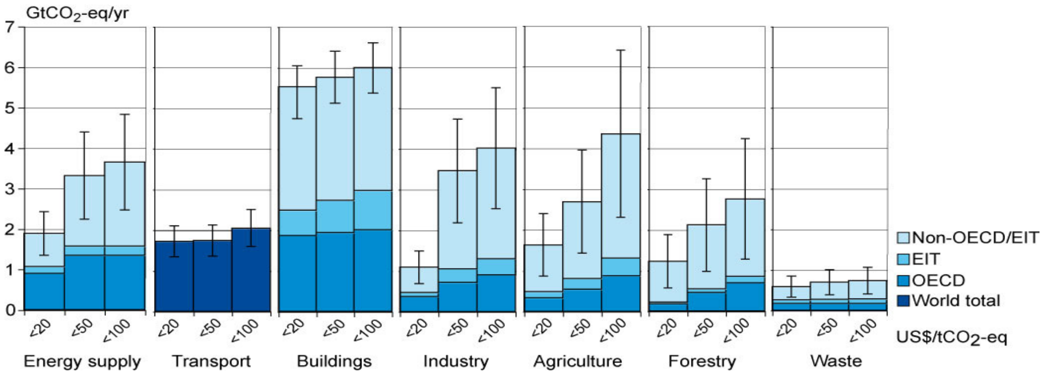


Figure 6.2 *Potential for GHG mitigation by sector, in 2030, based on three costs (US$ per tonne CO_2 equivalent)*

The prospects for mitigation are thought to be relatively high in non-OECD country agriculture and forestry, but with a high levels of uncertainty. Global emissions of nitrous oxide and methane are predicted to continue on a rising trend to 2020 to 8000 Mt of CO_2 equivalent, or about 60% more than in 1990. Minor decreases in Europe and a very minor increase in North America, will be overtaken by major increases projected in Sub-Saharan Africa, South and East Asia and in South America (FAO, 2007?). FAO (2007) estimates that 65% of the potential for mitigation lies in developing countries, and that 50% of the total could be due to reducing deforestation.

The prospects for mitigation within agriculture are summarized in figure 6.3, based on three different prices of a tonne of carbon dioxide (FAO, 2007?). Although livestock and rice are the main contributors of GHGs, the main potential for mitigation is thought to lie in the restoration of cultivated organic soils (predominantly peat lands in the tropics?) and associated measures to increase or restore the carbon content of depleted and degraded soils. Even a 1 percent increase in carbon content in the top 10cm of a soil translates into significant amounts over large areas – for example an increase of 1% carbon in the top 10cm of a typical soil with a bulk density of 1.5 t/m3 is equivalent to 15 tonnes of carbon per ha. Taking the irrigated area of the world (270 million ha), the potential is clearly there to the level of several Gt.

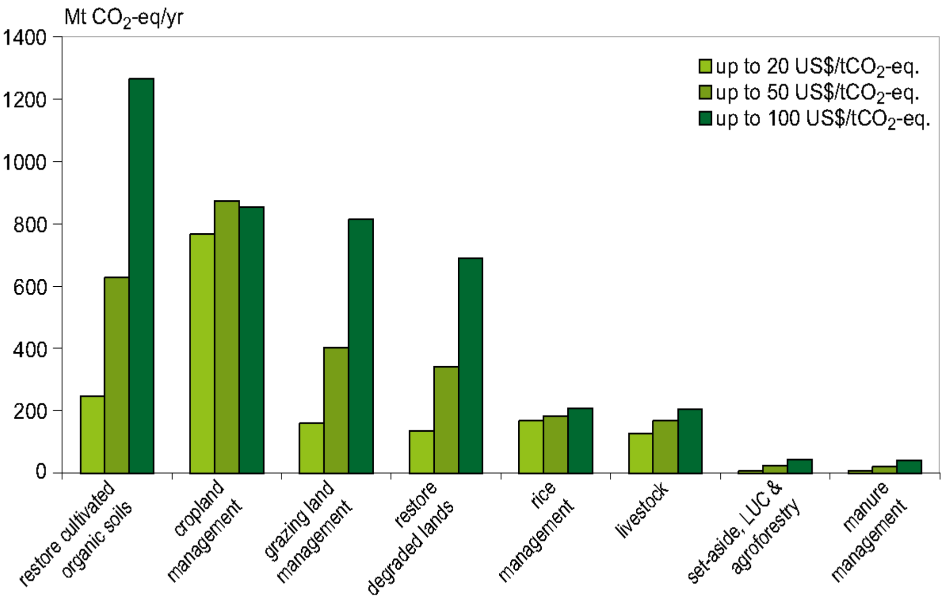


Figure 6.3 *Potential for GHG mitigation through different agricultural activities*

Improved agronomic practices that increase yields and generate higher inputs of carbon residue can lead to increased soil carbon storage (Follett, 2001). Examples of such practices include. using improved crop varieties; extending crop rotations, notably those with perennial crops that allocate more carbon below ground; and avoiding or reducing use of bare (unplanted) fallow (West and Post, 2002; Smith, 2004a, b; Lal, 2003, 2004a; Freibauer *et al.*, 2004). The key question is for how long and whether water management makes adoption of such practices easier or harder.

6.2 Agricultural water management and greenhouse gas emissions

Irrigated agriculture accounts for only 17% of the area of global agriculture, but is more intensively managed, and on average uses greater amounts of inorganic fertiliser (NPK) and other agro-chemicals to protect its relatively higher value production (REF). Where groundwater is used for irrigation, the fossil energy costs of supply may be high. Lemons et al (1998) report that US wheat and maize production use 4.2 and 3 times more energy respectively under irrigation compared to rainfed production, due to the combined effects of nutrient input, direct fossil fuel use and water pumping.

Comparisons between the direct fossil energy use in mostly small-scale developing country irrigation and rainfed farming (which, globally, is more mechanised) are harder to make. The greatest proportion of irrigated area lies in developing countries, with China and India combined accounting for almost 50% of the total. In developing country irrigation, direct fossil fuel usage is more modest (do we have estimates?) and fertiliser use is likewise relatively modest (Nangia et al, 2007), but likely to rise if productivity and water use efficiencies are to be raised in the wake of more variable and restricted rainfall and runoff.

Energy consumption for groundwater irrigation is a regionally important and significant quantum in India and China, and accounts for XX% of electricity consumed in Gujurat, Maharsthrya and Andra Pradesh, derived in turn from fossil fuel sources (80%?)

It is harder to estimate the contribution of net CO_2 emissions from irrigated farming nor how significant they are and the figures probably vary considerably case by case, and need further detailed elaboration and investigation. One concrete example is that, in Australia, agriculture is the second largest emitter of carbon and other greenhouse gases (17%) and larger than transport, due to 1) fertiliser production related emissions; and 2) fossil fuel use in cultivation, storage and cooling and transport costs (REF). This is in part related to the extensive and highly mechanised rainfed agricultural industry. At the moment there are no figures for the contribution of irrigated agriculture to this total.

The options for direct mitigation through irrigation, on balance, are those of agriculture as a whole, with likely greater potential in certain specific contexts (intensive groundwater irrigation in the US for example). The possibilities are governed mostly by the increased intensity of irrigation, allowing greater potential for carbon sequestration in tropical conditions and greater productivity, offset by more intensive use of inputs. Methane production from rice paddies is another concern.

6.2.1 The carbon question

About 18% of the world's croplands now receive supplementary water through irrigation (Millennium Ecosystem Assessment, 2005). There are recent indications from remote sensing analysis that the irrigated areas in India and China are both more than 50% greater than previous estimates (Thenkabail et al, 2006), in part due to un-regulated private groundwater development. The recent minor and major irrigation surveys in India have confirmed an irrigated area close to that estimated from remote sensing, and a similar result is reported in China (Chinese Academy of Sciences, 2007). Expanding this area where water reserves allow or using more effective irrigation measures can enhance carbon storage in soils through enhanced yields and residue returns (Follett, 2001; Lal, 2004a). However, water resources are a major constraint in South, South east and East Asia, and the current irrigation potential in Africa is limited (FAO, 2004). Some of the gains from expanded area may be offset by CO_2 from energy used to deliver the water (Schlesinger 1999; Mosier *et al.,* 2005) or from N_2O emissions from higher moisture and fertilizer N inputs (Liebig *et al.* 2005). The latter effect has not been widely measured.

Irrigators in many countries are seeking out ways of improving returns to land, capital and labour, including plantation and boundary plantings of fast growing trees, such as poplars, in the states of Haryana and Himachal Pradesh in northern India, with clear potential to earn carbon credits under the Clean Development Mechanism (Zomer et al, 2007), and generate higher returns for small holders than agricultural field crops. Other variants of agro-forestry may become increasingly popular. Fruit trees can presumably also claim carbon credits, but the potential area is more constrained by the high capital costs of production, the sensitivity to climatic variation and the need for high security irrigation supply, and by fairly narrow markets, in comparison even with vegetables.

A second important aspect of carbon mitigation directly related to irrigation in the tropics concerns the drainage of peat soils. Famously, peat soils in Kalimantan and Sumatra have been drained for both irrigation development and for plantation crop production with large releases of organic carbon, compounded by forest burning. Organic or peaty soils contain high densities of carbon accumulated over many centuries because decomposition is suppressed by absence of oxygen under flooded conditions. To be used for agriculture, these soils are drained, which aerates the soil, favouring decomposition and therefore, high CO_2 and N_2O fluxes. Methane emissions are usually suppressed after draining, but this effect is far outweighed by pronounced increases in N_2O and CO_2

(Kasimir-Klemedtsson *et al.*, 1997). Emissions from drained organic soils can be reduced to some extent by practices such as avoiding row crops and tubers, avoiding deep ploughing, and maintaining a shallow water table. But the most important mitigation practice is avoiding the drainage of these soils in the first place or re-establishing a high water table (Freibauer *et al.*, 2004).

Lastly, irrigation may be needed in the production of bio-fuels. In India, de Fraiture et al. (2007) note that of 100 million tonnes of sugar cane to meet the bio-fuel demand, requiring and addition 30 bcm of water per year, which would either be at the expense of environmental allocation, or existing food crops which would then have to be imported (ibid). Maize demand in China is modelled to rise to 195 million tons in 2030 (up by 70% from 2000), mainly because of growth in per capita meat consumption as a result of income growth. Part of the additional demand can be met through productivity growth and slight area increase but even under optimistic yield growth assumptions imports must increase to 20 million tons from 2 million tons in 2004. Under such a scenario, it is quite unlikely that the additional maize demand for bio-fuel can be met without further degrading water resources or inducing major shifts of cropping pattern at the expense of other crops. More likely, under an aggressive bio-fuel program, China would have to import more maize (or the crop displaced by maize), which will undermine one of its primary objectives, i.e. curbing import dependency.

6.2.2 The methane question

Cultivated wetland rice soils emit significant quantities of methane (Yan *et al.*, 2003). Emissions during the growing season can be reduced by various practices (Yagi *et al.*, 1997; Wassmann *et al.*, 2000; Aulakh *et al.*, 2001), such as aerobic rice, and alternate wetting and drying where conditions allow. Intuitively a shift to aerobic conditions should reduce methane emission, but some research shows that it may not (REF please, Phil). Early transplanting has been associated with increased methane (REF) and the reasons for this are (or need to be elaborated).

The natural habitat for rice is flooded land and much of the area grown is naturally flooded, often seasonally, in the monsoon. The actual accounting of the net contribution of methane from irrigated rice over and above emissions from seasonal and permanent natural wetland is not yet very refined, with recent projects initiated to assess the global area of rice using remote sensing (Xiao, 2007).

It is worth noting that the natural wetland area around the globe (900-1200m ha) is more than 10 times that of wet rice, and according to the US EPA (web REF), rice in the USA contributes 6-9 Tg of carbon every year, compared to 190 Tg from natural wetlands, which account 75% of total US methane emission. Other estimates of global rice-derived methane contribution are 92 Tg in 2005 and predicted to rise to 131 Tg in 2025 (USDA, XXXX website).

Many claims have been made for technologies such as SRI in reducing the extent of water use, but SRI is certainly not aerobic rice production and well-quantified data on reductions in methane emission are not available. An initial estimate can be made by estimating areas of rice where rice (usually second and third crops) are produced under conditions that would normally be aerobic, but are saturated through irrigation: at a very rough estimate of 100 million ha of irrigated rice, with a cropping intensity of 1.5 on average, around 33 million ha might represent the upper limit of potential conversion to aerobic rice. Currently, true aerobic rice yields tend to be poor (less than 2t/ha) and this in itself remains a strong disincentive to adoption even in situations where natural drainage conditions allow (Bouman et al, in CA, 2007).

6.3 The hydrological implications of forest-related mitigation

Both deforestation and afforestation have been singled out as the key landuse change with profound hydrological impacts. There has been some controversy over the consequences of afforestation (see Calder 2001) and it is increasingly realised that the hydrological consequences of upper catchment afforestation need to be understood and taken in to account so that existing downstream users are not compromised. Trees generally consume more water than shorter stature vegetation growing under the same environmental conditions, largely a result of being perennial, their ability to exploit a larger volume of soil to extract moisture and increased rainfall interception. Jackson et al. (2005) found that plantations decreased stream flow by 227 mm per year (52 percent), with 13 percent of streams drying completely for at least one year. A review of catchment experiments (Bosch and Hewlett 1982) found that, on the average, pine and eucalypt plantations cause a 40 mm decrease in runoff for a 10 percent increase of forest cover with respect to grassland. The equivalent responses of deciduous hardwood and shrubs are 25 and 10 mm decreases in runoff, respectively.

Zomer et al. (2007) noted that under irrigated conditions, water requirements for poplar at boundary or block plantings covering nor more 10% of farm area in Haryana consumed only about 1% (statistically insignificant) more water than under full cropping.

Larger forests also reduce advective energy locally, so although the catchment yield can be further reduced by new plantings. Zomer et al. (2006) also report on the potential increase in water use on land suitable for afforestation under the clean development mechanism, using a global water balance modelling framework. As part of the ENCOFOR project, they modelled reductions in runoff ranging from 50-400mm over all continents, with greatest reductions in South America and sub-Saharan Africa in absolute terms, but with much higher percentage reductions relative to total runoff in South Asia and South East Asia. At global scale, more than 50% of the suitable area would experience less than 60% reduction in runoff, meaning that there are significant implications of CDM plantings (affecting less than 1% of global carbon credits) and a strong need to factor this in to land use change and catchment management in developing countries. More detailed studies on four catchments in South America revealed similar findings.

6.4 The contribution of agricultural water management to hydropower generation

The difficulties in optimising the productivity of water in both hydropower and agriculture in the same basin are well known. Demand for hydropower, which usually cycles on a diurnal basis, is very different from that for agriculture which cycles seasonally. This difference can be expected to increase where crop seasons are moved to avoid peak temperatures to times of the year, especially when optimal cropping times may require hydropower dams to be drawn down to levels that seriously compromise power generation.

Monitoring techniques including remote sensing however can provide the dam operator with information that allows him or her to draw down a dam storage in favour of non-generating purposes in the knowledge that enough water is on its way down the catchment to maintain levels necessary for production, despite the "unscheduled" releases. With such new technology, old style operating rules which still tend to predominate can be replaced with new rules that favour agricultural production at crucial times of the year. This would avoid situations such as that encountered already in Madhya Pradesh, India, where the operating rules of hydropower dams do not permit the crucial watering of soybeans that would make it a highly competitive soybean production centre.

It is expected that the current advantages of the non-consumptive nature of hydropower will continue to be attractive although minimising evaporation losses from storage may become more important if drought periods are extended. However, there is evidence that CH_4 emissions are higher that originally predicted.

7 CONCLUSIONS AND RECOMMENDATIONS

Chiew (2003) provides a relevant quote from Roger Pielke's testimony to the US Senate:

> *"Policy response to climate variability and change should be flexible and sensible. The difficulty of prediction and the impossibility of verification of predictions decades into the future are important factors that allow for competing views of long-term climate future. Therefore policies related to long-term climate should not be based on particular predictions, but instead should focus on policy alternatives that make sense for a wide range of plausible climatic conditions. Climate is always changing on a variety of time scales and being prepared for the consequences of this variability is a wise policy".*

The agricultural implications of the IPCC Working Group reports and the subsequent Technical Paper on Water still need to be analysed with respect to operational water management systems and national economic progressions to check their sensitivity to climate projections.

Climate change will have far-reaching effects on water management in agriculture, even if adaptive capacity is relatively strong. In developing countries, the impacts will vary considerably from location to location, but will arise through a combination of less favourable conditions for plant growth, more variable rainfall, lower water availability for irrigation and higher crop water demands. These stresses will be additional to the pressures to produce more food, with less water and less land degradation in the face of rising global population and changing food preferences.

Climate change will have its greatest impact on agricultural water management in further sharpening the trade-offs between conservation and protection of natural ecosystems, which ultimately support agriculture, and allocation of land and water to productive agriculture. The decisions will be toughest in terms of surface and groundwater allocation between productive and environmental needs, as these are the two high volume but low value uses. Higher value, low volume allocations to cities, industry, rural water supply and sanitation are unlikely to be materially affected by climate change (even if the demanded volume is increased by climate change), but collectively will reduce the allocatable volume to agriculture and environment.

A lesson emerging from Australia is that consultation is a crucial aspect of vulnerability assessment and in the development and understanding of feasible adaptation strategies. In this conclusion we argue for a more detailed and regionally/nationally focused assessment of climate change impacts on agriculture in developing countries, and appropriate stakeholder participation is part of this process. FAO can help in brokering this aspect of climate change adaptation and study.

7.1 Improving understanding of impacts and adaptation strategies in developing countries.

There remains considerable uncertainty about the long terms changes in temperature and precipitation due to greenhouse gas accumulation. The uncertainty lies in the degree of outcome and its spatial and temporal pattern. This uncertainty does not undermine the severity of the challenge nor the need for adaptation (and mitigation), but requires such strategies to be formed and prioritised in a flexible and probabilistic way. Elaboration of multiple and competing projections, especially when further expressed in probabilistic terms, creates significant challenges for communication and common understanding about what to do in response.

FAO could play a key role promoting, assisting and backstopping a broad program of regional and national analysis to identify hot-spots and priority areas for coordinated national and regional response. It is suggested here that greater precision and focus is needed in the understanding of the nature, scope and location of climate change impacts in developing country water resources management for agriculture. A generic approach is outlined in Figure 7.1 that could be elaborated, promoted and supported by FAO programs to assist their clients in the preparation of adaptive strategies for agriculture and water management. At the moment, FAO is unlikely to have the in-house capacity to support the development and calibration of regional climate models and so it could partner with national climatic agencies and universities to accomplish this task.

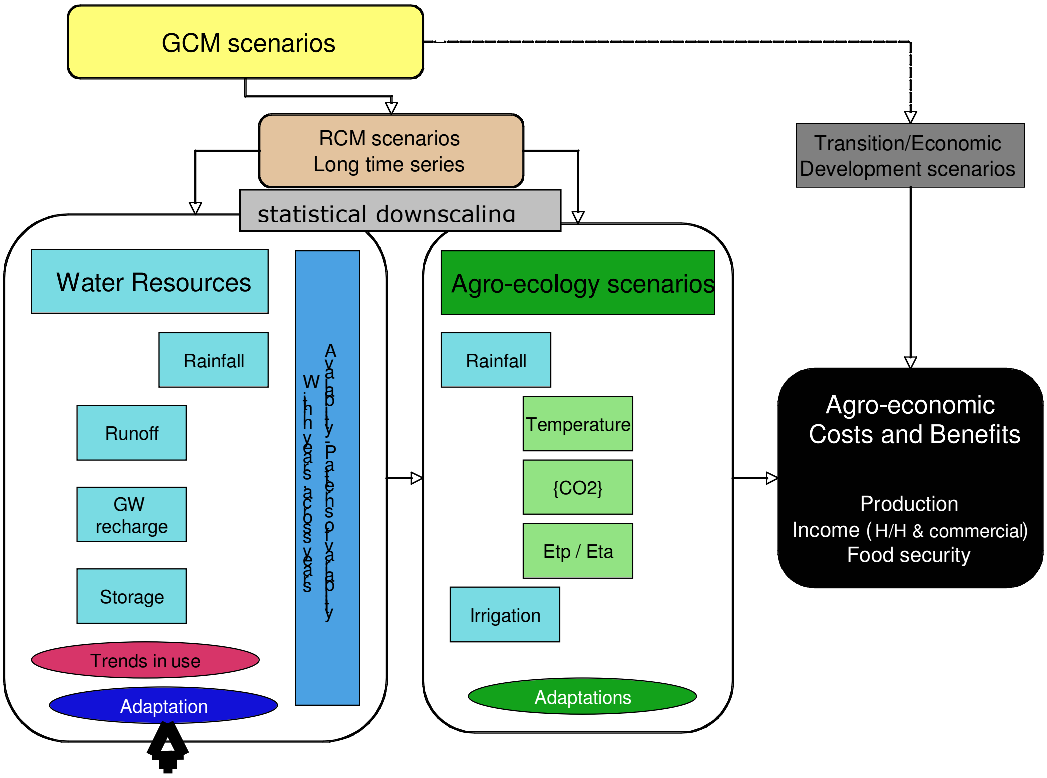


Figure 7.1 *Generic approach to determining climate change impacts and agricultural adaptation strategies*

FAO would also need to play a strong hand in promoting and assisting in the development of adaptive capacity. Initially, this could focus on promotion and capacity building in water resources accounting, assessment and planning, with a view to helping clients establish formal water allocation systems, and to develop sufficient diagnostic capacity and context to understand the likely detailed impacts of climate change. Since considerable hydrologic input may also be required in some circumstances, FAO could consider suitable partnerships – possible with national and international bodies associated with the International Hydrology Programme of UNESCO. FAO would seek to ensure an appropriate balance of analysis and focus between the multiple, competing stresses on water allocation and agriculture, to ensure the practical relevance of outputs and findings. Serious consideration needs to be given to the collection of data and to the substitution of historical data in many regions. This is normally not a popular activity for international organisations to engage in, and anyway should as far as possible be internalised in each individual country. One way to help stimulate this might be in assistance to establishing and maintaining regional networks, in collaboration with the development banks.

To support this, FAO could help establish a broader base of support for impact analysis and adaptive strategy formulation, through the development an provision of tools in addition to the analytical framework suggested above – this could included more detailed modelling strategies, risk analysis an prioritisation, development and promotion of climate forecasting tools for different regions. At the crop and field scale, FAO could become more closely involved the better calibration, development and adaptation of crop models which are used to assess future productivity under climate change scenarios: a particular focus would be on major developing country crops that are not well described in the current literature and databases.

7.2 Taking to scale - a regional and national approach

It is important that the spatial and temporal trajectories of climate change impacts be more tightly bounded at regional and national scales. There is increasing consensus that the climate models themselves are doing a more reliable and effective job of predicting real historical climate, and that spatial resolution can be improved through a variety of approaches, using both regional climate models and statistical downscaling. The breadth of outcomes under different forcing scenarios may remain wide, but if the spatial patterns at regional scale are better differentiated, then it becomes possible to assess relative risk, and to prioritise different areas for investigation and adaptation.

Therefore, mapping vulnerability becomes a key task at the national and regional level. Some countries, such as USA, Australia, and northern European countries, have been doing this for the past 10 years, but there is little that has been done within developing countries themselves, with a few externally funded investigations, such as the ADAPT project.

Irrigation in particular and agricultural water management in general, are highly impacted by temperature change and changes in the water cycle. These changes will be profound and negative in the areas already most under stress. Current predictions of future food production and security are undermined by the likely extent of reduction in utilisable water resources, as predicted, and seemingly emerging in Australia, a dry continent with the greatest variability in climate and hydrology in the world.

The key drivers of water and food stress remain population growth and changed food preferences, with a consequent demand for water – in terms of rainfall on catchments, runoff diverted from rivers and captured in dams, and groundwater.

There are many areas of the world that will not suffer increased stress, but may even have short and long term benefits in agro-ecology and growing condition. However, climate change applies significant additional stress in precise locations, which need to be better identified and characterised, especially in the more vulnerable developing world. From an agricultural perspective, and especially in irrigation or water management terms, these comprise:

1. large surface irrigation systems fed by glaciers and snow melt (most notably northern India and China);

2. (groundwater systems in arid and semi-arid areas, where rainfall will decrease and become more variable;
3. large deltas which may be submerged by seas level rise, increasingly prone to flood and storm cyclone) damage ore experience salinity intrusion through surface and groundwater;
4. seasonal storage systems in the monsoon regions, where the proportion of storage yield will decline but peak flood flows are likely to increase;
5. all supplemental irrigation areas where the consequences irregular rainfall are mitigated by short term interventions to capture and store more soil moisture or runoff.

7.3 FAO support to adaptive strategies

This document has identified weaknesses in the existing information bases, and institutional arrangements to oversee water resources management and the sustainable provision of water to agriculture. FAO's existing information and knowledge programme, including such products as AQUASTAT can help to provide a footing for much needed institutional development in water management. AQUASTAT itself can be expanded to include groundwater information and can provide assistance in establishing frameworks for rational water accounting (both use and resource availability) in many client countries. At scheme operational level, then the application of the CROPWAT successor, AQUACROP can be combined with operational assessments of through MASCOTTE.

FAO's role in helping member countries understand the water resources and agriculture implications of climate change and in assisting them to develop better regional and local projections of impacts in order to develop planned adaptive strategies. It can act as a "clearing house" to include climate change science and projections into its scenarios and support for global food security and similar national programmes. Since climate change impacts may be hard to internalise in some countries, given the host of other pressures on water resources and agriculture, FAO may also become something of an advocate.

The role of advocate and enabler would see FAO leading the integration of climate science with agricultural water management and including a strong focus on the preservation and enhancement of natural ecosystems, which are tightly bound to the development and management of irrigated agriculture. This will see further development of an integrated perspective a river basin level, and across a spectrum of irrigated and rainfed agriculture.

A fundamental issue to resolve is how yields and production are likely to change in the future, and to provide concrete examples of the extent to which crop adaptation to higher temperatures is possible. The international climate change literature is pessimistic and predicts significant reductions in yield and production, even with adaptation strategies. Recent modelling on global food security by FAO, CA and others assume continued possible improvements in land and water productivity, from a performance base that is well below potential at the moment in developing countries. It will be important to resolve the potential for increases in productivity against a declining potential due to climate change. A separate strand of FAO effort could therefore be directed to liaising with plant breeding centres in the CGIAR and in the member countries, to establish a public access database on climate adapted crop varieties. Some considerable thought and preparation would need to go into the structure of such a database, and into easy and accessible means of abstracting relevant data. It would be very useful if the construction of such a data-base were accompanied by some testing and evaluation of the field performance of adapted varieties, directly or from secondary data.

Finally, 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.

7.3.1 Applying a methodological approach

With respect to irrigation, climate impact analysis should be set in context of the other demographic, social, economic and water resources management situations at an appropriate scale. Careful regional analysis should be undertaken, preferably using regional scale climate models (50-75km grids) and the best statistical methods for downscaling spatial data. A clearly identifiable challenge is to improve the coverage, availability and quality of data required to do so.

From this point on, a probabilistic analysis should identify the areas most at risk climatically, and this should be coupled with other indicators of stress and adaptability to identify and prioritise areas and communities at greatest risk over different time horizons. In developed countries, great emphasis has been placed on stakeholder consultation and mobilisation in understanding vulnerability, risk and potential adaptive strategies. The Stern report commends this approach to developing countries too.

7.3.2 Planning adaptation strategies

It is important that planners in developing countries develop the capacity and have access to the tools to undertake this analysis, and to shore up the information base for decisions – particularly with respect to actual water use and current resource availability. Various adaptation scenarios can then be investigated in relation to 1) likely runoff 2) likely Et demand and 3) groundwater availability and use. Crop model based scenarios of production can be nested over this analysis to evolve the production outcomes, and the values of that production in addition to the likely range of impacts on the farming community – various adaptation strategies and there outcomes can then be investigated ranging across combinations of water availability through changed storage and operational regimes, coupled to changed crop selection and seasonality. Such scenarios need to be assessed against the existing range of climatic variability applied to changed climate, and complemented by stochastically generated changes in expected climate variability.

Where there is evidence or a likelihood of a step-change in climate, more drastic scenarios should be added – which will be as much about significant change in variability as in median and mean water availability.

A complementary entry point in for FAO's support to member countries to climate change impacts on agriculture should be to work more closely with environmental agencies to foresee and shape future trade-offs between environmental and agricultural water allocation.

7.4 Addressing identified knowledge gaps

The IPCC and FAO recently identified a number of information gaps, which are listed here, although some of them dovetail well into the approach outlined in the previous section (joint workshop, 2007).

In agriculture, forestry and fisheries, a need was identified for a comprehensive assessment of climate change impacts on agriculture and food security, resulting in the elaboration of adaptive strategies, for different scales and scenarios. In tandem, there needs to be a better identification of highly vulnerable micro-environments and households, and enumeration of well-tailored and practical coping strategies, across a range of economic and agronomic perspectives. FAO's existing work on poverty mapping and alleviation should be very useful in this regard.

Crop science needs include the investigation the response to enhanced CO_2 of other important developing country crops such as millet, roots and tubers. Similarly, further work is needed n the impacts of carbon dioxide enrichment on the nature and dynamics of pests, weeds and diseases for a large range of crops. It is suggested that there should be a comparison study of crop models, but this stops short of the suggestions made above. If the studies on developing country staple crops are developed accordingly, it would be possible to combine some model improvement directly with this research.

Finally, the impact of climate change on bio-fuel crops and better assessment of their carbon balances in different situations would help in planning mitigation and adaptation strategies and in finding an appropriate, productive and economically optimal balance. A more general goal was identified, in which synergies should be sought between adaptation, mitigation and sustainable development strategies. An economic valuation methodology is required to support such an analysis.

7.5 FAO actions on mitigation of greenhouse gas production through agricultural water management.

Two areas in which work could commence immediately are identified.

Work could begin by completing a GIS-based inventory of the locations where different types of mitigation activity are possible (methane reduction in paddy production, improved plant and soil sequestration in irrigated agriculture). Carbon balances could be derived from this, but better information on the actual performance and potential of different initiatives is probably required, especially with regard to the restoration of carbon contents in irrigated tropical soils.

FAO could convene a series of policy workshops that bring attention to the production, and hydrological tradeoffs of different mitigation strategies at river basin scale, accounting for GHG benefits, hydrological changes and the consequences for agricultural production. Scenarios could include planting of bio-fuel crops. The mitigation and production aspects can be consolidated under an economic analysis that values all components, and in terms of food self sufficiency at household and national scales – in order to elaborate the tradeoffs, and understand the broader consequences in terms of trade and other parameters of political feasibility.

7.6 Cooperation with international organizations and development partners

Policy clusters: food security, poverty alleviation, economic transitions all represent areas of potential collaboration in which climate change can be expected to figure.(TO BE COMPLETED)

8 REFERENCES:

Aerts J and Droogers P, 2004, Climate Change in Contrasting River Basins: Adaptation Strategies for Water, Food and Environment. Institute for Environmental Studies (IVM), Free University, Amsterdam, The Netherlands. CABI, Wallingford UK. ISBN: 9780851998350 288 pages

Ahmad, M.D., H. Turral, I. Masih, M. Giordano, Z. Masood 2006. Water Savings Technologies and Water Savings: Myths and Realities revealed in Pakistan's rice-wheat systems. Research Report, International Water Management Institute (IWMI), Colombo, Sri Lanka. In press.

Albinson, B. and C.J. Perry. 2002. Fundamentals of smallholder irrigation: The structured system concept. Research Report 58. Sri Lanka, International Water Management Institute.

Allen Consulting, 2005, Report to the Australian Greenhouse Office, Department of Heritage and the Environment, Canberra. 159pp

Alexandratos, N. 2005. Countries with rapid population growth and resource constraints: issues of food, agriculture, and development. Pop. Dev. Rev., 31(2): 237–258.

Arnell, NW, M.J.L. Livermore, S. Kovatsc, P.E. Levy, R. Nicholls, M.L. Parry, S.R. Gaffin. Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines. Global Environmental Change 14 (2004) 3–20.

Arnell, N. W., D. A. Hudson, and R. G. Jones (2003), Climate change scenarios from a regional climate model: Estimating change in runoff in southern Africa, J. Geophys. Res., 108(D16), 4519, doi:10.1029/2002JD002782.

Australian Rainfall and Runoff - A Guide to Flood Estimation, 1999 The Institution of Engineers, Australia, Barton, ACT, Australia.

Bakker, M., R. Barker, R.S. Meinzen-Dick, and F. Konradsen (eds.). 1999. Multiple Uses of Water in Irrigated Areas: A Case Study from Sri Lanka. SWIM Report 8. Colombo, Sri Lanka: IWMI. HTTP://WWW.CGIAR.ORG/IWMI/PUBS/SWIM/SWIM08.PDF

Barker, R. C. Ringler, N.M. Tien, and M.W. Rosegrant. 2004. Macro Policies and Investment Priorities for Irrigated Agriculture in Viet Nam. Comprehensive Assessment Research Report No. 6. Sri Lanka: IWMI.

Barker, R.; Molle, F. 2004. Evolution of irrigation in South and Southeast Asia. Colombo, Sri Lanka: Comprehensive Assessment Secretariat. (Comprehensive Assessment Research Report 5).

Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow dominated regions. Reviews . Nature. Vol. 438:17. pp 303-308.

Baron, C. Sultan B., Balme M, Sarr B, Traore S, Lebel T, Janicot S and Dingkuh M. 2005. From GCM grid cell to agricultural plot: scale issues affecting modelling of climate impact. Phil. Trans. R. Soc. (360) 2095–2108

Bastiaanssen, W.G.M., M. Menenti, R.A. Feddes, A.A.M. Holtslag 1998. A remote sensing surface energy balance algorithm for land (SEBAL), part 1: formulation, Journal of Hydrology. 212-213: 198-212.

Bathols, 2005a: Climate Change in Eastern Victoria. Stage 1 Report: The effect of climate change on coastal wind and weather patterns. Report to Gippsland Coastal Board. 26 pp.

Beare S and Heaney A. 2002. Climate change and water resources in the Murray Darling Basin, Australia. Impacts and Possible Adaption. World Congress of Environmental and Resource Economists, Monterrey, California. ABARE Conference Paper 02.11 Canberra, Australia.

Beven K and Freer J, 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology, Journal of Hydrology, Volume 249, Issues 1-4, 1 August 2001, Pages 11-29.

Bhattarai M. and A. Narayanamoortht. 2003. Impacts of Irrigation on Poverty Alleviation in India: A Macro level Panel Analysis, 1970 to 1994. Water Policy Vol.5. p. 443 - 458.

Bhattarai M., Barker, R., and Narayanamoorthy, A. (forthcoming). Who benefits from irrigation development in India? Implication of Irrigation Multipliers for Irrigation Financing. Accepted for publication in journal, Irrigation and Drainage.

Brabben, T, Angood C, Skutch J, and Smith L. 2004. Irrigation can sustain rural livelihoods: evidence from Bangladesh and Nepal, HR Wallingford.

Brown, C. and U. Lall, (2006): 'Water and economic development: the role of interannual variability and a framework for resilience', Working Paper, Columbia University, NY: International Research Institute for Climate Prediction.

Bruinsma, J., 2003: World Agriculture: Towards 2015/2030 – An FAO Perspective. Earthscan, London, 444 pp.

Burke, J.J and Moench, M. (2000) Groundwater and Society, Resources, Tensions and Opportunities. Themes in Groundwater Management for the 21st Century. United Nations, New York. 170pp

Calder, I. R. 2000. Land use impacts on water resources. Land-Water Linkages in Rural Watersheds Electronic Workshop, Background Paper No. 1. September 18 – October 27, FAO.

Calder, I.R. 2004. Forests and water — closing the gap between public and science perceptions. Water Science and Technology 49(7): 39-53.

Carruthers, I., M.W. Rosegrant, and D. Seckler. 1997. Irrigation and food security in the 21st century*. Irrigation and Drainage Systems* 11: 83–101.

Chiew, F.H.S., Zhou, S.L. and McMahon, T.A. (2003) Use of seasonal streamflow forecasts in water resources management. Journal of Hydrology, 270: 135-144.

Comprehensive Assessment, Water for Food, Water for Life. Ed D. Molden. IWMI / Earthscan. ISBN 978-84407-396-2

Conway, D (2005) From headwater tributaries to international river; Observing and adapting to climate variability and change in the Nile basin. Global Environmental Change (15) 99-114.

CSIRO. 2007. Climate change in Australia. CSIRO and Bureau of Meteorology. 137 p. ISBN 9781921232947. Canberra Australia.

Davis B. 2003. Choosing a method☐for poverty mapping. FAO. Rome. ISBN 92-5-104920-3

de Fraiture C., Giordano M and Yongsong L. 2007. Biofuels: implications for agricultural water use. XXXXXX

de Fraiture, C. 2005. Assessment of Potential of Food Supply and Demand Using the Watersim Model. Columbo: International Water Management Institute.

Dhawan, B. D. 1988. Irrigation in India's agricultural development: Productivity, stability, equity; New Delhi, India: Sage Publications India.

Doll, P (2002) Impact of climate change and variability on irrigation requirements: a global perspective. Climate Chaven (54) 269-293.

DSE (Department of Sustainability and Environment), Victoria, 2006. Climate change – what if the next 10 years are the same? Power Point Presentation. Nicholson Street. Melbourne. Australia.

Dubourg, W.R. (1998) Reflections on the meaning of sustainable development in the water sector. Natural Resources Forum.

Molle F. and Berkoff J. 2007 Eds.. Water Pricing – the gap between theory and practice. CABI. Wallingford. UK. 349 p ISBN 978-1-84593-292-3

Eddleston M. Karalliedde L. Buckley N. Fernando R. Hutchinson G. Isbister G. Konradsen F. Murray D. Piola JC, Senanayake N, Sheriff R, Singh S. Siwach SB. Smit L. 2002. Pesticide poisoning in the developing world--a minimum pesticides list. Lancet. 12;360: 1163-7.

EEA Technical report No 2/2007 European Environment Agency (2007) Climate change and water adaptation issues

Emerton, L., Bos, E. 2004 Value. Counting Ecosystems as an Economic Part of Water Infrastructure. IUCN, Gland, Switzerland and Cambridge, UK. 88 pp.

FAO (forthcoming). Irrigation management transfer: worldwide efforts and results. Rome.

FAO, 1999. Transfer of irrigation management services. Guidelines. FAO Irrigation and drainage paper No 58. Rome.

FAO. 2000. Global Agro-ecological Zones. Version 1.0. FAO Land and water Digital Media Series 11. Rome. CDROM.

FAO. 1997. Modernization of irrigation schemes: past experiences and future options. FAO Technical Paper No. 12, Rome.

FAO. 1999b. Modern water control and management practices in irrigation. FAO/IPTRID/World Bank. FAO Water Report 19, Rome.

FAO. 2000. Irrigation in Latin America and the Caribbean in figures. Rome.

FAO/World Bank. 2001. Farming Systems and Poverty. Improving Farmer's Livelihoods In a Changing World. Rome and Washington DC. 412pp.

Food and Agriculture Organization. 2002. The State of Food Insecurity in the World 2001 Food and Agriculture Organization, Rome.

FAO. 2003. World agriculture towards 2015/2030: An FAO perspective. Rome/London, FAO/Earthscan Publishers.

FAO. 2004a. Economic valuation of water resources in agriculture. From a sectoral to a functional perspective of natural resource management. FAO Water Report 27. 186pp.

FAO. 2004b. Compendium of food and agriculture indicators. Rome.

FAO. 2004c. Drought impact mitigation and prevention in the Limpopo River Basin. A situation analysis. FAO Land and Water Discussion Paper No. 4. 160 pp. Rome.,

FAO 2005. Forests and floods Drowning in fiction or thriving on facts?. RAP Publication 2005/03 Forest Perspectives 2.

FAO, 2005 Valuation of Water for agricultural development

FAO. 2005. Irrigation in Africa in Figures. Aquastat survey - 2005. FAO Water Report 29. Rome.

FAO, 2006 The Demand for the products of irrigated agriculture in Sub-Saharan Africa. FAO Water Report 31. Rome.

FAO. 2007a . Agricultural trends to 2050

FAO 2007b. Modernising irrigation management – the MASSCOTE approach. FAO Irrigation and Drainage Paper 63. Rome. 207pp + CDROM.

FAO. 2007c. Global map of irrigation areas (Version 4.0.1) FAO Land and Water Digital Media Series 34. CDROM.

FAO/IIASA. 2007a. Food Insecurity, Poverty and Environment Global GIS Database. DVD and Atlas for the year 2000. Environment and Natural Resources Working Paper 26.

FAO/IIASA. 2007b. Mapping biophysical factors that influence agricultural production and rural vulnerability. Environment and Natural Resources Series 11. Rome 81pp.

FAOSTAT (on-line database).

FAO/IPTRID. 1999. Poverty reduction and irrigated agriculture, Issue paper no. 1, International Programme for Technology and Research in Irrigation and Drainage, FAO.

Faures JM, Svendsen M and Turral HN. 2007. Irrigation Impacts. Ch.9 Comprehensive Assessment of Water Management in Agriculture. Earthscan. ISBN 978-1-84407-396-2

Fischer G. et al (2005) Socio-economic and climate impacts on agriculture; an integrated assessment, 1990-2080. Phil. Trans. R. Soc. B (360) 2067-283

Fischer G. et al. (2007) Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. Technological Forecasting & Social Change 74 (2007) 1083–1107

Fuhrer, J. (2003) Agroecosystem responses to combinations of elevated carbon dioxide, ozone and global climate change. Agriculture, Ecosytems and Environment 97: 1-20.

Galbraith H, Amerasinghe P., Huber-Lee A. 2005. The effects of agricultural irrigation on wetland ecosystems in developing countries: a literature review. CA Discussion Paper 1. Comprehensive Assessment Secretariat, Colombo, Sri Lanka. 23 pp.

Grey, D. and C. Sadoff. 2005. Water Resources, Growth and Development. A Working Paper for Discussion at the U.N. Commission on Sustainable Development, Panel of Finance Ministers. The World Bank.

Hewitson, BC and Crane RG (2006) Consensus between GCM Clmate Change Projections with Empiirical Downscaling: Precipitation Downscaling over South Africa. Ing J Climatol. 26 1315-1337

HM Treasury (2006) Stern Review of the Economics of Climate Change. HTTP://WWW.HMTREASURY.GOV.UK/INDEPENDENT_REVIEWS/STERN_REVIEW_ECONOMICS_CLIMATE_CHANGE/STERN_REVIEW_REPORT.CFM

Hofer, T and Messerli, B (2006) Floods in Bangladesh. History, Dynamics and Re-thinking the role of the Himalayas. UNU Tokyo, 468 pp.

Howden, S. M. and Meinke, H. (2003) Climate change: challenges and opportunities for Australian agriculture. In: Proceedings of the Conference on Climate Impacts on Australia's Natural Resources: Current and Future Challenges, Queensland, Australia, Canberra: Standing Committee on Natural Resource Management. Managing Climate Variability Program, pp. 53-55.

Huppert, Walter, Mark Svendsen and Douglas L. Vermillion with Birgitta Wolff, Martin Burton, Paul van Hofwegen, Ruth Meinzen-Dick, Waltina Scheumann and Klaus Urban. 2001. Governing Maintenance Provision in Irrigation: A Guide to Institutionally Viable Maintenance Strategies. Eschborn, Germany: GTZ.

Hussain, I. 2005. Pro-poor Intervention Strategies in Irrigated Agriculture in Asia – Poverty in Irrigated Agriculture: Issues, Lessons, Options and Guidelines, Final Synthesis Report submitted to the Asian Development Bank, International Water Management Institute (IWMI), Colombo, Sri Lanka.

IIASA/FAO (2002) Global Agro-ecological Assesment for Agriculture in the 21st Century: Methods and Results. IIASA, Vienna.119 pp + CDROM

IFAD. forthcoming. Agricultural water development for poverty reduction in Eastern & Southern Africa.

Inocencio, A., D. Merrey, M. Tonasaki, A. Maruyama, I. de Jong, and M. Kikuchi. 2006. Costs and Performance of Irrigation Projects: A Comparison of sub-Saharan Africa and Other Developing Countries. IWMI Research Report, International Water Management Institute, Colombo.

Institute of Tibetan Plateau Research, Chinese Academy of Sciences, HTTP://WWW.ITPCAS.AC.CN/SYSTEM/ENGLISH.ASP

IPCC (2001a) Third Assessment Report – Climate Change 2001. Intergovernmental Panel on Climate Change, Cambridge University Press.

IPCC (2001b) Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

IPPC http://www.ipcc.ch/

Johnson III, S., M. Svendsen and F. Gonzalez. 2004. Institutional Reform Options in the Irrigation Sector. World Bank Agriculture and Rural Development Discussion Paper 5. Washington, D.C.

Jones, W.I. 1995. The World Bank and irrigation. A World Bank Operational Evaluation Study. Washington, DC.

KELLER, J., AND A.A. KELLER. 2003. AFFORDABLE DRIP IRRIGATION SYSTEMS FOR SMALL FARMS IN DEVELOPING COUNTRIES. PROCEEDINGS OF THE IRRIGATION ASSOCIATION ANNUAL MEETING, NOVEMBER 18–20, SAN DIEGO, CALIF.

Kijne, J.W., Molden, D. & Barker, R. eds. 2003. Water productivity in agriculture: limits and opportunities for improvement. Comprehensive Assessment of Water Management in Agriculture Series, No. 1. Wallingford, UK, CABI Publishing.

Kikuchi, M.; Barker, R.; Weligamage, P.; Samad, M. 2002. The irrigation sector in Sri Lanka: Recent investment trends and the development path ahead. *Research Report 62*. Colombo, Sri Lanka: International Water Management Institute.

Kikuchi, M.; Inocencio, A.; Tonosaki, M.; Merrey, D.; de Jong, I.; Sally, S. 2005. Cost of Irrigation Projects: A Comparison of sub-Saharan Africa and Other Developing Regions and Finding Options to Reduce Costs. Report for the World Bank as part of the Investment in agricultural water management in Sub-Saharan Africa: Diagnosis of trends and opportunities. Pretoria, South Africa. – DID IT DEAL WITH CC AT ALL ?????

Kingwell R. 2006. Climate change in Australia: agricultural impacts and adaptation. Australasian Agribusiness Review Vol.14 29 p. ISSN 1442-6951

Kirshen. P (2007) Adaptation Options and Cost in Water Supply. Paper prepared for UNFCC. http://unfccc.int/files/cooperation_and_support/financial_mechanism/application/pdf/kirshen.pdf

Klein H, Douben KJ, van Deursen W, van Steveninck E de R.Water, 2004. Climate, Food, and Environment in the Rhine Basin. In ed. Aerts and Droogers, 2004. Climate Change in Contrasting River Basins: Adaptation Strategies for Water, Food and Environment. Institute for Environmental Studies (IVM), Free University, Amsterdam, The Netherlands. CABI, Wallingford UK. ISBN: 9780851998350 288 pages

Kurukulasuriya, P. and S Rosenthal, 2003: Climate Change and Agriculture: A Review of Impacts and Adaptations. World Bank Climate Change Series, Vol. 91, World Bank Environment Department, Washington,

Lemons J, Westra L and Robert J. A. 1998 Ecological Sustainability and Integrity: Concepts and Approaches, Springer. 315 pages ISBN 0792349091.

Lipton, M, Julie Litchfield, Rachel Blackman, Darshini De Zoysa, Lubina Qureshy and Hugh Waddington. 2003. Preliminary review of the impact of irrigation on poverty. AGL/MISC/34/2003. FAO. Rome.

M.G. Bos, M. A. Burton and D.J. Molden, 2005. Irrigation and Drainage Performance Assessment: Practical Guidelines. Wallingford, UK: CABI. viii, 158p.

MA (in press). MA inland waters chpt in press).

MA (Millennium Ecosystem Assessment) 2005. Ecosystem services and human well-being: wetlands and water synthesis. World Resources Institute, Washington D.C. 68 pp.

Malano H.M., Bryant M.J. and Turral H. 1999. Management of Water Resources - Can Australian Experiences be Transferred to Vietnam? Water International 24(1):307-315 International Water Resources Association. Reprinted in ESCAP Water Resources Journal, June 2000. pp76-85.

Malcolm, B. (2000) Farm management economic analysis: A few disciplines, a few perspectives, a few figurings, a few futures. Invited paper to the 44th Annual Conference of Australian Agricultural and Resource Economics Society, Sydney, 22-25 January, 2000.

Martin Parry M, Rosenzweig C and Livermore M. 2005 Climate change, global food supply and risk of hunger Phil. Trans. R. Soc. B (2005) 360, 2125–2138

Maslin□ M. 2004. ATMOSPHERE: Ecological Versus Climatic Thresholds Science 24: 2197 2198□DOI:10.1126/science.1107481

McInnes K.L., Suppiah R., Whetton P.H., Hennessy K.J. and Jones R.N. 2003. Climate change in South Australia . Assessment of climate change, impacts and possible adaptation strategies relevant to South Australia. Report to the South Australian Government by the Climate Impact Group, CSIRO Atmospheric Research. Australia.

McVicar, T.R. and Jupp, D.L.B. (2002) Using covariates to spatially interpolate moisture availability in the Murray-Darling Basin: a novel use of remotely sensed data. Remote Sensing of Environment (Invited paper in a Special Issue: Biophysical Remote Sensing). 79, 199-212

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z.-C. Zhao, 2007: Global climate projections. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 747-846.

Meinzen-Dick, Ruth and Wim van der Hoek. 2001. Multiple Uses of Water in Irrigated Areas. Irrigation and Drainage Systems 15 (2):93-98.

Mellor, J. W. 2002. Irrigation, agriculture and poverty reduction: General relationships and specific needs. In Hussain, I.; Biltonen, E. (Eds.), Managing water for the poor: Proceedings of the Regional Workshop on Pro-Poor Intervention Strategies in Irrigated Agriculture in Asia, Bangladesh, China, India, Indonesia, Pakistan and Vietnam, Colombo, 9-10 August 2001. Colombo, Sri Lanka: IWMI. pp.53-69.

Mellor, John W. 1999. Pro-poor Growth - The Relation Between Growth in Agriculture and Poverty Reduction, paper Prepared for USAID/G/EGAD under Purchase Order PCE-0-00-99-00018-00.

Mohamed, Y.A., van den Hurk, B.J.J.M., Savenije, H.H.G., Bastiaanssen, W.G.M., 2005, The Nile Hydro-climatology: Results from a regional climate model, Hydrology and Earth System Sciences, 9, 263–278.

Molden, D. J.; el Kady, M.; Zhu, Z. 1998. Use and productivity of Egypt’s Nile water. In Burns, J. I.; Anderson, S. S.(Eds.), Contemporary challenges for irrigation and drainage: Proceedings from the USCID 14th Technical Conference on Irrigation, Drainage and Flood Control, Phoenix, Arizona, June 3-6, 1998. Denver, CO, USA: USCID.

Molle, F., and J. Berkoff. 2006. “Cities versus Agriculture: Revisiting Intersectoral Water Transfers, Potential Gains, and Conflicts.” Comprehensive Assessment of Water Management in Agriculture Research Report 10. International Water Management Institute, Colombo.

Molle, F. and Berkoff, J. 2007 Irrigation Water Pricing. The Gap Between Theory and Practice. Comprehensive Assessment of Water Management in Agriculture Series. CABI. Oxon UK.

Nangia V. Turral H. and Molden D. In review. Increasing Water Productivity with Improved N Fertilizer Management. Agricultural Water Management.

Neumayer, E (2007) A missed opportunity: The Stern Review on climate change fails to tackle the issue of non-substitutable loss of natural capita. Global Environmental Change 17 (2007) 297–301

Onibon, H., Lebel, T., Afouda, A. & Guillot, G. 2004 Gibbs sampling for conditional spatial disaggregation of rain fields. Water Resour. Res. 40, W08401. (doi:10.1029/2003WR002009.)

Susan E. Page*, Florian Siegert†‡, John O. Rieley§, Hans-Dieter V. Boehm‡, Adi Jayak & Suwido Limink (2002) The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 420 61-65

Pakistan Country Water Assistance Strategy. "Water Economy – running dry". 2005 Agriculture and Rural Development Unit South Asia Report No. 34081-PK.

Parry, M.,Rozenzweig, C. and Livermore, M. (2005) Climate change, global food supply and risk of hunger. Phil Trans. R. Soc. B, 360, 2125-2138.

Peel, M. C, Geoffrey G.S. Pegram and Thomas A. McMahon, 2004 b. Run length analysis of annual precipitation and runoff**.** International Journal of Climatology.

Peel, M. C, Thomas A. McMahon and Brian L. Finlayson, 2004. Continental differences in the variability of annual runoff – update and reassessment. Journal of Hydrology.

Peel, M. C., T. A. McMahon, B. L. Finlayson, and F. G. R. Watson. 2001. Identification and explanation of continental differences in the variability of annual runoff. Journal of Hydrology 250: 224–240.

Pimentel, D. 2003. Ethanol fuels: energy balance, economics and environmental impacts are negative. Natural Resources Research 12(2): 127-134, June 2003.

Pittock, B. (2003b) Climate change and Australia's natural resources: A review. In: Proceedings of the Conference on Climate Impacts on Australia's Natural Resources: Current and Future Challenges, Queensland, Australia, Canberra: Standing Committee on Natural Resource Management. Managing Climate Variability Program, pp. 51-52.

Plusquellec, Hervé. 2002. How design, management and policy affect the performances of irrigation projects. FAO Regional Office for Asia and the Pacific, Bangkok.

Postel, S., 1999. Pillars of sand: Can the irrigation miracle last? New York: W.W. Norton.

Qian Zhengying. 1994. Water resources development in China. China water and power press.

Quiggin, J. and Horowitz, J. (2003) Costs of adjustment to climate change. Australian Journal of Agricultural and Resource Economics 47: 429-446.

Quiggin, John and John K. Horowitz, 1999. "The Impact of Global Warming on Agriculture: A Ricardian Analysis: Comment," American Economic Review, American Economic Association, vol. 89(4), pages 1044-1045.

Rees and Collins, 2004 Rees, G., Collins, D.N., 2004. An assessment of the potential impacts of deglaciation on the water resources of the Himalaya. SAGARMATHA Technical report, Centre for Ecology and Hydrology. NERC, Centre for Ecology and Hydrology, Wallingford. UK.

Repetto, R. 1986. Skimming the water: Rent-seeking and the performance of public irrigation systems. Research Report No. 4. World Resources Institute. Washington, D.C.

Revenga, C and Y Kura. 2003. Status and Trends of Biodiversity of Inland Water Ecosystems. Secretariat of the Convention on Biological Diversity. Technical Series No. 11, Montreal, Canada.

Ringler, C., M. Rosegrant, X. Cai, and S. Cline. 2003. Auswirkungen der zunehmenden Wasserverknappung auf die globale und regionale Nahrungsmittelproduktion. Zeitschrift für angewandte Umweltforschung (ZAU) Jg. 15/16 (2003/2004), H. 3-5, pp. 604-619.

Roberts J, 2005. Insurance of crops in developing countries. FAO Agricultural Service Bulletin 159. FAO. Rome.

Rockström J, Barron J and Fox F. 2001. Water Productivity In Rainfed Agriculture: Challenges And Opportunities For Smallholder Farmers In Drought-Prone Tropical Agro-Ecosystems. In Kijne, J.W., D. Molden, and R. Barker, eds. 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvement. Comprehensive Assessment of Water Management in Agriculture Series, No. 1. Wallingford, UK: CABI Publishing.

Rockström J, Barron J and Fox F. 2001. *Water Productivity In Rainfed Agriculture: Challenges And Opportunities For Smallholder Farmers In Drought-Prone Tropical Agro-Ecosystems*. In Kijne, J.W., D. Molden, and R. Barker, eds. 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvement. Comprehensive Assessment of Water Management in Agriculture Series, No. 1. Wallingford, UK: CABI Publishing.

Rosegrant MW., S. Msangi, T.Sulser, and R. Valmonte-Santos.2006. Bioenergy and agriculture: Promises and challenges. Biofuels and the Global Food Balance FOCUS 14 (3) Dec 2006. Washington, D.C.: International Food Policy Research Institute.

Rosegrant, M.W., M.S. Paisner, S. Meijer, and J. Witcover. 2001. Global food projections to 2020: Emerging trends and alternative futures. Washington, D.C.: IFPRI.

Rosegrant, M.W., X. Cai, and S. Cline. 2002. World water and food to 2025: Dealing with scarcity. Washington, D.C.: IFPRI and IWMI.

Rosegrant, Mark W. and Svendsen, Mark. 1993. 'Asian food production in the 1990s: irrigation investment and management policy', *Food Policy*, 18(2):13-32.

Rosenberg, D.M., McCully, P. & Pringle, C.M. 2000. Global-scale environmental effects of hydrological alterations: introduction. BioScience 50(9): 746-751.

Sanmuganathan, K. 2000. Assessment of irrigation options. World Commission on dams Thematic Review Options Assessment IV.2. Final Draft. Accessed at www.dams.org/docs/kbase/ thematic/drafts/tr42_finaldraft.pdf

Schmidhuber, J and Tubiello, F (2007) Global food security under climate change. PNAS 104 (50) 19703–19708

Science 24 December 2004: 2197-2198□DOI: 10.1126/science.1107481

Seckler, D., D. Molden and R. Sakthivadivel. 2003. The concept of efficiency in water-resources management and policy. In: Kijne et al. eds. 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvement. CABI Publishing, Wallingford , UK . Pp. 37-51.

Serrat-Capdevila Aleix, Juan B. Valde´s a,c, Javier Gonza´lez Pe´rez Kate Baird Luis J. Mata Thomas Maddock III. Modeling climate change impacts – and uncertainty – on the hydrology of a riparian system: The San Pedro Basin (Arizona/Sonora) Journal of Hydrology (2007) 347, 48– 66.

Shah T. 2006. The Groundwater Economy in South Asia: an assessment of size, significance and socio-ecological impacts. In ed. Giordano M and Vilholth K, The Agriculture Groundwater Revolution. CABI. UK. 403p.

Shah T. Forthcoming. Taming the Anarchy. Groundwater Governance in South Asia, Washington: RFF Press.

Smedema, L.K. and Shiati, K. 2002. Irrigation and salinity: A perspective review of the salinity hazards of irrigation development in the arid zone. Irrigation and Drainage Systems Vol. 16, No. 2, pp. 161-74.

Sperling F. (ed). (2003): 'Poverty & climate change: reducing the vulnerability of the poor through adaptation', Washington, DC: AfDB, AsDB, DFID, Netherlands, EC, Germany, OECD, UNDP, UNEP and the World Bank (VARG).

Stern, N (2006) The Economics of Climate Change. The Stern Review. Cabinet Office - HM Treasury. Cambridge. 712pp

Thenkabail P.S., Biradar C.M., Turral H., Noojipady, P., Li, Y.J., Vithanage, J., Dheeravath, V., Velpuri, M., Schull M, Cai, X. L., Dutta, R. 2006c. An Irrigated Area Map of the World (1999) derived from Remote Sensing. Research Report 105, International Water Management Institute. Colombo

Timmer, 1997. xxx

Turral H, Svensen M and Faures JM. 2008. Investing in irrigation. Special issue of Agruicultural Water Management, under review.

Turral HN. 1995. Devolution of Management in Public Irrigation Systems: cost shedding, empowerment and performance - a review. ODI Working Paper 80. London. ISBN 0 85003 2210

Turral HN. 1998. HYDRO-LOGIC? - reform in water resources management in developed countries with major agricultural water use: lessons for developing countries. ODI Research Study. Overseas Development Institute, London. ISBN 0 85003 331 4

Turral, H. N., T. Etchells, H. M. M. Malano, H. A. Wijedasa, P. Taylor, T. A. M. McMahon, and N. Austin (2005), Water trading at the margin: The evolution of water markets in the Murray-Darling Basin, Water Resources. Research., 41, W07011, doi:10.1029/2004WR003463

Udas, P.B. and M. Zwartveen, 2005. Prescribing gender equity? The case of Tukucha Nala irrigation system, central Nepal. in *Liquid relations: contested water rights and legal complexity. Rutgers university Press.*

Uhlenbrook S. 2007. Biofuel and water cycle dynamics: what are the related challenges for hydrological processes research? Hydrol. Process. 21, 3647 – 3650 (2007)

UNFCC (2007) Investment And Financial Flows To Address Climate Change. UNFCC. Bonn. 273pp

Van der Hoek W. Feenstra SG and Konradsen F. 2002. Availability of irrigation water for domestic use in Pakistan: its impact on prevalence of diarrhoea and nutritional status of children. J Health Popul Nutr.;20:77-84.

Van Koppen ......

van Koppen et al. 2002

Van Rooijen DJ, Turral H and Biggs TW. 2005, Sponge City: Water Balance Of a Mega-City: Water Use And Wastewater Use In Hyderabad, India. Irrig. and Drain. 54: 1–11 (2005), Wiley Interscience.

Van Rooijen, D. J.; Turral, H.; Biggs, T.W. 2007. Urban and industrial water use in the Krishna Basin. Irrigation and Drainage, under review.

Venot, J.P; Turral, H.; Samad, M.; Molle, F.; Landy, F. 2007 Shifting Waterscapes: explaining basin closure in the Lower Krishna Basin, South india. International Water Management Institute Research Report. Colombo, Sri Lanka: International Water Management Institute. Colombo

Wescoat, Jr., J. and G. White, 2003: Water for Life: Water Management and Environmental Policy. Cambridge University Press, 40 W. 20 th St., New York, NY 10011-4211

Wilks, D. S. & Wilby, R. L. 1999 The weather generation game: a review of stochastic weather models. Prog. Phys. Geog. 23, 329–357. (doi:10.1191/030913399666525256.)

Wolfenden J, Evans M, Essaw D, Johnson F, Sanderson A, Starkey G and Wilkinson W. 2007. Resilience Management: A Guide for Irrigated Regions, Communities and

Enterprises CRC for Irrigation Futures Technical Report No. 01/07 January

World Bank, 2005. Pakistan Country Water Assistance Strategy, Report No. 34081-PK. World Bank, Islamabad.

World Commission on Dams. 2000. Dams and development. A new framework for decision making. The report of the World Commission on dams. Earthscan Publications Ltd. London.

Zomer RJ, Bossio DA, Trabucco A, Yuanjie L, Gupta D.C., Singh V.P. 2007. Water and Trees: Small Holder Agroforestry on Irrigated Lands in Northern India. IWMI Research Report . IWMI Colombo, Sri Lanka.

Zomer, R. J.; Trabucco, A.; van Straaten, O.; Bossio, D. A. 2006. Carbon, land and water: A global analysis of the hydrologic dimensions of climate change mitigation through afforestation/reforestation and the Kyoto Protocol Clean Development Mechanism. Colombo, Sri Lanka: International Water Management Institute. (IWMI Research Report 101)

Zorita, E. & von Storch, H. 1999 The analog method - a simple statistical downscaling technique: comparison with more complicated methods. J. Clim. 12, 2474–2489. (doi:10.1175/15200442)

ANNEX

Facts on water and agriculture

In 2030, the population will have grown to about 8 billion people from about 6 billion in 2000. The increase in world crop production is projected to be 55 percent over the period 1997/99-2030 (for developing countries 67 percent). The increase in production will come from increasing yield (67 percent), extending arable land (21 percent) and increasing cropping intensity (12 percent).

FAO expects that the irrigated area in the group of 93 developing countries could grow by 0.6 percent a year over the next 30 years. This would lead to only 20 percent increase in irrigated area over this period (40 million hectares). However, when coupled with increased cropping intensity, the effective harvested irrigated area is expected to increase by much more: from 257 to 341 million hectares, a 33 percent increase;

Facts and figures

By 2030, one third of the additional land brought under cultivation in (93) developing countries will be irrigated;

In (93) developing countries, today about 29 % of harvested land is irrigated, in future it will be 32%;

Today 40% of total food production in the (93) developing countries comes from irrigated land. In 2030 it will be close to 50%;

Africa will have to depend largely on the improvement of rainfed agriculture to meet its food needs;

During 1961-99, the irrigated area in the world expanded at about 1.8 percent a year, resulting in a total increase of almost 130 million hectares;

During the period 1997/99-2030, irrigation water withdrawal in the 93 developing countries is expected to grow by a total of about 14 percent (from the current 2 128 km3/year to 2 420 km3/year in 2030).

For the 93 developing countries it is estimated that the irrigation efficiency, which is the ratio between the consumptive water use in irrigation and the water withdrawal for irrigation, was around 38 percent in 1997/99; it is estimated to increase to 42% by 2030.

Of the water withdrawals for Industry about 5% is consumed.
Of the water withdrawn for municipal use about 10% is consumed.

On average to produce 1 kg of wheat 1 m3 of water is needed; it takes about 13 m3 of water to produce 1 kg of beef.

[illegible]

Use of freshwater in the world, by sectors (2000)

World total (volume)	Domestic use	Industrial use	Agricultural use