Chapter 3

The baseline and trends in agricultural water demand

3.1. AGRICULTURAL PROJECTIONS TO 2030 AND THE ASSOCIATED DEMAND FOR WATER

3.1.1. Global analysis

This section briefly summarizes the challenges in food production without taking the added burden of climate change into account. Most global analysis of future food demand conducted prior to 2007 projected the needs for a world without climate change. Agricultural planning and associated water resources assessment in most developing countries has similarly turned a blind eye to climate change. The activities and investment associated with the ‘no-change’ perspective provides a convenient baseline for the analysis of the further impacts of climate change, using the projections of the IPCC Fourth Assessment (AR4) and subsequent analysis.

Current and projected trends in a) demand for food and b) agricultural production are given for 93 developing countries in FAO’s world agriculture perspective study towards 2015/2030 (FAO, 2003). They are based on the United Nations (UN) Statistics Division medium population projection, the World Bank income growth projections and FAO’s own estimates of future agricultural productivity. The pattern of this demand is analysed at country level and summarized at regional level in the report to give a global picture based on the analysis of national supply-utilization accounts (SUAs).

The total land area across the world amounts to around 13 billion ha, of which 1.5 billion ha is cultivated (12 percent) and a further 27 percent is managed as pastureland for livestock production. Between 1960 and 2000, the globe’s cultivated area increased by 13 percent, while population more than doubled. Of the 510,000 km^3 of water that falls on the earth each year, only 110,000 km^3 occurs over land, generating a runoff of roughly 44,000 km^3 (40 percent). It is estimated that total water use in crop production (evapotranspiration) amounted to 7130 km^3 in 2000 and is likely to rise to between 12,000 and 13,500 km^3 by 2050 (de Fraiture *et al.*, 2005).

An overall expansion in cropped area of 29 percent is forecast to 2050, with rainfed areas increasing from 549.812 million in 1998 to 698.743 million ha (27 percent). Irrigated area is forecast to grow by 33 percent, from 242 182 million ha to 318 million ha over the same period (Bruinsma, 2009).

In this analysis, and in the calculation of associated water demand, it has been assumed that all minimum demands for potable water and daily kilocalorie intake have to be met. Demand for water (stream flow or groundwater) reflects irrigation needs, whereas water use in rainfed agriculture is considered only in terms of evapotranspiration of water from the available rainfall. Hydrological balances at regional scale are determined by land use and land-use change (notably afforestation and urbanisation), although rates of evapotranspiration from agricultural landscapes are effectively consistent in a given agro-ecological zone, regardless of the precise mix of crops.

Locally, climate variability has significant impacts on crop area and crop production, especially in periods of drought or flood. Since the 1970s, the extensive development of irrigation supplies and flood control has smoothed out the impacts of climate variability and, with the benefit of Green Revolution farming techniques, increased productivity to the point that commodity prices fell year on year in real terms until the early 2000s. During this period many countries maintained high carryover stocks of grains, but these have dwindled for various reasons, stimulating a corresponding increase in market demand and resulting in price increases, beginning in 2002 with Chinese buying (FAO, 2006 – SOCO).

In 2007, continued drought in Australia reduced the export pool of grains, sending supply shocks through the market at the same time as significant land areas were planted to biofuel crops in the United States. Commodity prices spiked in 2007, when global cereal import bills more than doubled (127 percent) in two years from 2005/6 to 2007/8 (Burke and Kuylenstierna, 2008). Although they have fallen since then, rising prices are expected in the medium to long term and global commodity markets have become more sensitive (FAO, Food Outlook, 2007a).

3.1.2. Regional analysis

The historical and anticipated growth in harvested irrigated areas projected to 2015 and 2030 is summarized from the original in Table 3.1 (Bruinsma, 2009).

TABLE 3.1

Expansion of harvested irrigated areas from 1961 to 1997 and predicted to 2050 (Bruinsma, 2009)

	1961/63	1989/91	2005/07	2030	2050	1961-05	1990-05	1996-05	2005-50
	million ha					annual growth (percent p.a.)			
Developing countries	103	178	219	242	251	1.76	1.05	0.63	0.31
idem, excl. China and India	47	84	97	111	117	1.91	106	0.89	0.42
sub-Saharan Africa	2.5	4.5	5.6	6.7	7.9	2.07	1.49	0.98	0.67
Latin America and Caribbean	8	17	18	22	24	2.05	0.62	0.27	0.72
Near East / North Africa	15	25	29	34	36	1.86	1.21	1.30	0.47
South Asia	37	67	81	84	86	1.98	1.10	0.28	0.14
East Asia	40	64	85	95	97	1.42	1.00	0.80	0.30
Developed countries	38	66	68	68	68	1.57	0.38	0.20	0.00
World	141	244	287	310	318	1.71	0.87	0.52	0.24

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

TABLE 3.2

Summary of annual renewable water resources and irrigation withdrawals, now and to 2050 (without climate change) (Bruinsma, 2009)

	Precipitation	Renewable water resources*	Water use efficiency ratio		Irrigation water withdrawal		Pressure on water resources due to irrigation	
			2005/07	2050	2005/07	2050	2005/07	2050
	mm p.a.	cubic km	percent		cubic km		percent	
Developing countries	990	28 000	44	47	2 115	2 413	8	9
sub-Saharan Africa	850	3 500	22	25	55	87	2	2
Latin America /Caribbean	1 530	13 500	35	35	181	253	1	2
Near East / North Africa	160	600	51	61	347	374	58	62
South Asia	1 050	2 300	54	57	819	906	36	39
East Asia	1 140	8 600	33	35	714	793	8	9
Developed countries	540	14 000	42	43	505	493	4	4
World	800	42 000	44	46	2 620	2 906	6	7

* includes at the regional level 'incoming flows'

The regional summary presented in Table 3.2 masks the higher levels of water withdrawals on an individual country basis. In general, agricultural growth is likely to be restrained when more than 40 percent of annual renewable water resources are depleted. The food production projections by FAO and others (CA, 2007; Rosegrant *et al.*, 2002; 2001) anticipate further gains in land and water productivity that will reduce the total volume of future demand. Such gains are realistic and derive from the fact that current average levels of land and water productivity are considerably lower than attainable levels[1].

Many river basins around the world are either fully allocated or approaching full allocation. Almost without exception, these basins have extensive irrigation development; well-known examples include: the Indus in Pakistan; the Nile; the Jordan; the Syr Darya and Amu Darya basins in Central Asia; the Yellow River in China; and the peninsular rivers in southern India. Vietnam already has difficulty in meeting its Mekong Basin commitments as a result of the effective closure of the Srepok sub-basin 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 many examples, the excessive water allocations have largely concerned cash crops, specifically cotton (in Central Asia) and coffee and sugarcane (in Vietnam).

Basins are also becoming stressed as a result of water allocation for subsistence agriculture or large-scale cereal production (Batchelor *et al.*, 2003). The Rufiji and Pangani Basins in Tanzania for instance, are managed at their limit. Hydropower generation and pollution control are compromised and systemic integrity is threatened.

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[1] The gap between current and attainable yields is termed a 'Type II' yield gap by FAO. Attainable yields are based on what the better farmers can already achieve now, as opposed to theoretical potentials that require all conditions and factor inputs to be perfectly managed.

If the Rufiji Delta were 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 *et al*., (ed.) 1994). Equally, the coastal (prawn) fisheries in Mozambique and eastern South Africa are already suffering because the small coastal basins are drying out, largely because of withdrawals for cooling water and irrigated sugar cane (Maputo Basin) and the impacts of rainfed sugar cane production in KwaZulu-Natal Province.

Agro-chemical pollution of surface and groundwater places further constraints on water availability for agriculture, and more importantly for human and animal consumption. Nitrate runoff and pesticide accumulation can compromise groundwater, and phosphates are strongly implicated in algal blooms in rivers and lakes.

The Near East region faces considerable challenges in meeting future food and water needs, and will be further troubled by likely reductions in rainfall and increases in temperature due to climate change. More recent agricultural projections (to 2050) for the Near East and North Africa (FAO/NERC, 2008) are presented in Table 3.3 below:

TABLE 3.3
Crop production and land use in the Near East region*

		Rainfed land			Irrigated land			Total land		
		Area	Yield	Production	Area	Yield	Production	Area	Yield	Production
		Million ha	t / ha	Million t	Million ha	t / ha	Million t	Million ha	t / ha	Million t
Cereals (incl. rice paddy)	2005	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	2005	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	2005	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	2005	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	2005	33.8			22.4			56.2		
	2030	40.6			30.3			70.8		
	2050	44.7			34.3			79.0		
Cropping intensity (%)	2005	65			99			75		
	2030	77			117			90		
	2050	84			120			96		
Arable land	2005	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**		
excl. Sudan		59			33			77**		
Arable land as % of potential	2005	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, 2003; FAOSTAT

The associated water demands and proportions of renewable water resources used under climate change scenario SRES B1 are summarized in Table 3.4. Clearly, where stress is already evident and problematic, the impacts of climate change will be more severe.

TABLE 3.4

Annual renewable water resources (RWR) and irrigation water requirements for Near East and North Africa (FAO, 2007a)

Region		North East Africa	West Asia	North Africa	Arabian Peninsula	Total Region
		Water availability				
Precipitation	mm	308	225	102	78	177
Internal RWR	km^3	37.8	176.2	48.1	6.5	268.5
Net incoming flows	km^3	108.7	28.3	11	0	148
Total RWR	km^3	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	km^3	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	km^3	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	km^3	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	km^3	147.5	195.7	47.5	6.6	397.3
Water requirement ratio	%	71	67	64	65	68
Irrigation water withdrawal	km^3	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, 2003; FAOSTAT; IPCC, 2001c.

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.

Elsewhere (Northern Europe and Latin America), 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.

The environmental and economic impacts of existing development are becoming rapidly apparent, and climate change stresses will magnify the challenges. Climate change will, in most irrigation regions, decrease runoff, increase evaporative demand due to higher temperature, and increase the frequency of droughts and floods. Rainfed crop production in the most heavily impacted regions will be proportionately more severely affected. The current debate over the Murray-Darling Basin in Australia, which is facing contraction in agriculture as well as prolonged and unprecedented drought, can be seen as an exemplary warning for many other over-allocated river basins. Some of the earliest lessons of climate change will emerge from this region during the next decade.

Australia already has, by world standards, a very sophisticated water accounting and allocation system, based on volumetric measurement and water charging. Its water rights system internalizes natural hydrologic variability, but even without over-allocation of licenses, the system would be under severe stress from climate change, with an average reduction in runoff of 20 percent forecast for 2080. If emerging theories of a step change in climate in southeastern Australia prove correct, future runoff will be 40 percent less than the historical average. The implications for future allocation are stark – especially the balance between agriculture and environmental use – and involve awkward political and economic decisions.

In countries with less sophisticated water rights and water allocation mechanisms, as well as poor water accounting, it is evident that considerable effort is required to both understand and adapt to climate change impacts on water resources and agricultural water use. Even where water productivity and irrigation system/basin efficiency is low, the rapid development of effective and equitable water allocation and water rights systems should be a priority. Improving water productivity and realizing real water savings in poorly performing irrigation systems is an integral part of efforts to bridge the gap between present day and attainable yields (FAO, 2007b). The extent to which climate change impacts attainable, as opposed to theoretical, yields will receive plenty of attention in the coming years.

3.2. EMERGING TRENDS IN AGRICULTURAL WATER MANAGEMENT

The key trends in agricultural water management, identified prior to the IPCC AR4 are discussed in this section, which is based on the work of the Comprehensive Assessment of Water Management in Agriculture (CA, 2007: Ch. 3 Trends and Ch. 9 Irrigation) and others (Meinzen-Dick, 2007).

The major emerging water issue concerns water allocation, particularly in stressed basins, where there are strong political imperatives to continue water development, even after full allocation (India, Northern China, Pakistan).

Highly productive delta systems are under pressure from increasing population pressure and upstream flow variability, resulting from land-use change and upstream water developments. In many cases (Mekong, Hai He) increasing use of groundwater exacerbates saline intrusion to coastal aquifers and along rivers.

International concern and pressure to maintain and enhance productive environmental services (aquaculture, biodiversity) (MA, 2005) is increasingly being echoed at national level in non-government sectors and in official policy (for example efforts in China to address industrial pollution of major rivers).

Since the heyday of irrigation development in the 1970s, there has been a dramatic decline in public and international development assistance to the irrigation sector, as well as in the agriculture sector more generally. Irrigation development and expansion has however, not stood still, as there has been massive and extensive private investment in groundwater development throughout Asia. In India, the area serviced by private groundwater development significantly exceeds (doubles) the area of canal irrigation developed and managed by the state. The rapid expansion of groundwater has been aided by low or subsidized energy costs. The decline in public investment and the rise in private investment have mirrored continually declining real commodity prices over more than 20 years from 1978 to 2002. However, despite declining investment, there has been minimal cost recovery in public systems and widespread continuation of subsidies in their operation and occasional 'rehabilitation'.

Although it was expected that declining public investment in irrigation development would also stimulate increased emphasis and capacity in irrigation system management and the development of more service-oriented approaches, this has not happened to any real extent. Consequently, poor technical performance of surface irrigation systems in Asia has continued to be a concern – with equity, water use efficiency, salinization, and degradation of capital works being major issues.

The rate of increase in land and water productivity for staple crops in developing countries began to decline in the 1990s as the main benefits of the Green Revolution were realized and more incremental improvements in breeding, input use and support services took hold. Average yields in OECD countries have risen close to potential under subsidized production regimes, eventually necessitating the imposition of quotas and other restrictions on production in the European Economic Community. More than 70 percent of European grain farmers are reported to currently achieve wheat yields approaching 10 t/ha, compared with only 10 percent 20 years ago.

Strong donor interest has re-emerged in improving rainfed agriculture and in trying to establish better soil moisture conservation through a range of different techniques; this is focused on 1) greater equity in poverty alleviation and 2) significant theoretical potential to increase production. In practice, progress has been constrained by poor capital availability, poor design and construction of soil and water conservation programmes and continuing risk-averse behaviour by farmers.

Irrigation still mainly supports the production of low-value staple crops (wheat, rice, maize, pulses and oil seeds). However, 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 of such development are limited.

Raising water productivity

Water productivity is mentioned frequently in this document. There are high expectations that raising crop water productivity will offset increased water demand from crops that will result from increases in atmospheric temperatures. However, interest in water productivity is not a new concern, and much has been written in the past ten years in relation to managing increasing inter-sectoral competition for water, and in reducing agricultural water use in fully allocated river basins (CA, 2007 Ch. 7). Water use efficiency has long been a concern of crop physiologists and breeders; the surge of interest in the 1960s and 1970s was largely a performance measure for improved crop performance (Salter and Goode, 1967), where the main focus was on enhancing harvestable yield (land productivity). Water productivity is now considered in a wider landscape context, where both land and water resources are limiting (Molden *et al.*, 2010).

Physical water productivity is defined as the ratio of (useful) crop output (for instance one kilogram of grain) to the volume of water used to produce it (m^3/kg or mm/ha/kg). As water becomes more scarce, the traditional metric of yield (production per unit of land area) has been augmented by water productivity. Economic water productivity assesses the value of output per unit of water used and reflects crop choice, market conditions and the effectiveness of water management. Physical water productivity can be measured with reference to applied water or to transpired water and the difference between the two can be seen as a measure of both water management effectiveness and husbandry. The specific water use per unit of food produced (the inverse of water productivity) is presented for the main crop types in Table 3.5 in terms of both kilograms of production and a more uniform measure – per 1 000 kcal of energy contained in that food (Rockström *et al.*, 2007). This latter measure is less ambiguous than measurements per kilogram, even when adjusted to consistent moisture content. However, products that are high in protein, vitamins, fats or oils, which are also nutritionally important, are not properly evaluated in this sort of tabulation. Similar metrics of water use per unit of protein would give a more balanced and practically useful view and avoid the simplistic conclusion that all meat products would be more efficiently substituted by crops.

TABLE 3.5

Specific water use for crops, meat and dairy products (Rockström *et al.*, 2007), per kilogram output and energy value

Food type	m^3/kg	m^3/1 000 kcal
Cereals	1.5	0.47
Starchy roots	0.7	0.78
Sugar crops	0.15	0.49
Pulses	1.9	0.55
Oil crops	2	0.73
Vegetable oils	2	0.23
Vegetables	0.5	2.07
Meat		4
Dairy products		>6

No single indicator of water productivity carries great significance in terms of developing a strategy to improve farm-level management and adaptation, although it is less ambiguous at irrigation system and basin scale. Improving application efficiency in one part of a basin or system may improve water productivity, or it may actually reduce it, depending on what happens to the water savings and total water use throughout the basin. In the Murray-Darling Basin in Australia, application efficiency is important because any accessions below the root zone exacerbate water-table rise, secondary salinity and water logging.

As the efficiency of all biological processes declines asymptotically with satisfaction of each limiting factor, there is more scope to increase water productivity efficiently and effectively when it is low. Thus the addition of a small increment of water or fertilizer, or both, makes a large percentage change (but not necessarily such a great absolute change) in total product. This understanding supports a logic that there is considerable potential to raise the land and water productivity of rainfed crops, at least those grown in sub-optimal conditions, by improving soil-moisture status through better soil water conservation and harvesting technologies, or by providing supplemental irrigation where possible. A major reasoning behind widespread efforts to re-invigorate rainfed farming in this way is that it will allow for mitigation of damage to natural ecosystems from 1) abstraction of water for formal irrigation and 2) expansion of rainfed areas at the cost of forest and other natural ecosystems (Rockström *et al.*, 2001). However, farmers are traditionally risk-averse and will not overinvest (in fertilizer or time, for example), where they assess the risk of failure to be high. Water harvesting technologies can help in dry periods, but provide less insurance against drought (seasonal and annual). Both the conditions for rainfed cropping, and the hydrology of rainwater harvesting and conservation will deteriorate in the tropics and semi-arid tropics under climate change. Further investigation of these factors is due and will be timely in assessing future mixes of options between rainfed and irrigated agricultural development and intensification.

Interestingly, the breeding of high-yielding varieties has historically increased water-use efficiency by: shortening season length and dwarfing and improving harvest index, resulting in lower seasonal transpiration as well as greater harvestable production. There are many factors of yield that contribute to water-use efficiency. Where the management of inputs is poor or unbalanced, water productivity may be low due to depressed yield for reasons other than water supply. Nitrogen responsiveness has contributed to increased biomass accumulation (in a shorter season with a shorter plant) and has encouraged better early crop establishment, which (in rainfed, and possibly in irrigated conditions) results in less direct evaporation loss. Much of the gap between yield potential and actual yields (and hence water productivity) is due to poor husbandry and sub-optimal management of inputs – especially in irrigated agriculture. The corollary to this is that inputs are often in short supply in water-short, rainfed conditions.

Current controversy in the potential for further improvement of water use efficiency (WUE) percentage and of acquisition of drought-tolerance (Rebetzke *et al.*, 2008) centres on whether single-gene expressions can be found to confer drought tolerance or increased water productivity as have been found for genetically modified crops that are resistant to pesticides and herbicides such as BT Cotton. The opposing argument is that water productivity (and yield) are the expressions of complex genotype (with multiple genes) – phenotype – environment interactions that are better addressed by conventional plant breeding and cultivar selection methods. Secondary traits that are often identified as desirable, such as low specific leaf area to achieve a higher assimilate to transpiration ratio, may also be linked to other expressions, in this case low harvest index.

However, recent marker assisted wheat-breeding research indicates that there remains considerable potential to improve in areas such as transpiration efficiency, early season development, emergence in rainfed wheat in Australia (Rebetzke *et al.*, 2008). In other crops, like legumes and beans, (which are generally less bred and less researched), the dominant reason for variation in water use efficiency in screening trials is the relation between stomatal conductance and assimilation/transpiration (A/T) – so there is potential to screen and select when the gene pool is large and use marker technology to avoid linked but undesirable traits. Indeed one strategy to improve water use efficiency in wheat is to enlarge the gene pool from which selections can be made, and this means that the preservation of wild and old strains is very important.

Improving yield and water use efficiency in irrigated and rainfed agriculture follow different pathways. In rainfed cultivation, the focus is on increasing yield through good husbandry, best use of rainwater through soil moisture management and by the provision of more nutrients. In irrigated agriculture, the availability of water will dictate whether to focus more on yields (when irrigation is unconstrained by water availability) or on water productivity (when water is scarce), resulting in different combinations of area and water use for an optimum level of production.

3.3. ANTICIPATED TRENDS IN AGRICULTURAL WATER MANAGEMENT

3.3.1 Trends without climate change

A number of recent reports have summarized the main trends and drivers in agricultural water management that mainly respond to economic factors relating to rising water scarcity (FAO, 2003; FAO, 2007a; CA, 2007). All have assumed that past hydrology is a good guide to hydrology in the future, and they have (with the exception of FAO/NERC analysis (2008)) not quantitatively factored climate-change impacts on crop-water demand and on water availability into their analysis. Box 3.1 summarizes the main findings of the Comprehensive assessment of water management in agriculture about the future of irrigation (CA, 2007, Faurès *et al.*, 2007).

Many recent reports on adaptation to climate change (Fischer *et al.*, 2007; Nelson *et al.*, 2009; Climate Adaptation Working Group, 2009; Padgham, 2009) anticipate a substantial increase in irrigated area in response to global temperature rise, higher rates of crop water use, and declining and more variable rainfalls. The foregoing indicates, at least for many developing countries, that the options are limited and will need careful scrutiny.

BOX 3.1

Prospects for irrigation (adapted from Faurès *et al.*, 2007)

- The conditions that led to large public investment in irrigation in the past have changed radically and today's circumstances demand substantial shifts in irrigation strategies. Irrigation and drainage will still expand on to new land, but at a much slower pace. New investment will focus much more on enhancing the productivity of existing systems through upgrading infrastructure and reforming management processes. 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.

- More farmers around the world will integrate into a global market, which will dictate their choices and behaviour. 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.

- Irrigation will increasingly be under pressure to release water for higher value uses. 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.

BOX 3.1 *(CONTINUED)*

Prospects for irrigation (adapted from Faurès *et al.*, 2007)

- Irrigation and drainage performance will increasingly be assessed against the full range of their benefits and costs, not only against commodity production. The success of irrigation has often come at the environment's expense, degrading ecosystems and reducing water supplies to wetlands. It has also had mixed impacts on human health.

- Governance will need to adapt, and the recent trend to devolve the responsibility for irrigation management to local institutions, with more direct involvement of farmers, is likely to intensify while bulk water supply infrastructure, because of its multiple functions and strategic value, will usually remain in the hands of the state. Governments will need to develop compensating regulatory capacities to oversee service provision and protect public interests.

3.3.2 Analysis of economic drivers and future investments

Agricultural production patterns are determined largely by market demand and governing agroclimatic conditions in a particular region. It is anticipated that trade policies and subsidy programmes will exert greater influence on crop production patterns in the short term (5–15 years) than climate change. Irrigation is historically 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 poses potentially serious threats to agricultural water management, hitting hardest in poor, semi-arid areas that already suffer from erratic water variability.

Future investment needs in irrigation have been examined in several studies (CA, 2007; Faures *et al.*, 2007; Turral *et al.*, 2009). The summary provided in Table 3.6 is taken from these publications, and examines investment in relation to a simple typology of the dominant 'irrigated production systems' set in a broad economic context that is defined by contribution of agriculture to GDP and also reflects the level of economic competition for water (bottom row). Countries with a less than 9 percent contribution from agriculture may still have large rural populations, but have more diversified sources of income and are generally wealthier. Farming remains the backbone of the economy in countries where it accounts for more than 30 percent of GDP, although the number of countries in this category is rapidly diminishing. The potential impacts of different developments on aquatic ecosystems are indicated in the right-hand column. The table includes a number of other classifying factors, such as the state of competition for water and the level of environmental management, which in turn indicate further investment costs.

This investment typology has some commonality with the typology for climate change impacts and adaptation that are proposed later in this document. It can be adjusted to assess investment needs for adaptation and development responses to climate change in the future. It is, however, focused primarily on development options. There is some potential for confusion in meeting both development and adaptive investment needs; the two need to be integrated as far as is possible; a real and practical challenge in future years.

TABLE 3.6

Typology of irrigation contexts, conditions and sources for future investment

Financing	Agriculture > 30% GDP	Countries in transition	Agriculture < 9% GDP	PNIAE
Large public schemes in arid areas				
International	Large dams, drainage, Formation of WUAs	Large scale irrigation system control and operation, selective IMT/joint management of irrigation schemes	Environmental flow management	Scale: regional Q & q
National	Small dams, irrigation staff training, run-off river gravity supply	Large and small dams, rural electrification, drainage, bulk water allocation, staff training	Automation and SCADA, water quality monitoring, recycling return flow, IMT, environmental management plan and operation, sub-division to multiple autonomous management units, water conservation	
Cost recovery			Service provision, information systems	
Local / Farmer		Farm layout and land forming in surface irrigation, conjunctive use of surface water and groundwater		
Large public schemes in humid areas (rice)				
International	Formation of WUAs	Selective IMT/joint management, system control and operation	Environmental flow management	Scale: regional Q & q
National	Conjunctive use systems based on run of river diversion, irrigation staff training, run-off river gravity supply	Rural electrification, bulk water allocation, staff training, (dams)	Selective canal lining, IMT, Automation and SCADA, Environment management plans and operation, sub-division to multiple autonomous management units, water conservation	
Cost recovery			Information systems, service provision	
Local / Farmer		Conjunctive use of SW and GW		
Small scale community managed				
International	WUA formation, monitoring & support			Scale: local, depends on density of development Groundwater quality and depletion
National	Run of river - weirs, diversions	Local storages and small dams, improved water distribution infrastructure, recognition and formalization of water rights and bulk allocation, rural infrastructure, credit, market opening	Re-engineering and modernizaton - including pipe distribution systems, land consolidation, measurement and monitoring, information systems, regional water management	
Local / Farmer	Shallow GW within irrigation systems, riparian zones and deltas	Mechanized and deeper groundwater		

TABLE 3.6 *(CONTINUED)*

Typology of irrigation contexts, conditions and sources for future investment

System Type	Agriculture > 30% GDP	Countries in transition	Agriculture < 9% GDP	PNIAE
Medium scale commercial and private				
National	Export markets	Market chain, regulation and monitoring	Regulation and monitoring, export markets	Water quality
Local / Farmer	Pumped irrigation - surface and groundwater, on-farm mechanized systems, overhead irrigation (sprinkler and micro-irrigation technologies)	Precision farming - pivots, lateral moves, land forming, micro-irrigation, runoff recycling, automation of water supply	Irrigation scheduling and soil moisture monitoring, precision farming and fertigation, piped distribution systems	
Farm scale systems				
International	Low cost technologies - drip kits etc.			Water quality
National	Wastewater re-use - engineer supplies, market and infrastructure development, credit	Mechanized groundwater use, wastewater treatment and management	Water measurement and control, farm consolidation, water user and marketing groups	
Cost recovery		Rural electrification / Energy pricing (targeted subsidies)	Sprinkler and micro-irrigation for horticulture	
Local / Farmer	Low cost shallow groundwater & small pumps for surface water			

Note: GW: groundwater; IMT: Irrigation management transfer; PNIAE: Potential to negatively impact on aquatic ecosystems; Q&q: Quantity and quality; SCADA: Supervisory control and data acquisition; WUA: Water Users Association.

Chapter 4

Specific climate change impacts related to agricultural water management

4.1. INTRODUCTION

Climate change impacts are secondary drivers of agricultural water demand, which is responsive to a broad range of economic factors outlined in Chapter 3. At a global scale, it is possible, likely even, that further climatic stress on water-short river basins will be offset by higher rainfall in temperate zones. Conversely, it is possible that higher intensity rainfall events over temperate cereal production regions, coupled to more severe outbreaks of pests and diseases, will result in widespread crop damage, thus worsening the global supply shock arising from water scarcity.

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 likely trends from the perspective of the SRES alone (Parry *et al.*, 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 with 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, 2007a). To date there has been no formal resolution of the two approaches, and work continues to match these two perspectives. In the meantime, a number of assessments based on SRES scenarios have presented a more alarming picture (Nelson *et al.*, 2009).

4.1.1. Predictive modeling and its limitations in determining agricultural impact

Climate change effects on crop production are more complex than those related to changes in average temperature and rainfall: combinations of stress are common and important. Therefore effects of variability, frequency of extreme events and combinations of stresses should be specifically addressed in modelling scenarios (Porter and Semenov, 2005). Overall seasonal precipitation determines the yield over large areas, but stress and dry spells threaten productivity (even a few hours at critical growth stages) (Huntingford *et al.*, 2005). Thus the factors affecting crop productivity are predominantly weather based, rather than determined by long-term climate:

- changes in mean weather (temperature and rainfall);
- changes in variability or distribution of weather;
- combinations of changes in the mean and changes in its variability.

A simulation study coupling a stochastic weather generator to GCM predictions for wheat in Spain and the United Kingdom examined these weather combinations and demonstrated grave consequences of increased variability with marginal decreases in yield for increased temperature in Spain but a 50 percent chance of much lower yields with increased variance, mostly due to longer dry spells over the vegetative growth period, in both countries. Longer periods of dry weather with the same total precipitation increased simulated variability in yield and quality by 70–80 percent compared with baseline (Porter and Semenov, 2005).

Porter and Semenov (2005) conclude that yield-damaging weather signals for cereals are in the form of absolute temperature thresholds; these are linked to particular developmental stages and are effective over short time periods. Therefore global analyses based on annual and seasonal crop patterns may be wide of the mark: crop-climate models need to be able to work at a temporal resolution of a few days.

In addition to poor spatial representation of existing rainfall patterns, the current generation of models distribute monthly rainfalls uniformly for each day (IPCC, 2007). As with temperature, this smoothing must underestimate the impacts of within-season drought periods between rain events. Similarly, it is likely to underestimate runoff and overestimate infiltration, especially in flashy catchment settings.

Huntingford *et al.*, (2005) also identified other limitations in using GCMs to evaluate agricultural impacts. Ocean–atmosphere coupled models cannot duplicate the North African drought from 1971–1989, although (strangely) atmospheric only types can. Current thinking is that such weather patterns are driven more by local forcings rather than global climate changes. Although GCMs cannot currently reliably replicate cyclic weather patterns such as ENSO, modelling does suggest ENSO cycle periodicity could reduce from 5 to 3 years under CO_2 doubling in 2050.

4.1.2. Impacts on nations or river basins?

Patterns of production are currently confused by the actual impact of price signals on agricultural production (including biofuels) (Rosegrant *et al.,* 2006); these indicate the ability for rapid and sudden change in production patterns and the knock-on effects for the whole sector (Ch. 3). Although rapid improvements are being made in land-use classification from remote sensing, obtaining an accurate assessment of rainfed and irrigated areas and production will remain a continual challenge resulting from the relatively rapid short-term market-driven responses in crop choice.

In the end, an analysis of the sensitivity of agriculture water management to climate change only makes sense within a systemic context – the river basin and its related aquifers. For this reason, this section concentrates on the impacts across hydrological units. Despite the fact that adaptation and mitigation policies and strategies will be framed at national level, largely in response to macro-economic analysis, such a systemic approach will remain valid. National production in semi-arid countries, such as Morocco and Yemen, is an aggregate of harvests in individual river basin and aquifer systems. Further, many of the large basins and aquifers that support productive agriculture, such as the Aral Sea basin, Indus, Nile and Mekong, cross one or more national boundaries. Thus impacts on agriculture and hydrology and potential solutions have to be examined at levels broader than national interest; the river basin will remain an important arena (Svensen, 2008).

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 on food production are summarized 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 as yet only limited literature available on the prospective impacts of climate change on water balance and implications for irrigation, the impacts of these drivers are likely to include the following:

- reduction in crop yield and agricultural productivity where temperature constrains crop development (changes in diurnal fluctuation are as important as overall trends);
- reduced availability of water in regions affected by falling annual or seasonal precipitation (including southern Africa and the Mediterranean region);
- exacerbation of climate variability in places where it is already highest (Peel *et al.*, 2004 and 2004a);
- 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.

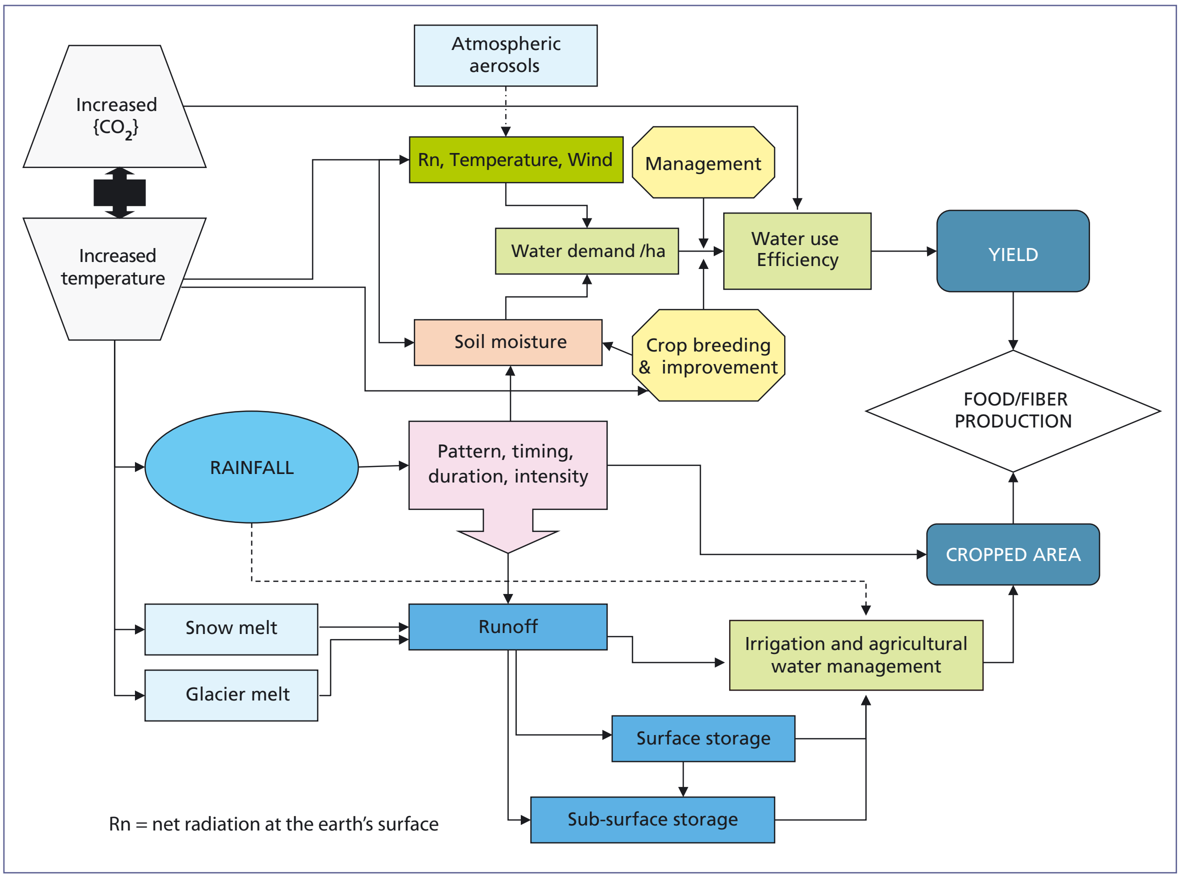
4.3. OVERALL IMPACTS ON CROP PRODUCTION

4.3.1. Direct effects of temperature and changes in precipitation

The writings connected to the IPCC, Stern Review and climate change literature are pessimistic about the impacts of climate change on agricultural production compared with recent analyses conducted by FAO and the Comprehensive Assessment of Water Management for Agriculture (CA, 2007). These analyses have focused on the future food and water demands up 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 very limited climate change impacts, and do not include the detail that became available in AR4, which was published later. To some extent, 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 approaches are valid, but this discrepancy clearly needs to be better resolved.

FIGURE 4.1
The agricultural production cycle, as impacted by climate change



Rn = net radiation at the earth's surface

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 likely to be outweighed by increased temperature and lower rainfall (Long *et al.*, 2005; Smith *et al.*, 2008, section 4.3.1). 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 (Porter and Semenov, 2005). Additionally, there is anticipation of greater fire risk and incidence of pests and diseases.

Growing season temperatures in the tropics and sub-tropics by the end of the twenty-first century are highly likely to exceed the most extreme seasonal temperatures recorded from 1900 to 2006 (Battisti and Naylor, 2009). These authors note that losses in French and Italian maize grain and fodder harvests were great in the hottest year on record (during the European heat waves of 2003), with 30 percent reductions; they note that there are many historical examples where high seasonal heat has had severe consequences, which resulted in price hikes. The tropics currently experience less summer season temperature variation than found in temperate areas, but this will change dramatically with climate change and this area will be the first to experience severe impacts.

Cereals incur major physiological damage when average season (92 days) temperature reaches 33 ˚C (Huntingford *et al.*, 2005). The effects of a modest, 2 ˚C, rise in temperature are likely to decimate the tea industry in Kenya, and coupled with declining rainfall, significantly reduce the productivity of cocoa in Ghana (Barclays and Met Office, 2009).

Global annual irrigation water water withdrawals are estimated at 2 710 km^3 (FAO, 2010) or about 70 percent of the total water withdrawals of 3 862 km^3 per year (FAO, 2010). Estimates of future irrigated areas are highly dependent on estimates of water use 'efficiency' – the ratio of crop water requirements to water withdrawals. This, in turn, depends on the interaction between negative effects caused by rising temperature (increasing evaporative demand and night-time respiration, resulting in declining potential net primary production) and CO_2 enhancements (increased photosynthetic efficiency, reduced water use and reduced respiration rates).

Average global irrigation demand is expected to increase by between 5 and 20 percent (Fischer *et al.*, 2007; Nelson *et al.*, 2009) as a result of rising temperature – somewhat lower than earlier estimates by Döll (2002). However, it has been observed that canopy and air temperatures over land irrigated in semi-arid conditions can be as much as 10 °C below ambient without irrigation (USDA, 2008). This has some important, and not fully explored, implications for the productivity of irrigated areas. A more bottom-up assessment conducted across the United States concludes that irrigation water requirements will increase by 64 percent by 2030, or 35 percent with CO_2 fertilisation effects (derived from FACE estimates) (USDA, 2008).

IIASA's baseline scenario (without climate change) projected a 45 percent increase in irrigated land to 393 million ha in southern Asia, Latin America and Africa in order to meet future food demands (Fischer *et al.*, 2007). This translated into a 66 percent increase in water requirement over present use when climate change was taken into consideration. Two thirds of the increase was attributed to temperature rise and rainfall changes and one third to extended crop calendars. It was estimated that only 50 percent of the water supplied to crops transpired in 2000; in other words, average global irrigation efficiency is 50 percent. The modelling scenarios allowed for modest increases in global irrigation efficiency to 60 percent in 2030 and to 70 percent in 2080. The broad distribution of future water stress is predicted to closely match that presently being seen. FAO had previously estimated that an extra irrigated area of 40 million ha will be needed to meet global food security needs in 2030 (FAO, 2002); this is substantially less, pro rata, than the 122 million ha increase estimated by IIASA for 2080. The broad conclusion is that the additional water required because of climate change will be nearly as great as the net increase in demand from present day to 2080 to meet additional food and other needs.

An implicit assumption in the IIASA study is that potential water productivity does not decline *per se*: although water demand will increase because of temperature effects, it is assumed that the underlying physiology will be maintained. The International Food Policy Research Institute (IFPRI) study is based on Decision Support System for Agrotechnology Transfer (DSSAT) crop modelling of four main representative crop types, with less delineation of global agro-ecological zones. The physiological processes represented in the crop model respond to temperature and evaporative demand, but the underlying efficiency of photosynthetic and respiration processes is not changed. A sophisticated study of irrigated production under climate change undertaken for Morocco (Gommes *et al.*, 2009) used a simpler modelling framework (FAO's Crop Specific Soil Water Balance Model) that is linked to downscaled climate prediction to derive complex multi-factor yield functions with up to 43 variables in the multiple linear regression. It assumes that present crop response functions will be unchanged in the future, and that future irrigation supply will satisfy all crop water demands. Crop physiologists would disagree with this assumption, but it seems likely that considerable further work needs to be done to develop integrated crop models that take all climate change effects fully into account. The study predicts net positive yield response to climate change and indicates that continued irrigation will isolate cropping from the broader impacts of climate change. Like all modelling, this result derives from its assumptions and does not address the impacts of climate change and variability on irrigation water availability and the consequent effect on production.

The increased frequency of extreme events may lower crop yields beyond the impacts of mean climate change. Impacts of climate change on irrigation water requirements will therefore be 'large' and countries with greater wealth and natural resource endowments can adapt more efficiently than those where water is already scarce.

There remains much to be done to improve and standardize on methodologies to assess future production potential at local, regional and global scales: a broader range of economically important crops and locally adapted varietal characteristics is required. The modelling should link future climate change patterns to more detailed and downscaled weather based models; it should account for short term (daily) and averaged effects of increased temperature and to extremes and variability in temperature and rainfall as much as to long-term trends. Such work is better undertaken at a local scale, by researchers who are strongly connected to the subtle detail of specific systems. More effective global assessment is likely to result from continued development and refinement of governing GCMs and RCMs, and the integration and amalgamation of more specific and detailed local assessments in different agro-ecological zones and regions around the world. Where irrigated agriculture is concerned, it is important to integrate the hydrology of water supply with the direct effects on crop growth.

4.3.2. Carbon dioxide 'fertilization' of crops

Higher atmospheric concentration of CO_2 stimulates yield by decreasing photorespiration in C3 crops and transpiration in all crops. However, the initial expectations of increased productivity from enhanced atmospheric CO_2 have been downgraded, because the very local scale of experimental measurement (point and leaf scale in chambers) tended to exaggerate field and larger-scale responses.

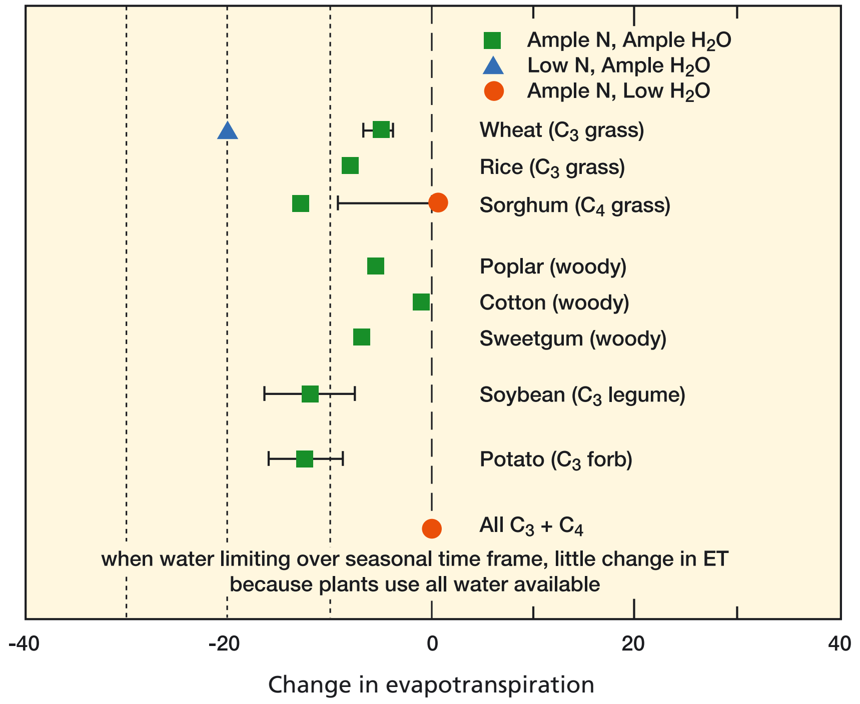
In general, plant response to elevated CO_2 alone, without climate change, is positive and may be relatively greater for crops under moisture stress compared with well-watered crops (IPCC, 2007). The effects on plant growth and yield depend on photosynthetic pathway, species, growth stage and management regime, including the application of water and nitrogen (N). On average, across several species and under unstressed conditions compared with current atmospheric CO_2 concentrations, crop yields in growth chambers increase at 550 ppm CO_2 in the range of 10–20 percent for C3 crops and 0–10 percent for C4 crops. However, the effects of elevated CO_2 are inevitably limited by other agronomic factors at field scale, including pests, weeds, soil and soil-moisture availability (Fuhrer, 2003). In addition, modelling studies suggest crop yield losses with minimal warming in the tropics and predict that mid- to high-latitude crops will benefit from a small amount of warming (about +2 °C), although plant health declines as temperatures rise.

Free-Air Concentration Enrichment (FACE) technology allows investigation of the effects of rising CO_2 concentration and ozone on field crops under open-air conditions at a field scale. Experiments with rice, wheat, maize and soybean show smaller increases in yield than anticipated from studies in chambers. More worryingly, experiments with increased ozone show large yield losses (~20 percent), which are not yet accounted for in projections of global food security (Long *et al.*, 2005). C4 crops are generally much less sensitive to ozone, but impacts derived from soy (C3) experiments across the United States showed an average 34 percent reduction in biomass, accompanied by a 24 percent reduction in grain yield, but only a 20 percent fall in the rate of photosynthesis. Ozone is already thought to be limiting present yields and will impair them further as levels rise.

Much of the work elaborating positive CO_2 responses has been undertaken in the United States, and USDA (2008) maintains that responses from FACE experiments broadly corroborate growing chamber experiments. Rates of evapotranspiration at an atmospheric CO_2 concentration of 550 ppm are reduced by around 10 percent for well-watered crops with adequate access to nitrogen (see Figure 4.2), a situation that is increasingly unlikely to prevail for rainfed crops. One consequence of stomatal closure is reduced evaporative cooling, so crop canopy temperature has been observed to rise, thus increasing rates of respiration.

FIGURE 4.2

Summary of evapotranspiration effects of elevated CO_2 concentration, for different categories of limiting conditions under current temperature conditions – determined in FACE experiments in the United States (USDA, 2008)



Current thinking in the United States is that the net reduction in evapotranspiration at 440 ppm (2030) will be negligible and growth improvement could be as much as 10 percent (on projections of 30 percent increase for C3 plants to 700 ppm), depending on whether growing season temperature is more or less favourable. The assessment of temperature limits for different crops in the United States is quite elaborate, based on extensive experimental evidence at all stages of growth, and further supported by crop modelling studies. Temperatures over the southern, central and western United States will generally become sub-optimal. Overall, potential yield is generally expected to decline as a result of rising temperature, with only limited mitigation or mild improvement with CO_2. By the time CO_2 levels reach the more stimulating 2x level (700 ppm around 2050 without mitigation), the rise in atmospheric temperature will have negated its positive contributions to net yield.

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 percent at a CO_2 concentration of 550 ppm, compared with 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 evapotranspiration) will more than offset CO_2 enhancement to production; the result being an overall decline in productivity (CSIRO, 2007).

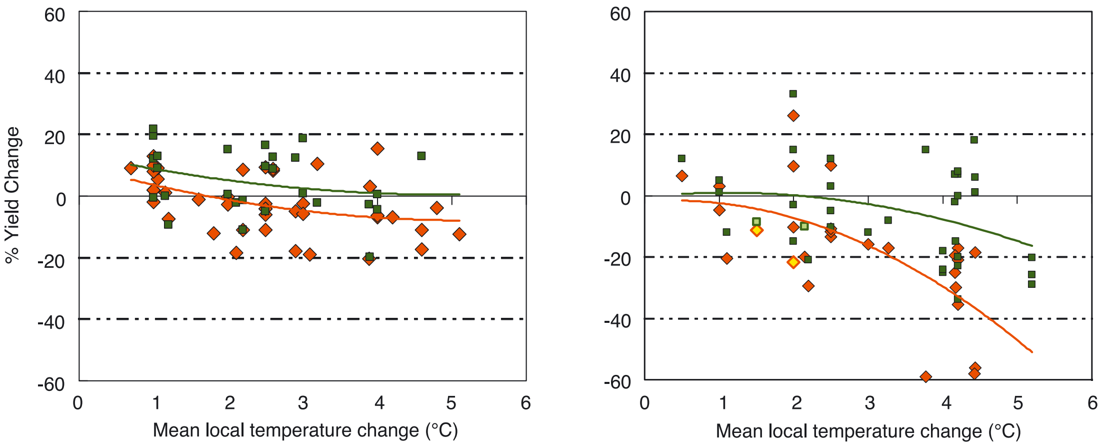
Expected yield trends for rice wheat and maize at low altitude, derived from modelling over a range of temperatures and carbon dioxide concentrations, are shown in Figure 4.3 (IPCC, 2007). The orange markers indicate performance without adaptation and the green assume a variety of adaptations, including irrigation. The lighter coloured markers indicate rainfed 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.

Most recent detailed Australian analyses show that, despite adaptation, production and productivity will fall, mainly because of 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, possibly because of the high ranges of temperature 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 echoed in the Australian horticultural industry, where temperature regimes are optimized to 1 °C. It also has great resonance to Europeans and North Americans, because of the vernalization 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 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.

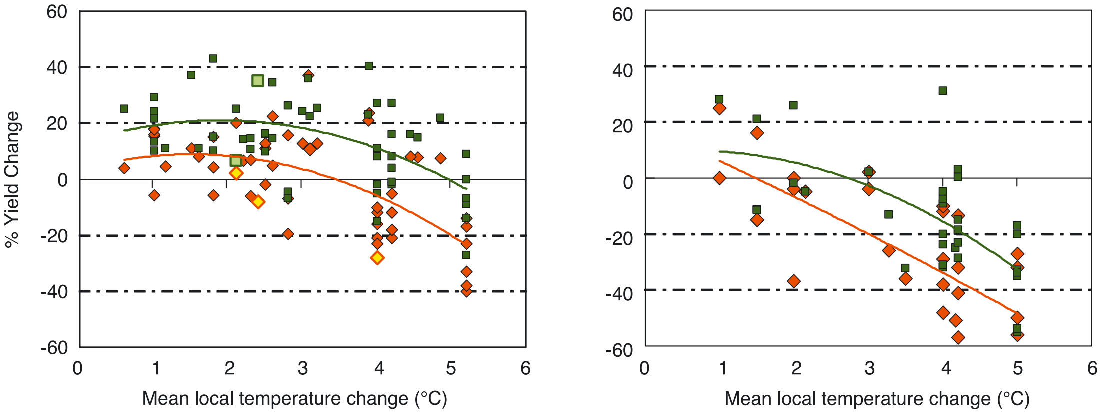
FIGURE 4.3

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



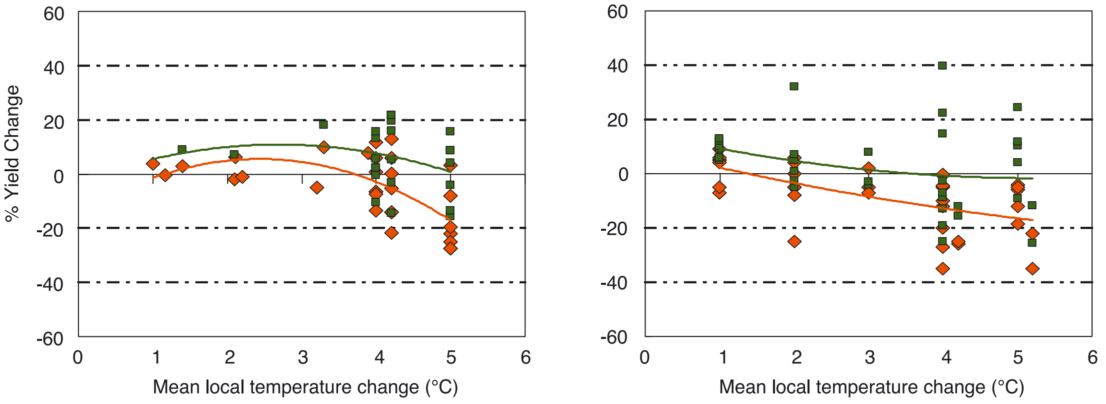
(a) Maize, mid- to high-latitude

(b) Maize, low latitude



(c) Wheat, mid- to high-latitude

(d) Wheat, low latitude



(e) Rice, mid- to high-latitude

(f) Rice, low latitude

Climate Change 2007: Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 5.2. Cambridge University Press.

4.3.3. Pests and diseases

The following points on pests and diseases are summarized from the recent World Bank publication on adaptation to climate change in agriculture (Padgham, 2009):

- Climate change is likely to increase pest pressure on agriculture. Changes in temperature and precipitation, increases in extreme events, and loss of ecosystem integrity could increase pest reproductive rates and virulence, shift the distribution and range size of pests, and lead to greater frequency of new emerging diseases and invasive alien species.
- Current evidence of range expansion linked to higher minimum temperatures, new pest outbreaks, or more intensive infestations linked to El Niño episodes, presage an increase in biotic stress to agriculture from climate change.
- Climate change has the potential to reduce the effectiveness of current pest management strategies, requiring the dedication of additional resources for developing new knowledge systems and appropriate measures to counter new pests or the intensification of existing pests. A narrowing of pest management options could potentially occur with management strategies that rely on host resistance breeding, use of biological control, and pesticides.
- Adaptation to heightened biotic stress from climate change will require significant investments in enhancing national pest management surveillance, diagnostic and management capacity, and knowledge systems, in terms of local and traditional pest management knowledge, as well as training in molecular methods for characterization of pest populations and breeding.
- Better institutional coordination, information sharing, and public awareness are needed to counter the threat from invasive alien species.

4.4. IMPACTS ON WATER SUPPLY AND DEMAND – A GLOBAL PICTURE

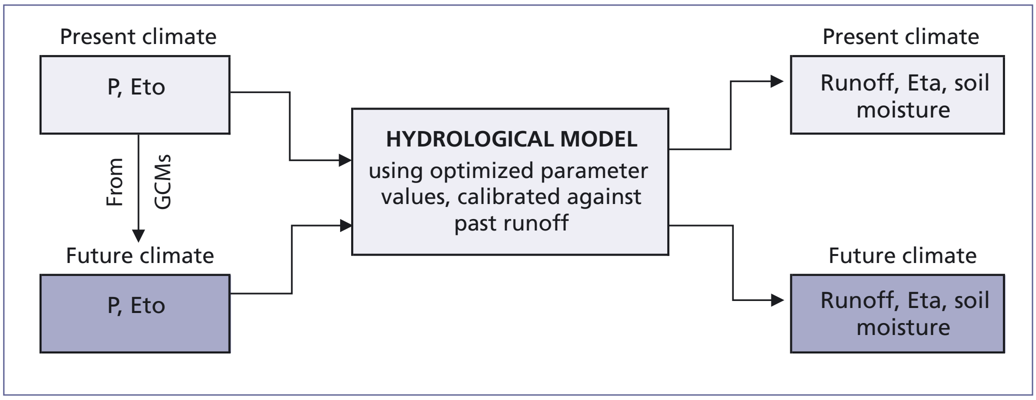
4.4.1. Overall water supply impacts

Rainfall is the key climatic variable for agriculture but the prediction of rainfall by GCM simulation is not as accurate as that for temperature and pressure. GCM resolution is at a larger scale than that at which weather processes are driven (Huntingford *et al*., 2005). In AR4, there is some indication that the uncertainty associated with rainfall has been increased further 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 4.4 (Chiew *et al*., 2003)). The uncertainity associated with the combination of downscaling methods and rainfall-runoff models has been illustrated by Chiew *et al*. (2010). Two systematic sources of uncertainty 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 for concern within the international irrigation community.

FIGURE 4.4
Prediction of runoff under climate change (adapted from Chiew *et al.*, 2003)



4.4.2. Groundwater

Aquifers have an important strategic value as accessible over-year stores of water in a relatively stable condition without evaporation losses. In addition, percolating water is naturally de-contaminated along diffuse recharge and circulation pathways. The development of groundwater has therefore been an important structural adaptation to drought and is likely to be more so in the future. Clearly this character of groundwater is of more strategic importance to potable water supply than agriculture since agriculture is generally indifferent to the quality of most freshwater stored in accessible aquifers. However, agriculture has been quick to exploit groundwater circulation and now accounts for over 80 percent of all groundwater withdrawals (Siebert *et al.*, 2010).

Patterns of groundwater recharge drive groundwater circulation and are determined both by rainfall (direct recharge) and transmission losses along watercourses (indirect recharge) (Döll and Fiedler, 2008). When localized alluvial aquifers are annually replenished, they 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 more understanding.

A good and clear understanding of the likely impacts of climate change on groundwater circulation is therefore very valuable, but is unfortunately bedevilled by the general uncertainty surrounding the prediction of rainfall and runoff under current conditions (Scanlon *et al.*, 2006; Döll and Fiedler, 2008; Döll, 2009) . The sustainability of groundwater use is determined by the rates of abstraction and recharge, and also quality of the recharge water. In broad terms, recharge is expected to be high where rainfall is high and vice versa (Dragoni and Sukija, 2008). Recharge will also increase where permafrost thaws and may increase when runoff increases, particularly if over-bank flood events occur more frequently. Although there is a broad correlation between recharge rate and rainfall, replenishment in a specific aquifer is further governed by geology, topography and land use. Forested catchments tend to have lower rates of aquifer recharge than agricultural and cleared catchments, and afforestation, although desirable to sequester CO_2, will probably reduce recharge; this would require compensation if groundwater resources are to be maintained.

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 overland flooding in climatic contexts as different as Australia and Bangladesh.
- If drought frequency, duration and severity increase, the cycle time will lengthen and abstraction will require better balance, with less in sequences of wet years and more in dry years. There is 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 snowmelt 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.

The vulnerability of groundwater systems across different continents has recently been assessed (World Bank, 2009b) in relation to existing utilization, the effects of climate change on recharge and sea-level rise, and wealth; this is summarized in Table 4.1.

As aquifers in humid and even semi-arid zones are intimately connected to streams and other water bodies, changes in aquifer level can lead to changes in network behaviour, such as the reversal from recharge from a river to discharge into it and vice versa. The dynamics of many aquifers are complicated, and the transit time for recharge may be very long indeed. Changes in runoff and rainfall may be amplified in the groundwater response, and in arid and semi-arid conditions, falling rainfall and runoff are accompanied by proportionately greater reductions in aquifer recharge.

TABLE 4.1
Vulnerability of groundwater to climate change (World Bank, 2009b)

	Sensitivity	**Exposure**		**Adaptive capacity**	
World Bank region	**Utilization of groundwater**	**Climate change impact on recharge**	**SLR[1] & storm surge exposure**	**Per capita income**	**Vulnerability**
East Asia & Pacific	Moderate	Increase	Medium	Moderate	Moderate
Europe & Central Asia	Low	Increase	Low	High	Low
Latin America & Caribbean	Moderate	Reduction	Medium	Moderate	Moderate
Middle East & North Africa	High	Uncertain	Low	Moderate	Moderate
South Asia	Moderate	Negligible	High	Low	High
Africa	Moderate	Reduction	Low	Low	High

Abstraction over recharge rates results in aquifer depletion and increased abstraction costs but can also induce water quality changes as saline groundwater and other natural mineral contaminants such as Arsenic and Fluoride are mobilized. Longer periods of drought in arid conditions will result in greater build-up of solutes in the soil and increase the frequency of saline flushes to groundwater following rainfall events.

Throughout much of the world, even in countries with strong water management systems, groundwater remains poorly understood. The increasing realisation of its strategic importance has prompted a wave of activity in trying to understand surface water - groundwater interactions better and to monitor and study systems accordingly. The literature on climate change impacts on groundwater remains thin, and modelling is often the only way to assess a possible future. Groundwater modelling is constrained not only by uncertainty in climate change hydrology but also by the coarse description and understanding of many aquifer systems.

Private groundwater development has propelled a massive increase in irrigation areas since the introduction of the mechanized borehole, and aquifers are being depleted rapidly in many parts of the world, from California to Gujarat. The on-demand, just-in-time availability of groundwater has made its exploitation difficult to resist, even in surface irrigation commands (Shah, 2009). Despite this, the literature dealing specifically with groundwater impacts is limited and often general. In dry zones, groundwater recharge is only a fraction of rainfall, most of it being lost in evaporation, and is difficult to assess accurately. The estimation of groundwater trends under climate change is further complicated by its place in the hydrological cycle and the relative difficulty of measuring and modelling its dynamics, and by current uncertainty in the prediction of rainfall and the impacts of future land use.

A sophisticated analysis, incorporating land-use interactions with crop selection driven by profit maximizing, was undertaken for the eastern United Kingdom (Holman, 2006), where low-lying areas will also be more frequently inundated with rising rainfalls and sea levels. The nested modelling study concluded that climate induced changes in precipitation dominated socio-economic and temperature effects in governing distributed groundwater recharge. In contrast, an aquifer dominated by flood plain recharge in Canada will experience increased annual recharge from increased rainfall and runoff, but there will be little impact on maximum groundwater level because of changes in timing and volume of peak flows (Scibek *et al.*, 2007); this points to the inherent damping in groundwater systems. In the arid San Pedro Basin that flows from Arizona (United States) to the Sonora (Mexico), the principle source of groundwater recharge is over-bank flooding. Despite more frequent high-intensity storms, climate change models predicted a 21 percent decline in annual recharge as a result of a general decline in rainfall and runoff (Serrat-Capdevila, 2007). The work also predicted a decline of 31 percent in riparian vegetation, which might normally moderate over-bank recharge rates. The implication from these studies, though far from universal, is that semi-arid and arid groundwater systems will be highly susceptible to further reductions in rainfall.

4.4.3. Implications for water institutions

The institutional arrangements for water resources management, and particularly for irrigation provision, have been subject to intense scrutiny for their cumulative shortfalls in providing adequate service to users and in safeguarding the sustainability of water resources and environmental values. Climate change will exacerbate water scarcity in existing and newly stressed locations and add additional complexity to already tough issues that traverse large and far-flung communities as well as multiple sectoral interests. As the constraints and requirements in water allocation and the management of water distribution, flood prevention and drought management become sharper, there will be ever greater impetus to find effective answers to institutional problems that have been treated with token and prescriptive 'solutions' to date. Practical and effective communication, representation, delegation and responsibility will be sought and the likelihood that cross-sectoral integration will lead to bureaucratic inertia should be circumvented. Institutional reforms, though widely aired and promoted, take a long time to implement and are closely bound to the prevailing views and understanding of society at large. They need to be flexible, logical and strategic, but water is a highly political subject and it is common for short-term political imperatives and realities to stymie longer-term goals.

A cogent review by Meinzen-Dick (2007) observes that different panaceas for better institutional arrangements have been promoted over the past 30 years to largely reflect the predispositions of their promoters: 1) state intervention and control; 2) user participation and control; and 3) market solutions. Elements of all three approaches are commonly required, defined by different social, economic and political settings that include the resources system and resource unit; the governance system; the users and uses. Rather than base reforms on any one agenda, there is emerging consensus on the need for effectiveness of partnerships between the state, the civil society and the market. In relation to climate change, Meinzen-Dick notes that water scarcity tends to promote better management, but that this rapidly breaks down with more severe scarcity and competition, and can quickly result in organisational breakdown. Robust functional institutions will rely on the continued existence of a viable and manageable resource base in the future.

4.5. REGIONAL IMPACTS

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, and Latin America are likely to be affected most through higher temperatures, more rainfall variability, and greater frequency of extreme events (IPPC, 2007; Kurukulasuriya *et al.*, 2003).

The predicted temperature increases are very likely to lead to reductions in crop yields, particularly in C4 crops, and it would be unwise to expect any net positive effects from higher atmospheric CO_2. Farmers might be able to adapt to temperature increases by changing planting dates, using different varieties, or switching to different crops (Aerts and Droogers, 2004; Droogers and Aerts, 2005). 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 relatively certain, future precipitation rates and patterns within regions are not. Most climate models agree on a global average precipitation increase during the twenty-first century but they do not agree on the spatial patterns of changes in precipitation (Alcamo *et al.*, 2005), and some forecast a trend of declining soil moisture (Dai *et al.*, 2003).

Most climate change models indicate a strengthening of the summer monsoon. In Asia this might increase rainfall by 10 to 20 percent, but more importantly will be accompanied by a dramatic increase in inter-annual variability (Kumar *et al.*, 2006). 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 will become even drier, including the Near East, parts of China, the Mediterranean Basin (southern Europe and North Africa), northeastern Brazil, and west of the Andes in southern South America, West Africa 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 is already unreliable, this might have severe impacts on crop production (Kurukulasuriya *et al.*, 2003) 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 percent of the population could be at risk of hunger in Africa (FAO, 2003). Since Africa presents the greatest cause for concern, and because its limited economic development increases its vulnerability and limits its adaptive capacity, it is useful to elaborate further. In North Africa and along the Sahel margin, rainfalls and runoff are expected to decline, 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 currently home to the majority of the population, are expected to be affected by sea-level rise and flooding. In East Africa and its heartland in the Ethiopian highlands, rainfall and runoff are expected to increase, 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 and the potential for water storage and local use in the Blue Nile Basin could be realized without seriously compromising existing downstream commitments to Egypt. The risk of malaria and other water-related diseases is expected to increase in a more humid, warmer climate.

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

In Asia, water stress will increase, particularly in areas currently supplied with water from Himalayan snow and ice which are expected to witness accellerated mass losses from glaciers and reduction in snow cover. In addition, irrigation demand is expected to increase by 10 percent for every degree rise in temperature in arid and semi-arid East Asia, bringing water scarcity to between 0.12 and 1.2 billion people by 2050. Crop yields are predicted to rise by up to 20 percent in eastern and Southeast Asia, but expected to fall by 30 percent and become more variable in central and southern Asia. Sea-level rise will threaten farming in the major deltas, affecting 3.5–5 million people. The IPCC estimates that a 1 m rise in sea level will result in the flooding of 15-20 000 km^2 in the Mekong delta alone.

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 rainfall will see a natural conversion of jungle to savannah and valuable niches for coffee production will decline.

It is expected that temperature rise will be more pronounced at higher latitudes (IPCC, 2007). This means that crop production will be possible at higher latitudes than is currently the case because of lengthening of possible growing seasons, although this opportunity could be somewhat compromised by decreasing vernalisation, especially in parts of Canada and Russia.

All this has several strategic implications for climate change adaptation that can be summarized as follows:

- Cereal production is expected to fall by between 9 and 11 percent in the developing country regions and Australia/New Zealand, but it is expected to increase by as much as 11 percent in the developed countries, including Russia, thereby reinforcing existing disparities in food production.
- However, the temperature increases that open up 'new' growing seasons for cereals in the higher latitudes and the associated increases in evapotranspiration rates will increase the demand for irrigation.
- Where irrigation is already commonplace and rainfall declines, such as in southern Europe, crop water productivity will have to increase or crop areas will contract.

The arid and semi-arid regions (mid-latitudes) face the double burden of declining and more erratic rainfall, and increases in temperature that surpass the threshold limits for major stable crops. At the margins, land will be retired from agriculture, and elsewhere cropping will be increasingly precarious, even in irrigated areas. National food policy will face tough choices, such as deciding whether to maintain irrigation (and subsidies) to secure subsistence farmers and traditional crops from perennial drought, whether to make better economic use of limited water supplies in reallocating irrigation supply to more secure, and higher potential areas, or to grow high-value (export earning) crops. Many solutions will be possible and all will have particular benefits and downsides.

Elsewhere, in tropical and sub-tropical regions where more rainfall and run-off is expected (southeastern South America, east Africa and Southeast Asia), it will be possible to expand irrigated production, but greater rainfall variability suggests additional water storage facilities will be necessary. If food security is less pressing in these areas, increased water availability may justify and facilitate diversification into cash cropping.

Other parts of the tropics, including places where wetland rice is commonly grown, are expected to become drier (e.g. Gulf of Guinea, Central America, northeastern Brazil). Trends used in AT2015/2030 (FAO, 2003) indicate that the area of wetland rice in these areas would expand (in a constant climate), and if this is to happen under climate change, less water intensive forms of rice irrigation will be needed (alternate wetting and drying or aerobic rice).

Small islands are threatened by climatic and sea-level rise impacts, which are likely to affect most of their inhabitants. Although island populations are small compared with those of the Asian sub-continent, agriculture is important and sustains livelihoods and food supplies; freshwater is sourced from rain, shallow groundwater and freshwater lenses in the surrounding sea. Some 295 Atolls with freshwater lenses have been identified as highly vulnerable and likely to disappear. Agricultural land will also be lost along the coastline, and economic costs without adaptation are predicted to reach 17–18 percent of GNP by 2050 for SRES scenarios B2 and A2 (IPCC, 2007).

Countries with a variety of climates and agro-ecological zones may have the option of relocating agriculture from highly impacted areas, to higher potential areas, providing that there are sufficient land and water resources available.

The variety of situations and the generalization of this section suggest a need to consider impacts and adaptive strategies on a more detailed and local basis.

4.6. IMPACTS AT RIVER BASIN LEVEL: SYSTEMIC CONSIDERATIONS

4.6.1. Introduction

A water management perspective is essential to the analysis and management of the impacts of global warming on agriculture and agricultural water management. Climate change impacts at basin level will integrate considerable spatial variability in all the variables affected by global warming – temperatures, evaporation, rainfall, runoff, and at the river mouth – sea-level rise. The effects in any one place will be moderated by land use and by the hydrological pathways taken through surface and groundwater. The challenges of river basin management will remain essentially as they are now, although the impacts and vulnerabilities of different land units may change, as may the priorities in managing them.

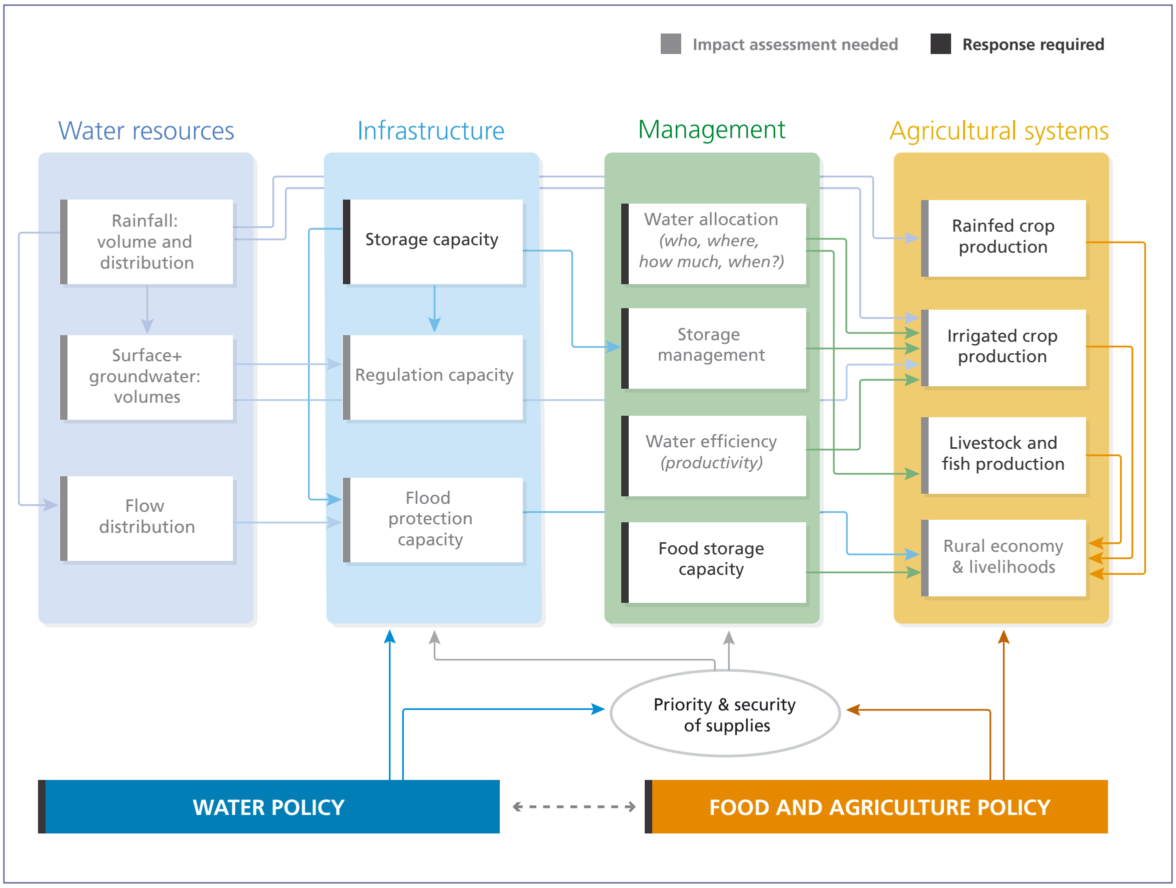
In the United States there are at least five macro regions with substantially different climatic conditions, ranging from the semi-arid west and south-west to the cool temperate east coast. Nationally, precipitation and stream flow will increase from 2050 to 2100 and drought frequency will decline (USDA, 2008). At regional level, runoff will increase in the eastern region, and decline substantially in the interior of the west (Colorado and Great Basin): in between (Missouri and Mississippi), little change is expected. At the same time, the mountain snowpack will continue to melt and decline, with earlier spring snow-melt and associated changes in flow regime. More severe droughts have occurred in the past 2000 years than have been observed in the instrumental record, indicating past variability that exceeds predictions of future systematic change. Some river basins cross the boundaries of these macro-regions. The availability of publicly funded data collected in the United States is extensive, much of it managed by the USGS. It covers an impressive range of situations, and supports and is fed by local intelligence in many different departments. For many developing countries, collecting data is one thing, but making it available to researchers, managers, and policy advisers is another. Data is subjected to close scrutiny when made available to the broad public, and as the connection between cause and effect becomes ever more complex, more sophisticated statistical and analytical techniques will be brought in to play, requiring ever better data quality.

In a long, slow and adaptive process, it will be beneficial if river basin managers can distinguish between ‘natural’ variability and progressive change. Since many other factors (not least land-use change) will be impacting basin hydrology, it will be difficult to determine cause and effect, and at times problematic even to determine trends in data. In many parts of the world, data collection has been one of the first casualties of tighter budgets, and (short-sightedly) of sector reforms. Adaptive management is an intuitive idea, but it is harder to determine practically what to adapt and why, at the appropriate time. Where bureaucratic inertia and conservatism are too entrenched, the time for adaptation may be missed, but over-hasty corrective action is equally likely to have unwanted consequences. Understanding climate change will require not just restoration of data collection but also considerable expansion of spatial and temporal coverage, and also of the types of data to be monitored.

Climate change will impact food production through distinct but linked effects on agriculture and on hydrology, which are summarized in Figure 4.5. Each component implies data collection and analysis. 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 disaggregation the use of higher resolution models and statistical downscaling (Zorita and von Storch, 1999) coupled to scenario analysis that is complemented by risk assessment.

FIGURE 4.5

Elements of water and natural resources management that should be put in place in order to 1) assess climate change impact on agriculture and 2) develop adaptive strategies



There are a number of points that arise from Figure 4.5:

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. Strategic alternatives between food storage and water storage will be one of the key links between agricultural and water resources policy in the future.
3. A system of water accounting (and the supporting hydrology) should be in place to monitor and predict change and additional stress. Water allocation

systems in most developing countries are very ad hoc, which needs attention to detail.

4. Improvement of 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. The increasing importance of establishing effective institutional arrangements for water management, allocation and response thus becomes evident. Such processes take a long time to evolve, and cannot be created overnight.

4.6.2. Glaciers and runoff

The most immediate and large-scale impacts on runoff are likely to be due to reductions in snowmelt and retreat of glaciers (Barnett *et al.*, 2005). Worldwide, measurements have shown glaciers to have been in retreat since 1850, and there are some Chinese historical records indicating that certain areas started to decline some 150 years before (WWF, 2005).

In the Himalaya, summer accumulation glaciers depend on high monsoon precipitation and cool temperatures; the annual mass balance equates to summer mass balance (WWF, 2005). The estimated area of glaciers in the Himalaya in 1978 was 33 200 km^2, equivalent to 17 percent per cent of the total mountain area, with a further 30–40 percent having seasonal snow cover. Surprisingly, the overall contribution to total runoff was estimated to be only 5 percent (WWF, 2005), but winter season low flows are crucially maintained. A longitudinal study using remote sensing and old survey data has recently quantified glacier loss in three large Himalayan River Basins - Chenab, Parbati and Baspa (Kulkarni *et al.*, 2007). Between 1961 and 2007, the total area of 466 glaciers reduced from 2 077 to 1 628 km^2. Using simple relationships between landform and depth, volume was estimated with an estimated error of 15–20 percent, with the estimated loss in volume of 21 percent in 46 years. Small fragmented glaciers are more sensitive to warming, and contributed 38 percent of the volume lost compared with 12 percent from large ones, which are also becoming fragmented.

The science behind glacier melting will receive much attention in the coming years. Glaciers contribute 60 percent of the sediment load from the Karakorum but only 35 percent of mean annual flow at the head of the upper Indus Basin is contributed from glaciers, which cover 17 percent of the mountains (Collins and Hasnain, 1995). Later work has divided the Upper Indus Basin into three zones: the high zone generates temperature-controlled glacial runoff, which is stored and lagged in winter accumulation in the mid-altitude zones, and instantaneous runoff is generated by rainfall in the lower zones. Summer temperatures have been cooling, possibly due to an increase in cloudiness, with broader and more complex interactions between East (ENSO) and West (NAO) climate signals having been identified – the strong relationship between ENSO and the Indian monsoon has been weakening, and it is hypothesized that the Upper Indus Basin is responding to effects of the northern jet stream; NAO is an indicator of this (Fowler and Archer, 2005).

Three runoff-producing regions have been defined for the whole Himalaya (Hannah *et al.*, 2005):

- Low runoff. July–August peak regimes in the central to eastern High Mountains and High Himalaya and the eastern Middle Mountains, where the summer monsoon arrives earliest. Melt water contributes to runoff but topography limits the amount of precipitation.
- Low–intermediate runoff. August–September peak regimes dominate the central Middle Mountains as the result of an extended summer monsoon and substantial groundwater contributions.
- Intermediate–high runoff. Occurs along the Middle Mountain–High Mountain boundary with July–August peaks in western–central areas and marked August peaks at higher elevations in eastern–central and eastern Nepal, reflecting differences in summer monsoon penetration.

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 percent of long-term mean in the Punjab in Pakistan. There is clear evidence of an average warming of 4 °C (1980–2005) and loss of 7 percent 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). Low headwater flows have been attributed to the associated decline in glacier area (YRCC, personal communication, 2004).

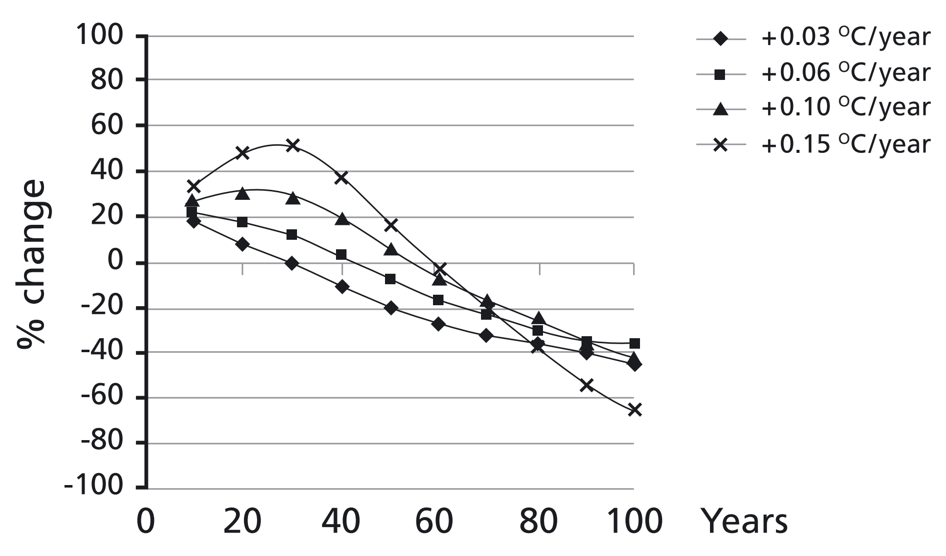
However, the science and understanding behind these changes remains contradictory and is not yet resolved. WWF (2002) contentiously suggested that a global temperature rise of 4 °C would cause melting of all glaciers in the Himalaya, resulting in a long-term decline of 65 percent of mid-summer flows (June-September), and affecting up to 500 million people in the mid and lower Ganges. A later, and more scientific review (WWF, 2005), has estimated that by 2100, runoff from Chinese glaciers will contribute between 1 and 10 10^9 m^3 per year, which is about 0.45 percent of estimated future total runoff.

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 and Collins, 2006). 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 mudflows from the Tien Shan Mountains and new periods of late season melt and mudflows (Raivodhkhoz, Osh, Kyrgizstan, personal communication, 2007).

Given the importance of snowmelt to irrigation supplies throughout the sub-Himalaya (India, Pakistan, Bangladesh, Vietnam and China) and other mountainous regions in the United States (Rocky Mountains) (USDA, 2008), the Andes and 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 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, 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 runoff while temperature mostly changes the timing of the runoff (Barnett *et al.,* 2005). Increasing temperatures lead to earlier runoff in the spring or

FIGURE 4.6
Predicted patterns of Indus flows above Tarbela with changes in snow-melt patterns and volume under climate change (World Bank Pakistan Country Water Assistance Strategy, 2005, quoting Rees and Collins, 2006)



winter and reduced flows in summer and autumn. Furthermore, where temperatures rise such that the melt quantities exceed precipitation, 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. 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. 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. Barnett (2005) suggests that one sixth of the world's population lives in areas that are or will be affected by declining snowmelt and changing hydrographs; one quarter of global GDP is generated in these areas, which include much of North America.

4.6.3. Arid basins

Where water is available – usually in great rivers or in groundwater – irrigation development has been the major structural innovation to securing crop production in arid and semi-arid conditions – notably in China, northern India and Pakistan, Central Asia, western United States and Australia. It is likely that runoff in arid and semi-arid areas will decline, and that groundwater recharge will do likewise. Thus, massive investments made to secure livelihoods and food production will be more vulnerable than at present and require correspondingly better management.

Salinity is a major constraint to cropping in the arid and semi-arid tropics, where rates of evapotranspiration exceed precipitation. Decreasing runoff will have a variety of effects on salinity: dilution flows will reduce, but so may the 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, any declining salt mobilisation will be offset by more limited leaching resulting from lower rainfall and reduced 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.*, 2008).

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, abstraction of groundwater can result in saline intrusion, which would require leaching and therefore additional water. However, 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 runoff decreases and evapotranspiration increases. Again, it may be possible to deal with this either by means of salt-tolerant trees and crops, or where there are marked flood seasons, by growing wetland rice as a means 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, there has been limited assessment of salinity effects resulting from climate change and this has been based on scenario analysis coupled to soil-crop-water modelling in countries such as Iran.

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 currently extreme events will increase dramatically (IPCC, 2007) 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.

Sub-Saharan Africa and parts of 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, generally does not have the luxury of a 'reliable and steady' Himalayan type of water source – that which buffers against inter-annual variability in rainfall, and 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 for the enormous number of people already dependent on irrigation, and more so for the food surplus currently 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, 2006; Dinar and Xepapadeas, 1998).

Changing rainfall patterns affect both the seasonal availability and the manageability of water. By 2070 there will be less water available in Central America, southwestern South America, northeastern Brazil, the Eastern United States, West Africa, southern Africa, South Europe and the Mediterranean Basin, the Near East and Australia. Furthermore, supplies everywhere will vary more greatly than at present. Even in some of the areas where climate change is expected to result in greater run-off (much of the Amazon Basin, central and eastern United States, central and East Africa, South Asia, parts of Central Asia and Australia (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 to match the seasonal crop water requirements. 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 can result in reduced availability.

There are several options available for addressing food security or other factors that result in reduced or unmanageable supplies, or changed patterns of supply. If demand cannot be restrained, supply-side options include surface or aquifer storage or afforestation and forest management to stabilize more limited supplies.

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 be increasingly expensive, involve difficult ground conditions and have steep stage-discharge characteristics and therefore high evaporation and seepage losses. The use of multiple storage structures across large basins as opposed to single large dams may offer alternative benefits and distribution of risk, but when taken to scale, for example, the tank systems in Peninsular India, the aggregate impact can still bring a system to its hydrological limit (Batchelor *et al.,* 2005).

Another challenge associated with surface storage concerns the need for increasingly sophisticated spillways, probably with variable capacity and elevation, in order to deal with increasingly intense storm events. Modern technology, such as remote sensing, gives greater flexibility in storage management, providing timely and quantitative information on: 1) how much water flow there is in the river basin; 2) the probability attached to that flow; and 3) when it will arrive at its destination. Overall, conjunctive management of dam storage and the use of near-real-time flow data can improve flood attenuation and optimize release rules to benefit hydropower generation and downstream agricultural uses.

Finally, where water rights are in operation, there is the possibility of establishing water banks such as those pioneered by sugar growers in KwaZulu-Natal in South Africa. There, rights-in-use that are not required at a certain time can be kept for later use by the rights holder (seasonal or trans-seasonal use). Such facilities are small, generally community driven and may find good application where water management is decentralized. The use of 'carryover' is also practised in large systems in Australia. Carryover volumes are typically restricted to between 10 and 25 percent of entitlement and are reset to zero if the dam either fills or empties. A more ambitious method, known as continuous accounting, is practiced in the Namoi River valley – where the entitlement is managed as a share of storage by the rights holder and released 'whenever' they request, allowing full carryover if so desired.

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 for cultivation of staple crops; the aquifers should also be organized 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 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 utilized.

4.6.4. Recycling water

Supply-side problems can also be partially addressed by greater reuse of agricultural run-off, or by the use of urban wastewater. In the Nile River system, field irrigation efficiencies are low, particularly in the delta, but return flows and drainage are substantially reused, resulting in high efficiency of water use at the basin scale. One of the major challenges for water managers in many developing country basins lies in accounting properly for existing levels of recycling between upstream and downstream use.

An informal water market operates along the Jatilahur River in Indonesia, where savings from group rights-in-use are left in the river for high-value potable water supplies further downstream, while facilitating an increase in capture fishery yield along the way. Risk of accumulating agrochemicals must be managed: chemical treatment would be excessively expensive, whereas artificial wetlands could do the job effectively, if at the cost of some extra evaporation loss.

The continued migration from rural areas to the cities and their own internal growth will generate much larger quantities of wastewater than are available to farmers at present. Since potable and sanitation water supplies will have highest priority, urban wastewater will become a highly reliable secondary source of irrigation, whether treated or not. The Werribee Irrigation District, a horticultural area southwest of Melbourne in Australia, has experienced nearly 11 years of drought. During this time, groundwater use was initially increased and then banned as saline intrusion further degraded the declining coastal aquifer. Channel water has been very limited and its salinity has steadily increased to the point where almost no surface water is supplied from local sources. This has been substituted by treated urban wastewater (90 percent of total supply) from Melbourne, purchased on a rolling two-year contract. Interestingly it has a much higher level of supply security than the historical average for the surface water it replaces (Southern Rural Water, 2009).

Urban wastewater by definition also needs to be treated 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 flowers or fodders, does not need to be treated to the same level as water applied to salad greens or root vegetables. The decision is usually made on economic grounds, although in many parts of the world, wastewater is used without even primary treatment (settling). Urban wastewater, including storm run-off, will be more widely used for peri-urban irrigation, for mostly high-value fruits and vegetables. Future developments in wastewater treatment will require adapting to provide adequately treated and affordable wastewater for agricultural use.

4.6.5. Land-use change in river basins – afforestation and sediment management

Global land use has changed rapidly since 1950, and further changes are expected. Despite major efforts to replant forests in China, India, the United States and other countries, net forest area continues to decline alarmingly (at a rate of more than 50 000 km^2/year). Deforestation rates are highest in South America and Africa, mostly to clear land for grazing and cropping. Land use and topography are important factors governing evaporative loss, runoff, groundwater recharge and water quality.

Under global warming, land-use change is likely to be significant, as the boundaries and nature of agro-ecological zones differentiate and systems morph at the margins (see Ch. 5). Crop patterns will be adapted to changing conditions and, where land pressure is high (probably a large area), growers will try to extract livelihoods from marginal and fragile lands both in the wetter tropics and in the semi-arid and arid zones.

Afforestation has the potential to not only attenuate flood peaks and maintain base flows but also sequester carbon while contributing to or maintaining biodiversity. However, well-established tree stands mobilize soil moisture from deeper soil horizons and the hydrological impact of afforestation can also include significant reductions of base flow (Calder, 2004), even as they stabilise it. In some cases, the many 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 deforestation, also lose water, either to seepage (which can often be recaptured as groundwater) or to evaporation. Reservoirs may contribute to GHG emissions as a 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 is severely compromised by accumulation of sediment, for example, the Tarbela Dam on the Indus in Pakistan and the Aswan Dam on the Nile. Sediment loads further upstream on the Blue Nile are impacting the operation of large irrigation schemes in Sudan. Long-term land-use management strategies will be more complex, with multiple objectives in mitigating greenhouse gas emissions and maintaining productive agriculture, healthy ecosystems and in moderating runoff. Land-use management will be closely linked to water storage strategies, both for surface and groundwater, and in protecting existing infrastructure investment from sedimentation.

4.6.6. Basins with increasing runoff – managing deltas

Increased annual runoff is predicted in the higher latitudes and in the tropics, 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 – the Yellow River, the Yangtze Delta and Bangladesh are prime examples. Millions have died or been 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 diking and dam construction, have been widely used, sometimes at high human and financial cost, to protect agriculture and habitation. As physical measures are still susceptible to events of probability lower 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, 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 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: this is mostly agricultural land with relatively low population density, although populations tend to rise rapidly in flood plains protected by structural measures (Red River and Yangtze Deltas, Yellow River, and the Mississippi, for example).

With increasing flood frequency and severity, these two broad trends are likely to continue, especially in transition countries with rapidly developing high capital value infrastructure. 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, not least in irrigated systems within the humid tropics and deltas.

4.6.7. The susceptibility of wetlands to climate change

For people living in sensitive wetland areas, food security depends on the dynamic relationship between social and environmental variables beyond their control. Inland fisheries are 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. 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, has been neglected too often in upstream water management.

Irrigation and associated water storages may provide additional opportunities for both capture fisheries and aquaculture, but these alternatives are often poor substitutes for the loss of environmental services in natural wetlands.

The lifecycles of fish and other aquatic organisms are closely adapted to the rhythmic rise and fall of 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. Flash floods may wash juvenile fish and eggs out of their normal habitats, thereby increasing chances of starvation or predation. Prolonged periods of drought will reduce available fish habitat, especially during the dry season.

Although rising water temperatures may benefit the farming of tropical species in colder climates, capture fisheries will experience stress from increased temperature 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 percent (Reilly, 2003). In the Mekong, home to the most significant inland fisheries in the world, 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 (MDB), 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 high impact in semi-arid and arid Australia. Reduced rainfall and higher evapotranspiration rates are likely to cause dramatic reductions in runoff by 2070 – 20 percent overall in the basin (CSIRO, 2007) and up to 40 percent in some sub-basins, such as those in NW Victoria (DSE, 2006). 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 the MDB is presented in Box 4.1.

4.7. FOOD SECURITY AND ENVIRONMENT LINKAGES

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

- that currently lie at the edge of their climate tolerance and where that tolerance will be further eroded;

BOX 4.1

Climate change in the 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 cities are likely to be significantly affected.

Adaptive capacity: Adaptive capacity of the agricultural systems is high, although it will take planning and some time to realise. There is considerable scope to adapt to reduced 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 percent 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.

Source: The Allen Consulting Group, 2005

- that are already stressed as a result of economic, social or biophysical condition (e.g. threatened by salinization 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 (Allen Consulting Group, 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 excessive abstractions impact biodiversity associated with natural flow regimes, including economically important capture-fisheries. Less obvious and often ignored is the risk that stored water will be released and appear as dry season flows when local eco-systems have adapted to dry riverbeds and wetlands. Such flow reversal is one of the main negative in-stream impacts along the tributaries of the Murray-Darling System.

While increasing attention is being paid to the maintenance of environmental stream flows, or reserve flows as they are called under South African Water Law, the importance of flood peaks is ignored. Storage facilities that capture or over-attenuate low and medium return period flood peaks can seriously disrupt food chains, especially important marine food chains that depend on reliable annual flood peaks to bring fresh sediment into the brackish habitats in estuaries and along the coastline. Interestingly, many dams do little to attenuate extreme floods and so the environmental values derived from them are often preserved. In addition, dams capture crucial sediments, thereby reducing the seasonal nutritional value of the overall river regime in sediment-dependent aquatic/marine ecosystems.

Elsewhere, the sustainability of other kinds of ecosystem depends on sediment-free waters, including 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 complex and often economically significant ecosystems. Australia's Great Barrier Reef is suffering from the combined effects of agricultural runoff (N and P fertilizer) from irrigated and rainfed farming, in addition to suspended matter from rainfed agriculture (WWF, 2001).

All these risks can be expected to both expand and intensify as new irrigation and storage facilities are built in response to climate change.

4.8. CLIMATE CHANGE IMPACT TYPOLOGY

Following on from the impact pathways outlined in Figure 4.1, 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 4.2). We propose a number of situations based largely on agro-ecological and climate impact factors. This typology is different from the one proposed for irrigation investment in the Comprehensive Assessment (Table 3.6), which emphasizes scale, economic setting 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.

The typology could be refined in a number of ways, and it makes sense to do so when considering specific locations within a country or region. Since any specific location will likely fall within one agro-ecological zone, the most obvious candidates for refining the typology are the extent and nature of water resources development. The existing level of water development is an important factor that could be represented in a second level of the typology. The current literature on adaptation contains many references to the benefits of increasing irrigation efficiency (usually not defined) as a means of saving water, with little or no reference to basin-level water use and the possibility of making real net water savings at basin level.

A third level of the typology could (in nearly all categories) be extended to groundwater resource characteristics and use. Groundwater becomes an increasingly attractive mode of storage under climate change scenarios – to minimize infrastructure costs, maximize flexibility, and manage both short- and long-term variability in surface water supplies.

Examples of where groundwater system characteristics are distinct include the dominant processes of recharge, for example whether from flooding, seasonal saturation in rainfall periods, or from snowmelt. In arid areas groundwater recharge is often dominated by river flows or recharge from lakes or other forms of surface-groundwater interaction with complex shallow to deep groundwater connection and disconnection (as in the Murray-Darling Basin). In Deltas, net behaviour is dependent in the balance of inflow patterns, sea-level variation, and water abstraction patterns from the shallow 'groundwater' and from stream flow. The geology and parent material in different locations tends to determine whether recharge and groundwater cycling is 'fast' or slow, which also has major implications for management, restoration and adaptation.

The typology somewhat neglects small-scale and traditional systems within humid, arid and semi-arid conditions. Eight hundred million people are estimated to be involved in urban and peri-urban agriculture with 200 million producing vegetables,

TABLE 4.2

Typology of climate change impacts on water management in major agricultural systems

System	Current status	Climate change drivers	Vulnerability	Adaptability	Response options
1 Snowmelt systems					
Indus System	Highly developed, water scarcity emerging.Sediment and salinity constraints	20 year increasing flows followed by substantial reductions in surface water and groundwater recharge. Changed seasonality of runoff and peak flows. More rainfall in place of snow. Increased peak flows and flooding. Increased salinity. Declining productivity in places	Very high (run of river): medium high (dams)	Limited room for manoeuvre (all infrastructure already built)	Water supply management: Increased water storage and drainage; Improved reservoir operation; Change in crop and land use; Improved soil management; Water demand management including groundwater management and salinity control
Ganges Brahamaputra	High potential for groundwater, established water quality problems. Low productivity		High (falling groundwater tables)	Medium (still possibilities for groundwater development)	
Northern China	Extreme water scarcity and high productivity		High (global implications, high food demand with great influence on prices)	Medium (adaptability is increasing due to increasing wealth)	
Red and Mekong	High productivity, high flood risk, water quality		Medium	Medium	
Colorado	Water scarcity, salinity		Low	Medium: excessive pressure on resources	
2 Deltas					
Ganges Brahmaputra	Densely populated. Shallow groundwater, extensively used. Flood adaptation possible; low productivity	Rising sea level. Storm surges, and infrastructure damage. Higher frequency of cyclones (E/SE Asia); Saline intrusion in groundwater and rivers; Increased flood frequency. Potential increase in groundwater recharge	Very high (flood, cyclones)	Poor except salinity	Minimize infrastructure development; Conjunctive use of surface water and groundwater; Manage coastal areas
Nile River	Delta highly dependent on runoff and Aswan Storage – possibly to upstream development		High (population pressure)	Medium	
Yellow River	Severe water scarcity		High	Low	
Red River	Currently adapted but expensive pumped irrigation and drainage		Medium	High except salinity	
Mekong	Adapted groundwater use in delta - sensitive to upstream development		High	Medium	
3 Semi-arid / arid Tropics: limited snowmelt / limited groundwater					
Monsoonal: Indian sub continent	Low productivity. Overdeveloped basin (surface water and groundwater)	Increased rainfall. Increased rainfall variability. Increase drought and flooding. Higher temperature	High	Low (surface irrigation); Medium (groundwater irrigation)	Storage dilemma; Increase groundwater recharge and use; higher value agriculture (Australia)
Non monsoonal: sub-Saharan Africa	Poor soils; Flashy systems; over-allocation of water and population pressure in places. Widespread food insecurity	Increased rainfall variability. Increase frequency of droughts and flooding. Lower rainfall, higher temperature. Decreasing runoff	Very high. Declining yields in rainfed systems. Increased volatility of production	Low	
Non monsoonal: Southern and Western Australia	Flashy systems; overallocation of water; competition from other sectors		High	Low	

TABLE 4.2 (*CONTINUED*)

Typology of climate change impacts on water management in major agricultural systems

System	Current status	Climate change drivers	Vulnerability	Adaptability	Response options
4 Humid Tropics					
Rice: Southeastern Asia	Surface irrigation. High productivity but stagnating	Increased rainfall. Marginally increased temperatures. Increased rainfall variability and occurrence of droughts and floods	High	Medium	Increased storage for second and third season; Drought and flood insurances; crop diversification
Rice: Southern China	Conjunctive use of surface water and groundwater. Low output compared to northern China		High	Medium	
Rice: Northern Australia	Fragile ecology		Low	High	
Non-rice - surface or groundwater irrigation			Medium	Medium	
5 Temperate areas					
Northern Europe	High value agriculture and pasture	Increased rainfall; Longer growing seasons; Increased productivity	Surface irrigation: medium; groundwater irrigation: low	Surface irrigation: low; groundwater irrigation: high	Potential for new development. Storage development; Drainage
Northern America	Cereal cropping; groundwater irrigation	Reduced runoff, increased water stress	Medium	Medium	Increased productivity and outputs; Limited options for storage
6 Mediterranean					
Southern Europe	Italy, Spain,Greece	Significantly lower rainfall and higher temperatures, increased water stress, decreased runoff	Medium	Low	Localised irrigation, transfer to other sectors
Northern Africa	High water scarcity		High	Low	Localised irrigation, supplementary irrigation
West Asia	Fertile crescent, increasing water scarcity	Loss of groundwater reserves	Low	Low	Integrated water resources management
7 Small islands					
Small islands	Fragile ecosystems; groundwater depletion	Sea water rise; saltwater intrusion; increased requency of cyclones and hurricanes	High	Variable	Groundwater depletion control; Water demand management

fruit, meat, dairy and fish for market (Padgham, 2009). In particular contexts, more attention could be paid to the following niches that occur within the broader categories:

1. **Garden irrigation systems:** for fruits, vegetables and (possibly) fodders. These are ubiquitous in Southeast, East and Central Asia, and are common in many parts of India. They are perhaps the most important irrigation niche in Africa. Generally they are ‘off the radar’ in terms of public policy and monitoring. In many countries they are part of an informal economy.

2. **Peri-urban and urban irrigation systems** (more formal than gardens); using fresh water or urban wastewater. They have worldwide importance, acknowledged economic and nutritional benefits, and are potential (often cited) public health hazards.
3. **Wetland agriculture:** significant in Africa and the poorest countries in Asia (Laos, Cambodia).
4. **Intensive horticulture:** shade-house and greenhouse production systems; orchards and vineyards. These tend to be at the forefront of technology, where the value of production and associated risk justify higher levels of investment in technologies such as drip irrigation, fertigation, and automatic control of watering based on soil moisture and plant leaf potentials. However, their significance in terms of potential impacts in reducing water use and mitigating GHGs are limited by their small scale and small proportion of total agricultural water use.

All four niches require reliable water supplies: gardens, peri-urban systems and intensive horticulture tend to be market oriented, providing high-value crops with relatively high levels in investment in capital, inputs and/or labour. Although they will be especially sensitive to the hydrological impacts of climate change, they are also likely to witness early innovation and adaptation, and growers have strong motivation to secure scarce water supplies, through a variety of means. Wetland agriculture has typically been undervalued and ignored in the development and management of river basins, often resulting in a loss or diminution in the livelihoods of the poorest. The amplifying effect of climate change in water-scarce areas will pose higher levels of risk to this group. Groundwater use is already high in many of these niches and continued development will exert considerable and difficult-to-govern pressure on aquifers. The institutional, monitoring and compliance issues related to water allocation and management will typically be complex and challenging to administer.

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 the variability of precipitation, which together with the loss of mountain snow packs, decreases the security provided by irrigation (IPCC, 2001a). 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, in particular between irrigation 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 (Rockström *et al.*, 2001), if there is no rain, then there can be no agriculture, thus 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 below potential in many regions, notably the Indian sub-continent; significant productivity increases can be expected in both yield and water use efficiency by better management of all farm inputs and with optimal use of nitrogen fertilizer (Nangia *et al.*, 2008). Irrigated agriculture, even with declining water availability, generally offers a more secure risk environment for more intensive management.

Projections developed in the Comprehensive Assessment (CA, 2007, Ch. 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 is 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 as snow at higher elevations. This effect is already causing peak runoff to occur earlier in the year in snow-fed rivers such as the Columbia in the western United States and is reducing summertime flows, when demand for irrigation is the greatest. This loss of natural storage has powerful negative implications for extensive irrigated areas that depend on snow and glacier-fed rivers for their water supply, such as the vast Indo-Gangetic Plain and large areas of northern China. At the same time, evaporation losses from 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 through 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 as 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 sub-region is a case in point, as a large share of the world's irrigation depends on 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. 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 the greatest productivity is achieved through concentrated management or diffuse, low intensity investment, needs to be determined: 1) for specific locations, 2) with techniques that increase certainty in the predicted impacts, and 3) with good consideration of the environmental externalities created by each option.